

# U.S.-Iran Symposium on Resilient Cities

June 16-18, 2014

Irvine, California



THE UNIVERSITY  
OF ARIZONA



NATIONAL ACADEMY  
OF SCIENCES



Sharif University  
of Technology

The U.S.-Iran Symposium on Resilient Cities was held in Irvine, CA on June 16-18, 2014. Experts in urban planning and the design and maintenance of infrastructure systems including water, buildings, transportation, communications and social and health services from Iran and the United States gathered to share their knowledge and visions for developing resilient cities. The Symposium's goal was to contribute to the development of an improved roadmap for collaboration among national and international specialists concerned with the sustainability and resiliency of cities.

### **Symposium Committee**

Kevin Lansey, Co-Chairman

Hassan Vafai, Co-Chairman

David Quanrud, Executive Editor and Conference Coordinator

Therese Lane, Senior Business Manager

Ivy Hasman and Sierra Lindsay, Graphic design and preparation of Proceedings

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# Preface

## 1. THE ORIGINS OF THE NOTION OF RESILIENCE AND RESILIENT CITIES

The term resilience was introduced into the English language in the early 17th Century from the Latin verb *resilire*, meaning to rebound or recoil. In 1973, Crawford Holling first introduced the concept of resilience to ecology and the environment [1]. The concept of resilience now increasingly appears in scientific articles, covering topics from psychology to management and strategy.

Rapid urbanization in the world from 28.3% in 1950 to 50% in 2010 [2], their environmental impacts in multiple spatial scales and their vulnerability to natural hazards and risks has brought the notion of resilient cities to the forefront. The study of urban resilience and planning began in earnest in the late 1990s [3]. The concept and topic of resilient cities was first introduced by Godschalk [4] and Pickett et al. [5]. The main focus of early studies was on physical and infrastructure improvements to mitigate impacts of external changes and disturbances [6] and responding actively and positively to risks [7].

## 2. DEFINITIONS OF RESILIENCE AND RESILIENT CITIES

Holling originally proposed the concept of resilience as a descriptive ecological term [8,9]. In the context of ecology, resilience is referred to as a basic capacity of an ecosystem to maintain desirable services when confronting environmental changes and human exploitation [10]. In another definition, resilience is the capacity of ecological-social systems to minimize disorder from disturbances and maintain the feedbacks, processes and necessary inherent structures of the system [11].

Holling [12] described urban resilience as the ability of a city to absorb disturbance while maintaining its functions and structures. This is similar to ecological resilience and does not address the ability to recover from a loss of function or change in the face of a disturbance. Lu and Stead [6] add this property and resilience as a system's resistance to change and recovery from it. That is, resilience can be seen as minimizing disturbances (or change) through actions to prepare for and respond to acute and chronic disturbances. It represents an on-going process, a time-scale of reshaping, reorganizing and developing new adaptive strategies [6].

Based on resilience thinking, approaches to affect the urban environment have evolved from static protective-conservative to continuous, systemic, cross-linked and dynamic [13]. In cities and urban regions, new planning strategies intend to avoid structural changing, fragmenting, and isolating natural habitats [14]; hydrological system failures [15]; and changes in the energy flow and food cycles [16]. All of these conditions lead to lower resilience and make urban systems more vulnerable. By addressing the shocks (earthquakes, fires, floods, etc.) and stresses (inefficient public transportation system; endemic violence; or chronic food and water shortages), a city becomes more adaptable and responsive to adverse events and can better deliver basic functions to its populace.

In recent years, substantial organizational efforts have been made towards promoting Resilient Cities. These efforts include the selection of 100 Resilient Cities pioneered by The Rockefeller Foundation, the Annual Global Forum on Urban Resilience and Adaptation (ICLEI), the Making Cities Resilient: 'My City is getting ready!' campaign by The United Nations Office for Disaster Risk Reduction (UNISDR), and The Center for Resilient Cities.

### **3. THE U.S.-IRAN SYMPOSIUM ON RESILIENT CITIES**

Iran and the U.S. share common issues related to community development and urban planning. The similarity is particularly sharp between the US southwest and Iran with its multiple large cities, limited water supply, transportation issues, high temperatures and heat island effects, and air pollution potential from natural and man-made sources. As such, to promote science diplomacy and improve understanding of this important topic and its breadth, the Symposium on Resilient Cities was held on 16-18 June, 2014 in Irvine, California, USA. The Symposium was organized by the University of Arizona, National Academy of Sciences and Sharif University of Technology and attended by scientists from universities in the United States and Iran.

The goal of the U.S.-Iran Symposium on Resilient Cities was to gather experts in the various fields of resilient cities to discuss and inform on the important aspects of this issue based on experiences in the two countries.

### **4. RESEARCH FIELDS OF RESILIENT CITIES**

The scientific committee of the U.S. Iran Symposium on Resilient Cities, after several meetings, decided to break down issues of Resilient Cities to three main areas as follows:

- Development of resilient cities

The focus of this portion of the symposium was on strategies and policies to plan and attain a resilient community. Presentation topics included maintaining the diversity of ecosystem services that improve the urban landscape, short and long term policy development to enhance community resilience, and approaches to urban planning and assessment.

- Atmosphere of resilient cities

At the core of a resilient community is a social fabric for individuals and communities to thrive. This atmosphere of well-being and security relates to both the individual and society. Talks in this area ranged from developing and maintaining social capital such as institutions and social networks to aesthetics, diversity of social interactions, and economic opportunities and resources.

- Utilities of resilient cities

The foundation of resilient cities is the ability to provide services and resources through physical infrastructure. Discussions in these sessions covered innovations in lifeline infrastructures through enhanced knowledge of sources of internal and external disturbances, improvements to gain robustness against failure, and preparation to respond to and recover from natural disasters.

### **5. WHAT WE LEARNED FROM THE SYMPOSIUM ON RESILIENT CITIES**

Overall, the content of the Symposium was highly appreciated by the participants. The purpose, results and outcomes were regarded as relevant and meaningful. In particular, the broad scope of the presented topics and fields reinforced the need for interdisciplinary thinking and collaboration to solve these complex problems. If the notion of resilient cities is to move from a scientific trend and buzzword to lasting practical strategies, resilience requires proper, formal, and agreed upon definitions and indicators. Further, participating scientists and engineers agreed that these universal problems need international solutions. The Symposium focused on the following:

- Developing integrated metrics to measure resiliency of urban regions.
- Emphasizing multidisciplinary studies incorporating social, economic, cultural, environmental and spatial dimensions of the urban environment.

- Developing mitigation and adaptation strategies such as reducing greenhouse gas emissions, addressing climate change, renewable energy, and improving urban structures.

Over the three days, in addition to formal presentations, three breakout sessions were convened on the aspects of resilient cities noted above. Notes from those sessions are included in these proceedings.

## **6. ACKNOWLEDGEMENTS**

We are grateful to the persons and institutions that have made this symposium and the publication of these proceedings possible. In particular, we would like to thank: the Richard Lounsbery Foundation, the International Visitors Leadership Program, the United States National Academy of Sciences and the United States National Academy of Engineering.

Further, we express our thanks to Mr. Maxmillian Angerholzer of the Richard Lounsbery Foundation and Mr. Larry Moody of the International Visitors Leadership Program for their dedication and devotion to the promotion of science. We also express thanks to Mr. Glenn Schweitzer of the United States National Academy of Sciences for his tireless efforts to enhance and promote Science Diplomacy.

We also thank Dr. Masoud Tajrishi, Vice Chancellor of Research at Sharif University of Technology, Dr. Soroosh Sorooshian of University of California at Irvine, Ms. Jaqueline Martin of the U.S. National Academy of Sciences, and the staff at the Arnold and Mabel Beckman Center for their contributions towards the success of the Symposium.

In addition, we acknowledge the participants for joining us in Irvine to present their research results, participate in a wide ranging discussion and provide the papers making up this document; their scientific contributions were the basis for the meeting and their enthusiasm enhanced the quality of the meeting.

We are indebted to Dr. David Quanrud of the University of Arizona for his excellent job as Executive Editor and for leading the on-site symposium coordination.

Finally, our special thanks to the staff of the University of Arizona Department of Civil Engineering and Engineering Mechanics, in particular Ms. Therese Lane, Senior Business Manager, and Ms. Ivy Hasman and Ms. Sierra Lindsay for their assistance in the organization of the Symposium and preparation of the proceedings.

Kevin Lansey, Co-Chairman  
Hassan Vafai, Co-Chairman  
June, 2015

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Attendees of the U.S.-Iran Symposium on Resilient Cities on Monday, June 16, 2014.

## **BREAKOUT SESSION: INFRASTRUCTURE AND UTILITIES**

The group identified a set of questions/issues that should be addressed to move the field ahead:

### *Fundamental concepts*

How can we add redundancy/resilience/reliability to systems? – Physical, planning, community inputs. Interdependence between infrastructures is critical and should be treated as a system of systems

### *SMART systems/data*

Is a SMART infrastructure resilient? Contributes to demand side management and long term sustainability. Are they more fragile (likely to fail)?

### *Disturbances*

What failures/disturbances should be considered and how does their consideration affect resilience and reliability?

Disturbance types are both shock (acute - earthquake, hurricane) and slow and progressive (chronic – climate change, population growth).

Are they different or treated separately/independently?

### *Measuring properties*

How to measure resilience/sustainability and its related objectives? What indices/metrics are available?

### *Decision making/tradeoffs*

What is the balance of cost/(resilience/robustness) and what are the tradeoffs between \$/resilience and other social objectives?

Who makes decisions/how to represent tradeoffs?

### *Knowledge/training*

Are lessons transferable given differences between locations with respect to geography and human conditions?

### *Education is needed*

- On resilience/robustness
- For engineers and the general public

## **BREAKOUT SESSION: URBAN PLANNING AND SOCIAL ASPECTS**

### *Present Conditions*

1. Cities have become the major type of settlements the new century. More than 60 percent of people live in cities around globe
2. Cities are complex systems: system of systems, including social, economic, natural and man-made (physical) systems
3. Rapid growth of cities, during recent decades, has increased the interdependencies of its subsystems
4. Changing conditions have increased the risk of hazards for cities.
5. Natural and man-made hazards have different processes and impacts on cities.



6. Considering the risk of natural hazards for cities, in a global scale, we are in a condition of uncertainty in prediction of hazards, inefficiency in prevention of vulnerabilities and shortage in mitigation of risks.
7. Resilience is a term with different meanings for different disciplines.

#### *What to Do*

1. Approach
  - a. Adopting a holistic approach for risk reduction in cities, based on a systemic view.
  - b. Finding common grounds for defining resiliency.
  - c. Definition of resiliency by considering these aspects: resilience of what, to what, for whom?
  - d. Collaboration between different disciplines dealing with various aspects of city resilience.
  - e. Inclusion of social science perspectives; urban geography, behavior sciences, psychology, etc. in resilience studies.
2. Research
  - a. Encouraging interdisciplinary and multidisciplinary research for resilient cities.
  - b. Ground truthing of broad models, assessments and hypothesized functions; for example: links between ecological structure and function, testing landscape ecology principles, testing efficacy and scaling of green infrastructure and restoration
  - c. Study on indices for measuring resilience in different aspects and levels of urban systems.
3. Education
  - a. Developing education for risk reduction and resiliency in different levels.

#### **BREAKOUT SESSION: EARTHQUAKE AND CLIMATE**

1. Need Indices
  - a. Find quantitative measures of resiliency
  - b. Resiliency multi-dimensional
  - c. Distinguish between daily steady state (climate) and uncertain extreme events (EQ)
  - d. Integrate human impact with engineering parameters for resilience
2. Educating Citizens
  - a. change behavior - local activities effect global
  - b. public awareness and early warning
  - c. need government to consider the consequences up front ‘
3. Multidisciplinary/Interdisciplinary
  - a. Resilience will not happen without cooperation of different fields
  - b. takes time, need a common language
  - c. Sustainability – gradient; Resilience – system state characteristic
  - d. Integrate concepts resilience and sustainability - health effects with planning; recycling of debris from construction sites
4. Products
  - a. Joint research efforts with a paper as a tangible product
  - b. Work on a paper - get visibility

# Event Program

## Monday, June 16

8:00 – 9:00 a.m.

*Registration*

9:00 – 10:30 a.m.

*Opening Session*

**Welcoming and Opening Remarks** – Dr. Kevin Lansey,  
University of Arizona

**U.S.-Iran Bilateral Scientific Collaborations** – Dr. Hassan Vafai,  
University of Arizona

**Keynote Address: Simulating and Visualizing Urban  
Sustainability** – Dr. Paul Waddell, University of California at  
Berkeley

### **General Session I — Development of Resilient Cities**

Moderator — Dr. Kevin Lansey

11:00 – 11:20 a.m.

**Urban Resilience and Peace-Building in Cities of Conflict** – Dr.  
Scott Bollens, University of California at Irvine

11:20 – 11:40 a.m.

**Towards Resilient and Sustainable Cities: A Conceptual  
Framework** – Dr. Manouchehr Tabibian, University of Tehran

11:40 – 12:00 p.m.

**Community Resilience through Maintenance of Sense of  
Community: Some Lessons from Disaster Affected Cities in Iran**  
– Dr. Zahra Ahari, Shahid Beheshti University

12:00 – 12:20 p.m.

**Post-Disaster Blight Flight: Demonstrating the Merit of Creating  
a Composite Blight Index Map for Your City** – Dr. Sudha Arlikatti,  
University of North Texas

12:20 – 1:30 p.m.

*Lunch*

### **General Session II — Development of Resilient Cities**

Moderator — Dr. Arsalan Ghahramani

1:30 – 1:50 p.m.

**The Complexities of Establishing Seismic Performance  
Objectives for Building Structures** – Dr. Farzad Naeim, John A.  
Martin & Associates

1:50 – 2:10 p.m.

**From Endurance Time to Value-Based Seismic Design of  
Structures** – Dr. Homayoon Esmailpur Estekanchi, Sharif University  
of Technology

2:10 – 2:30 p.m.

**Enhancing Resiliency through Building Code Enforcement** – Dr.  
Ifa Kashefi, City of Los Angeles Department of Building and Safety

- 2:30 – 2:50 p.m. **Latest Development in Iranian Building Codes and Guidelines to Achieve Safer and More Resilient Cities** – Dr. Mohammad Taghi Kazemi, Sharif university of Technology
- 2:50 – 3:10 p.m. **New Construction for Resilient Cities: The Argument for Low Damage and Damage Free Building Structures in the 21<sup>st</sup> Century** – Dr. Robert Fleischman, University of Arizona
- 3:10 – 3:40 p.m. *Break*
- General Session III — Atmosphere of Resilient Cities**  
Moderator — Dr. Soroosh Sorooshian
- 3:40 – 4:00 p.m. **Construction Waste Management: An Effective Approach to Sustainable Development** – Dr. Mohammad Mehdi Mortaheb, Sharif University of Technology
- 4:00 – 4:20 p.m. **Data Rich Advanced Infrastructure Systems** – Dr. Lucio Soibelman, University of Southern California
- 4:20 – 4:40 p.m. **Urban Ecosystems Services as a Foundation for Planning and Designing Resilient Cities** – Dr. Mitchell Pavao-Zuckerman, University of Arizona
- 4:40 – 5:00 p.m. **Application of Resilience Thinking to Evaluate the Urban Environments: A Case Study of Tehran, Iran** – Dr. Parastoo Parivar, University of Tehran

## Tuesday, June 17

- General Session IV — Atmosphere of Resilient Cities**  
Moderator — Dr. Abbas Aliakbari Bidokhti
- 8:30 – 8:50 a.m. **CyberShake: Physics-Based Urban Seismic Hazard Maps for Los Angeles** – Dr. Thomas Jordan, University of Southern California
- 8:50 – 9:10 a.m. **Resilient Cities: A Key Solution to Safeguard the Environment** – Dr. Yasaman Aghajani, Tehran University of Medical Sciences
- 9:10 – 9:30 a.m. **Resilience Approach Toward Urban Development in Lake Catchments, Case of Urmia Lake** – Dr. Aida Ahmadi, Islamic Azad University
- 9:30 – 9:50 a.m. **Consideration of Climate Uncertainties in Urban Planning: Challenges in Predicting Future Trends and Hydrologic Extremes** – Dr. Soroosh Sorooshian, University of California at Irvine
- 9:50 – 10:30 a.m. *Breakout Session I*
- 10:30 – 11:00 a.m. *Break*

## **General Session V — Development of Resilient Cities**

Moderator — Dr. Farzad Naeim

- 11:00 – 11:20 a.m. **A Case Analysis of Air Quality in Tehran and Considerations for City Sustainability and Resilience** – Dr. Armin Sorooshian, University of Arizona
- 11:20 – 11:40 a.m. **Some Climate and Meteorological Aspects of Air Pollution in Tehran, Iran** – Dr. Abbas Aliakbari Bidokhti, University of Tehran
- 11:40 a.m. – 12:00 p.m. **Global Earthquake Model for Forecasting Seismic Risk in Urban Regions** – Dr. Jonathan Stewart, University of California at Los Angeles
- 12:00 – 12:20 p.m. **Effect of Geotechnical Works on Sustainable and Resilient Cities** – Dr. Arsalan Ghahramani, Shiraz University
- 12:20 – 1:30 p.m. *Lunch*

## **General Session VI — Utilities of Resilient Cities**

Moderator — Dr. Manouchehr Tabibian

- 1:30 – 1:50 p.m. **Upcoming Challenges of Future Electric Power Systems: Suitability and Resilience** – Dr. Mahmud Fotuhi-Firuzabad, Sharif University of Technology
- 1:50 – 2:10 p.m. **Reimagining Electric Power to Enhance Urban Resilience** – Dr. Clinton Andrews, Rutgers University
- 2:10 – 2:30 p.m. **Role of ICTS in Creating Intelligent and Resilient Cities** – Dr. Zahra Kavehvasht, Sharif University of Technology
- 2:30 – 2:50 p.m. **The Efficacy of Remote Sensing Technologies for Building Damage Assessment: An Analysis of the December 26, 2003 Bam, Iran Earthquake** – Dr. Ronald Eguchi, ImageCat Inc.
- 2:50 – 3:30 p.m. *Breakout Session II*
- 3:30 – 4:00 p.m. *Break*

## **General Session VII — Utilities of Resilient Cities**

Moderator — Dr. Clinton Andrews

- 4:00 – 4:20 p.m. **Water Reuse: A Bridge to Sustainable Water Management** – Dr. Richard Nagel, WaterReuse Research Foundation
- 4:20 – 4:40 p.m. **Integrated Water Management for Resilient Cities** – Dr. Medhi Borghei, Sharif University of Technology
- 4:40 – 5:00 p.m. **Role of Natural Attenuation Processes in Water Reuse Systems** – Dr. David Quanrud, University of Arizona
- 5:00 – 5:20 p.m. **Sustainability, Resilience, and Robustness of Regional Water Supply Systems** – Dr. Kevin Lansey, University of Arizona

## Wednesday, June 18

### General Session VIII — Utilities of Resilient Cities

Moderator — Dr. Medhi Borghei

9:00 – 9:20 a.m.

**Resilient Transportation** – Dr. Abi Mogharabi, Principal Consultant

9:20 – 9:40 a.m.

**Shared Ride Systems for Mass Transport** – Dr. Jay Jayakrishnan,  
University of California at Irvine

9:40 – 10:00 a.m.

**Advancements of Regional Transportation Modeling Capability  
for City Mobility and Resiliency** – Dr. Yi-Chang Chiu, University of  
Arizona

10:00 – 10:30 a.m.

*Breakout Session III*

10:30 – 11:00 a.m.

*Break*

11:00 – 11:45 a.m.

**Closing Remarks/Rapporteur Comments**

11:45 a.m.

*Lunch*

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## U.S.-Iran Symposium on Resilient Cities

June 16-18, 2014

Irvine, California



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# Urban Resilience and Peace-Building in Cities of Conflict

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### ***Abstract***

This paper examines how urban policies and strategies can help build peace and inter-group co-existence in cities of intense political conflict. The discussion synthesizes findings from hundreds of interviews with political leaders, planners, architects, community representatives, and academics in the politically contested cities of Jerusalem, Beirut, Belfast, Johannesburg, Nicosia, Sarajevo, Mostar, Bilbao, and Barcelona. Such cities are “polarized” where two or more ethnically-conscious groups—divided by religion, language, and/or culture and perceived history—have been or currently are in deep and intractable conflict over issues of political control and sovereignty. Recommended intervention strategies and tactics are to engage in equity planning that addresses underlying root issues; use planning process and deliberations to empower marginalized groups; create flexibility and porosity of urban built form; intervene in city landscape with sensitivity to differences across sectarian geographies; protect and promote the collective public sphere; and emphasize short-term tactical physical interventions while articulating a peace-promoting long-range strategic vision. Although urban actions cannot create peace where it does not exist in people’s hearts and souls, what urban policies can do, however, and it is significant, is to create physical and psychological spaces that can co-contribute to, and actualize, political stability and co-existence in cities. Urban interventions need to be part of a broader and multi-faceted approach addressing root issues of political grievance related to political disempowerment and institutional bias.

***Keywords: Peace-Building, Urbanism, Polarized Cities***

## **1. INTRODUCTION**

Planning interventions and policies in cities can play supportive and even catalytic roles in regional and national peace-building. There exist several types of practical policy approaches able to move cities of deep ethnic and nationalistic conflict toward greater normalization of daily and political life. This discussion synthesizes findings from 17 years of research involving over 240 interviews with political leaders, planners, architects, community representatives, and academics in the politically contested cities of Jerusalem, Beirut, Belfast, Johannesburg, Nicosia, Sarajevo, Mostar, Bilbao, and Barcelona [1]. These cities are “polarized” where two or more ethnically-conscious groups—divided by religion, language, and/or culture and perceived history—have been or currently are in deep and intractable conflict. Ethnic identity and nationalism combine to create pressures for group rights, autonomy, or even territorial separation.

Cities matter amid nationalistic and ethnic inter-group conflict. Many immediate and existential foundations of inter-group conflict frequently lie in daily urban life and across local ethnic divides and, importantly, it is at this micro level that antagonisms can be most directly influenced by government interventions aimed at their amelioration. After overt conflict and war, debates over urban space and its remaking can become potent proxies for addressing unresolved and inflamed socio-political issues that are too difficult to directly confront after societal breakage [2]. The city is important in peace-building because it is in the streets and neighborhoods of urban agglomerations that there is the negotiation over, and clarification of, abstract concepts such as democracy, fairness, and tolerance. Debates over proposed projects and discussion of physical place provide opportunities to anchor and negotiate dissonant meanings in a post-conflict society; indeed, there are few opportunities other than debates about urban life where these antagonistic impulses take such concrete forms in need of pragmatic negotiation. The city, asserts Berman [3], offers perhaps the only kind of environment in which modern values such as tolerance and freedom can be realized. Peace-building in cities seeks not the well-publicized handshakes of national political elites, but rather the more mundane, yet ultimately more meaningful, nods of respect and recognition of ethnically diverse urban neighbors as they confront each other in their daily interactions.

Lefebvre [4] views cities as the territorial locations most likely to generate democratic institutions and practices. The importance of the local place is brought out by Harvey [5], who argues that globalization should be rooted in human experience and specific places rather than linked to illusory, universal ideals that cause more harm than good on the ground. He contends that processes aimed at justice and liberation “can never take place outside of space and time, outside of place making...” (p. 260). Polese and Stren [6] identify several local policy domains—including governance, social welfare, public services, housing, transport, employment, and building of inclusive public spaces—that can be employed in ways to increase institutional and territorial inclusion and help build durable urban bridges.

It is in a city where urban practitioners and leaders must do the hard work of creating the practical elements of a multinational democracy, one that avoids the extremes of an engineered and subordinating assimilation, on the one hand, and an unbounded and fracture-prone multinationalism, on the other. Such a balancing act takes place most fundamentally in decision-making forums and lived experiences grounded in the city. Through our shaping of the city, we construct the contours of multinational democracy.

But you cannot show me--even supposing democracy is possible between victors and the people they have captured--what a democratic space looks like. What effect can the mere shape of a wall, the curve of a street, lights and plants, have in weakening the grip of power or shaping the desire for justice?

Anwar Nusseibeh [7] (p. 274)

The politics of conflict is hard to relate to urban design [7] (p. 274).

Planning practitioners intervening in ethnically volatile cities operate in a political labyrinth, confronting the “contradictory, idiosyncratic, and microscale territorial conflicts” that characterize divided cities and rival groups [8] (p. 172.) They are faced with a challenging dilemma—to respond to group wishes and sharpen territorial identity or to focus on the commonalities of the city and lessen divisions. For some urban scholars, the key is for practitioners to become more attuned to group identity as a criterion within planning processes and decisions [9-13]. This implies an “expanded view” of planning practice wherein planning plays a more deliberative role in improving intergroup relations [14]. For others, the critical objective is for planners to recognize but also help transcend such urban and societal divisions [15,16]. Borja and Castells [17] assert that city residents’ ability to maintain distinct cultural identities stimulates a sense of belonging that is



needed amidst globalization; at the same, communication between cultures must be present to counter cultural fragmentation and local tribalism.

Cities, by definition, are about conflict and contested space. It's how you manage conflict that is the issue.

Paul Sweeney, Advisor, Department of the Environment for Northern Ireland  
(interview) [18]

A common reaction by planners and policymakers in politically contested cities has been to create urban spaces that are anonymous or neutral in character, assuming that if space belongs to no one in particular that it can be used by everyone. Yet, Sennett [19] cautions against such an approach, asserting that character-less neutrality actually helps us learn how to hide from difference. The open consideration of violence, of the “other”, in the making of urban form has been repressed and not openly acknowledged [19]. Is there a way, alternatively, for policymakers to more openly acknowledge group based differences and their important influences on urban life and function, and to build an urban policy framework for understanding and dealing with such differences in constructive ways? Can practitioners in urban polarized places go beyond the “mantra of neutrality” and engage more explicitly with the challenge of multiple and contesting publics? [8] (p. 171). It is to this possibility that I now turn.

I examine interventions and strategic approaches that employ urban planning and policy to advance urban peace and co-existence. Many of these strategies seek to enhance urban stability and mutual co-existence through manipulation of the built environment. Such modification of the built environment amid conflict and contestation is certainly not an end-all. Practitioners must not fall into an environmental determinist frame, believing that changes in the physical environment shape social behavior so extensively that urban peace will result. Planning actions will not turn around a society that is politically splintered or unraveled; they cannot create peace where it does not exist in people’s hearts and souls. What urban policies can do, however, and it is significant, is to create physical and psychological spaces that can co-contribute to, and actualize, political stability and co-existence in cities. Deeply entrenched problems of nationalistic conflict are certainly not amenable to simple, one-dimensional solutions. Thus, urban planning interventions need to be part of a broader and multi-faceted approach addressing root issues of political grievance related to political disempowerment and institutional bias.

In the face of conflict and violence, the challenge is not whether public authorities should or should not take action amidst an unstable city. In almost all cities, governments take action when the personal safety of their middle and upper classes is threatened. Rather, the question becomes what types of governmental actions will be undertaken and how these can contribute to urban peace, stability, and mutual co-existence. A common response by politicians and developers in the midst of such crises is to build walls and dividers, increase police and military presence, and build gated communities that seal the middle class, elites and members of an advantaged in-group away from problems. Yet, actions that create physical segregation of groups or facilitate psychological separation may purchase short-term relief at the costs of long-term societal instability. An exclusionary, unequal metropolis does not enhance urban stability and co-existence. Rather, it is the increased interaction of diverse groups and individuals in workplace and neighborhood and the normalization of urban fabric, *in combination with* a frontal assault upon the root issues of political grievance, that are critical elements in the strengthening of urban co-existence in politically contested cities.

Urban policymakers and practitioners in the fields of planning, urban design, and engineering have within their power the capacity to foster an “unconventional” sense of urban stability, one built on sustainable co-existence rather than constructed through the more conventional means of police and military might and walled and divided districts.

## 2. INTERVENTION STRATEGIES AND TACTICS

I advance for consideration by local government administrators and nongovernmental organizations a set of city-building and urban design principles that aim to mitigate socio-economic and political tensions in situations of inter-group conflict.

### 2.1. *Engage in Equity Planning That Addresses Underlying Root Issues*

Material improvement in urban life is essential to enhancing human well-being for those least well off or historically disadvantaged, but is not sufficient in cities of nationalistic conflict if processes of political inclusion, acknowledgement and reconciliation are absent. It is crucial that policymaking aimed at alleviating the urban symptoms of poverty and inequality be linked with policies that directly confront the structural inequalities and power imbalances that are at the root of inter-group conflict and violence. Development interventions should not only address physical urban inequalities, but seek to counter individual and group-based feelings of historic grievance, marginality, disempowerment, and discrimination. In post-conflict situations, reconstruction must not solely be physical but also address the social and psychological scars that remain after the active conflict period ends. The psychological and political insecurities that led to intergroup violence and physical division, if left unaddressed after active conflict, will obstruct spatial and political normalization over time.

Planning practitioners and policymakers should be cognizant of, and seek to counter, the structural causes of people's grievances—those pervasive factors that have become built into the policies, structures and fabric of a society and which create the pre-conditions for violent conflict [20]. Urban strategies and interventions should be targeted in ways that address the local manifestations of long-term structural causes of conflict and tension. Development and planning priorities involving the allocation of basic infrastructure, services, and employment assistance should be used to counter individual and group-based feelings of marginality, disempowerment, and discrimination; in addition, they should address the meeting of basic human needs—public services, human rights, employment opportunities, food and shelter, and participation in decision-making. Several types of governance programs can compensate for past marginalization—employment equity initiatives, political inclusiveness mechanisms, municipal assistance to community organizations, increased access and equity in service delivery, anti-racism initiatives, and use of inclusive municipal images such as symbols and language [21]. Building capacity for a historically disadvantaged group in the city may require some autonomy in city governance, sufficient and contiguous land available for development, mobility and permeability of city boundaries, and security.

The use of planning and policymaking to advance redistribution and reconciliation borrows from the “equity planning” approach developed by American urban scholars Davidoff [22] and Krumholz and Forester [23], a strategy based on social justice goals that employs progressive planning actions to lessen urban inequalities (the United Nations uses the label “pro-poor” to describe such redistributive urban policy; another example of the equity approach is the “inclusive city” strategy [28]). Such an approach has been used in the conflict- and violence-prone Columbian cities of Medellin and Bogota, where there has been the purposeful and progressive use of public investment (in particular, parks, open space, and transit access) to enhance poorer areas and lessen crime rates [24,25]. Under former Mayor Enrique Penalosa, Bogota positioned the re-direction of urban priorities and policies as key in promoting social equity and instituted a policymaking model based on equal rights of all people to transportation, education, and open space.

## *2.2. Use Planning Process and Deliberations to Empower Marginalized Groups*

Urbanists and planners have power emanating from the fact that they engage at the interface between the built environment and political processes. Urbanists have the ability to connect the local/urban level to the national/political level, to link everyday problems faced by city residents to unjust political structures that underlie and produce these urban symptoms. In three of the cases I have studied, urbanists used neighborhood-based planning deliberations to empower marginalized groups and to connect to broader political opposition to existing regimes. In Johannesburg during the last years of the South African apartheid regime, protests over local payments for rent and city services in Greater Soweto were connected by local activists to more fundamental challenges of the apartheid state, in particular the need to restructure local government along non-racial lines. In Belfast, working class neighborhood planning efforts countering plans for demolition and population displacement existed alongside the Catholic republican insurrection against the state and British direct rule [26]. And, in Barcelona, urbanists during the Franco regime helped local neighborhood groups connect local place-based problems to larger political ailments [27].

The process of planning and policymaking is itself important and should be used in a deliberate fashion to empower excluded groups and build civil society. Project design and interventions should empower those groups in the city working toward peaceful solutions and co-existence, and the process of project design should be structured to increase communication across different urban groups. In cities of competing nationalistic group identities, public participation from the start is vital in urbanism processes. Beyond the project benefits, this participation in deliberations is of vital significance in reconstructing a politically contested and fragmented city because it demonstrates how democratic deliberation works. The process of planning and urban development should be organized in ways that engage city residents across ethnic backgrounds in projects having common and shared benefits.

Inclusive processes can generate new relationships and new knowledge about how to cope with, and address, inter-group conflict. Concrete, tangible city building issues provide a laboratory and incubator for cross-ethnic intergroup dialogue, negotiations, and joint production of outcomes. In contrast to the common win-lose psychological dynamic associated with ideology, identity, and nationalism, negotiations over tangible urban projects and issues often allow for win-win situations. These inclusive processes should not be viewed as a one-time, project-based endeavor, but rather as sustained over time and ongoing. Such processes allow participants to get to know each other as pragmatic partners, even if nationalistic differences remain. The planning process should be positioned not as a technical exercise, but as a social, political, and organizational mechanism that can increase feelings of inclusion, recognition, and group self-worth.

## *2.3. Create Flexibility and Porosity of Urban Built Form*

Urban planning and policy interventions should seek as much flexibility of urban built form as possible, choosing spatial development paths that maximize future options. Except in conditions where extreme need dictates their use, walls, urban buffers, and other urban forms that delineate physical segregation of groups or facilitate psychological separation should not be built. This strategy allows for greater mixing and freedom of choice of populations in the future, if and when inter-group conflict abates and there can be some normalization of urban living. This does not constitute an integration or coercive assimilation strategy, but rather seeks to create an urban porosity that allows normal, healthier urban processes to occur when individuals and governments are ready.

The design of spaces to encourage interaction and positive behaviors should be prioritized ahead of design approaches that discourage unwanted behavior and commonly separate and contain antagonistic groups. In spaces constructed to encourage interaction, there should be an

absence of undesirable, intimidating, and single group identifying artifacts. Instead, there should be functional and aesthetic equal treatment of different ethnic users of such facilities as multicultural community centers. Facilities and activity zones should be built that attract desired clientele who can crowd out undesirables. In terms of specific project or building design, there should be dual entry/exit ways for antagonistic communities so that a facility is perceived by all as located in shared space but is nonetheless functionally connected to ethnic space on either side. Uses that promote interaction are distinctly different from designs such as target hardening, access control, fences and physical boundaries, natural territorial enforcement, and natural surveillance that retard interaction.

A strategic intervention approach to increasing flexibility and porosity of urban form places premiums on actions at borders and interfaces that exist between different ethnic neighborhoods. It is at these places where different parts or layers of the city meet that hybridization can increase, connecting people and activities at “points of intensity” and along “thresholds” [29]. Creation of urban porosity must take place, however, simultaneous with or after the addressing of core issues of political inequality, disempowerment, and group identity that ignites nationalistic conflict. Absent such engagement with root causes of conflict, interventions such as the building of streets in a way that encourages travel across different parts of the urban fabric or the creation of ethnically mixed housing complexes may actually stimulate violence and conflict [30]. It is critically important to address core issues prior to, or concurrent with, manipulation of urban built form. With core issues included as part of the strategy, urban interventions can increasingly knit different parts of the city together and have an increased chance to enhance mutual co-existence in residential and non-residential environments.

Creating flexibility and porosity of urban form should not be confused with integration of individuals and groups. Indeed, inter-group segregation is an important means for stability in the short term. Amid nationalistic conflict and material imbalances, the mixing of population is not possible in the short term and there often is the need to maintain group identity boundaries. Peace processes can make identity boundaries uncertain and permeable. Thus, in the short term, such boundaries should be respected so that feelings of fear and threat do not retard progress in peace-building. Usually interaction between urban ethnic groups would lessen conflict, but positive evolution in intergroup relations that is natural in other cities is not possible in polarized cities if political root issues and grievances are unaddressed. Efforts to bring peoples together prematurely will increase—not attenuate—conflict, at least in the short term. At the same time, public interventions should not foreclose through the physical hardening of divisions the *option* of ethnic integration for those people and groups who are ready for such a move in the future if and when the city normalizes.

#### *2.4. Intervene in City Landscape with Sensitivity to Differences Across the Sectarian Geographies*

When contemplating interventions into the polarized city, planners should be cognizant of differences between urban ethnic homelands and frontiers and between “hard” and “soft” interfaces. In cities where ethnic and religious identity are primary drivers of political action, local authorities should, through their regulatory powers, locate sensitive land uses having cultural and historic salience (churches, mosques, private schools, monocultural community centers) within urban ethnic homeland neighborhoods identified with specific cultural groups. At the same time, they should encourage in interface, or frontier, areas between cultural neighborhoods those types of land uses that encourage mixing of different groups in a supportive environment. Joint and mixed land uses (public space, residential, commercial) can be intentionally placed at interface areas between competing (potentially conflicting) groups of an ethnic or other identifiable nature. In this strategy, there is the creation of “everyman’s land” of mutual use and benefit where each side can

use or pass through to the other side without being cut off; continuity replaces cut-offs and enclaves; porosity replaces borders.

In order to combat hardened enclaving and partitioning created during conflict periods, policymakers should establish a clear spatial-tactical programming orientation to future urban interventions that includes prioritization and sequencing components. In some urban districts, connectivity across the ethnic divide is a suitable goal; in others, consolidation of ethnic neighborhoods should be preeminent. Where there exist “soft”, ambiguously delineated interfaces, the enhancement of permeability of spatial divisions through joint use and mixed activities should be a first priority. Interventions should seek connectivity and linkages building outward from middle class or ethnically mixed areas. In contrast, consolidation of ethnic territoriality and identity should be the guiding criterion where there exist “hard” interfaces of strict definition, lingering violence, and the presence of ethnic militia guardians.

This interface strategy uses the “soft” edges of sectarian territories to create common ground and cross-cultural meeting places [31]. There is the creation of “weak borders rather than strong walls” and the enabling of uses and activities in certain neutral areas that will not give the impression that a particular community’s territory is being invaded [31] (p. 142). Illustrative of this thinking, Israeli planner A. Mazor [32] uses the metaphor of a river whose banks are on separate sovereignties. Rather than being seen as a dividing line, the river can be viewed as providing mutual benefit, wherein “both sides can row together in the river without being regarded as crossing the border.” Spaces are constructed malleably enough to permit constant alterations and shifts; porous and malleable demarcations are established rather than confining and exclusionary boundaries. Planners and policymakers should also seek to proactively counter development patterns that are potential precursors to physical partitioning in contested urban settings--biased urban service distribution, residential group clustering, growing symbolism of local residential territoriality, and emergence of informal ethnic demarcations in residential space [8]

In cities such as Belfast where there are efforts to advance national political progress through local actions, planners in housing and development agencies are debating the tactics and timing of interventions aimed at normalizing the hardened sectarian geographies of that city. The Northgate development strategy of the mid-1990s in volatile North Belfast illustrates how there could be the tactical introduction of a new development project to justify physical alterations to a potentially inflammatory interface area. It also shows how a public agency is capable of analyzing the potential social, spatial, political and psychological impacts of their actions on ethnic community identity. The analysis takes stock of each of the major participant groups in the urban sub-system and how negative public reaction may be mitigated within a contested, sectarianized environment.

The local problems in the planning area—Duncairn Gardens—were multiple and intense [33]. A permanent peacewall was constructed during the sectarian “Troubles” that divided the Catholic New Lodge neighborhood from the Protestant Tiger's Bay neighborhood. Catholic housing stock, insufficient to meet demand, was endangered further by violence. Much of the Catholic housing fronting the peacewall had front sides grated to prevent damage from petrol bombs, and back doors were used instead for access. Tiger's Bay was fast becoming a ghost town due to Protestant out-migration with major dereliction of building stock. The remaining Protestant population felt frightened, embattled, and insecure (B. Murtagh, interview) [34]. Into this volatile ethnic environment, public authorities proposed an economic development district on the Protestant side that aspired to create neutral and mutually beneficial territory. There would also be redevelopment and consolidation of housing in Tiger’s Bay. The strategy overall was intended to soften the rigidity of this line of confrontation; as one government participant stated (identity withheld upon request), this represented a “novel approach for effectively fudging the line of division.”

The Northgate strategy employed a finely tuned sensitivity to sectarianism and its social, spatial and psychological correlates; this report by DOENI, Northgate Enterprise Park: Interim Report, was never published. This confidentiality is indicative of the perceived sensitivity of dealing with

sectarianism in a candid way. The project itself never broke ground. Sectarian geography is mapped in detail, documenting potentially inflammatory Catholic residential incursion into formerly 'mixed' areas. The report states that "there is a collective perception in the Protestant Tiger's Bay community of being gradually outflanked by Catholic territory." Most revealing of government's awareness is the section examining the possible community responses--from local residents, local politicians, local church authorities, and local commercial interests--to DOENI's economic and housing actions. The area is characterized as one of mutual suspicion, home to strong paramilitary organizations on both sides, and where Protestants are afraid of the Catholic spread into Tiger's Bay. The major problem, cites the DOENI report, is that the project "might be opposed on sectarian grounds, as taking away too much of the former Tiger's Bay area." The working group worries that "major irrational opposition could create significant obstacles; and that many of the local residents could be easily persuaded by individual politicians or others claiming to represent the community." To diffuse possible negative reaction, the report suggests that an existing Tiger's Bay community group with views sympathetic to the project's overall goals be nurtured and supported. In this way, local politicians and extremist residents may be effectively countered.

In order to guide public interventions in contested urban settings toward more ethnically sensitive outcomes, planners should develop new methodologies that will evaluate in systematic ways the effects on urban ethnic groups of proposed land uses of certain types (those having cultural importance) and in certain spatial areas (areas of interface and mixing). Ethnic impact assessments can explicitly account for potential social-psychological impacts of the proposed land use on the respective cultural communities of the city, and should be used in the decision-making process regarding development proposals. Planners should seek to understand the "micro" structure of the city in terms of identity and people's perceptions of places and spaces. Special focus should be on "spaces of risk" in the urban landscape-- lived spaces that have low levels of trust and where people feel vulnerable and defenseless against conflict [35]. In such volatile areas, an ill-conceived project can activate latent urban tension to a more intense level.

Ethnic impact analysis at the urban level may borrow some of the nascent methodologies being developed by international and nongovernmental organizations. An example of conflict-sensitive analysis pertaining to public intervention is United Nations Development Programme [36], which advocates for a better understanding of the linkages between development and conflict. It proposes a methodology, "conflict-related development analysis", which focuses attention on the structural, underlying issues that lay the foundation for conflict and upon which more visible and immediate causes take place. The Federation of Canadian Municipalities has proposed that a systematic "peace and conflict impact assessment" (PCIA) be included in the design, implementation, and evaluation of all municipal activities in conflict-prone areas [37]. Meanwhile, a group of nongovernmental organizations recognizes that development can help prevent violent conflict, yet sometimes also inadvertently exacerbate it, and calls for greater "conflict sensitivity" in humanitarian interventions and development project planning [20].

## *2.5. Protect and Promote the Collective Public Sphere*

In order for the seed of urban stability and co-existence to grow, the public sphere should be developed physically. Planners should revitalize and redevelop public spaces, historic areas, and other urban public assets as places of interaction and neutrality that promote healthy inter-group and interpersonal life. Instead of focusing on the inflammatory choice between segregation versus integration of residential areas, concentration on improving public spaces offers a third approach less politically difficult. Here, there is the push for mixed public spaces rather than mixed neighborhoods. The goal is to enable increased cross-ethnic mingling in non-hostile, non-polarizing public environments rather than try the more contentious approach of having different ethnicities co-habitat residentially.

The physical creation of public spaces, as part of a comprehensive set of interventions that address root issues of conflict, can encourage activities that are the grounds for remaking an urban cross-ethnic citizenship. In Barcelona, in the early democratic years after Franco, architects and designers employed small scale and context-sensitive improvements in numerous public spaces throughout working class neighborhoods as a way to illuminate the benefits of the new democracy [27]. Public areas can facilitate mix and contact among a heretofore fragmented populous, facilitate and provide avenues for collective expression, and can contribute to cohesion and social equality.

## *2.6. Emphasize Short-term Tactical Physical Interventions While Articulating a Peace-promoting Long-range Strategic Vision*

Planning and development agencies should balance emphasis on creating a peace-promoting long-range vision with short-term physical interventions that create and reinforce urban peace. Long-range visions should clearly demarcate a break from the past and articulate a shared city of co-existence. At the same time, for actions in the short term, development agencies should concentrate on specific interventions in the urban fabric that have palpable impacts on people's daily lives and that illuminate principles of inter-group mutual co-existence and tolerance. These improvements should have explicit and noticeable equalization objectives and be focused in poorer areas and in areas where aggrieved groups live.

A strategy of "urban acupuncture" consists of "catalytic small scale interventions with potentially wide-ranging impacts" which are realizable in a relatively short time [38]. Acupuncture interventions in polarized cities should occur at strategic points in the urban fabric—points of rupture, stagnation, trauma, and dysfunction. These interventions contribute to activating places by making connections and caring for neglected or abandoned "in between" spaces or "no-man's lands" [29]. Because urban acupuncture can be more responsive to site-specific social tensions, it is commonly more suited to politically contested cities than is long-range, comprehensive master planning with its efforts at control and order at a larger scale.

Small-scale tactical interventions should seek to modify or soften the rigidities of conflict-period community dynamics in a local area. Wood and Landry [39] suggest that particular attention be paid to "zones of encounter"—housing and neighborhoods, education, workplace, marketplace, sports, arts, and the public domain (both public space and public institutions). The making of intercultural spaces should focus on these domains of day-to-day exchange rather than try to create highly designed and engineered spaces that lack salience to everyday life.

Public interventions in the physical landscape should have a spatial-tactical orientation that both repairs past damage and disparities and sets the foundation for more organic integration of divided districts. Post-conflict urbanists will need to address city spaces of overt conflict and war that have robust psychological and symbolic meanings—places of loss, fear, and martyrdom that often contain different and opposing interpretations [40]. In its most blatant forms, the legacies of conflict consist of sites of domination and control that embed historical differences and create physical legacies of inequality and denial. In addressing reconciliation through urban interventions, there should be the acknowledgement of the co-existence of multiple groups and narratives rather than the inscription and imposition of only the victor's narrative in the built landscape.

In the end, politically contested cities challenge us to confront whether we are hopeful or pessimistic about our ability to get along together. A puzzle faced by policymakers in multicultural cities—whether Beirut or Los Angeles, Sarajevo or New York, Jerusalem or Amsterdam, Johannesburg or Paris—is a basic one that forces us to confront our own beliefs and predilections. In an urban situation where there are antagonistic, or potentially antagonistic, ethnic or racial groups, do we as city-builders create opportunities for these groups to mix and interact or do we accommodate and reinforce the development of ethnically pure neighborhoods and districts? Decisions such as these will



send emotive symbols to future generations about what we either aspire to in hope or accept in resignation.

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# Towards Resilient and Sustainable Cities: A Conceptual Framework

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### **Abstract**

Cities are complex and dynamic Meta systems in which technological and social components interact. They are made up of dynamic linkages of physical and social networks. Planning for resilience in the face of urban disaster requires designing cities that combine seemingly opposite characteristics, including redundancy and efficiency, diversity and interdependence, strength and flexibility, autonomy and collaboration, and planning and adaptability. We are just beginning to realize the scope and magnitude of the challenges inherent in making our cities resilient to threats from natural hazards and terrorism. To meet these challenges, a national resilient cities initiative, aimed at the vision of the resilient city is the goal that covers all types of hazard mitigation. To succeed, this initiative will require changes in national disaster policy, funding for basic and applied urban systems research, support for advanced education programs and active collaboration among the city planning, design and construction professions.

**Keywords:** *Sustainability, City, Resilience*

## **1. INTRODUCTION**

With the September 11<sup>th</sup>, 2001 attacks, New York City sustained an iconic urban systemic shock. Three years after a monumental storm Hurricane Katrina, only an estimated two thirds of the pre-Katrina population remains and large areas of the city sit vacant. New Orleans as a whole is struggling to develop the capacity to adapt and to rebound [1]. While these two examples might not seem comparable, they both point to the importance of designing cities that are resilient.

Rapid urbanization and growing mega-cities point to a need for smarter and more resilient cities that possess the capacity to withstand the shocks of population growth, world economic crises, rapid demographic shifts in population, and environmental catastrophes. In addition, resilience must also be displayed in terms of events that have a more long term horizon such as when we see cities in decline. Cities are complex and interdependent systems, extremely vulnerable to threats from both natural hazards and terrorism. The very features that make cities feasible and desirable--their architectural structures, population concentrations, place of assembly, and interconnected infrastructure systems--put them at a high risk to floods, earthquakes, hurricanes, and terrorist attacks. Increasing support for the notion of resilient cities is found in the hazard mitigation literature. Godschalk et al. proposed a sustainable mitigation policy system whose goal is developing resilient communities, capable of managing extreme events [2]. Many other recent

disaster studies also call for the development of resilient communities. Beatly noted that a sustainable community is resilient-seeking to understand and live with the physical and environmental forces present at its location [3]. Vale and Campanella explore the historic meanings of resilience and urban trauma [4]. Despite such interest in the concept of resilient communities, few studies have formulated systematic principles of resilience and applied them at city scale. Regarding the above, it is essential to understand why a city must be resilient. How can cities, as complex systems, be resilient? Building capacity for resilience may be a daunting task when one considers the multitude of components, processes and interaction that take place within and beyond a city's physical, logical and virtual (cyberspace) boundaries. The aim of this paper is to introduce a conceptual framework for launching a resilient city national initiative. This framework entails changes in national disaster policy, funding for basic and applied urban systems research, support for advanced education programs and active collaboration among the city planning, design, and construction professions.

## **2. WHAT IS A RESILIENT CITY**

When resilience is the aim, it is crucial to understand what the term means and what a resilient city should comprise. As may be expected, there are many definitions of a resilient city, ranging from very narrow to very broad and reflecting different cultural values.

One feature that seems to always be present is 'strength'- making communities and cities stronger against forces that put their citizens and structures at risk. Generally, resilience is also linked to sustainable principles. To the World Bank, for example, "a resilient city is one that is prepared for existing and future impacts, thereby limiting their magnitude and severity." The World Urban Forum's Vancouver Working Group takes a more confined approach and links resilience to the ability of a city to expand its production base (e.g. from depending on one industry to attracting and embracing a broader base and economy).

Yet another definition links resilience directly to peak oil and name resilient cities "that can last, make through crises, [possess] inner strength and resolve, as well as appropriate built form and physical infrastructure" [5].

The European Environment Agency (EEA) sees a resilient city as an "urban ecosystem" that is dynamic: consuming transforming and releasing materials and energy in an adaptive way and interacting with other ecosystems, tackling mitigation and adaptation efforts and addressing quality of life through better and greener urban planning [6].

As a final and comprehensive approach, the International Council for Local Environmental Initiatives' (ICLEI) Bonn resilient cities conference defines a resilient city as [7]:

- A city that supports the development of greater resilience in its institutions, infrastructures, social and economic life.
- Resilient cities reduce their vulnerability to extreme events and respond creatively to economic, social and environmental change in order to increase their long term sustainability.
- Resilient city activities are sensitive to distinctive unique local conditions and origins. Efforts undertaken to prevent crisis or disaster in one area should be designed in such way as to advance the community resilience and sustainable development in a number of areas.
- Resilient cities define a comprehensive 'urban resilience' concept and policy agenda with implications in the field of urban governance, infrastructure, finance, design, social and economic development, and environmental resource management.
- Local resiliency with regard to disasters means that a locale is able to withstand an extreme natural event without suffering devastating losses, damage, diminished productivity, or quality of life and without a large amount of assistance from outside the community [8].
- A resilient city is a sustainable network of physical systems and human communities.

Physical systems are the constructed and the natural environmental components of the city. The physical system act as the body of the city: its bones, arteries, and muscles. During a disaster, the physical system must be able to survive and function under extreme stresses. A city without resilient physical systems will be extremely vulnerable to disasters. Human communities are the social and institutional components of the city. They include the formal and informal, stable and ad hoc associations that operate in an urban area: schools, neighborhoods, agencies, organizations, task force and the like. In sum, the communities act as the brain of the city, directing its activities, responding to its needs and learning from its experience. During a disaster, the community networks must be able to survive and function under extreme and unique conditions. If they break down, decision making falters and response drags. Social and institutional networks exhibit varying degrees of organization.

Resilient cities are constructed to be strong and flexible, rather than brittle and fragile. Their life line systems of roads, utilities, and other support facilities are designed to continue functioning in the face of rising water, high winds, shaking ground and terrorist attacks.

### **3. WHY IS RESILIENCE IMPORTANT**

Resilience is important for two reasons:

First, because the vulnerability of technological and social systems cannot be predicted completely, resilience--the ability to accommodate change gracefully and without catastrophic failure--is critical in terms of disaster [9]. If we knew exactly when, where, and how disaster would occur in the future, we could engineer our systems to resist them. Since hazards planners must cope with uncertainty. It is necessary to design cities that can cope effectively with contingencies.

Second, people and property should fare better in resilient cities struck by disasters than in less flexible places faced with uncommon stress [10,11]. In resilient cities, fewer building should collapse, fewer power outages should occur, and fewer households and business should be put at risk. Fewer deaths and injuries should occur. Fewer communications and co-ordination breakdowns should take place.

Some skeptics argue that the pursuit of community resilience is laudable but unpractical using a conceptual framework based on the theoretical models of mitigation, recovery, and structural cognitive interaction. Tobin examined data from the state of Florida to assess the possibility of developing sustainable, resilient communities, analyzing the state as a whole rather than any individual cities [12]. Tobin concluded that major (unlikely) changes in political awareness and motivation would be necessary to overcome obstacle to resiliency and sustainability from Florida's existing demographic traits, spatial patterns, and hazard conditions.

### **4. QUALITY THAT CHARACTERIZE A SUSTAINABLE CITY**

A sustainable city is one that is reducing its ecological footprint, its resource consumption, land consumption and waste production, whilst simultaneously improving its quality of life (its health, housing, work opportunity and livability). The three characteristics of a sustainable city are thus [13]:

- The city “recognizes” there are real limits to its ecological footprint and that it cannot continue to expand its use of energy, and water and materials.
- The city sees its innovations in economic and social development to be essential but not divorced from the need to reduce its footprint. Most programs must do more for people with less from the earth.
- The city has a governance system that rewards sustainability innovation that integrates the contributions from the business, community and government. That rejoices in the creative expressions of its artist in expanding sustainability sensitivities that build its particular

sustainability approaches on the identity and sense of place in the city and communicates it for all other cities to learn from.

## 5. RESILIENCE, AND/OR SUSTAINABILITY

Resilience and sustainability are not mutually exclusive but should be seen as powerful companions to shape both the future planning and daily management of cities. Sustainability represents the end goal that forward-thinking cities are pursuing, to secure a good quality of life for all people, today and to the future, through strong and prosperous communities, a vibrant stewardship of both local and global environmental assets. Resilience works within the context of long-term sustainability objectives but specifically embrace the turbulence of daily life. Resilience is about learning with the spectrum of risks that exist at the interface between people, the economy and the environment and maintaining an acceptable stability or equilibrium in spite of continuously changing circumstances. Resilience also addresses the independencies between systems and minimizes unforeseen 'gaps' in risk management. Therefore, system planning and design should seek to measure performance against both resilience and sustainability indicators.

There are two more points that a resilient city needs to take into consideration. One is that becoming resilient is a process that demands continual improvement and that, by definition is an ever-evolving effort. This process is adaptive because it aims at a continual improvement of the decisions taken (e. g. in rethinking urban planning, in increasing local renewable energy supply or in putting alert systems in operation) and the action implemented. The second point that a resilient city needs to consider is that resiliency should be embedded in the context of sustainability. Resilient solutions, which are largely addressed through climate change adaptation, climate change mitigation, and disaster risk reduction need to contribute to the amelioration of environmental degradation and of the realities of poverty and inequality, as shown in Fig. 1 below. Otherwise, solutions will not be effective in the long term.

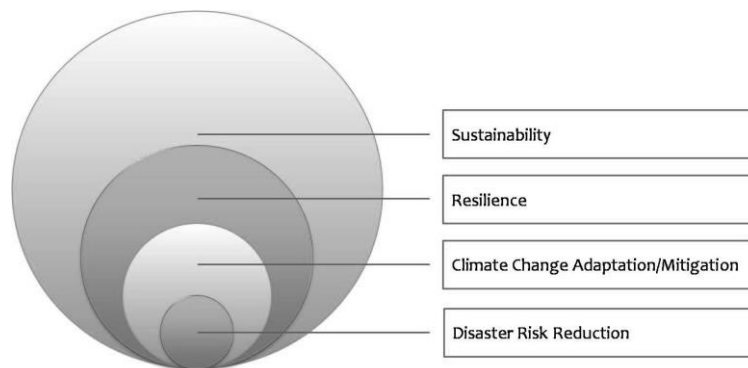


Figure 1: The context of resilience [14].

As Fig. 1 shows, addressing disaster risk reduces vulnerability, as do sustainable measures to deliver climate change (and mitigation, at least in long term). These two fields--disaster risk management and climate change adaptation – are becoming closer in their approaches, as disaster risk management moves from reaction to also including prevention as major objectives. These efforts enhance a community's or a city's resilience (the second biggest ball), and they contribute to sustainability and to the long-term prevalence of communities, cities, and human biodiversity only if they are shaped with sustainability criteria (the biggest ball).

## 6. THE COST AND BENEFITS OF BEING RESILIENT

There is abundant literature on the economic costs and benefits of adaptation and mitigation; whereas the cost of resilience remains more ‘obscure’ and more difficult to define. One smart way to reduce the need for dedicated adaptation funding and to efficiently use resources to reduce vulnerability in cities is to incorporate climate change, adaptation and resilience criteria into present investments on urban fixed assets (many of which stem from private sector). This concept of ‘resilience upgrading’ looks at enhancing the city’s resilience by increasing its performance--its ability to deliver a high quality of life and quality services to its residents. Instead of approaching the topic of adaptation and disaster risk from a perspective of ‘escaping risks’, it rather looks at the benefits of that smart, climate–proof investments that can deliver to the city and to the service or product providers (Figs. 2 and 3).

The European Union’s 2020 strategy is centered on growth. It aims to achieve smart growth, sustainable growth and inclusive growth. Growth in a world that is dominated by unsustainable practices, where the global population depletes natural resources and ecosystem services faster than the planet can replenish them, is a major challenge. The symbolism used by the global footprint network to describe the problem of growth and unsustainable use of resources is an effective way to transmit the message: today we consume the resources equivalent to 1.5 planet earths—that is, it takes “the earth one year and six months to regenerate what we used in a year” and to absorb the waste we generate—and by year 2020 we are likely to need two planet earths [15].

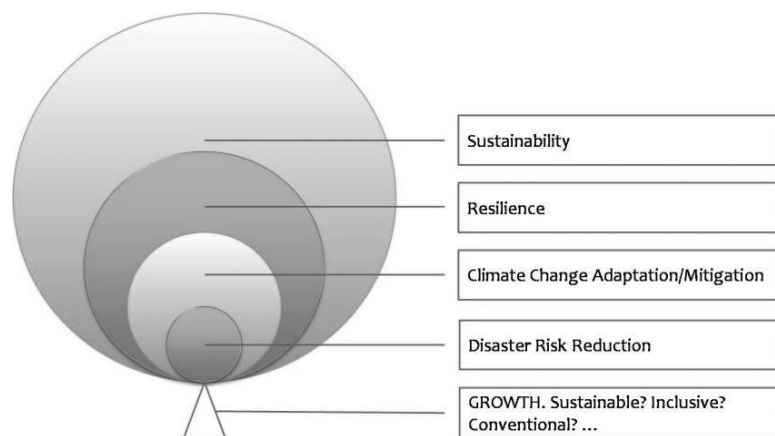


Figure 2: Striking a balance between growth, sustainability, resilience, climate change adaptation/mitigation and disaster risk reduction [14].

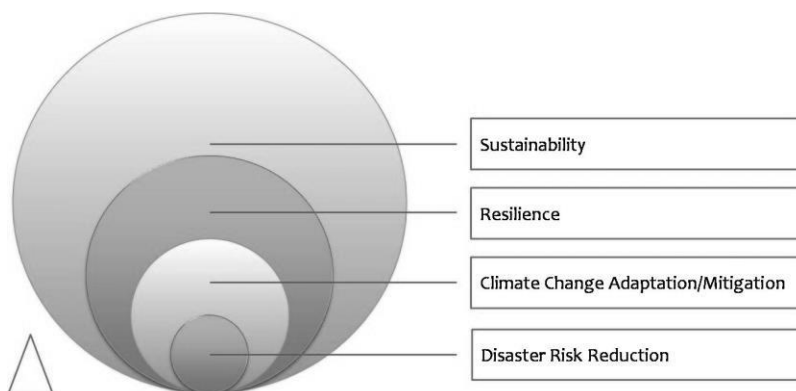


Figure 3: Framework for resilience work at the local level [14].



The complicated systems of cities and regions need management on various levels. To name but a few, the economy, the social sector and personnel are all managed in one way or another. Managing tasks individually and sectorally, however, is most often inefficient and leads to increased workload and weak results. Re-organizing and integrating existing practices, plan and strategies under one steering wheel, the integrating management system (IMS), will systemize the work, boost efficiency and provide a multitude of positive outcomes. It will direct all available resources towards the goals defined and secure the transparency and democratic principles of decision making. In the IMS, the effort lost in running several parallel management systems can be turned into sustainability. The IMS consists of five major steps repeated in annual cycles. Although the system follows an annual cycle, full revision will be required once per election period and preferably at the outset.

## **7. CONCLUSION: BUILDING RESILIENT CITIES AS A NATIONAL PRIORITY**

Cities are complex and dynamic meta systems in which technological and social components interact. They are made up of dynamic linkages of physical and social networks. Planning for resilience in the face of urban disaster requires designing cities that combine seemingly opposite characteristics, including redundancy and efficiency, diversity and interdependence, strength and flexibility, autonomy and collaboration, and planning and adaptability. We are just beginning to realize the scope and magnitude of the challenges inherent in making our cities resilient to threats from natural hazards and urban terrorism. To meet these challenges, I propose a national resilient cities initiative aimed at the vision of the resilient city as the goal that bridges natural hazard mitigation and counterterrorism practice. To succeed, this initiative will require changes in national disaster policy, funding for basic and applied urban systems research, support for advance education programs and active collaboration among the city planning, design and construction profession. It is comprised of the following elements:

### *7.1. Basic and Applied Research*

While we have learned a great deal about the behavior of various urban systems in recent years, there are still many gaps in our knowledge about how physical and social systems within cities respond to extreme stress. A national program of basic and applied research on this topic could generate valuable contributions to our understanding of how to plan and design resilient cities. The National Research Council [16] list a number of critical long-term research needs. It notes the need for developing new ways of understanding and modeling complex, adaptive systems. Urban planning researchers have made a promising start in this direction by using GIS to analyze, model and visualize dynamic and interdependent urban systems such as linkages between land use and transportation [17]. The new GIS contingency models are able to respond to what if questions that asks about potential system responses to future changes of various types.

### *7.2. Education Program*

In concert with the research campaign, we need to strengthen education and training in designing and managing resilient urban systems. The goal here is to increase our pool of human resources to prompt future engineers, scientists, planners and emergency managers to enter practice and become educators and researchers. The National Research Council report recommends a human resource development program aimed at producing at a sustained increase baccalaureate and doctoral degrees in fields consistent with long-term periods for homeland security [16]. Such a program should include support for university training for students in disciplines that can contribute to urban resiliency. These would include the physical science, social

science, planning, design, and engineering and management fields. This program should be discussed in the Symposium to reach to certain collaborations.

### 7.3. Professional Collaboration

If we are to take the achievement of urban resiliency seriously, we need to build the goal of the resilient city into the every practice of city planners, engineers, architects, emergency managers, developers and other urban professionals. This requires a long-term collaborative effort to increase knowledge and awareness about resilient city planning and design. Prieto notes that, because engineering tends toward specialization, engineers have difficulty translating lessons learned to a broad range of disciplines. He suggests that the National Academy of Engineering could play an important role in disseminating lessons from disasters [18]. Other professions face similar difficulties and would benefit from both intra-professional and inter-professional collaboration. Such an effort could start with a summit conference to convene leaders of all the professions concerned with city design and development to develop resilient city in practice guidelines. This could be kicked off by a national conference on planning and building Resilient Cities. The objective of the conference would be to discuss principles for building resilient cities and ways of incorporating these principles into the practice of engineers, planners, architects, administrator's developers, and other city designers, builders and managers. The program would look at both physical systems and social systems, and their linkages.

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# Community Resilience through Maintenance of Sense of Community: Some Lessons from Disaster Affected Cities in Iran

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### **Abstract**

Community resilience is defined as a process linking a network of adaptive capacities to adaptation after a disturbance. Sense of community (SOC) is regarded as one of the attributes of community resilience and is defined as an attitude feeling of having ties with other members of one's group or locals, including mutual concerns and shared values. SOC is characterized by caring for community issues, respecting other members, feelings of connectedness, and needs fulfillment. Intersections of SOC with place should be considered regarding the importance of place in resiliency. Place attachment, community identity, social interaction and public places for interaction can be seen as attributes connecting sense of community with place characteristics.

Results of several qualitative and quantitative research studies carried out in two disaster affected cities in Iran show that SOC can play a crucial role in different phases of a disaster cycle. According to these findings, close ties between members of the community and their sense of belonging helped the community to become resilient against disaster. Social networks among members of the community, in time of hazard happening, helped reduce vulnerability. Mutual needs and shared goals facilitated reconstruction and accelerated it. Reconstructing the community and its public spaces promoted a sense of identity and belonging. People rebuilt the communal places of the community, which promoted community identity and in return, preserved place characteristics. Spaces created as such facilitated social relations. Rites, rituals and public gatherings provided collective memories and sustained the spirit of the community. Thus, the community could return to a normal or new normal life.

**Keywords:** *Community Resilience, Sense of Community, Disaster, Iranian Cities, Manjil Earthquake, Neka Flooding*

## **1. INTRODUCTION**

Iran is part of the arid belt that stretches from the Sahara in the west to the deserts of the Central Asia in the east. It is also a part of the Eurasian mountain belt, which runs from the Iberian Peninsula in the west to the Iranian highland rims of the Elburz and Zagros. Two ranges of

mountains emerged due to uplifting and folding effects of three giant plates pressing against each other: the Arabian Plate, the Eurasian Plate, and the Indian Plate [1]. Major faults occur along these mountain chains and have been the cause of strong earthquakes during centuries. Along the foothills of the high mountain chains and in inter-mountain basins are located settlements with access to water as the main source for living in a hot arid zone [1,2]. Many of the cities were built in the Sassanid era as a policy to establish political-administrative centers to control the surrounding regions [3], and were adjacent to active faults. Some cities were isolated after destruction by natural disasters- especially earthquakes- or by man-made disasters, but many of them, including Tabriz, Kashan, Qazvin and Tehran have survived and sustained their populations until the present time.

Traditional settlements were usually resilient against disasters and could continue their normal or new normal life after a period of dis-function. The current situation is rather different because urban inhabitants now exceed 70 percent of the total population in Iran. Many cities have experienced rapid growth during a short period of time, without being equipped with necessary infrastructures. This, along with intra- and inter-urban migrations, has led to a transformed topography of population in cities, changes in social structure of residential quarters, and escape of original residents of city centers to outer districts, leaving the central districts, which are old historic parts, in a state of decay and decline. These conditions make the resiliency of cities a critical issue. Considering the present complex conditions, city resilience has acquired significant importance for planning and design of cities.

The purpose of this article is to explore the relationship between existence of a sense of community and resiliency in cities, with a focus on the interrelationships between building community (especially of public places) and sense of community in resiliency.

## **2. COMMUNITY RESILIENCY**

The term resiliency has been applied in different fields of study and with different definitions. After early usage in psychology in the 1940s, the term was used in environmental and life sciences to describe the adaptation capacity of system against shocks (natural and man-made) [3,4]. The devastating impacts of natural hazards on economic and social condition of societies extended the studies in the socio-economic areas and gradually the role of social and human factors on economic and social resiliency of societies became the focus of interest among a group of scholars [5-7]. Since the 1980s, and after announcing the 1990s as the “International Decade for Natural Disaster Reduction,” resiliency studies have been vastly extended and different definitions and attributes have been introduced for it.

Although, resiliency has been defined in many different ways, Norris et al. suggest that it is “fundamentally” a metaphor in social and psychological sciences; the term originated in physics and mathematics to refer to the capacity of a material to bend and bounce back when stressed [8]. So, Norris et al. suggested studying human resilience, without giving undue concern to its meaning in relation to physical property or law [8]. In recent decades, some definitions of resiliency have focused on its relations with place characteristics when defined as disaster resiliency. In place-based resiliency against disasters, Cutter et al. suggest that resiliency is realized on the basis of total characteristics of place which comprises not only geographical and environmental aspects but also social, economic, cultural and even political ones [9].

One of the aspects of resiliency studies, which can be of interest for urban planners, is community resiliency. Community resiliency –like the concept of resiliency itself- has been defined in many ways with a focus on different aspects or different levels [8]. Community resiliency can be described in several interdependent levels. In one of the recent definitions, Norris et al. defined it as a “process linking a network of adaptive capacities (resources with dynamic attributes) to adaptation after a disturbance or adversity” [8]. Paton et al., in a similar definition, describe it as the

ability of a community to bounce back and recover using its own resources (physical and economic), and the capacities and capabilities of the community members to use these resources [10]. Sense of community has been regarded as one of these resources [10-13], while some scholars consider it as one of the constituent elements of social capital, as one set of resiliency resources [8].

### **3. SENSE OF COMMUNITY**

'Sense of community' is an attitude of feeling of having ties with other members of one's group or Locals; including mutual concerns and shared values [14]. Caring for community issues, respecting other members and helping them, feelings of connectedness, and needs fulfillment are characteristics of sense of community [8,15,16].

The term was first coined by psychologist Seymour Sarason [17] who founded a theory for it. After his early explorations of sense of community, many scholars have worked on the theory. Four theoretical factors proposed by McMillan and Chavis [15] and later revised by McMillan [16] have been frequently adopted. The four factor model includes: feeling of belonging and integration into a community, Membership [15] / Spirit [16]; having mutual Influence [15] / Trust [16]; Integration and Fulfillment of Needs [15] / Trade [16]; and Shared Emotional Connection [15] / Art [16]. Although it has been defined in different ways by various scholars; in this study the measures proposed by McMillan and Chavis are adopted.

### **4. SENSE OF COMMUNITY AND PLACE**

The relations of Place and sense of community have been studied in various fields. Many community psychologists have mentioned the relationship between SOC and neighborhood context [18,19]. This is based on one of the definitions of the community as community of place [20], which is in turn on the basis of the definition of community as an entity with geographical boundaries that is comprised of natural, social and built environments with mutual influences in complex ways [8]. According to Garcia et al., physical environment is one of the two elements which comprise the structural elements of a community, people being another element [21] and as such inseparable from the community definition.

Thus, ties between community and place are generally accepted. This is because of a 'Shared collectively conditioned consciousness' which reinforces the identity of community and place simultaneously and thus giving them a same identity [22]. However, Kim and Kaplan note that physical attributes of place are not generally considered in SOC studies [23].

For understanding how sense of community and place are related, one should explore the community's 'relationship' and 'interaction' with the 'particulars' of the residential settings [3]. Place attachment has been regarded by some scholars as one attribute which connects people with places [22-24], while some others regard them as intertwined and parallel concepts [25]. The perceptions of people of 'places' and their ability to meet their needs and goals, develops place attachment and incorporates these feelings in their psychological sense of community [22].

Community identity is being regarded as another concept when relating physical aspects with sense of community [22,23]. Strong feelings towards particular places strengthen sense of community. This is in part because of the process of identification which takes place through place identity. Place identity is an emotional attachment and is related to 'symbolic importance of a place as a repository of emotions and relationships that give meaning and purpose to life' [26]. Identification by a place is part of self-identification and thus refers to bonds between place and people [27], which people develop when their sense of belonging to a community increases [22]. Chavis and Pretty comment that it may be 'that attachment and identity mediate between the geographical community and the SOC of residents [18].

Social interaction is another aspect of relationship of place and community [19,23]. Public spaces for interaction [23] and as settings for shared collective emotions [15,16], can be another attribute of physical aspects. The attributes of physical environment connect community to place, but how they develop a sense of community is debated.

## **5. BUILDING COMMUNITY, CREATING SENSE OF COMMUNITY**

In planning professions, especially within the framework of the New Urbanism debates, some scholars advocate the role of physical design of neighborhoods in fostering a sense of community, based upon studies carried out on New Urbanism Projects in the USA [23,24,28,29]. They suggest that by designing public spaces, places to encounter people, designing the houses so that neighbors can see and familiarize with each other, etc., a sense of community can be developed among community residents. Talen criticizes the claims of New Urbanism about creating a sense of community by the built environment, but she accepts that environmental factors are influential in residents' interaction and a sense of community [30,31]. However, role of physical environment in building sense of community has been identified by community psychologists as well. [18,21]. As Garcia et al. indicate, to understand how people bond to a place and identify with it, the historical context of the community should be considered [18]. People who live in a community and take part in its events and participate in its history, they know its history [21], its dramatic moments, how things happened, how things were arranged, etc. In other words, history of the community can be regarded as a "collective memory" which strengthens the self-identification and belonging of the individuals in the community [21]. History of a community is not a passive contextual matter [21]. It should be 'conceived in terms of how people relate to it in an active way' [21].

Participating in the history of the community can be realized by participation in community development, a process which produces a sense of community on a parallel developmental process [21]. Community development by residents has a great power to affect SOC at its most fundamental level [18]. Exploration of Garcia et al. illustrates the psychological importance that creating one's home has for the people of the community regarding basic shelter and safety needs [18]. As Garcia et al. suggest; the sense of community by integration of members' feelings facilitates a series of processes which have close relations with community development [21]. Building a community, especially housing, is an important 'planning-related factor' in post-disaster activities [32] and plays an important role in returning the community to normal condition; sustaining resiliency.

## **6. SENSE OF COMMUNITY AND RESILIENCY**

Although the sense of community has many intersections with place and feelings that community members have towards it on different levels, few studies have been carried out on the relation between sense of community and physical characteristics of place in strengthening resiliency. Sherraden and Fox have found that social networks facilitated by physical structure improve recovery from disaster [33]. Regarding that resiliency is a process which adapts a network of adaptive capacities to a disastrous situation [8], relations of sense of community with resiliency should be considered in different phases of the disaster response-recovery-mitigation cycle.

In emergency phase, sense of community can encourage community involvement in rescue and relief operations by mutual feelings and affections of members [12]. Interaction between people of the community and their mutual understanding becomes more intense because of their similar needs and problems [21] in the emergency phase and later in temporary settlement and reconstruction phases. People negotiate in situations that include shared concerns, or personal or group problems [21].

As discussed before, a sense of community has been seen as a product of the developmental processes of the community. Regarding the importance of community development for bringing

people to a normal condition- in disaster aftermath, the role of sense of community becomes crucial. This means that in the process of reconstruction, mutual feelings of community members help them sustain their spirit and participate in the re-development of their community.

Resiliency is defined as returning a community to its normal or new normal conditions after a disturbance [8]. After a natural disaster, one of the prime tasks in this regard would be reconstruction of the disaster affected physical environment. People, by participating in the process of reconstruction, can reinforce their mutual ties and feelings. Moreover, their mutual needs and goals strengthen their bonds with their community. Structural patterning like location of houses and public spaces created for public interaction permits the appearance of community interaction and participation; community life [21].

Reconstructing public spaces of the community provides necessary settings for fulfillment of shared emotions and feelings, an aspect which is considered an important element of sense of community [15,16]. McMillan proposes "Art" instead of 'Shared Emotional Connection in Time and Space' that was suggested by McMillan and Chavis [15]. It is based on experience which is obtained by contact of members with one another. McMillan introduces a concept, 'Shared dramatic moment', to suggest that a community chooses the events that become a part of its collective heritage and are represented in its symbols. He; based upon various studies, comments on the importance of collective rituals, rites, myths, symbols, and ceremonies in strengthening the sense of belonging and togetherness. These collective experiences form the collective memories of the members of the community and are basis of its spirit. According to McMillan, 'Art Supports the Spirit that is the first element of sense of community and thus, the four elements of community are linked in a self-reinforcing circle'. [16]

Rites, rituals and shared experiences are being realized in the communal spaces and places of the community and thus it can be suggested that sense of community has impact on how and with what qualities people shape their communal places and in return, how communal spaces and places of the community influence the sense of togetherness, belonging and identity of community members. An increased SOC bonds community members to their place, promotes mutual feelings and needs and participation in community affairs and thus strengthens the social capital as one important aspect of resiliency.

## **7. THE CONTEXT OF THE STUDY**

The role of sense of community and its interrelationships with place, in different phases after disaster, has been the core issue in a series of research studies carried out in some disaster affected cities of Iran during the past 25 years. Two cities were selected: one affected by earthquakes (Manjil, in Gilan Province in north Iran which suffered from a great earthquake in 20 June 1990) and the other affected by flood (Neka, Mazandaran, in north Iran which the core of the city in vicinity of the river was damaged due to two floods which washed up the area within 12 hours).

In a series of studies, the followings were investigated: the role of sense of community in some disaster affected residential quarters of these two cities ; the consequences of existence of sense of community in rescue and relief conditions; the role of ties and mutual belongings and needs of members of the community in helping them to return to a normal condition; the role of place in formation of collective memories and the way people provide places for their shared moments and how these shared moments strengthen feelings of mutual ties and belongings.

### *7.1. Neka*

Neka is a small town in the northern part of Iran and is the center of a county in the province of Mazandaran. It was given a legal state as a city in 1954 when it reached a population of 5,000 persons. Its population was 35,107 persons in 2013. Increase in population was due to the



establishment of an electric power station in Neka and some other industrial plants which transformed the city into an industrial one in the years before the Islamic revolution and as a consequence, emigration for finding jobs in the new factories was accelerated. In addition, Neka has a good natural condition for cultivation and forestry which has favored it for immigration of villagers from surrounding areas. Settlement developed at first along the Neka River and has expanded in an east-west direction (along the transit road which passes through the center of the city) in recent years. The Neka River is prone to flooding; frequent devastating floods have been recorded in the history of the city.

In 27 July 1999 and after heavy rains which had begun the previous day, the city of Neka was flooded which had disastrous consequences; about 3,440 houses and 600 shops were destroyed; 130,000 buildings were damaged; 37 persons were killed and 12 were lost; forests and fields were destroyed and infra-structures and facilities were ruined [34]. Some of the neighborhoods of Neka, which were located in the flood plain area, were more devastated than others. These neighborhoods included: *Narenjbagh*, *Turk Mahalleh*, *Chamazi*, *Shahrdari*, and a commercial district in the junction of the river and transit road. Some of these neighborhoods, which had been developed in the river basin, accommodated low income immigrants which were daily or seasonal workers in the adjacent factories.

## 7.2. Harzevil

Harzevil, located in a mountainous area, was one of three villages which shaped the first nucleus of Manjil city, developed near a new built dam of Sefidroud in 1957. As a village, it had a long history and its name was mentioned in an itinerary by Naser Khosro, an Iranian famous traveler who passed through the village in the 11th century B.C. and reposed under a cedar tree there.

Construction of the main transit road, which connected capital city of Tehran to north provinces and passed through Manjil, helped the city flourish. The strategic location of the city in the natural gate to the inner plateau of Iran and building a garrison in the city was another factor for its growth.

French Workers of the dam and power station were accommodated in houses which were built in a new developed area in down skirts of the village of Harzevil and named ShahrakHarzevil. ShahrakHarzevil had its own neighborhood facilities like church, cinema, etc. In 1981 a new town for workers of the power station (ShahrakTavanir) was built near ShahrakHarzevil. Other parts of the city grew around the transit road, downhill. Thus Manjil-in its final form-constituted a central nucleus and three periphery districts; Harzevil was one of them in the northeast of the city, in a steep terrain.

At midnight on 21 June of 1990 a devastating earthquake shook a great part of Iran; Manjil was near the epicenter of it. Harzevil was among those parts of the city which sustained enormous damages, because of its location. In relief phase, residents of Harzevil were temporarily settled in their fields and in gardens down skirts of their quarter; regarding the total destruction of the old quarter, difficulty in cleaning the rubble and instability of the land due to probability of a landslide. The temporary settlement was then transformed into the new quarter of Harzevil residents. Their new quarter was formed of two parts (Harzevilbala and HarzevilPayin) in two sides of two previous quarters (French workers quarter and Shahraktavanir), based on the land ownership of Harzevil residents.

## 8. RESEARCH METHOD

Cases were studied in several phases and on the basis of different research approaches. In Neka a survey was performed and 57 questionnaires were distributed randomly in those parts of five neighborhoods which were damaged. The survey was based on a sense of community scale (SCS)

which was designed for the research. The findings of this survey were analyzed using factor analysis and later checked and completed with several in-depth interviews with some of the community leaders and inhabitants which was done by one of the researchers, a native resident of Neka.

In Harzevil a research survey was carried out in 2009 with 20% of households. Questionnaires were distributed randomly in the neighborhood. Later, in another study, a qualitative approach was adopted. By living in Harzevil in residents' houses and participating in their ceremonies, in several occasions and in-depth interviews with residents, researchers could understand how people felt about their community and how attached they were to it. The findings of the two research studies were compared and checked against sense of community index (SCI) measures.

## **9. RESULTS AND DISCUSSION**

### *9.1. Emergency Phase*

The sense of belonging to a community and feeling like a large family, in which everyone should help the others and thus mutual needs be satisfied was a main factor during the rescue phase in both Neka and Harzevil. In Neka, the disaster happened at midnight. People who were alerted tried to save the lives of their families and neighbors [36]. According to the surveys carried out, and regarding the ratio of losses, there was a direct relationship between the degree of damage and sense of community in peoples of destroyed residential quarters [36]. They voluntarily helped to remove bodies from the debris, pulling out assets, settling displaced persons and showing their sympathy to harmed people.

In Harzevil, external help arrived at Manjil almost 24 hours later, because of the blockage of roads and difficulties in reaching the site. Regarding the criticality of the first hours after disaster in rescue operations, mutual feelings between residents of Harzevil played a crucial role in saving their lives. The Old quarter of Harzevil was near the epicenter and was situated in a steep terrain. Vernacular buildings made from mud in a traditional way were characteristics of this region. Residents of Harzevil helped their families and neighbors to escape from the debris and sustain their lives; within the first hours after disaster. So, although Harzevil was in a close distance to the epicenter of the quake and damages were more than 90 percent, it experienced less human losses than in Neka.

During the Relief phase, people helped their neighbors and friends by giving them food and clothes on a daily base in Neka. All these activities were done spontaneous and voluntarily [36,37]. In Harzevil, due to instability of the land; people were displaced and moved to safer lands in their downhill fields and gardens. The process of choosing the land, parceling lots and temporary settling were managed by the people themselves. In both cases, social networks reduced vulnerability and accelerated recovery. Social networks as part of social capital can play an important role in community resiliency [10,32]. In Harzevil, trust among the residents and their mutual connections helped them to settle in temporary settlements and stabilize their conditions. In Neka, some of the residents stayed in their semi-destroyed houses, even in disaster prone areas near the river and opposed the municipality for evacuation of the houses [35], in a joint effort and because of the existing social networks.

### *9.2. Place-making in Recovery Phase*

Close ties and strong feelings of belonging and mutual needs have been strong incentives for place-making after these disasters and in the reconstruction phase. In Neka, except those parts which were in the bed of the river or adjacent to it and were totally destroyed, other parts were reconstructed in situ. Even some parts of the residential quarters, located in flood prone areas and

partly damaged, were reconstructed for temporary settling but became permanent settlements, in contrast to planned efforts of authorities [35].

People reconstructed their public places as well. This was done by voluntary participation of residents. Thus, they rebuilt mosque, *takyah* (place for Muharram theatre), *hosseinieh* (place for mourning ceremony of Muharram) and other religious places which were destroyed by the flood. They gave financial help or joined those who were actually involved in reconstruction [36] (See Table 1). In this process, the number of gathering places, built by people, has even increased in comparison to the pre-flood condition.

TABLE 1: WAYS OF PEOPLE'S PARTICIPATION IN BUILDING PUBLIC PLACES IN FLOOD AFFECTED RESIDENTIAL QUARTERS OF NEKA.

Public Places and Urban Spaces of Neighborhoods	Before Flooding	After Flooding	Ways of people's participation
<b>Shahrdari</b>			
Shahid Beheshti Mosque	+	+	Manual and financial
Lands around river		Exercise and weekly markets	None (built by Municipality)
Zolfaghar swimming Pool	Vacant Lands		None (built by Municipality)
TarbiatBadani Pool	Vacant Lands		None (built by Municipality)
Sunday Market	In Chamazi quarter	In vacant lands near river	None (built by Municipality)
<b>Chamazi</b>			
Sahebolzaman Mosque	+	+	Manual and financial
Friday Mosque	+	+	Manual and financial
Nowrouzi Gymnasium	+	+	None (built by Municipality)
Madar Park		+	None (built by Municipality)
Bagher-al-olum Library	+	+(moved to another place)	None (built by Municipality)
<b>Commercial district</b>			
ShahmirzadihaHosseinieh	+	+	Manual and financial
Library and city Park	+	+(replaced by a fruit and vegetation market)	None (built by Municipality)
<b>Turk Mahalleh</b>			
Mosque of Turk Mahalleh	+	+	Manual and financial
<b>Narenjbagh</b>			
Fatemieh	+	+	Manual and financial
Coffee house (near crossroad)	+		Private
Coffee house (in front of Mahdieh mosque)	+		Private
Coffee house-Kebab house	+	+	Private
Rah Ahan Mosque	+	+	Manual and financial
Mahdieh Mosque	+	+	Manual and financial
TakyahNarenjbagh	+	+	Manual and financial
Quranic Society		+	Private
House of Quran		+	Private
Bordbar Sport Complex		+	None (built by Municipality)
Hosseinieh Martyrs of Qala-Sari		+	Manual and financial
Park & Pool of Narenjbagh hill		+	None (built by Municipality)

These spaces and places facilitate social interaction and needs fulfilment of residents. Built by community members' financial and manual assistance, they show their solidarity and caring for their community. People gather there for meetings, seeing each other and especially for religious rituals, which are the main public events in the community life. These ceremonies shape their collective memories and the community shared history.

Within the neighborhoods or in their vicinity, other urban spaces existed before the disasters or were created after it. These spaces, including public parks, libraries, and pools, were began at first by government aids for rehabilitation / renovation and then the municipality took the responsibility for finishing the projects. These places are mostly used by young people [36].

In Harzevil, houses were built by the residents of the community in the place of their temporary settlement. It was a group activity which was carried out by all of the residents and in the process, mutual needs and group interests strengthened their ties with the place [37]. It affirmed the psychological importance that creating one's home has for the people of the community regarding

basic shelter and safety needs [18]. Belonging to their place was so strong that those who left after the earthquake returned there after a while and rejoined their community [37]. Being a member of Harzevil quarter is an honor for residents. They, even confessing the better situation and land value of those quarters that are located near the transit road, don't like to leave their place for those ones. They value their quarter for its network of acquaintance, security, the quarter's prestige, its landscape, and climate due to distance from road [37]. The new quarter, built in accordance with their needs and imitating the structuring pattern of their old quarter, is so familiar to them that residents don't differentiate between the old and new quarter and consider them a single one [37]. It means that they not only have returned to a new normal life, but regard their life as a continuous process with the past.

People of the quarter have daily interaction with their neighbors. Women do their domestic affairs together and gather and chat in doorsteps or in house courts. Children play in the alleys and in front of the doors. Men gather and chat in haunting places or public spaces of the community in the afternoon [37]. They built new public places with characteristics similar to those which were in their previous quarter. A mosque was built by financial and manual help of residents in place of a mosque which was damaged by the earthquake [37]. Near the mosque a gathering space has been shaped for Moharram rituals and is almost an enclosed space functioning like a *Takyah*. The cedar tree, which is more than a thousand years old and is a symbol and also a sacred tree for people [37], has maintained its role as focus of gathering in Friday night's alms giving and feast of *Sizdahbedar*, a celebration dating back to pre-Islamic times. The Cedar T Junction (a point symbolizing the entrance to the previous French quarter), has maintained its role as a gathering place for men and young boys as well. These two locations in the old quarter; however, are among the main nodes of the community [37].

Thus, public places, built by the assistance of residents, encourage social gathering and develop social networks, which is an important factor to impact resilience [8,32]. People identify themselves with these places and their symbols. They provide settings for social interaction and religious rituals (especially Moharram rituals). In these occasions, people gather together and participate in processions; events that become dramatic in their lives and shape their collective memories and their shared history. History of the community and collective memories associated with it is much known among residents, so that, urges especially younger ones, who have left the community for working elsewhere, return to it for ceremonies like Ashura.

## 10. CONCLUSION

In summary, the evidence suggested that having feelings about and ties with the community where people live can play a crucial role in different phases of the disaster cycle. Close ties and interrelationships of members can be of great importance in the rescue-relief phase. Regarding the usual shortcomings in help operations by official organizations, the voluntary activities of residents of a community including: recognition of lost people; finding their actual condition in the time of hazard happening and providing manual and other kinds of help, can be of great importance in reducing losses and damages.

In the reconstruction phase, the mutual needs and shared goals of a community in providing shelter and developing their community is facilitated by mutual interaction of them and their active participation in building their homes and public places. Appropriating their public spaces according to their needs promotes identity and belonging and facilitates social relations. Mutual feelings about the community and its places help preserve place characteristics.

The process of building houses and especially public places of the community helps the residents in returning to a normal condition and providing them well-being and pleasure: the basic qualities of resiliency. When they participate in rebuilding their homes and public spaces, they shape their community history as an active context, a feature that ties them together and gives

them pride and identity. Feelings toward community and identification by it can help its residents to take an active role in community life and sustain its spirit. Public spaces and places of the community, built in this process, can become a setting for ceremonies, rites, rituals and events that create shared emotional moments of the community and build their collective memories. This shared history strengthens the sense of community among members and sustains their resilience.

Mutual feelings and social networks among the members of a community, as attributes of social capital, are adaptive capacities which help sustain resilience and should be considered in the process of resilience planning. However, these capacities can have negative effects on sustainable planning of communities, regarding the different interests and implications of the city and local communities, which should also be considered in the planning process.

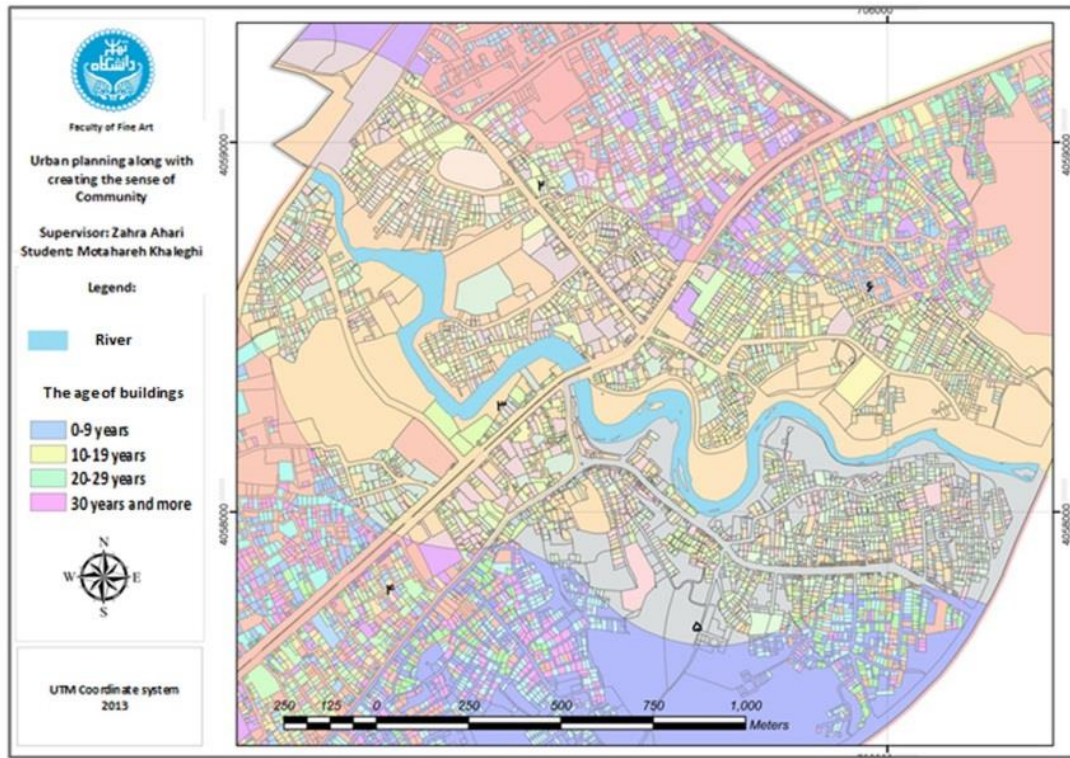


Figure 1: Location of disaster affected quarters of Neka and present condition of houses [36].



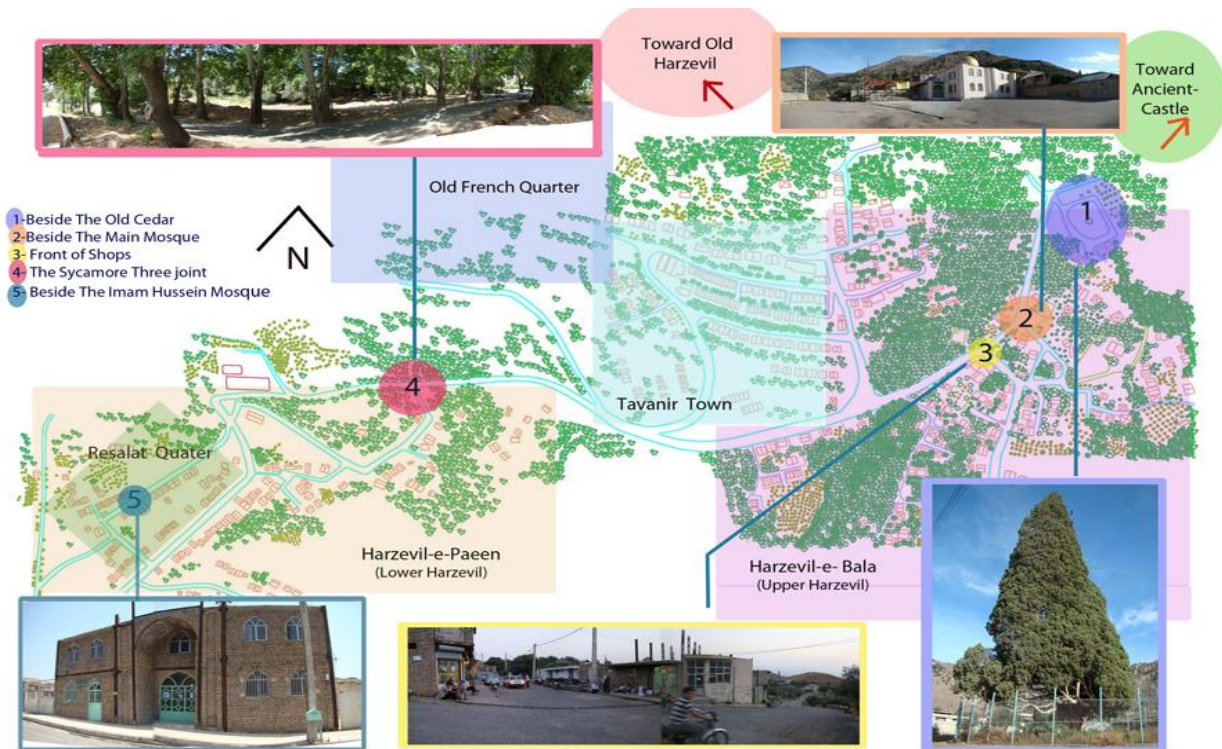


Figure 2: Location of reconstructed and old residential quarter of Harzevil and its public spaces and places [37].

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# Post-Disaster Blight Fight: The Merit of Creating a Composite Blight Index Map for Building City Resiliency

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### ***Abstract***

In the past decade hurricanes Katrina and Rita (2005), Gustav and Ike (2008) and Sandy (2012) have wrought havoc leading to mass evacuations in numerous U.S. coastal states including Louisiana, Mississippi, Alabama, Texas, New York and New Jersey. Subsequently, achieving sustainable and equitable recovery and building community resiliency to mitigate against future threats remains a challenge in these states. At the most general level, the term “community resiliency” refers to the capability of a community to rebound from an adverse situation. To achieve these goals recovery policies and projects often require resettling a large segment of the population away from unsafe housing. This inevitably leads to the depopulation of some neighborhoods leading to an increase in the number of uninhabitable abandoned homes further exacerbating the problem of blight. To ensure that true post-disaster recovery is accomplished, it is essential to create a comprehensive blight identification and management strategy. This paper discusses the steps taken to create a Composite Blight Index map for the City of Dallas, Texas using secondary data sources and GIS to serve as a tool for monitoring housing construction, rehabilitation and development changes and to calculate the cost of blight. In conclusion it is suggested that other cities could explore the creation of such a Composite Index to serve as a mitigation strategy for ensuring a healthier, safer and more resilient city.

***Keywords: Post-disaster Recovery, Blight Reduction, GIS Mapping, Composite Blight Index***

## **1. INTRODUCTION**

In the past decade hurricanes Katrina and Rita (2005), Gustav and Ike (2008) and Sandy (2012) have wrought havoc in numerous U.S. coastal states including Louisiana, Mississippi, Alabama, Texas, New York and New Jersey. Subsequently, achieving equitable long-term recovery remains a challenge in these states. The emphasis here is not only to help impacted cities and neighborhoods recover but also to build community resiliency as a means of mitigating against future threats. At the most general level, the term “community resiliency” refers to the capability of a community to rebound from an adverse situation. The concept has gained widespread interest since the adoption of the Hyogo Framework for Action 2005-2015, which called for building the resilience of nations and communities to disasters [1-3]. While disaster researchers have developed numerous

indicators to measure resiliency within the past decade, few agree on what and how the term should be measured. The dimensions of interest however, have been broadly classified as ecological, social, economic, institutional, infrastructure, and community competence [4-8].

Disaster recovery in an urban environment thus portends the restoration and enhancement of social networks, economic assets and livelihood rehabilitation, institutional and public infrastructure, and the revitalization and stabilization of affected neighborhoods through housing repair and redevelopment and blight eradication [9]. For example, in 2006, the City of New Orleans spearheaded post-hurricane Katrina rebuilding and redevelopment efforts that not only allowed for the expropriation of blighted properties but also served as a more comprehensive neighborhood redevelopment and commercial redevelopment approach. However, to achieve these goals, recovery policies and projects often require resettling a large segment of the population away from hazard prone areas and unsafe housing. While the effect of disasters on local communities varies, large-scale disasters calling for mass evacuations inevitably lead to the depopulation of some neighborhoods. This increases the number of vacant and uninhabitable abandoned homes, further exacerbating the problem of blight. This issue of post-disaster blight subsequently poses a serious obstacle to long-term planning and recovery processes. Further, if not properly addressed, blight can spread into surrounding neighborhoods and bring issues of safety, destabilization of the tax-base, and make building community resiliency even more difficult. Thus, to ensure that true community resiliency is achieved, it is essential to create a comprehensive blight identification and management strategy.

A disaster can either accelerate previously established blight or cause blight in what was previously a stable neighborhood. In this paper we discuss the steps taken to create a Composite Blight Index map for the City of Dallas, Texas using secondary data sources and GIS mapping tools to identify established blight, its causes, and cost to the city. The blight index includes physical and socio-economic indicators which have been confirmed as key dimensions in adding to, or detracting from community resiliency [4,5,8]. Consequently, we suggest that this index will be a useful tool in identifying hot spots of blight in the city and help inform and plan intervention programs and allocation of resources. The visual classification and depictions of blight on a map will also help city governance and urban planners expand their community's understanding of the problems and buy in support for policy initiatives. The following sections start with a literature review detailing the evolving definitions of blight by planning scholars and the blight indicators selected by various US cities to target blight eradication strategies. This is followed by the methods section which introduces the reader to the City of Dallas, and outlines how data was collected and mapped. The discussions and conclusions elaborate on the merits of creating such an index for every city to serve as a tool to identify blight, adopt remedial programs and measure their successes in post-disaster contexts.

## **2. EVOLVING CONCEPTS OF BLIGHT IN CITY PLANNING**

Numerous studies have described "urban blight" as a multidimensional concept and agree that collectively these dimensions have an adverse effect on surrounding neighborhoods. Wilson and Kelling's [10] notion of a "broken window syndrome" suggests that urban blight can be captured through the severity of untended properties and abandoned structures, reflecting the breakdown of physical, social, and economic conditions of a neighborhood. These conditions also signal lax code enforcement and control mechanisms for ensuring proper maintenance by property owners. Blight has also been defined in terms of the willingness of local residents in safeguarding the general welfare of others, as well as a reflection of police power that a city commands to coerce property owners to repair and invest in the upkeep of physical structures through special building codes and municipal zoning codes [11].

During the progressive era, the term “urban blight” referred to conditions of substandard housing, where urban ills could be tackled by providing families with decent homes. Achinstein [12] argued that a blighted area differed only in “degree” from an area that was not blighted. The doctrine of eminent domain was used to acquire and revitalize condemned neighborhoods. The U.S. federal government also played an active role by instituting the National Housing Act of 1937 aimed at resolving structural problems by providing loans and grants in aid to local governments. The statute provided funds for the production of homes for low income households. By the late 1940s, local governments (housing authorities) could use federal funds to purchase and clear slum neighborhoods and sell them to private developers. Housing studies at this time were based on the physical appearance of homes with the assumption that during strapped economic times residents lacked the incentive to reinvest or spend on the upkeep of their homes leading to general neighborhood deterioration.

While the 1950-60s continued to focus on structural conditions, newer studies also began examining the effects of blight leading to loss of productivity, capacity to render services or decline in demand for services, and depreciation of property values related to land-use conflicts. This shift in focus was largely concerned with the loss of neighborhood quality characterized as loss of prestige, an atmosphere related to despair, lack of aesthetics, and crime and disease, rather than what the property was used for. In the 1970s, blighted areas were defined as those with a high incidence of urban poverty, slums, and ghettos located in inner cities with old, substandard overcrowded housing, high crime rates, high concentration and proportion of blacks and other minority households. During this period, urban blight was regarded as a “pervasive process” that operated independent of the urban structure. By the mid-1970s, blight was predominantly associated with how it might impact health and safety of the residents. During this period, legal and statutory definitions of urban blight appeared in federal and state funded proposals associated with redevelopment and revitalization programs such as the Community Development Block Grant program and the Tax Increment Finance (TIF) laws in the 1970s and 1980s [11].

Scholars, in the 1980s, were influenced by the “spatial process” approach and argued that blighted areas had the tendency to affect other neighborhoods within a region. The idea that ghettos can spread to adjacent areas further prejudiced the real estate industry and financial institutions in redlining and selectively choosing who to provide loans to [13], having a negative spillover effect. In the 1990s attention focused on the “powerful negative mental image” of blight stemming from a “lack of order and social control in the community” [14] (p.413). Thus noise, graffiti, vandalism, abandoned buildings, people hanging out on the streets, unpleasant neighbors, crime and drug use and the inability to do anything about it, were considered indicators of blight. Recent studies have operationalized the concept of urban blight in terms of neighborhood attributes including crime, heavy traffic, and environmental degradation, and employed survey instruments as a way to subjectively assess blight [15].

This synthesis of literature from the progressive era of the 1930s-1940s until the present time in the United States demonstrates the ever evolving concept of blight and blight defining characteristics. Major scholarly work related to the conceptual definition of blight suggests that research has moved from objective measures such as the structural aspects of condemned housing, to a more process driven subjective assessment of understanding what leads to blight by examining neighborhood quality and socio-economic characteristics of neighborhood residents. Most empirical studies have used secondary data sources such as U.S. Census data, local housing survey data, American Housing Survey (AHS) datasets, Realtor databases, and have used a few physical and socio-economic indicators to study blight. However, it is evident that creating a ‘Resilient City’ calls for tackling the problem of blight as its negative spillover effects are numerous and hamper development.

TABLE 1: COMMON INDICATORS USED TO MEASURE BLIGHT.

Physical Indicators	Socio-economic Indicators
Abandoned properties	Low median income
Vacant land / Percent vacant land	Poverty level
Vacant properties	Change in renter occupied
Foreclosed properties	Change in home purchases
Demolition inspected	Growth ratio
Structural complaints	Declining population
Fire hazards	Single mother families
Structure sweeps/ re-inspection	Unemployment rate
Graffiti, overgrown weeds, litter	Low high school attainment rate
Lien foreclosures	Percent Ethnic minority
Deferred property maintenance	Percent foreign Born
Deteriorated / unkempt	Total population
Dilapidated buildings	Lower number building permits
Unkempt sewage maintenance	Percent sub-prime loans
Illegal dumping	
Vandalism and crime	
Broken/ boarded up windows	

### 3. MEASURING BLIGHT IN EIGHT US CITIES

The fight against blight is not new. In order to identify which indicators are commonly used to measure blight, an extensive review of efforts by eight U.S. cities: New Orleans, Detroit, Pittsburgh, Oakland, Springfield, Cincinnati, Atlanta and Philadelphia, was conducted (see Table 1 for the indicators used). Of these abandoned properties, vacant lots and properties, foreclosed properties, demolition inspected, and lien foreclosed properties were used by more than four of these cities. Socio-economic characteristics pertaining to population, race, ethnicity, income below poverty line, number of renters, unemployment rate and single mother families were the most common ones obtained from the US Census – American Housing or Community Survey.

#### 3.1. Abandoned Properties

According to Whitaker and Fitzpatrick [16] (p. 5), “[a]bandonment usually occurs when a property’s carrying, operating, or rehabilitation costs are too high relative to the property’s value.” However, there appears to be a pervasive problem in identifying abandonment. Bender [17] utilized a definition of abandonment in his Chicago study as title forfeiture. That is, if the private owner ceded the title to the City of Chicago and the building was subsequently demolished by the city, it was an abandoned structure. White [18] used neighborhood level data from New York City, and labeled properties that were in tax arrears for 18 months to 3 years as abandoned. Arsen [19] suggested that if one assumes that some landlords would eventually pay their delinquent property taxes, a building can be characterized as abandoned only if the building was in the process of foreclosure proceedings brought by the City of New York. More recently Whitaker and Fitzpatrick [16] noted that foreclosure was a very noisy measure of the impact of vacancy and abandonment and suggested that abandonment be looked at in conjunction with vacant and tax delinquent properties. Due to limitations in gathering empirical data from home owners that abandon their properties scholars are using aggregated data available through the AHS.

#### 3.2. Vacant Lots and Buildings

A vacant property, defined as a building or lot that has been vacant for two or more years, can attract crime, cause blight, and pose a threat to public safety [20]. According to 2010 Census Bureau data, non-seasonal vacant properties have increased 51 percent nationally from nearly 7 million in

2000 to 10 million in April 2010, with 10 states seeing increases of 70 percent or more. High foreclosure rates have also contributed to the additional vacancies. Scholars have blamed these increasing vacancy rates in inner cities on ill-conceived federal policies that have subsidized outmigration of the middle class from the central cities since World War II, as well as the political and economic fragmentation of our metropolitan areas [21]. With the demand for homes in inner city neighborhoods falling, the spiraling effects are evidenced through deferred maintenance, defaulting on mortgage obligations and property tax payments and finally loss of ownership or abandonment [22]. Thus vacant properties “impose a significant externality (cost) on neighboring property owners by lowering the market value of their properties, which reduces their equity and thus their wealth, and makes resale of their properties very difficult. ...which forces central cities to either raise real property tax rates or suffer reduced tax revenues” (p. 303). There is ample evidence to suggest that these locales are then plagued with crime, vandalism and arson [23].

### *3.3. Mortgaged Foreclosed Properties*

Mortgage foreclosure is the result of a process that lasts at least 60 days and most often significantly longer. When a homeowner fails to pay her mortgage debt for more than 60 days, the property is considered to be in default and the holder of the failed mortgage (e.g., a bank, lender) may act to foreclose on the property. Several studies have examined the spillover effects of foreclosures. Immergluck and Smith [24] measured the effects 1-2 years after foreclosures and found that they caused a 0.9% decline in house value for all homes within an eighth of a mile radius. More recently Leonard and Murdoch [25] used the 2006 housing data obtained from the Dallas Central Appraisal District to indicate that nearby foreclosures produced a reduction in home prices. They found that an additional foreclosure within 250 feet of a sale negatively impacts selling price by approximately \$1,666 (p. 317). Thus, mortgage foreclosure events might have long-term impacts on neighborhoods as they accelerate the degradation of quality of life.

### *3.4. Tax Foreclosed Properties*

While some foreclosed properties may be vacant only temporarily, others may take longer to be occupied if repair and rehabilitation of the properties require additional investment and time to market the properties to potential buyers or investors. The problem of vacant properties defaulting on tax liens is particularly acute in blighted neighborhoods given an already depressed local housing market. Whitaker [26], for example, found that “foreclosed properties in high-poverty areas can remain vacant for years.” Although, according to the “Uniform Standards of Professional Appraisal Practice 2010-2011”, foreclose liquidations sales may not be used when selecting comparable properties. The literature on the impact of tax foreclosure properties consistently finds that tax foreclosures negatively affect home sales in surrounding properties [26].

### *3.5. Tax Delinquent Properties*

The properties with tax liens indicate residential or commercial property owners that have not paid their property taxes. The effect of delinquent property taxes on the value of surrounding properties is not immediately evident unless the property is taken from the owner through tax foreclosure and left vacant or abandoned [16]. The assumption is that property owners are aware of the risk of losing their property if they default on their property taxes, and those with no capacity or incentive to pay property taxes are less likely to maintain and invest in the up-keep of their property, thus accelerating the process of neighborhood decline. Once the property is not physically maintained and deteriorated--- it further depresses the local housing market. According to Alexander [27], tax delinquency is “the most significant common denominator among vacant and

abandoned properties.” Furthermore, a high volume of tax-delinquent properties presents administrative challenges in managing the properties given the length of time to foreclose a property, therefore making the number of tax delinquent properties an appropriate indicator of blight conditions.

#### **4. METHODS**

##### *4.1. Background*

In an effort to better meet its neighborhood revitalization goals, Dallas Area Habitat for Humanity (DAHfH) a nonprofit organization that builds homes for the needy in the City of Dallas, sought to determine the impact of blight on Dallas neighborhoods. To achieve this goal, they commissioned us (four faculty from the Department of Public Administration at the University of North Texas) in 2012. The intended purpose of the study was to identify and create a blight index map for the city of Dallas; to estimate the economic cost of blight to the City of Dallas using this Composite Index; to help inform blight reduction policies; and to allow DAHfH to use these findings to advocate for Dallas’s forgotten neighborhoods by presenting its neighborhood revitalization goals to private donors and other funders.

The operational definition of blight provided by DAHfH was “*Neighborhood blight consists of those conditions that threaten the health and safety of neighborhood residents, depress an area’s quality of life and jeopardize the social and economic viability of an area.*” This definition and an extensive review of scholarly literature elaborating the multidimensional nature of blight, along with an understanding of key indicators of blight gleaned from examining eight U.S. city efforts, guided our methodology for the creation of a Composite Blight Index using U.S. Census Data, secondary data from City and County officials and GIS mapping tools.

##### *4.2. Study Site – City of Dallas, Texas*

Dallas is currently the third-largest city in the state of Texas with a population of approximately 1.2 million [28]. It encompasses a land area of 384.93 square miles and is the ninth-largest city in the U.S. and part of the fourth-largest metropolitan area in the nation. According to the 2010 Census, 50.7% of the population was White (28.8% non-Hispanic white), 25.0% was Black or African American, 0.7% American Indian and Alaska Native, 2.9% was Asian, and 2.6% was from two or more races. Hispanic or Latino origin comprised 42.4% of the total population (they may be of any race). It is worth noting that although Dallas started out as a predominantly white city in the 1940s, non-Hispanic whites now represent less than one-third of the city's population. At the 2010 census the city's age distribution of the population showed 26.5% under the age of 18 and 8.8% who were 65 years of age or older with the median age at 31.8 years. The population distribution by gender was equal with 50.0% male and 50.0% female. According to the 2008-2012 American Community Survey [29], the median income for a household in the city was \$42,436. Male full-time workers had a median income of \$35,905 versus \$34,936 for female full-time workers. The per capita income for the city was \$27,011. About 20.1% of families, and 37.7% families with female householder with no husband present, were below the poverty line, including 19.6% between the ages of 18-64 and 14.2% aged 65 or over.

The City of Dallas is characterized by an aging housing and commercial building stock. About 40% of known dated commercial properties and 54% of residential properties were built before the 1970s. The home ownership rate is at 45.2%, which is 19.3% less than the state average, with the median value at \$129,600 of owner occupied housing units in 2007-2011. The housing occupancy and housing tenure data available at the United States Census Bureau (2011) American Community Survey indicates that there are 515,515 housing units in the city of Dallas with 455,371

(88.3%) of them occupied and 60,144 (11.7%) vacant. Housing tenure data shows that of the 455,371 occupied housing units only 198,413 (43.6%) are owner-occupied and the remaining 256,958 (56.4%) are renter-occupied. The presence of a high percentage of vacant units and renter occupied tenure, compounded by an aging housing stock, with limited reinvestment or revitalization efforts, have contributed to neighborhood decline, and blight producing factors.

Parts of the city of Dallas lie within five counties: Dallas, Denton, Collin, Kaufman and Rockwall. The census tracts that overlap the boundaries of the City of Dallas are located in these five counties. In all, 383 census tracts overlap with the city of Dallas. For the purpose of consistency and ease of data collection and management, this study investigated the conditions of blight for the tracts that overlap with the city limits and fall within Dallas County resulting in a total of 350 study tracts (see Fig. 1).

#### *4.3. Blight Indicators Selected and Mapped*

Although not meant to be comprehensive, a list of seven **Physical Indicators** and seven **Socio-economic Indicators** were selected for the City of Dallas after having informal face-to-face conversations with key personnel from various departments including the Department of Code Compliance, County Tax Assessors office (properties with outstanding property tax), City Police Department (violent and nonviolent crimes), Housing Development Corporation, and Real Estate Management Department. As charged, we were cognizant in ensuring that the data were available online from publically available databases and news reports, and most importantly through numerous Open Records requests to various city departments. It was with the intent that our index could be updated with new census data or city initiatives e.g. code enforcement, mortgage foreclosures, crime prevention strategies etc. over time, and be replicable so that other cities could use it in their blight reduction endeavors and also to build in resiliency.

Further, for classifying and comparing the conditions of blighted neighborhoods at the census tract level across the city, a Composite Blight Index Map was created using all 14 indicators. The seven physical indicators selected used were, 1) Abandoned properties, 2) Vacant residential properties, 3) Vacant commercial properties, 4) Mortgage foreclosed properties, 5) Tax foreclosed properties, 6) Tax delinquent properties, 7) Demolished structures; while the seven socio-economic indicators were, 8) Poverty, 9) Unemployment, 10) Ethnicity, 11) Race, 12) Renter household, 13) Population, and 14) Single-Parent Household.

As the city of Dallas lacks a clear definition of abandonment or a systematic data gathering mechanism for abandoned properties, we utilized data from the U.S. Postal Service (USPS) as a proxy for identifying abandoned structures with the assumption being that if mail is not picked up from, or delivered to, certain properties for over 90 days they are likely to be abandoned. The USPS data was downloaded for the four quarters of 2011. Each quarter lists the total number of properties that did not pick up any mail for at least 90 days at the census tract level. Since some of these properties may remain abandoned even during the 2nd, 3rd and 4th quarter, the total counts of abandoned properties were averaged for the year of 2011.

A list of vacant (commercial) and vacant (residential) properties was obtained from two sources –the Dallas Central Appraisal District (DCAD) and Dallas City Hall. The process of identifying vacant structures was complicated by a lack of standard definition on the length of time the property is left vacant. There was also a lack of systematic data on vacant structures. Moreover, even when a property is vacant, it does not imply it is abandoned or in disrepair due to neglect by the property owners. Our list of addresses for vacant properties from DCAD is an aggregated number of all properties containing vacant land and structures identified as “land only” for residential and “Vacant” for commercial and does not disaggregate vacant structures per se.

Data was obtained on mortgage foreclosed properties for 2011 from the North Texas Real Estate Information Systems, Inc. (NTREIS). The NTREIS data, although deemed reliable, is not

guaranteed for accuracy and it has been suggested that it be independently verified. The list of properties on the land bank database for 2011 was used as a measure of tax foreclosed properties. Data on properties that had defaulted in paying property taxes was obtained from the Dallas County Tax Office, IT Department at census tract level for 2011. The ASCII dataset obtained from the Dallas County Tax File (TRW File) containing delinquent property tax information was used to obtain the account ID and the levy balance (property tax balance). The data was spatially joined with the respective GIS parcel data from DCAD. DCAD is responsible for appraising property for the purpose of property tax assessment on behalf of the 61 local governing bodies in Dallas County. The data was then saved as a DBF file and imported into ArcGIS where the account was “summarized” by aggregating the “Levy Balance.”

A list of properties that had either court orders on them, or were City owned, and demolished from 2007-2011, was obtained through an Open Records request from the Sustainable Development and Construction Department at City Hall. This list included City initiated demolition of commercial/ residential apartments and houses, as well as demolition due to structural fires. These addresses were geocoded using GIS and combined with DCAD parcel data to arrive at the total square footage of demolished properties to calculate the cost of demolition.

## 5. ANALYSIS AND RESULTS

The data for the seven physical indicators obtained as detailed above were geocoded and aggregated (counted) and merged at the Census Block/ Tract level along with the seven socio-economic indicators downloaded from the U.S. Census data [28]. Considering that there was no consensus regarding which measure or indicator of blight was more important or severe than the other, and whether physical indicators of blight led to social and economic degradation or vice versa, a decision was made to assign all 14 indicators “**equal weights**,” so that the total added up to 100. The data was analyzed using the Quartile Method to categorize the indicators into 4 groups: (1) No Blight, (2) Low Blight, (3) Moderate Blight and (4) Blighted. This results in each category having an equal number of tracts.

The method is especially useful in this case because of the unavailability of thresholds to define what constitutes the point when a neighborhood becomes blighted and the specific factors contributing to this change. Fig. 2 illustrates the Composite Blight Index which is useful in first identifying and then focusing blight reduction strategies in selected neighborhoods and then monitoring the positive changes over time. The frequency distribution of the blight index by census tracts for physical indicators, socio-economic indicators, and the combined Composite Index is presented in Table 2. Based on 14 equally weighted blight indicators, 48 of Dallas’ 350 census tracts fall into the most blighted category. These 48 census tracts represent 16% of the area within the City, but account for much of the burden created by blight.

Combining physical risk factors to socio-economic factors is important for several reasons. Firstly, blight is a function of both physical and socio-economic factors and hence should be assessed comprehensively. Secondly, most policies developed to mitigate the effects of blight have been piecemeal and independent of the influence of social factors on blight and vice versa. Thirdly, using spatial mapping technology for this index allows us to visually understand the spatial correlation of these indicators on blight and the geographical influence and diffusion leading to increase or decrease of blight in the surrounding neighborhoods.



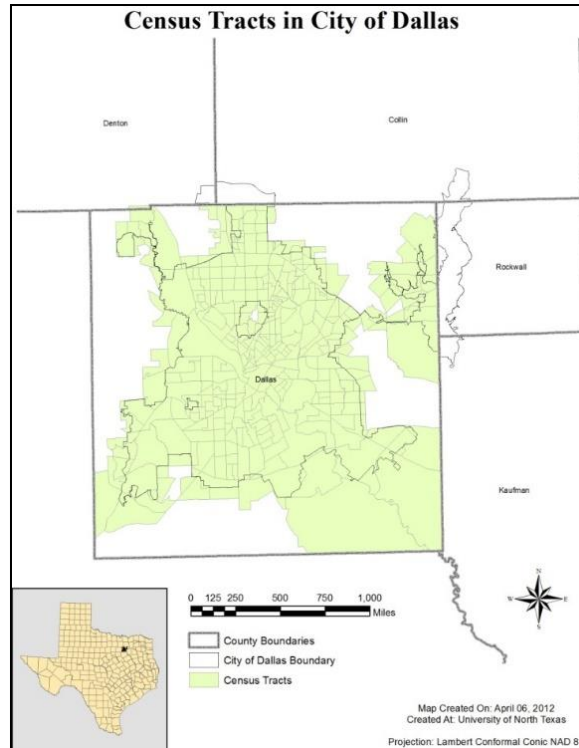


Figure 1: Map Identifying Boundaries for the City of Dallas.

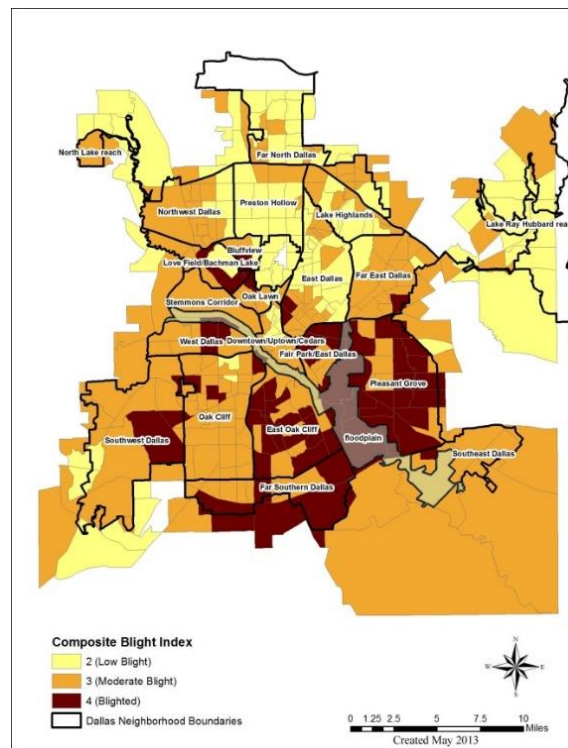


Figure 2: Composite Blight Index Map for the City of Dallas.

TABLE 2: NUMBER OF CENSUS TRACTS IN THE THREE BLIGHT CATEGORIES.

Categories	Physical Indicators		Socio-economic Indicators		Composite Index	
	# of census tracts	Sq. Miles	# of census tracts	Sq. Miles	# of census tracts	Sq. Miles
1 No blight	7	11.02	9	1.86	0	0
2 Low blight	172	172.94	102	172.18	118	162.52
3 Moderate blight	127	299.47	134	355.81	184	359.11
4 Blighted	44	140.32	105	93.9	48	102.12
Total	350	623.75	350	623.75	350	623.75

*Note: The frequency table illustrates that none of the 350 Census tracts constituting the City of Dallas is free of all 14 measures of blight suggesting that urban blight is a matter of degree.*

### 5.1. Merits of a Composite Blight Index

There are several advantages to creating such a Composite Blight Index. First it uses secondary data gathered from the U.S. Census Bureau website, Dallas Central Appraisal District, and City Hall allowing for changes to be tracked over time. Using open source data also makes it accessible to practitioners and policy makers. The standardized measure allows us to track changes and also suggests replication of the methodology. The Composite Index takes into account the multidimensional aspects of blight conditions including physical quality of life indicators and social dimensions. The use of a GIS platform allows for better visualization of the patterns of blight and directs attention to hotspots within political boundaries for targeted intervention programs and comprehensive land use planning.

There are benefits to further examining the seven physical indicators (i.e. abandoned properties, vacant residential and vacant commercial properties, mortgage foreclosure properties, tax foreclosed properties, tax delinquent properties and demolished properties) to help in calculating the cost of blight to the city. For example we found that,

1. Properties delinquent in paying taxes were mainly found in the moderate and high blight areas, with 49.4% individual properties in moderate blight areas, and 40.8% found in the 48 high blight census tracts.
2. About 35.9% of vacant structures with reported fire incidents were also delinquent on property tax payments, leading us to estimate that 4 out of every 10 vacant properties reporting fire incidents will also be delinquent on their property tax payments.
3. Compared to properties in the high blight category, properties in the low or moderate blight categories are less likely to have an outstanding non-tax lien. Specifically, a property in the high blight category is 23% more likely to have an outstanding non-tax lien than a property that falls in the low blight category.
4. The total demolition costs for residential properties in the “low blight” category totals only \$4,326. The total cost of demolition in the “moderate blight” category totals \$871,244.50, which is approximately 53% of the total cost. The total cost of demolition in the “high blight” category totals \$771,609.50, which is approximately 47% of the total demolition costs.

## 6. CONCLUSIONS

This study sought to create a Composite Blight Index for the City of Dallas that the city officials, nonprofit agencies and policy makers can use to observe the patterns of blight and target interventions appropriately. Extant literature on building community capacity and resiliency

confirms that enhancing physical infrastructure and the increasing social and economic competencies are key dimensions in increasing city resiliency. Thus we are confident that the physical and socio-economic indicators we have used in creating the Composite Index captures these significant dimensions of resilience at a macro scale for Dallas. Tracking these indicators over time can help decision-makers understand the impact of changing policies on the reduction on blight and the associated costs.

Moreover, as the index uses public data, it can also be replicated and adapted by other municipalities for the specific purposes of increasing disaster resiliency. Unique threat characteristics such as risks from coastal surge, seismic, flood or tornado risks and previous disaster history data can be included as map layers for adding identified risk areas in the city. The use of standardized data allows policy makers and researchers to track changes over time and potentially evaluate impact of policy intervention in specific geographic areas of choice. The comprehensive knowledge that is achieved from the Composite Index will help cities overcome tentative and piecemeal efforts of recovery and adopt more sustainable measures to enhance resiliency. In addition, the visual classification of blight can help increase community engagement about policy initiatives at city hall meetings or through the media.

One of the major benefits of monitoring blight through this composite spatial index is its utility in educating planners, city governance staff, citizens and policy makers in understanding the risk of blight at present and in the future. This is especially salient, considering that natural and human induced threats continue to be on the rise, often leading to deterioration of otherwise vibrant neighborhoods in their aftermath. Second, it can serve as a tool for scenario development, to estimate the impact of such disasters on different census tracts and the resulting increase of blight in one, or the reduction in another from housing loans, grants or intervention programs. Subsequently, mitigation plans can be created by emergency management departments in conjunction with the city planning department in anticipation, thereby helping to build city resiliency. Third, indicators that best measure resiliency, identified through literature and expert opinion, can be added to develop a resiliency index for blighted neighborhoods. Also, future improvements in data collection techniques can help add additional critical indicators to monitor blight. This can then be used as another element in the Comprehensive Planning documents developed for a city or a metropolitan region.

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# From Endurance Time to Value Based Seismic Design: A Path towards Seismic Resiliency

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### **Abstract**

Assessment of seismic safety and performance of buildings and structural components in cities is one of the major challenges in Earthquake Engineering. Various limitations of simplified seismic analyses have increased the need for more realistic and reliable dynamic analysis procedures. Endurance Time (ET) method is a response-history based analysis procedure where structures are subjected to gradually intensifying dynamic excitations and their performance is assessed based on their response at different excitation levels correlated to specific ground motion intensities. This procedure considerably reduces the required huge computational demand of a complete response history analysis while maintaining the major benefits of it, i.e. accuracy and insensitivity to model complexity. The objective of this research is to introduce the concept of a new design methodology based on the total value of the structure namely Value Based Design of structures (VBD) by the use of potential benefits of the ET method. In this approach the design sections of structural elements are assumed as optimization parameters and a design with the minimum total cost during its life span is being sought. This will result in maximized value of the structure in its life time. For each possible candidate design the damages due to probable earthquakes in its life time is estimated by the ET method and the expected cost of damages is calculated using Life Cycle Cost Analysis (LCCA). LCCA has provided a reliable tool for estimating damage cost due to future earthquakes during the design life of a structure. This analysis in companion with an optimization algorithm can result in a design with the least total cost. Application of ET method in combination with the concept of LCCA can pave the way for practical Value Based Seismic Design of structures. This methodology and potential benefits when considering the need for moving towards more resilient cities is discussed.

**Keywords:** *Earthquake Engineering, Value Based Seismic Design, Structural Assessment, Endurance Time Method, Nonlinear Dynamic Analysis*

## **1. INTRODUCTION**

The resilience in cities and meanwhile optimum allocation of public resources necessitates structures with predictable and reliable performance in the case of natural hazards during their life time. Earthquakes are considered to be one of the most destructive and costly natural hazards that threaten cities in seismically active regions. So, assessment of seismic safety and performance of

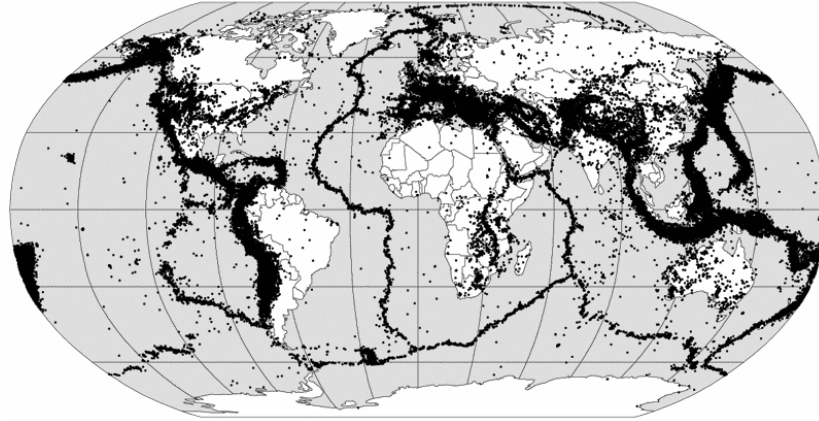
buildings and structural components in cities is one of the major challenges in Earthquake Engineering. Reliability and accuracy of seismic analysis procedure is a key concern in almost all seismic assessment procedures for both new and existing structures especially in modern approaches of seismic design. Various limitations of simplified seismic analyses have increased the need for more realistic and reliable dynamic analysis procedures. Endurance Time (ET) method is a response-history-based seismic assessment procedure where structures are subjected to gradually intensifying dynamic excitations and their performance is evaluated based on their response at different excitation levels correlated to specific ground motion intensities [1]. This procedure considerably reduces the required huge computational demand of a complete response history analysis while maintaining the major benefits of it, i.e. accuracy and insensitivity to model complexity. This viable advantage provides the prerequisites to directly incorporate the new age design concerns such as life cycle cost of the structure in design procedure [2].

Life-Cycle Cost Analysis (LCCA) can be used in order to evaluate the performance of the structure during its life span in economic terms. The LCCA principles are based on economic theories and it was mainly implemented to introduce financial concerns in structural design area. However, this analysis can provide a baseline to incorporate technical, economic and social or any other intended measures thought to be impressive in resilience of cities in design procedure. The broad concept of resilience demands a flexible design framework to employ these several criteria from various fields of expertise in design stage. LCCA demands performance assessment of the structure in multiple hazard levels. Considering the required repetitive and massive analyses in this procedure, application of ET method in combination with the concept of LCCA can pave the way for practical Value Based seismic Design of structures. This methodology and its potential benefits will be discussed.

The objective of this research is to introduce the concept of a new design methodology based on the total value of the structure namely Value Based Design of structures (VBD) by the use of advantages of the ET method. In this approach the design sections of structural elements are assumed as optimization parameters and the optimization goal is to minimize the total cost of the structure during its life span resulting in maximized value of the structure in its life time. Reduced computational demand in ET analysis method provides the prerequisites to use optimization algorithms in design procedure. For each possible candidate design the damage due to probable earthquakes in its life time is estimated by ET method and then the probabilistic cost of damages is calculated by the presented method. The optimization algorithm used in this research is genetic algorithm as used in a work by Estekanchi and Basim [3] and the calculated damage cost added to the initial cost i.e., the total cost is used as the cost function of the optimization problem to be minimized.

## **2. EARTHQUAKES AND RESILIENCY**

Cities cannot be considered resilient if they are not protected against the dangers and potential damages that may be imposed by natural hazards. Earthquakes are considered to be one of the most destructive and costly natural hazards that threaten cities. So, stability of community during and after seismic hazards is thought to have a determinative impact on the resilience of cities in seismically active regions (Fig. 1).



*Figure 1: Epicenters of known Earthquakes 1963-1998 [4].*

On this issue, resilience may have broad measures in the whole city as a body or sub-measures in individual buildings. Also, the impact of seismic hazards on a community may be studied from various points of view and also various concepts may be defined as resilience such as time to recovery, life safety or damage reduction. For example, “downtime” seems to be an impressive resilience measure for a hospital building or a fire station besides life safety and it is wise to consider these measures with reasonable portion in design stage. Some limitations may be required for such critical facilities too. In Fig. 2 a fire station which has known role in cities recovery is shown that is heavily damaged and obviously has lost its functionality in Bam earthquake (2003) in southeastern Iran. Appropriate measures, in a quantifiable manner, seem to be required to incorporate such consequent events in earthquake engineering scope.



*Figure 2: A fire station heavily damaged by the Bam earthquake [5].*

Incorporation of seismic resilience factors in design procedure requires mitigation from common design procedures intended to focus on a limited number of objectives such as structural performance or loss prevention to a broader one with the capability to incorporate any desired and advancing terms in priority measures among design alternatives. Codes for building design, commonly, set some minimum compliance-based standards and in performance terms, we can be confident that they will provide safe buildings, but they promise little in terms of recovery. Readily



introduced value based design can provide a wider description of design target by defining the earthquake consequences such as structural damages, loss of contents, losses due to downtime, human injuries and fatalities in the form of quantifiable parameters. In this way, it is expected that the resultant design will perform with desired post-earthquake capabilities with manageable disruption.

### **3. LIFE CYCLE COST ANALYSIS**

LCCA has become an important part of structural engineering to assess the structural comeback and evaluate the performance of the structure during its life span in economic terms and has gained considerable attention of decision making centers to decide on the most cost effective solution related to the construction of building structures in seismic regions. LCCA has provided a reliable tool for estimating damage cost due to future earthquakes during the design life of a structure. Instead of “cost” in dollars, in decision making process, any other measure can be used to compare and evaluate design alternatives’ expected operation. Although in construction industry LCCA was firstly introduced in economical investment assessment of infrastructures, nowadays, this analysis as an essential component of the design process is used to control buildings in seismically active regions and is widely used in risk assessment and decision analysis. Here, total expected cost imposed by earthquake occurrences during a structure’s life span is selected as an evaluation measure since engineers might be more familiar with this concept. A correlation will be required to express other measures mentioned above such as downtime or social impacts in economic terms and dollars. By the use of this method the expected total cost of a structure including the initial cost and also losses resulting from earthquakes during its life span can be considered as the main indicator of the priority of design alternatives. This analysis in companion with an optimization algorithm can result in a design with the least total cost. LCCA demands the calculation of the cost components that are related to the performance of the structure in multiple earthquake hazard levels. However, these calculations require repetitive and massive analyses of performance assessment and huge computational demand and sophistications involved may make optimization algorithms impractical or the simplifications used decrease the reliability of the outcome. Application of ET method in combination with the concept of LCCA can lead to development of a framework for practical Value Based seismic Design of structures.

### **4. CONCEPTS OF ENDURANCE TIME METHOD**

A reliable estimation of the damage to various structures and their compartments requires realistic evaluation of seismic response of structures when subjected to strong ground motions. This in turn requires the development and utilization of advanced numerical techniques using reasonably realistic dynamic modeling. While any serious development in the area of seismic resistant design has to be backed up with decent real world experimental investigation, the type and number of decision variables are usually so diverse that numerical investigations remain to be the only practical alternative in order to seek good solutions regarding performance and safety.

In the Endurance Time (ET) method, structures are subjected to a predesigned intensifying dynamic excitation and their performance is monitored continuously as the level of excitation is increased [6]. A typical ET Excitation Function (ETEF) is shown in Fig. 3. Level of excitation or excitation intensity can be assumed to be any relevant parameter considering the nature of the structure or component being investigated.

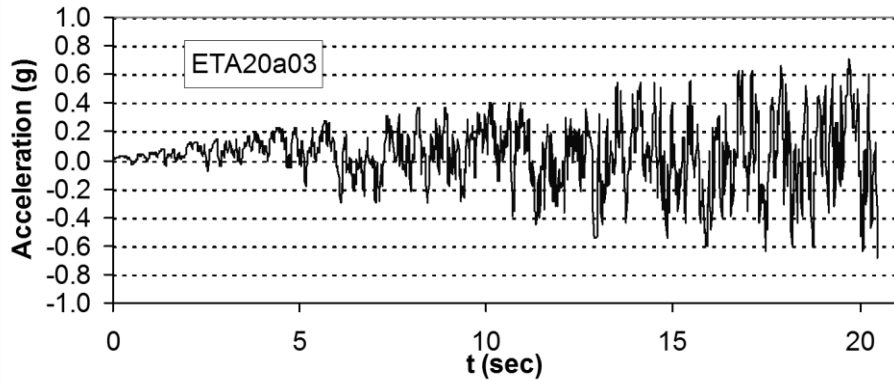


Figure 3: Typical ET record incorporating intensifying dynamic excitation.

Classically, parameters such as peak ground acceleration (PGA) or spectral intensity have been considered most relevant parameters in structural design. More recently, parameters based on input energy, displacement and damage spectra are also being proposed as a better representative of the dynamic excitation intensity considering structural response. Fig. 4 shows the response spectra produced by a typical ETEF at various times. Various ETEFs are publicly available through Endurance Time Method website [7].

While response spectra has been considered to be a standard measure of intensity in producing currently available ETEFs, other intensity measures can also be considered as well. As can be expected, most of these intensity measures are correlated to each other and the problem is to choose a best combination of various parameters to achieve better intensifying excitations that can produce better output. Here, the response spectra have been considered as the intensity parameter and ETEF has been produced in such a way that the response spectra produced by each window from time 0 to  $t$  is proportional to a template response spectra.

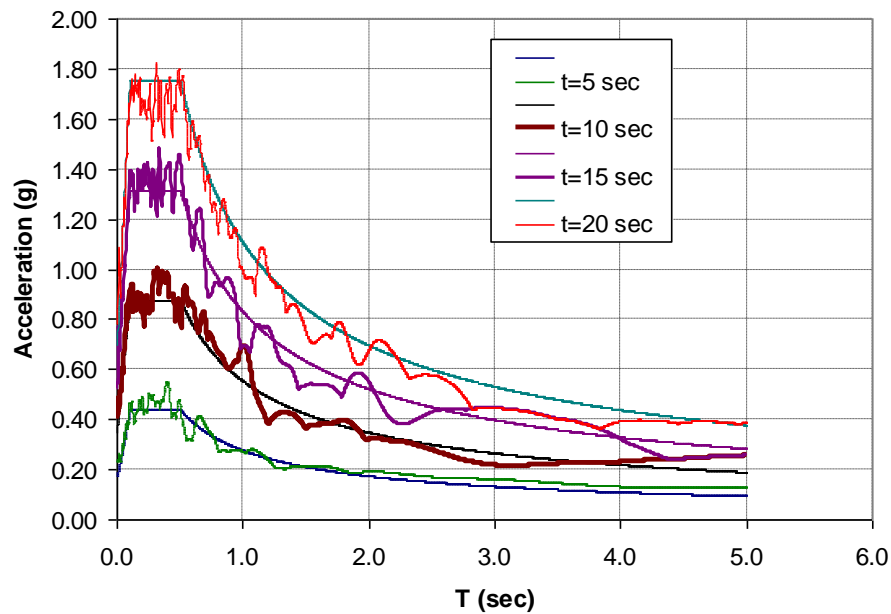


Figure 4: Typical response spectra of ET records at various times (ETA20a02).

The application of the ET method in performance-based design was studied by Mirzaee et al. [8] introducing “ET curve” and the “Target Curve”, which expresses respectively the seismic performance of a structure along various seismic intensities and their limiting values according to code recommendations. Substituting return period or annual probability of exceedance for time in the expression of the performance will make the presentation of the results more explicit and their convenience for calculating probabilistic cost will be increased [9]. Also, damage levels had been introduced to express the desired damage states in quantifiable terms.

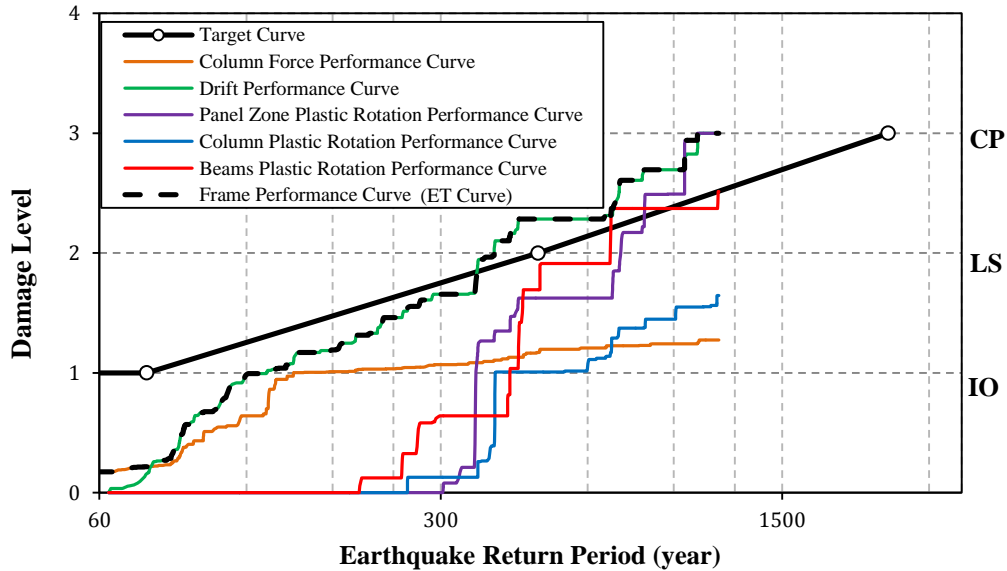


Figure 5: Performance assessment by ET method.

Hazard return period corresponding to a particular time in ET analysis can be calculated by matching the response spectra at effective periods, e.g. from 0.2 to 1.5 times of structure’s fundamental period of vibration. The procedure is based on the coincidence of response spectra obtained from the ET accelerogram at different times and response spectra defined for Tehran at different hazard levels. In Fig. 5 a sample target curve and performance curve considering various performance criteria is depicted where ET analysis time has been mapped into return period on horizontal axis. As it can be seen the structure satisfies the code IO (Immediate Occupancy) level limitations but it has violated the LS (Life Safe) and CP (Collapse Prevention) levels limitations and the frame does not have acceptable performance. It can be inferred one of the advantages of ET method is that the performance of the structure in continuous increasing hazard levels can be properly depicted in an easy to read figure.

## 5. VALUE BASED SEISMIC DESIGN BY THE ET METHOD

ET analysis provides a proper baseline to perform economic analyses on design alternatives with acceptable computational cost. While value can be defined and considered in its broad sense for design purposes, for the clarity of explanation, in this research we consider the structure that is more economical to construct and maintain, to be the most valued. Initial construction cost and expected seismic damage cost throughout the life time of the structure are usually the two most important parameters for decision making [10]. In this study, the cost of exceedance of a damage state is obtained as a percentage of the initial cost from a table of ATC-13 [11] (Table 1) and also piecewise linear relation has been assumed to establish a continuous relation between drift and cost [2]. This is a very rough estimate of cost components and a detailed assessment is necessary to

evaluate the expected cost, especially, human fatality and injury related losses has a determinative portion in expected costs. The method, with no limitation, has the capability of incorporating detailed calculation on cost components and will be investigated in further studies.

One of the major obstacles in seismic damage cost assessment of structures is response estimation of structures subject to ground motions in multiple intensities. Various simplified procedures for seismic analyses have been used by researchers in order to overcome huge computational demand involved in assessment of several design alternatives. Nevertheless, cost assessment has been mostly used in comparative study among limited number of design alternatives and incorporation of life cycle cost directly in design process has attracted the attention of researchers [10,12,13]. Push-over analysis has been widely used as seismic assessment tool in this area. However, well known limitations of this analytical tool besides its disability in estimating non-structural cost components due to floor acceleration have increased the need for more realistic and reliable dynamic analysis procedures with a tolerable computational demand. In this section, ET analysis has been used to estimate seismic response of the structure and the procedure to calculate the required cost components has been demonstrated.

TABLE 1: DAMAGE STATES, DRIFT RATIO LIMITS AND CORRESPONDING COSTS [11].

<b>Performance level</b>	<b>Damage states</b>	<b>Drift ratio limit (%)</b>	<b>Cost (% of initial cost)</b>
I	None	$\Delta < 0.2$	0
II	Slight	$0.2 < \Delta < 0.5$	0.5
III	Light	$0.5 < \Delta < 0.7$	5
IV	Moderate	$0.7 < \Delta < 1.5$	20
V	Heavy	$1.5 < \Delta < 2.5$	45
VI	Major	$2.5 < \Delta < 5$	80
VII	Destroyed	$5.0 < \Delta$	100

Expected annual damage cost is found to be the most proper intermediate parameter to calculate life cycle cost of structures using ET method. A practical approach to express the concept of seismic damage cost is considering the average annual repair cost. To calculate this parameter, the annual probability of exceedance of drift ratio should be determined. By reversing the return period on the x-axis of the ET curve to obtain the mean annual rate of exceedance and using it on the y-axis, the annual rate of exceedance of the interstory drift can be obtained. If the interstory drift is replaced by damage cost applying the linear relationship discussed previously the annual rate of exceedance for damage cost can be obtained as shown in Fig. 6. This curve is called "Loss Curve." The area under the loss curve represents the mean annual total damage cost caused by all earthquakes in one year [14].

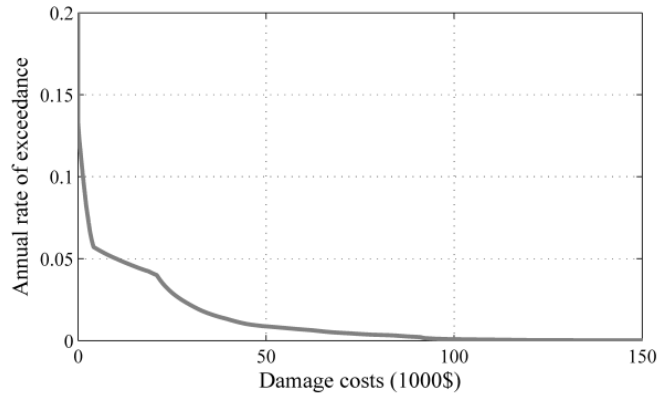


Figure 6: A typical Loss Curve for the 3 story frame.

The total life-cycle cost is considered as the sum of the initial construction costs (\$300 per m<sup>2</sup> over the 200 m<sup>2</sup> total area of the structure) and the present value of the annual damage costs summed up through the life time of the structure. A discount rate equal to 3% over a fifty-year life of the building has been considered to transform the damage costs to the present value and calculate the expected damage cost of the structure in its life time. This total cost is used as the cost function in optimization algorithm and due to capabilities of genetic algorithm the resultant design is the global optimum alternative with a high chance.

## 6. CASE STUDY: 3 STORY STEEL MOMENT FRAME

In order to demonstrate the method a three story and one bay steel special moment frame is optimally designed according to Iranian National Building Code (INBC), which is almost identical to the ANSI/AISC360 [15] LRFD (Load and Resistance Factor Design) design recommendations. Also, the frame is designed optimally to conform to FEMA350 [16] limitations as a performance based design criteria. The performance of the designed frames is investigated by the ET method and as a third step a new design sections has been acquired through the introduced method to have the minimum total cost during its life time that is assumed 50 years. For the value based design the total cost of the structure is selected as the optimization objective to be minimized. Genetic algorithm (GA) has been used to find the optimum design. Alternative designs should meet some initial constraints. One of the constraints is strong column and weak beam criterion which should be checked and the other constraint that should be considered before the analysis phase is that the selected sections for columns in each story should not be weaker than the upper story. Beside these constraints, all AISC 360 checks must be satisfied for the gravity loads. Once the expressed constraints are satisfied, the LCC analysis is performed. It is important to note that each of these feasible organisms is acceptable design according to the code ignoring seismic actions. But, in order to reach the optimum solution, algorithm will reproduce new design alternatives based on the initial population and mutate until the stop criteria is met.

Genetic algorithm with an initial population size of 100 leads to an optimum design after about 1800 ET response history analyses. Total costs for feasible design alternatives in optimization procedure are depicted in Fig. 7.

The resultant prescriptive, performance based and value based designs of the frame are different due to their distinct basic design philosophies. Design sections for each method are depicted in Fig. 8. Seismic performance of each design of the frame is shown in Fig. 9. It can be seen that for the value based design the structure satisfies performance limitations of FEMA350 with a margin that is justified by economic concerns.

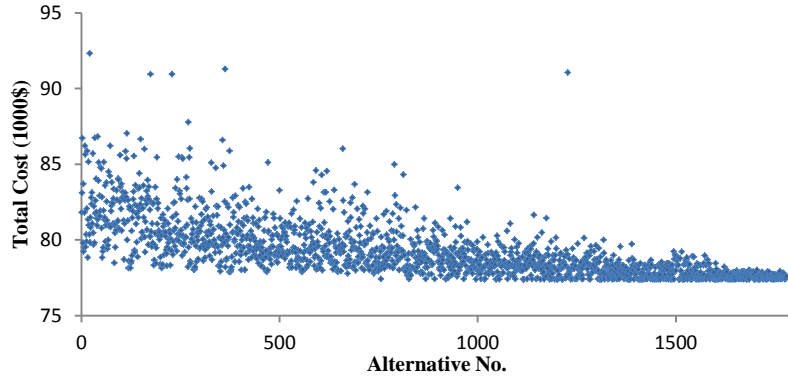


Figure 7: Total costs for feasible design alternatives in optimization procedure.

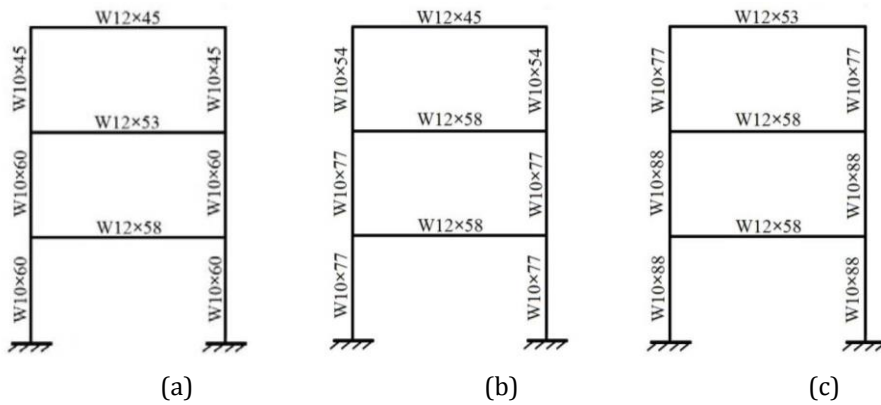


Figure 8: Frame design results after optimization: (a) Codified Design; (b) Performance Based Design; (c) Value Based Design (least LCC).

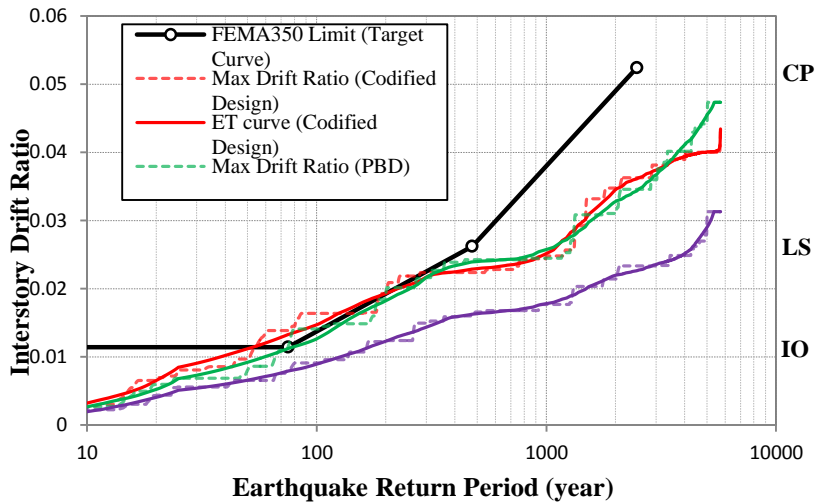


Figure 9: Comparison of the frames response at various hazard levels.

Components of life cycle cost for the three structures (i.e. prescriptive, performance based and value based designs) are compared here. These structures are designed optimally based on various design philosophies. In Table 2 initial costs based on used initial material, present value of damage

costs due to seismic hazards with various exceedance probabilities and the determinative part i.e. expected total cost of three structures are presented. It can be verified that a value based design has the least total cost and would be an economical alternative in long term. An increase of \$2,300 in initial material cost over the prescriptive design will lead to a decrease of \$4,600 in expected damage cost having totally \$2,290 profit. Although performance based design has a minor expected total cost in comparison with the prescriptive design, neither the prescriptive design criteria nor the performance based one will necessarily lead to an economical design in long term.

TABLE 2: VALUES OF LIFE CYCLE COST TERMS FOR THE THREE DESIGNS (IN \$1,000s).

Design Type	Initial cost	Damage cost	Total Cost
Prescriptive	60.14	19.55	79.69
Performance based	61.22	17.77	78.99
Value based	62.44	14.95	77.40

## 7. SUMMARY AND CONCLUSIONS

A framework for direct use of the concept of value in the structural design procedure incorporating the benefits of Endurance Time (ET) method has been established. Application of the ET analysis in Life Cycle Cost Analysis (LCCA) has been briefly explained. ET method and resultant performance curve has provided a proper baseline to calculate expected damage cost, while the required computational effort is in an acceptable range to be used in conventional optimization techniques. To demonstrate the method and compare it with prescriptive and performance based design criteria, a three story moment frame has been optimally designed according to three distinct design philosophies: a prescriptive design code, a performance based design guideline and also the introduced methodology namely Value Based Design of structures (VBD). Structural performance and life cycle cost components for the three structures have been compared. The resultant prescriptive, performance based and value based designs of the frame are different due to their distinct basic design philosophies. Results show that the code based design of the structure will not necessarily result in an economical design with lower total cost in life time of the structure. Performance based design in this case turns out to require higher initial material cost in comparison with the prescriptive design due to its more restricting limitations, and as expected, better performance in various hazard intensities. The value based design, however, demands the highest initial material cost, yet the least total cost among three, justifying the increased initial cost.

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# Enhancing Resiliency through Building Code Enforcement in the City of Los Angeles

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### **Abstract**

The Los Angeles Department of Building and Safety (LADBS), the largest organization of its kind in the United States, and many other Public organizations are working actively to improve the Los Angeles City's resiliency. This paper presents an overview describing the functions and responsibilities of the LADBS. It provides a summary of the Department's code adoption, approval processes for construction projects and role of enforcement of the City's building construction codes in the enhancing resiliency of the City. It also, reviews the significant contribution of the lessons learned from the past earthquakes in enhancing the construction standards that mitigate the effect of future earthquakes. Furthermore, it briefly describes role of the Department's Emergency response Preparedness plan for major disasters, which is established to carry out recovery activities and minimize social disruption after a disaster event.

## **1. BACKGROUND**

### *1.1. City of Los Angeles*

With a population of more than 3.8 million (2012), the City of Los Angeles (LA) is the largest city in California and the second largest city in the United States. LA is located in high seismic category zones and the City limits cover more than 470 square miles (1217 square kilometers). It is one of the most complex megacities of the world, centers for culture, media, academics, business and international trade. The map of the City of LA and its 15 council districts and some of the known earthquake faults in the LA vicinity are shown in Appendix A.

### *1.2. Los Angeles Department of Building and Safety*

The Los Angeles Department of Building and Safety (LADBS) is the largest building department in the United States with 200 engineers, 430 inspectors and 280 administrative and support staff. The Department provides services to the residents of the City of LA through 5 construction services centers, 2 testing laboratories and 6 satellite inspection offices.

## 2. WHAT DOES LADBS DO?

### 2.1. Mission Statement

The Mission of the Department of Building and Safety is to protect the lives and safety of the residents and visitors of the City of Los Angeles and enhance the quality of life, housing, economic prosperity, and job creation citywide. Through a timely, cooperative, and transparent process, the **DEPARTMENT ADVISES, GUIDES, AND ASSISTS CUSTOMERS** to achieve compliance with the Building, Zoning, Plumbing, Mechanical, Electrical, Disabled Access, Energy, and Green codes and local and State laws **TO BUILD SAFE, WELL, AND FAST.**

### 2.2. Functions and Responsibilities

The responsibilities of the Department of Building and Safety are assigned to the following four bureaus:

**The Engineering Bureau** is primarily responsible for the plan checking, product approvals, and permit issuance related to building and land use projects within privately owned properties in the City of Los Angeles. In the course of carrying out these responsibilities, the Engineering Bureau enforces the structural, building, disabled access, green building standards, plumbing, mechanical, electrical, grading and zoning regulations of the City. In addition, the Engineering Bureau is responsible for reviewing requests for building, plumbing, mechanical and electrical product approvals through its Building Research Section and its Electrical and Mechanical Testing Laboratories.

**The Inspection Bureau** is responsible for inspection of all construction activities for new and existing buildings, plumbing, mechanical, electrical, elevator and pressure vessel systems, the enforcement of applicable State and Local laws relating to existing buildings and properties, and the administration of various special programs mandated by the City Council. The Inspection Bureau also provides tests and licensing of the deputy inspectors, fabricators and certified testing laboratories.

**The Code Enforcement Bureau** is responsible for the enforcement of Municipal Code requirements for all violations in existing buildings in the City of Los Angeles except for rental multi-family dwellings. The Bureau handles complaints, citations, processing of vacant and nuisance buildings for repair or demolition, Signs, the Vehicle Establishment Inspection Program, the Proactive Code Enforcement Program, and many more.

**The Resource Management Bureau** is responsible for the direction and coordination of administrative and financial projects, system development and training. It acts as the emergency disaster coordinator for all Department operations and has developed response and recovery plans for major disaster events.

### 2.3. A Few Facts About LADBS

The following statistics represent the Department's annual construction activities workload:

- Reviews and approves plans for over 41,400 projects
- Issues over 126,000 permits with an estimated valuation of over \$3.8 billion
- Issues over 30,000 e-Permits over the Internet
- Conducts over 674,000 inspections
- Serves over 372,000 walk-in customers
- Serves over 644,500 phone customers
- Brings over 5,900 properties back to compliance

- Issues nearly 14,000 trade licenses for 14 different occupations

All of these are accomplished by our dedicated, knowledgeable and hardworking team of over 830 employees.

### **3. ENHANCING RESILIENCY THROUGH CODE ENFORCEMENT**

The following code adoption, implementation and enforcement measures essentially contribute in resolving building safety and seismic safety issues, mitigating earthquake hazards in buildings and enhancing the City's resiliency.

#### *3.1. LA City Codes for Design and Construction*

The City of LA Building Code was established in 1889 with the appointment of the first Superintendent of Building. The LA Seismic code design requirements were initiated as a result of a 6.25 magnitude earthquake that struck the City of Long Beach in California on March 10, 1933. Since then, through the intervening years, the LA codes have been amended and revised regularly. The City now, follows the State Building Code which is revised every three years to keep pace with the ever-changing technology of the construction industry and the new proven concepts of structural design.

##### *3.1.1. Three-year code cycle adoption*

The building code is an evolving system. Every three years the International Code Council (ICC) publishes the International Building Code (IBC) and International Residential Code (IRC). Nation-wide, these codes are commonly referred to as the model building codes. In between the publications of the code, ICC holds code hearings throughout the country to gather input and comments from building officials, engineers, architects, building organizations and other building experts. During this process, the proposals and comments brought up by the various stakeholders are taken to committees within the ICC and to the public for comments. Ultimately, approval by voting is necessary on the proposed changes in order to be included in the next cycle of codes.

Once the IBC and IRC are published, each state within the country adopts these codes in a certain timeframe. The State of California, like most of the other states, adopts the California Building Code (CBC) and the Residential Code (CRC) after making necessary amendments to the IBC and IRC. Local amendments are necessary because the model codes are in a sense too broad, and in some cases they can lack specific details for certain regions within the country.

The state of California mandates that all of its local jurisdictions, such as the City of LA, adopt the California Codes (Building, Residential, Green Building standards, Mechanical, Plumbing and Electrical) six months after their publications. However, during this period local jurisdictions have the ability to make any necessary amendments to the California Codes. The local amendments to the State codes can only be made due to geologic, topographic or climatic findings and can only be more restrictive.

The City of LA adopts the Los Angeles Building Code (LABC) and Residential Code (LARC) after making the necessary amendments to the CBC and CRC. The LA City has made various local amendments through the years to the California State Codes, which are also carried forward in every three-year code cycle. The new amendments to the Building and Residential Codes are made by collaborative efforts of committees formed with in-house staff, other local jurisdictions, the Structural Engineers Association of Southern California (SEAOSC), the American Institute of Architects, Los Angeles Tall Buildings Structural Design Council, and other stakeholders. The code enhancements are carefully reviewed based on the past knowledge and experience brought by these highly qualified stakeholders and lessons learned from the past earthquakes.

### *3.1.2. Current building code*

The current 2014 LABC and LARC are the adopted 2013 CBC and CRC, based on the 2012 IBC and IRC, with LA's amendments. Earthquake engineering requirements are based on ASCE7-10 published by the American Society of Civil Engineers.

## *3.2. Approval Process for Construction Projects*

The Department provides independent review of engineering plans and reports, issues permits and provides inspection at various stages of construction.

LADBS has knowledgeable and experienced plan check engineers and inspectors to perform the work. Most of the engineers are registered Professional Engineers with the State of California. In addition, LADBS has more than 18 supervisors and managers who are registered as Structural Engineers with the State. The Department provides training on a continual basis to its engineers and inspectors to keep them up to date with current engineering practices and code changes and even offers training outside of the Department, for entities such as other agencies and the industry.

### *3.2.1. Preparation of plans by licensed design professionals*

Construction plans and design calculations for projects are required to be prepared by design professionals and submitted to the LADBS for review and approval. A licensed architect or engineer by the State of California is required for most projects.

### *3.2.2. Plans/Reports review and permit issuance by LADBS*

The plan review process of projects, approval and construction inspections of permitted projects by LADBS engineers and inspectors are the Department's primary means of ensuring safe buildings. The construction plans, design calculations, and soil and geology reports for building permits are reviewed by the LADBS plan check engineers, soils engineers and geologists for compliance with the City's codes and regulations. All new buildings, additions, alterations, and tenant improvements require plan check review, permit issuance and inspection process. This applies to all residential (single family and multi-family dwellings), commercial, industrial and private school projects. Public schools are handled by a California State Agency.

The scope of plan review, permit issuance and inspection of projects are for building, structural, seismic, grading, disabled access, zoning, green building standards, electrical, mechanical, plumbing, etc.

### *3.2.3. Required construction inspections by LADBS inspectors*

Constructions are inspected by LADBS inspectors at different stages to ensure compliance with the approved plans and to provide quality control and quality assurance necessary for the approved construction. Approval by an LADBS inspector is required before proceeding to each new construction phase. The contractor has to request for inspection after completion of each phase of construction such as grading, foundation, underfloor, framing, shear wall, roof, interior finishes, plumbing, mechanical, electrical and eventually final inspection. The LADBS inspector identifies work that does not match the approved plans or comply with the city's codes and then prepares written correction notices as needed. Upon completion of the corrections, the contractor requests another inspection to show compliance and proceed to the next phase of construction.

In addition to the inspections conducted by the LADBS inspection staff, LADBS requires periodic visual structural observations of the engineer or architect of record to assure that major structural elements and connections are properly installed as designed and approved in the construction plans and submittal of structural observation reports to the LADBS Inspector.

Also, any phase of work that requires continuous inspection, such as concrete placement or field welding, is required to be witnessed by a third party deputy inspector approved by the City of

LA. The LA City licensed deputy inspector provides continuous inspection of the work being performed and provides reports to the LADBS inspectors in order to ensure quality construction.

The contractor is held accountable to correct all deficiencies including those identified by the structural observer and deputy inspectors.

#### *3.2.4. Certificate of occupancy*

After completion and approval of all required inspections, a Certificate of Occupancy is issued by an LADBS building inspector that allows the building to be occupied. This certificate documents the successful compliance with the requirements of the City's codes and becomes part of the Department's permanent records.

#### *3.2.5. Alternate materials and products approval*

To assist designers and contractors with selecting code compliant alternate materials and products, LADBS reviews, evaluates and approves technical reports of alternate materials and products submitted for the Department's approval. These reports are prepared by independent testing agencies approved by the LADBS using established criteria for fire resistive components, structural connections, alternate materials, etc. The product evaluation criteria are based on American Society for Testing and Materials (ASTM) standards, which are approved by the International Code Council and/or other nationally recognized organizations that develop codes and test standards. The LADBS policy on the approval process is outlined in the LADBS Information Bulletin, "P/BC 2014 -119 Policy on Accepting Alternate Building Materials or Products" can be obtained at: <http://ladbs.org/LADBSWeb/information-bulletins.jsf>.

### *3.3. Lessons Learned from the Past Earthquakes*

Every major earthquake provides new knowledge on ground motions and their impact on the buildings. It allows engineers and researchers to observe and study the performance of the various building constructions during the earthquake. Their efforts will identify necessary modifications to the codes in order to build or retrofit with construction standards that mitigate the effects of future earthquakes. The lessons learned from the Northridge Earthquake, a major earthquake that hit the LA Basin, have made a significant contribution in enhancing the seismic design requirements of the building code.

In the early morning of January 17, 1994, a 6.7 magnitude earthquake struck Northridge, a populated suburb of the City of Los Angeles (about 30 km northeast of downtown Los Angeles) in the San Fernando Valley and caused a lot of damage particularly in low-rise buildings. This was the worst earthquake to hit the Los Angeles basin since the 1971 San Fernando Earthquake. The Northridge earthquake shaking lasted about 20 seconds. Seventy-two deaths were attributed to the earthquake and over 9,000 people were injured. The earthquake caused over \$30 billion dollars in estimated damage, and it was one of the costliest natural disasters in U.S. history.

Immediately following this earthquake, LADBS established a Joint LA City/SEAOSC engineering Task Group to study the earthquake damage to various types of construction. The Task Group looked into the performance and damage of wood frame construction, concrete parking structures, steel frame buildings, non-ductile concrete frame buildings, ground motions, tilt-up wall construction and nonstructural elements, i.e. piping, chimneys, ceilings, etc.

The Northridge earthquake taught us many lessons about the performance of these types of buildings. The results of the studies were used to develop and implement emergency code changes, retrofit standards and code amendments. Some of the reported problems were:

- Narrow wood shear panels, stucco and drywall construction did not perform as expected.
- Numerous hillside residential buildings had severe damage and some collapsed and caused

injuries and a few deaths.

- Masonry and tilt-up concrete wall buildings with wood flexible roof diaphragms failed at the roof to wall connections.
- Numerous steel moment frame welded joints were found to have fractures through the welds and beam-column panels.

The task group later expanded to form a joint venture of the Structural Engineers Association of California (SEAOC), Applied Technology Council (ATC) and California Universities for Research in Earthquake Engineering to develop solutions to the problems observed in steel moment-frame buildings. This eventually evolved into the Federal Emergency Management Agency (FEMA) study and the FEMA 350 through 353 documents for steel moment-frame buildings. These documents recommended seismic design criteria for new buildings, seismic evaluation and upgrade criteria for existing buildings, post-earthquake evaluation and repair criteria, and quality assurance guidelines, respectively.

LADBS was proactive in proposing code amendments for new construction and mandatory and voluntary seismic retrofit ordinances for existing buildings to mitigate loss of life and damage to property caused by the effects of the next earthquake. Some of the changes were implemented within weeks of the earthquake by passing urgency ordinances or directives.

The Northridge Earthquake pointed out the importance of proper detailing and assurance that the load path be maintained. This eventually led the City of Los Angeles to require visual observation of the structural system by the registered design professional responsible for the structural design of the project, called "Structural Observation". The Structural Observation is performed for general conformance to the approved construction plans at significant construction stages and at completion of the structural system. The Structural Observation does not include or waive the responsibility for the inspection required by the LADBS inspectors.

The Northridge earthquake also resulted in improved hillside building constructions by requiring new hillside structures to be horizontally anchored to their foundations. In addition, existing wood frame cripple wall buildings are voluntarily being retrofitted with the Los Angeles City's developed standards, and these are also being used outside the City by other agencies.

### *3.4. Seismic Retrofit Programs in LA*

Four mandatory and five voluntary Seismic Retrofit Programs have been implemented and enforced in the City of Los Angeles to mitigate loss of life and damage to property caused by the effects of a moderate to a severe earthquake in vulnerable buildings. These programs are summarized in Tables 1 and 2.

### *3.5. Earthquake Recording Instrumentation*

The LABC assists with the future development of earthquake design by requiring strong motion recording instruments to collect data during seismic events. The LABC requires every new building over ten stories in height or over six stories and more than 60,000 square feet to be equipped with at least three approved recording accelerographs. Installation criteria are described in the LADBS Information Bulletin, "P/BC 2014-048 Specifications for Strong-Motion Accelerographs and Requirements for Installation and Servicing."

In addition, buildings designed using time history analysis methods are required to be equipped with additional instruments. Locations of these instruments are identified during the structural engineering review process. These more complicated building designs are required to use the strong motion system design and criteria described in the LADBS Information Bulletin, "P/BC 2014-117 Structural Monitoring Equipment in Buildings Designed with Nonlinear Response History

Procedure.” Both of these bulletins may be found at <http://ladbs.org/LADBSWeb/information-bulletins.jsf>.

TABLE 1: MANDATORY EARTHQUAKE HAZARD REDUCTION PROGRAMS.

Type of Building / Program	Starting Date
Existing Unreinforced Masonry Buildings - <i>designed Prior to October 1933</i> (LABC Chapter 88) <ul style="list-style-type: none"> <li>• <i>Mandatory installation of wall anchors, additional shear resisting elements and diaphragm strengthening.</i></li> </ul> 8,080 Buildings Affected 8079 Buildings Complied	1981
Existing Tilt-Up Concrete Wall Buildings - <i>designed Prior to January 1976</i> (LABC Chapter 91) <ul style="list-style-type: none"> <li>• <i>Requires installation of anchors between walls and roofs and strengthening of roof diaphragms to improve collapse prevention.</i></li> </ul> 2,638 Buildings Affected 2638 Buildings Complied	1994
Special Provisions for Repair of Welded Steel Moment Frame Buildings in High Earthquake Damaged Areas (Ordinance No. 170406, effective 3/7/95) <ul style="list-style-type: none"> <li>• <i>Owners were required to sample beam to column joints and provide LADBS with a report. If damage was found, then additional testing and repair were required.</i></li> </ul> 255 Buildings Affected 254 Buildings Complied	1995
Initiation of Seismic Gas Shutoff Valves (Ordinance No. 170406, effective 3/7/95) 30,000 complied per year	1995

\*The above Chapters of the LA City Building Code are found at <http://ladbs.org/LADBSWeb/codes.jsf>

TABLE 2: VOLUNTARY EARTHQUAKE HAZARD REDUCTION PROGRAMS.

Type of Building / Program	Starting Date
Existing Wood Frame Residential Buildings with Weak Cripple Walls and Unbolted Sill Plates (LABC Chapter 92) • <i>“Cripple Walls”: walls between foundation and first floor • Most cripple walls constructed without complete “load path” between floor and foundation • Applies to one to four-family dwellings • Installation of anchor bolts and shear connections</i> Anchor LA Program-Los Angeles City’s developed standard Plans are also being used outside of the City by other agencies.	1996
Existing Wood Frame Residential Buildings with Soft, Weak or Open Front Walls (LABC Chapter 93) A current motion is placed to make it mandatory and the Department is working on it. • <i>Applies to buildings used as apartment houses, hotels, lodging houses, or congregate residences. • Upgrade lateral load resisting systems of the first levels that were constructed without adequate lateral load resistance</i>	1998
Existing Hillside Buildings (LABC Chapter 94) • <i>Upgrade of the structure at below the “base-level-diaphragm” of buildings constructed on “hillsides” • Installation of anchor bolts to the foundation and additional shear resisting elements below base-level-diaphragm</i>	1996
Existing Reinforced Concrete Buildings and Concrete Frame Buildings with Masonry Infills - <i>designed Prior to January 1976</i> (LABC Chapter 95) • <i>The engineer may upgrade the lateral load capacity to 75% of the current code level forces • Currently under review for a mandatory seismic retrofit consideration</i>	1996
Existing Reinforced Concrete and Reinforced Masonry Wall Buildings with Flexible Diaphragms - <i>designed after January 1976</i> (LABC Chapter 96) • <i>Upgrade of cast-in-place concrete or masonry wall buildings constructed under building codes effective prior to January 1, 1995 • Upgrade of tilt-up concrete wall buildings constructed under building codes effective after January 1, 1976 • The engineer may upgrade the lateral load capacity to 75% of the current code level forces</i>	1996

\*The above Chapters of the LA City Building Code are found at <http://ladbs.org/LADBSWeb/codes.jsf>

### 3.6. Emergency Response Preparedness

When an earthquake disaster strikes a city, there is an immediate need for trained inspectors and engineers to evaluate the safety of the city’s buildings and structures. Thus the training of the

jurisdiction's inspectors and engineers, architects, and other city's building inspectors that may assist through mutual aid programs is critical. The Applied Technology Council (ATC) report, ATC-20, has been widely used in earthquake recovery efforts.

The LADBS is a key member of the City's Emergency Operations Center (EOC). The EOC will coordinate all resources (i.e., personnel, food, shelter, etc...) within the City family. The LADBS has developed response and recovery plans for major disaster events and continues to update them on a periodic basis in order to carry out recovery activities and minimize social disruption. Most of these plans are reviewed annually.

In the event of a catastrophic earthquake, LADBS will take the following actions:

1. Send mass notification messages to all LADBS employees alerting them of the event and asking them to report their availability.
2. Deploy a team of cadres to respond and assist at EOC.
3. Set up the Building and Safety's Department Operation Center to coordinate all resources within the Department.
4. Set up an Incident Command Post near the epicenter to coordinate all resources within the affected area.
5. Deploy specially trained teams of inspectors and engineers to evaluate whether Essential Government Buildings are safe for continued occupancy or they must be vacated immediately.
6. Direct all other inspection and engineering staff to meet at the Department's Incident Command Post before conducting safety assessment of all other buildings to receive instructions.
7. Gather damage information quickly and report to the Mayor and the City Council. Mutual aid may be requested at this time.
8. Provide rapid evaluation of damaged buildings and post the buildings in accordance with ATC - 20 guidelines to inform owners, occupants, and the public about the condition of a damaged building in terms of its suitability for occupancy and general use following an earthquake.

### *3.7. ATC-20 Rapid Evaluation of Damage and Posting Procedures*

The primary goal of safety assessments is to quickly determine the safety of essential facilities, to identify those structures that can be fully or partially occupied, and to identify safe shelter for those left homeless. Staff will be teamed up with one or two other individuals, with ideally at least one inspector and one engineer per team. The team will be given a list of addresses or city blocks to survey for damages utilizing the ATC-20 procedures.

#### **[Evaluation Levels]**

**Rapid Evaluation:** This first level of evaluation is normally simple. It is designed to quickly designate the apparent **SAFE** and the obviously **UNSAFE** structures. Doubtful structures should be designated for a "Detailed Evaluation".

**Detailed Evaluation:** The Detailed Evaluation is the second level of examination. It consists of a thorough examination of a structure, inside and out, and is designed to result in the rating of such structures as either **SAFE** for use, potentially dangerous (i.e., **RESTRICTED USE**), or **UNSAFE**. It is normally performed by a structural engineer or building inspector/structural engineer team.

**Posting Placards:** Inspected buildings are posted by either green, yellow or red placards according to extent of damage and condition of the building.

**Inspected (Green):** An inspected building will be posted Green, when there is no restriction on use or occupancy and the lawful entry, occupancy, and use of the building is permitted. Any building with observed damage that does not appear to pose a safety risk can be posted Green.

**Restricted Use (Yellow):** An inspected building will be posted Yellow, when there are some risks from damage in all or part of building and is off limits to unauthorized personnel. In this case, possession recovery may or may not be permitted and a detailed evaluation will be required for re-



occupancy.

**Unsafe (Red):** An inspected building will be posted Red, when there are severe structural damage, signs of falling, collapse or other hazards exist in the building. In this case, the building cannot be entered or occupied and the owner must mitigate hazards to satisfaction of jurisdiction to gain entry. This does not necessarily indicate that the building has to be demolished.

#### 4. CONCLUSIONS

As described above, the following key functions play critical roles in achieving the LADBS mission of enhancing seismic safety in the City of Los Angeles, mitigating earthquake hazards and enhancing the City's resiliency.

- The updated and current City Codes for design and construction with the amendments developed and implemented from lessons learned from past major earthquakes are expected to result in buildings with reliable performance in resisting earthquake forces.
- The LADBS approval process for construction projects has been designed to include independent review of plans and related reports by the Department's experienced and knowledgeable engineers. It also includes inspections by LADBS inspectors in different stages of construction. This process ensures compliance with the City Codes and policies, and construction compliance with the approved plans. It also provides the quality control and quality assurance necessary for the approved constructions.
- Seismic retrofit programs in Los Angeles mitigate earthquake hazards in the existing buildings.
- The City of Los Angeles earthquake recording instrumentation requirements are result of the Department's remarkable efforts to assist the future development of earthquake designs.
- The Department's emergency response preparedness and recovery plans for major disaster events will assist the City to carryout recovery activities and minimize social disruption after a catastrophic event.

All these core functions, along with the LADBS's constant efforts to improve quality control and quality assurance in building constructions, collectively, enhance the ability of the City in containing the effects of occurring earthquakes and rebound more quickly from a major disaster event.

Information presented in this paper is available from the following sources:

- [1] City of Los Angeles Building Code, 2014.
- [2] Los Angeles Department of Building and Safety Information Bulletin, P/BC 2014-119 Policy on Accepting Alternate Building Materials or Products.
- [3] Los Angeles Department of Building and Safety Information Bulletin, P/BC 2014-048 Specifications for Strong-Motion Accelerographs and Requirements for Installation and Servicing, Retrieved from <http://ladbs.org/LADBSWeb/information-bulletins.jsf#ib3>.
- [4] Los Angeles Department of Building and Safety Information Bulletin, P/BC 2014-117 Structural Monitoring Equipment in Buildings Designed with Nonlinear Response History Procedure, Retrieved from <http://ladbs.org/LADBSWeb/information-bulletins.jsf#ib3>.
- [5] Applied Technology Council (ATC). ATC 20, Procedures for Post Earthquake Safety Evaluation of Buildings, 1989, and Addendum, 1995.

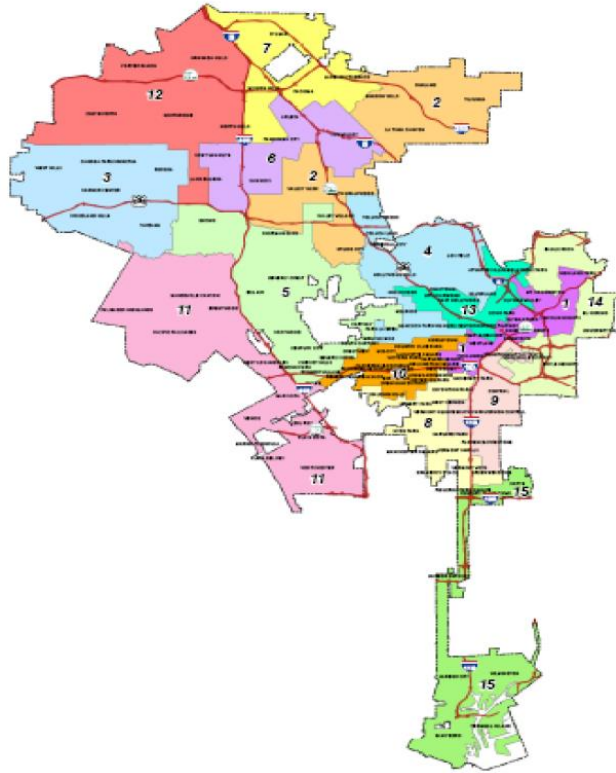


Figure 1: Map of City of Los Angeles; 15 Council Districts of Los Angeles.



Figure 2: Seismic fault lines in Los Angeles vicinity. Source of map: [http://earthquake.usgs.gov/earthquakes/recenteqscnv/FaultMaps/Los\\_Angeles.html](http://earthquake.usgs.gov/earthquakes/recenteqscnv/FaultMaps/Los_Angeles.html)

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## U.S.-Iran Symposium on Resilient Cities

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# Latest Developments in Iranian Building Codes and Guidelines to Achieve Safer and More Resilient Cities

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### **Abstract**

To increase sustainability and resiliency of the cities and built environments, improvements in the building codes and rehabilitation guidelines and their proper enforcement are essential requirements for the governments and the local administrations. These requirements are more important for the developing countries. In this paper, some of the recent modifications in the Iranian building codes and rehabilitation guidelines, as a developing country, are reviewed and their improvements and shortcomings, in regard to resiliency and sustainability of the cities, are presented. It is observed that a considerable advance has been achieved by the preparation of the new codes and guidelines and by the modification of the previously existing editions, which could increase the safety and resiliency. In the same time, more effective enforcement policy and quality control are needed by the city administrations. Training of the construction work force and increasing the public awareness requires more effective approaches, too.

**Keywords:** *Building Code, Resilient Cities, Earthquake, Seismic Rehabilitation*

## **1. INTRODUCTION**

Rapid growth of the population and the increasing density of the population have increased settlements in hazard-prone areas of the large cities of the developing countries. Increasing the number of unsafe dense structures, to overcome the housing problem of immigrants, has raised the vulnerability level of the many cities. Resilient cities are those cities which could absorb the shocks and effects of disasters and overcome their consequences by adapting consistent multi-lateral policies. As a contribution to the global campaign, to make cities more resilient, the United Nations International Strategy for Disaster Reduction (UNISDR) program has suggested ten essentials for implementation by the local governments of both developed and developing countries [1]. The ten essentials of UNISDR include: organization and coordination, assigning a budget, preparing risk assessment, maintaining the critical infrastructures, upgrading the safety of essential buildings, applying and enforcing realistic building regulations and land use planning principles, ensuring education programs and training, protecting ecosystem and natural buffers, installation of early warning systems, and after the disaster, ensuring that the needs of the affected population is placed at the center of any reconstruction policy.

Recognizing the vulnerabilities, increasing preparedness for the probable hazards, and employing preventative measures are some of the basic requirements for enhancing the resiliency

of the cities. Collaboration of the citizens and nongovernmental organizations with the city administration, to mobilize the local capabilities, could increase the resiliency. Reviewing the regulations governing the city affairs, to improve and facilitate their use, is very important step. To increase sustainability and resiliency of the cities and built environments, improvements in the building codes and rehabilitation guidelines should be considered by any national and local government.

The sixth essential of UNISDR [1] suggests the enforcement of risk compliant building regulation, identification of safer lands for low income citizens, and upgrading of informal and unsafe settlements. In the developed countries, the building codes have, relatively, longer history and they have an evolutionary modification process. By comparing, as an example, the basic building code of Building Officials and Code Administrators (BOCA) of 1975 [2] and the International Building Code (IBC) of 2009 [3], one could observe the dramatic changes in the different parts of the code. Building codes are much younger in the developing countries and they need more investment for this essential need. It has been observed that the developed countries are stricken by disasters as much as the developing countries [1], but their sources, capabilities, shortcomings, and resiliencies are not the same.

The majority of developing countries do not have complete and consistent building codes and those codes are not enforced by the city officials properly. Many engineers and people are not aware of their importance and do not respect the code. In Iran, as an example of the developing countries, the building codes are relatively young and are not properly observed and implemented by the cities. In this paper, some of the recent modifications in the Iranian building codes are presented. Also, the seismic rehabilitation guidelines, for the existing structures, are reviewed. The improvements and shortcomings of those codes and regulations, in regard to resiliency and sustainability of the cities, are discussed.

## **2. NATIONAL BUILDING CODE**

First noticeable attempts to establish building regulation in Iran date back to the 1960s, when some governmental offices and the Iranian National Standards Organization (INSO) published several regulations and standards concerning construction and materials. The subjects of Iranian standards and related news, in Persian, may be found in the web site of INSO [4]. Based on one of the items of the law of “organization for the construction industry and engineers,” passed by the Iranian parliament in 1995, several organizations were established and the first unified National Building Code (NBC) was prepared in twenty Articles. A few of the subjects had earlier editions, which were integrated in the NBC.

The Organization for the Engineering Order of Building (OEOB) is, partially, a nongovernmental organization and its council of directors is elected by the engineers. OEOB issues identification cards for the engineers and supervises their practice. More information and news about OEOB may be accessed from its web site in Persian [5]. Also, the Office of National Building Code Affaires (ONBCA) was created in the ministry of housing. ONBCA supervises training programs for the engineers and conducts the professional engineering exams. ONBCA uses its web site in Persian [6] to inform engineers about the construction rules and the code. Up until 2013, ONBCA managed the preparation process of NBC. At the end of 2013, the Road, Housing & Urban Development Research Center (RHUDRC) became responsible for the further developments of NBC. The web site of RHUDRC in Persian and English [7] provides some information related to NBC and its other activities. Most of the members of the code council and its committees have changed in 2014, which may hamper the continuity and sustainability of the NBC.

All articles of the NBC are prepared and modified by a technical committee and are published in separate volumes, after approval by the code council. The main sources for the NBC are the available codes from other countries and limited Iranian references. Based on the experience

obtained by enforcing the earlier editions of the code, harsh environmental occurrences of recent years, and manmade hazards in the fast growing cities, the code committees modified and extended the contents of most of the Articles. Some new editions of building codes in other countries were also considered in the modification process of the NBC Articles. Most of these new revisions were published in 2013 (see Table 1). The last two Articles of the NBC were published, recently, for the first time. City officials should control the process of design and construction of all structures based on the NBC and any extra city rules, which may be approved, considering the local necessities, by the city councils. Some of the recent modifications in the NBC will be reviewed in the following subsections.

TABLE 1: ARTICLES OF IRANIAN NATIONAL BUILDING CODE.

Article	First and Last Editions Publication years
1 - Definitions	2013 and 2013
2 - Administration	2005 and 2005
3 - Fire Protection	2001 and 2013
4 - General Requirements	2008 and 2013
5 - Materials and Products	1990 and 2014
6 - Loads on Structures	2001 and 2013
7 - Foundations	1990 and 2013
8 - Masonry Buildings	2005 and 2014
9 - Reinforced Concrete Buildings	1989 and 2014
10 - Steel Construction	1989 and 2013
11 - Industrialized Construction	2004 and 2013
12 - Precautions During Construction	1993 and 2013
13 - Electrical Equipment	1993 and 2003
14 - Mechanical Equipment	2001 and 2012
15 - Elevators and Escalator	2001 and 2013
16 - Plumbing and Drainage	1993 and 2012
17 - Natural Gas Piping	2002 and 2010
18 - Acoustic and Sound insulation	2001 and 2011
19 - Energy Saving	1991 and 2010
20 - Signs and Billboards	2005 and 2005
21 - Passive Defense	2012 and 2012
22 - Maintenance of Buildings	2014 and 2014

### 3. GENERAL REQUIREMENTS AND FIRE PROTECTION

Most of the buildings in Iran have masonry, reinforced concrete, and/or steel structures, and wooden structures have limited use, mainly in the north parts of the country. Some older masonry buildings have composite mud and wood roofs. The extended use of plastic materials inside the buildings with residential and business use groups, due to cheaper price, has increased the fire risk in the populated cities. In addition, the sanitary facilities of many of the old buildings are poor. To improve the safety and sanitary conditions of buildings, some parts of Articles 3 and 4 were modified. Regulations regarding exit facilities, in the case of fire, were modified depending on the use group.

### 4. MATERIALS AND BUILDING PRODUCTS

In recent years, the variety of materials and building products, which are used in construction industry, has increased dramatically. The public and many engineers have little knowledge of the new materials and may use those products improperly, which could yield safety, health hazard, and property loss. To address this rapid changing situation, the fourth edition of the fifth Article was published in 2014. In this Article, the safety and quality requirements for commonly used building

materials, such as various brick units, gypsum, natural stone, cement and cement-based products, mortar for masonry, and concrete aggregates were presented and the national standard numbers for their quality assurance tests were assigned. Regulations for fiber reinforced concrete were extended and use of asbestos was prohibited. The section for polymer building materials was extended to address safety and health concerns. A new short section was added for nonmaterial's use in building products and their health and safety concerns. Environmental impact of for different materials was also addressed.

## **5. STRUCTURAL DESIGN AND CONSTRUCTION**

A high growth of the population and the fast expansion of the cities dictated new policies for land use. The Iranian government and city officials allowed construction of taller buildings. The life cycle of many buildings in Iran are less than fifty years. Demolishing the older low rise houses and replacing them with medium or high rise buildings is very attractive for construction business. To build safer structures, several of the NBC Articles pertain to the design and construction of foundations and various types of structures.

Adverse weather condition of the last decades has caused considerable damage to the population centers. Flooding has become a major problem in some parts of Iran. A major highway bridge collapsed last year in Tehran, due to flooding of the Kan River, which is dry for most of the year. The city officials have failed to prevent building of houses around seasonal rivers in many places. Several roofs collapsed in the city of Rasht and in the southwest of Caspian Sea, during winter of 2014. In the recent edition of the Article six, to address the effects of extreme weather conditions, new sections for rain, ice, and flood loads were added and the section for snow was modified and extended to address the interaction of adjacent buildings. ASCE 7 [8] and Canadian code were the main sources of the Article six.

To finance the new infrastructures of the populated cities and reduce the traffic, city officials have sold permits to businessmen to construct taller buildings. This policy has increased the population density in some areas and attracted more cars to the streets. Building new high rises in the cities with deep basements, also, has damaged many surrounding older buildings and caused a number of casualties in Tehran and other fast growing cities in recent years. New rules were adopted in the Article seven to ensure safer rebuilding and excavation in the cities. Also, a pocket size instruction pamphlet was prepared to be used by engineers and the city administration. It makes clear the responsibilities of different parties in the construction industry, to increase the safety of the citizens and their properties.

Reinforced Concrete (RC) structures are safer than steel structures, considering fire and explosion impacts. In the Article nine, new topics were added in response to the use of newer cement-based materials and technologies. A section was provided for the durability of RC structures. Another section was written for special concretes, including high strength concrete, fiber-reinforced concrete, Self-Consolidating Concrete (SCC), and lightweight concrete. The section for seismic design was adapted from ACI 318 [9]. A new section on prestressed concrete was also added to the new edition.

In the Article 10, the Load and Resistance Factor Design (LRFD) provisions were adapted from AISC 360-10 [10]. The seismic design of steel buildings, adopted from AISC 341-10 [11] and AISC 358-10 [12], has emerged in the main body of the Article 10, due to the high importance of seismic design for most parts of country. This Article does not cover composite systems and steel shear walls, although they are getting used in some of the new projects. Several guidelines are under preparation for design of steel shear walls and some other building systems such as Reinforced Concrete columns and Steel beams (RCS) using the existing guidelines and some experimental studies. Fig. 1 shows a specimen of beam-through type interior RCS connection, recently tested in

the structural engineering laboratory of Building and Housing Research Center [13]. SCC used in the connection to ease the casting of the concrete.

Prefabrication and modularization in the Iranian construction industry is very poor and weak. The aim of the Article 11 is to encourage and regulate prefabrication industry. General and specific regulations were provided for several prefabricated and partially precast systems. Also, light steel frame structural systems, which could be rapidly erected, were regulated in the Article 11. At the same time, a separate design and construction code was published in 2011 [7]. This system was used after the devastating 2003 Bam earthquake for temporary houses and later for the housing of the low income people. Article 11 also covers some of the precast concrete products and structural systems.

## 6. MECHANICAL AND ELECTRICAL UTILITIES AND EQUIPMENT

In response to increase in the height of buildings, demand has increased for newer technology and materials. To address these needs, some parts of the Articles 14 to 19 were revised. In these revisions, energy saving, health, safety, and environmental effects were major concerns. In Article 14, the requirement for using thermoplastic pipes was extended. In the Article 15, due to aging problem, the height limit for not having an elevator, reduced to buildings with four stories. Natural gas is the main source of energy in the Iranian buildings. It is used for heating and cooking and it is a major cause of fire and explosion in the buildings. Unfortunately, the Article 17 allows the direct use of natural gas in the buildings with any height and use group, although with safety precautions, due to economical preferences.



Figure 1: Testing a RCS connection [13].

## 7. PASSIVE DEFENSE

The new Article 21 published for the safeguarding of the buildings against explosions should be considered in the architectural and structural design of the important buildings. It should also be



considered in design of mechanical and electrical components and utilities of buildings. In the Article 6, a moderate load is assigned for the design of envelopes of the essential buildings.

## **8. BUILDING MAINTENANCE**

The maintenance of the existing buildings, especially medium and high rise buildings, is a major concern in the large and fast developing cities. For the first time, the Article 22 prepared to increase the resiliency of the buildings and to facilitate the maintenance management. In this Article, the responsibilities of owners, residents, managers, and the city officials are defined. Relevant regulations were included to increase the safety and health levels and to save more in the energy and the repair costs. The time intervals and procedures for inspection of various parts of the buildings by the technicians and the engineers were suggested.

## **9. SEISMIC DESIGN CODE**

For the majority of cities in Iran, the earthquake hazard is the most important concern of the people and the officials. A first code, which addressed the seismic loads, was published in 1965 as the Standard 519 [4]. It assigned minimum design loads for the buildings and other structures. The seismic load section of Standard 519 was very brief and inadequate for Iran. A special seismic design code was later developed [7], observing devastating damage and life loss caused by the several strong earthquakes, and finally approved by the cabinet of ministers in 1986. INSO [4] assigned a standard number and is framed as the Standard 2800 [6].

The 4<sup>th</sup> edition of the Iranian seismic design code, Standard 2800, with several new chapters and extended modifications, will be published during 2014. In this edition the research results on special types of structures and the new developments in some other codes [3,8] are considered. The recent earthquakes have shown that the structures designed based on the existing version of Standard 2800, have acceptable performance, but they may suffer considerable damage on their nonstructural components. In the new version of Standard 2800, the seismic design requirements for the nonstructural components have been extended and modified as a new chapter to increase the resiliency of the buildings in the case of strong earthquakes. A separate chapter was assigned for the non-building structures, to better address seismic design of industrial structures. Also, the number of prequalified structural systems was increased to allow the diversity of building types for different interests.

## **10. GUIDELINES FOR THE REHABILITATION OF THE EXISTING BUILDING**

Most of the existing buildings in Iran are not designed and built using a reliable seismic code and they could suffer high amount of damage in the case of strong and even moderate earthquakes. In the same time, the current building codes provide the minimum requirements to insure mainly the life safety target, which is not enough to reach the resiliency goals, completely. To increase the safety, sustainability, and resiliency of the cities, a seismic rehabilitation guideline has been prepared using the existing sources, mainly FEMA 356 [14] and ASCE/SEI 41-06 [15], and considering different types of traditional constructions, adapted structural systems from Europe, and their various mixes. This document and its simplified versions have been used in rehabilitation programs of many schools, a few hospitals, and some other essential buildings. The third edition of this guideline was published in 2014 to include lessons and experience obtained during the last two decades [16].

To encourage the residents of cities to upgrade their buildings, with an affordable cost, several simplified rehabilitation guidelines have been prepared or are under preparation [7]. The guideline for rehabilitation of the structures using fiber reinforced polymers was published in 2013, which



could be used for reinforced concrete and masonry structures. Another guideline will be published in 2014 for the existing unreinforced or partially confined masonry buildings.

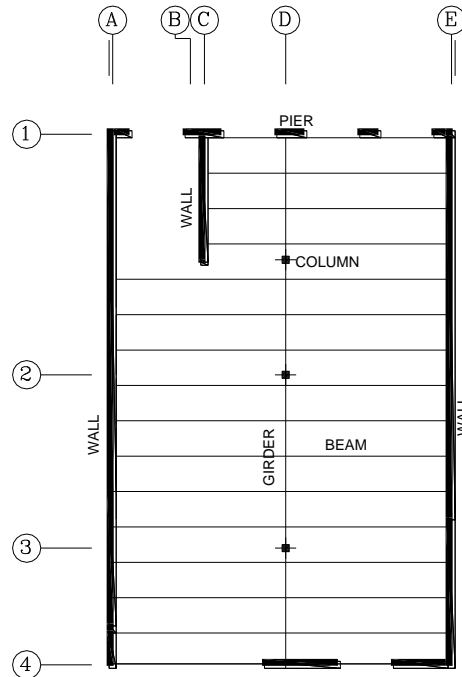


Figure 2: Half-skeleton buildings do not have enough masonry walls to resist against earthquake.

By importing steel sections and bars and establishing cement factories, the use of steel and reinforced concrete structures dominated the public buildings, since eight decades ago. At the same time, to reduce the size of space occupied by the thick internal masonry walls, and to increase the size of windows and doors, various mixes of steel frames and masonry walls were attempted in the construction of the buildings, especially after the Second World War II. This popular hybrid frame and masonry building system was named the half-skeleton system by the people and considered to be much stronger than traditional masonry buildings. In reality, they are very weak and dangerous, since they do not have enough masonry walls, at least, in one of the two perpendicular directions (Fig. 2). In most cases the integrity of the roofs with the walls and the columns are very weak, too. A simplified guideline for the seismic rehabilitation of the half-skeleton buildings was published in 2013 and different upgrading techniques were suggested [7]. Many of the existing houses in Tehran and large cities have half-skeleton system and are vulnerable. To upgrade this group of buildings, in a large scale, low interest rate loans for low income residents and technical support are the essential actions.

## 11. IRAN AND TEHRAN

Tehran is the largest city of Iran and immigrants from all places of the country, as well as some of the neighbor states, have gathered there to have a job and better life. Tehran is also the model city for the other cities of Iran. Citizens, mayors and other officials of the cities around the country monitor changes in the streets and neighborhoods of Tehran to follow the new trends and fashion. Any attempt to raise the resiliency of Tehran could affect the resiliency of other cities. Construction of many highways, bridges, tunnels, and railways in Tehran has changed its built environment dramatically. Concerns about the safety and sustainability of the capital have caused the parliament

and the government in the one side and the city council and administration in the other side to initiate various plans and actions, which are, in some cases, contradictory. The seismic hazard, air pollution, high population, and traffic congestion are the main sources of concern.

The birth control policy of the country, which started in 1990, has been under attack by some officials since 2005. The policy was reversed in 2013 by modifying main related laws and regulations. Similar to some other countries, mainly based on geopolitical basis, it was emphasized that the improvement in the sustainability and the resiliency of the country requires more population, with a higher percentage of younger age people. Due to dryness of most parts of Iran and economic conditions, this policy requires more effective water resource management. Encouraging poor people to increase their number could make the resiliency measures more challenging for Tehran.

In 2009, based on an unreliable prediction about the closeness of an inevitable large earthquake by a person close to the government, the government decided to transfer the offices of some organizations to other cities and encouraged employees to move to the other places by promising them a raise in their salary. This plan failed and those offices returned back to Tehran after a year. Fear of a major earthquake did not disappear, however. At the end of 2013, the parliament asked the government to prepare a plan for relocating of the capital from Tehran to a better location. They hope it will reduce the vulnerability of Tehran and increase the resiliency of the government. This study is under way, but it could take many years with no specific results.

For the Iranian government, the sustainability and the resiliency of the whole country have the first priority, rather than a specific city. In the other side for the citizens and the city administration, some of the policies of the government are not desirable. The National Disaster Management Organization (NDMO) of Iran is responsible for the mitigation of seismic and other hazards in the country. A brief explanation of the activities of NDMO may be seen at its web site [17]. Unfortunately, the NDMO activities were, mostly, limited to the post-disaster recovery programs, in the recent years. It seems that NDMO is planning to be more active in the area of the preparedness in future. Based on the approval of NDMO in 1999, the city of Tehran began establishing a center for disaster management. In 2003, the Tehran Disaster Management and Mitigation Organization (TDMMO) started its activities in the current form. TDMMO had considerable achievement in the establishing of crises management centers in the city and NDMO will help other cities to establish similar centers. In the Persian web site of TDMMO [18], there are instructions for the citizens to organize in the various neighborhood-based groups and participate in the mitigation and preparedness programs.

Unfortunately, many of the bridges in Tehran, which are older than 20 years, do not have as built drawings and documents. Since 1995, the municipality of Tehran has started to gather and generate the as built documents for the existing bridges. Later a group of consultant engineers started a seismic evaluation of those bridges, which was supervised by a group of experts. Based on the result, the group advised further study for approximately one hundred bridges. Currently, under supervision of a committee, more detail evaluation is being conducted on some of the susceptible bridges. Based on the results, around 30 bridges could require seismic rehabilitation.

It should be noted that in the area of constructing new infrastructures and upgrading the existing ones a good progress have been achieved, but in the area of enforcing the building codes the city is, practically, inactive and acts irresponsibly. The research program of partial strengthening of the masonry and half skeleton houses, which was underway by TDMMO, abounded in 2009. Selling permits to increase the height of the buildings and their number of apartment units has resulted in the demolishing of existing buildings with poor structures and their replacement with taller buildings and more units but smaller sizes. This policy may improve the safety of the buildings, but due to the increase in the population density, the enhancement in the resiliency is questionable. Selling lands of some of the public parks, to raise revenue for the city infrastructures, could reduce the resiliency of the city. Unfortunately, transferring some of the unsafe mountainous

areas of north Tehran by some influential organizations to the related businessmen, to build high rise buildings, has made those areas very vulnerable to seismic events and landslides. In most cases the city is silent against those activities.

In the case of schools, the State Organization of School Renovation, Development, and Mobilization (SOSRM) implemented, relatively, a vast program for the rehabilitation and renovation of the existing schools in Tehran. The organization also is responsible to build new schools and they conduct fund raising programs to finance part of their projects. More information and news about their programs may be obtained from DOSRM Persian web site [18,19]. Many of these schools had partially or improperly confined masonry and half- skeleton structures. There exists a considerable study on the confined masonry structures in Iran and there are special chapters for this system in the Standard 2800, the Article 8 of NBC, and the guideline for the rehabilitation [16]. Fig. 3 presents a shaking table study of a confined masonry building [20]. Different approaches have been used for the rehabilitation of the schools. Using a layer of reinforced mortar, with a thickness of 50 mm on the masonry walls is a popular technique for upgrading the masonry schools.



*Figure 3: Testing a confined masonry structure on the shaking table of Sharif University [20].*

The various plans and actions of different state and city organizations have resulted in some improvements in the resiliency level of Tehran. Table 2 summarizes the relative progress made in the ten essentials [1] required to reach to the higher levels of resiliency and sustainability, for Tehran. Bonowitz [21] has compared San Francisco and Tehran and noted that the resilience measures appropriate to one city might not apply to another. The difference is larger and more diverse for a city in a developed country versus another city in a developing country. Although there are many differences, it seems that the ten essentials of UNISDR [1] could provide a suitable common ground for measuring the efforts of the different cities, and may facilitate their communication and collaboration in making the earth more resilient.

TABLE 2: PROGRESS IN MAKING TEHRAN MORE RESILIENT.

<b>Essentials [1]</b>	<b>Progress made</b>
1- Institutional and Administrative Framework	Moderate
2- Financing and Resources	Moderate
3- Multi Hazard Risk Assessment, Know your risk	Fair
4- Infrastructure Protection, Upgrading and Resilience	Fair
5- Protect Vital Facilities	Moderate
6- Building Regulations and Land Use Planning	Moderate
7- Training, Education, and Public Awareness	Moderate
8- Environmental Protection and Strengthening of Ecosystems	Poor
9- Effective Preparedness, Early Warning and Response	Poor
10- Recovery and Rebuilding Communities	Poor

## 12. CONCLUSIONS

1. A considerable progress is observed in the recent preparation of the new, and the improvement in the existing, building codes and rehabilitation guidelines in Iran. Observing and enforcing these documents could increase the safety, sustainability, and resiliency of the cities.
2. Rehabilitation programs for the existing infrastructures and essential facilities are slow and require more investment.
3. Supporting, financially and technically, the rehabilitation program of the existing half-skeleton and masonry buildings could dramatically reduce life loss in the event of major earthquakes. The prepared documents could help this program.
4. Training the involved people, and increasing the public awareness, need more attention at the national and the local levels.
5. Some policies of the central government and the city administration could be not in line with each other and contradictory, especially in the developing countries, which makes the resiliency programs more challenging for those cities.
6. Collaboration of the different states and cities is essential for hazard mitigation and resiliency of any city on the earth.

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# New Construction for Resilient Cities: The Argument for Sustainable Low Damage Precast/ Prestressed Concrete Building Structures in the 21st Century

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### ***Abstract***

Thoughtfully-chosen and properly-designed new construction can significantly improve both the resilience to natural and man-induced disasters and the long-term sustainability of modern urban environments in the 21<sup>st</sup> century. In particular, precast/prestressed concrete construction has the ability to provide low-damage or damage free building forms at similar costs to traditional construction while also providing a more sustainable construction form, in terms of higher energy efficiency and lower embodied energy, in comparison other methods. In this paper, low-damage sustainable precast concrete seismic systems are described. With respect to sustainability, the prestressing of precast concrete leads to less material required and hence less embodied energy; the piece erection leads to cleaner, quieter construction sites; and the insulation and architectural finish can be integrated directly into the precast unit, increasing energy efficiency and consolidating construction operations. With respect to resilience, earthquake damage is avoided by taking advantage of the inherent jointed nature of precast concrete construction, thereby promoting opening of gaps between precast units rather than cracking of the concrete itself, and using unbonded post-tensioning concepts to restore the structure to its original centering. The potential use of precast concrete in developing countries where no precast industry exists is considered in the context of global sustainability. The performance of precast concrete in recent earthquakes is presented, including past non-conforming designs, more recent construction emulative of well-detailed reinforced concrete, and newer low damage forms, as an example of a resilient construction.

***Keywords: Seismic-resistant Structures, Precast Concrete Structures, Resilient Construction, Sustainable Construction***

## **1. INTRODUCTION**

Community resilience for sustainable urban environments involves the ability for the sustaining urban community to rapidly regain its regular function, in terms of habitation, commerce, public services, local culture and way of life, after a sudden and disruptive natural or manmade event [1].

Fig. 1 shows a schematic of this process, indicating the difference between resilience and sustainability. As seen, the factors that influence community resilience can be divided in two groups: (1) those that pertain to the actions the community can take prior to an event to lessen the immediate impact of the event on loss of function (i.e. increase robustness), termed *ex ante* mitigation; and (2) those that pertain to the actions of the community can take in response to the event (rapidity of recovery), termed *ex post* actions. This process can apply to natural and man-made hazards in general, and thus while the paper focuses on earthquake resilience, many of the points are applicable generally to multi-hazard resilience.

For earthquake resilience, *ex ante* mitigation primarily refers to hardening of infrastructure, for instance retrofitting (or demolition) of vulnerable structures and promoting new construction that is more resistant to earthquake hazards [2]; the *ex post* actions refer to the preparedness of the community [3]: in the immediate aftermath emergency responders and critical care facilities, and government leaders, decision makers and public service broadcasters; and in the longer term, inspectors and engineers, city planners, urban and public policy, community organizers, insurance companies, etc. Note that though the *ex post* actions occur after the event, effective preparedness to execute these actions requires significant planning, coordination, and preparation *prior to the event*.

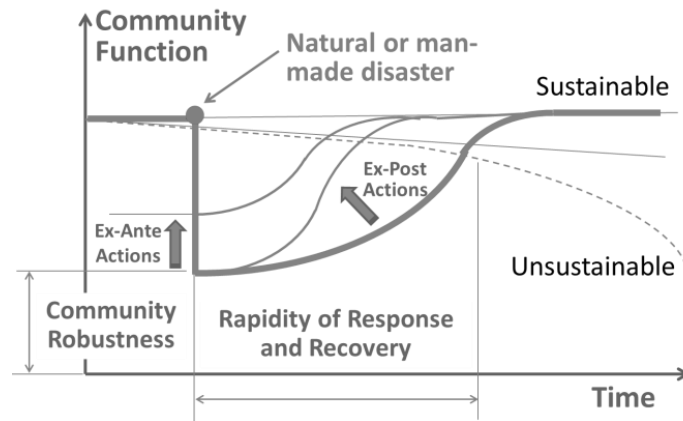


Figure 1: Loss triangle: actions influencing resilience.

It may be claimed that, historically, governing bodies have tended to be more reactive than proactive to natural disasters with a focus on post-event response. In recent years, however, great advances in assessing the vulnerability of individual infrastructure assets and communities have provided unparalleled opportunities, including the use of geospatial information, remote sensor data, analytics and visualization to interpret and gain knowledge for the purpose of planning for, responding to, and recovering from disaster events [4]. A key step for community earthquake resilience is to inventory existing or planned infrastructure in terms of vulnerability and consequence and relate it to anticipated seismic hazard [5]. However, as urban communities have become more complex, where the lifelines (power grids, utilities, communication and transportation networks, etc.) are intertwined into coupled integrated systems that provide normal business and daily life; and infrastructure may be aging while the population remains dense; the interactions of these failing critical lifelines can have cascading effects to a community and surrounding regions [6]. Business interruption, dislocation of the populace, and loss of normal activities can have severe negative societal, cultural and economic effects locally, regionally or nationally, leading to natural disasters events overwhelming even the most carefully planned response [7]. Thus, the importance of building inherent robustness into the community infrastructure has risen in relative importance [8], and comprehensive *ex-ante* mitigation strategies have been found to be effective [9].

Community resilience efforts have to be considered in the context of sustainability [10]. Sustainability refers to the ability of a system or process to endure (or thrive) over its intended duration. In the context of modern urban environments, sustainability pertains to ecological impact, durability, energy and resource consumption relative to supply, and economic viability for continued functionality based on operational requirements, long term deterioration, and changes in the surrounding environment [11]. Thus, while community resilience might be viewed as the ability to restore functionality after a singular event, sustainability is the ability to maintain functionality over the expected life-cycle (Refer to Fig. 1). Community resilience often poses competing requirements to the parallel requirements for sustainability; at a minimum, policies for these critical aspects are fighting for the same scarce resources [12].

This paper will focus on ex ante mitigation of building structures, and in particular, new sustainable construction for developed or developing countries that is more resilient to earthquake hazards. The discussion focuses on precast/ prestressed concrete, a construction form with characteristics that lead to advantages in resilience and sustainability.

## **2. SUSTAINABILITY ISSUES FOR BUILDING STRUCTURES**

Sustainability for buildings focuses on environmental effects and energy use through the construction, operation, and demolition of the structure, including those associated with the raw materials used in the process. These factors are often evaluated in a Building Life Cycle Assessment (LCA) covering construction and operation [13].

### *2.1. Concrete Building Construction: Embodied Energy and CO<sub>2</sub> Emissions*

Key aspects of sustainability for concrete include embodied energy and carbon emissions in its construction:

About 6% of all energy consumed is used to manufacture and transport building materials [14]. The Process Energy is the measure of energy directly related to manufacture of the material (raw material extraction, transportation to plant, product manufacturing costs), and is more commonly reported than a total embodied energy (business overhead costs, etc.) [15]. The structure, envelope, and finishes comprise over 60% of the “cradle-to-gate” embodied energy in an office building, including non-trivial amounts of energy required to transport materials to a project site [16]. Thus, while embodied energy depends on material and building techniques, it can be reduced significantly when local materials are used for building construction [17]. Fig. 2a shows the embodied energy density inherent in different construction materials [18]. Though not possessing the highest density, the significant percentage by weight of concrete used in structures tends to render it the most significant contributor in construction (e.g., Fig. 2b [15]).

Typical concrete contains approximately 10-12% cement by volume. Significant CO<sub>2</sub> emissions occur in cement production due both to fuel use (combustion-generated, 1/3<sup>rd</sup>) and heating of the calcium carbonate (calcination, 2/3<sup>rd</sup>) [19]. Since the 1970's, the U.S. cement industry has reduced CO<sub>2</sub> emissions and energy usage per ton of cement by approximately one third [20]. The global cement industry reduced its specific net CO<sub>2</sub> emissions per ton of product by 17% since 1990. However, overall cement production has increased by 74% in that same time, leading to an absolute CO<sub>2</sub> emissions increase of 44%. Today, cement production still accounts for approximately 5% of global CO<sub>2</sub> emissions, one of the more significant contributors outside electric generation and transportation [21].



## 2.2. Building Operation

Worldwide, approximately 70% of generated electricity is being consumed by buildings. Buildings employ 40% of raw materials (3 billion tons annually) for construction and operation worldwide [21]. In the U.S., buildings consume 65% of the electricity generated and more than 36% of the primary energy (such as natural gas); they produce 30% of the national output of greenhouse gas emissions; and they use 12% of the potable water [22].

Many developing nations have increased energy demands due to increased manufacturing and urbanization. For instance in China (See Sec. 3.5), energy demand has increased dramatically as it has become one of the major manufacturing centers of the world with demand expected to exceed current supply [23]. A major contributor to reducing demand would be more energy efficient buildings, which can lower operating costs by a factor of two [22].

It is important to holistically view embodied energy in the context of the buildings overall lifecycle [24], as tradeoffs exist between initial vs. operational energy costs. For instance, providing good thermal mass for energy efficiency (See Sec. 3.3) may be associated with a higher embodied energy; as buildings consume less energy in operations, the energy embodied in the building's materials will become increasingly important as a percentage of a building's total energy footprint [16]. However, if an infrastructure asset is durable (See Sec. 3.1) and thus can remain in service longer, the operational energy efficiency can become more significant than the one-time embedded energy demands (See Fig. 2c), even if the thermal mass high in embodied energy, leading to a net savings [25].

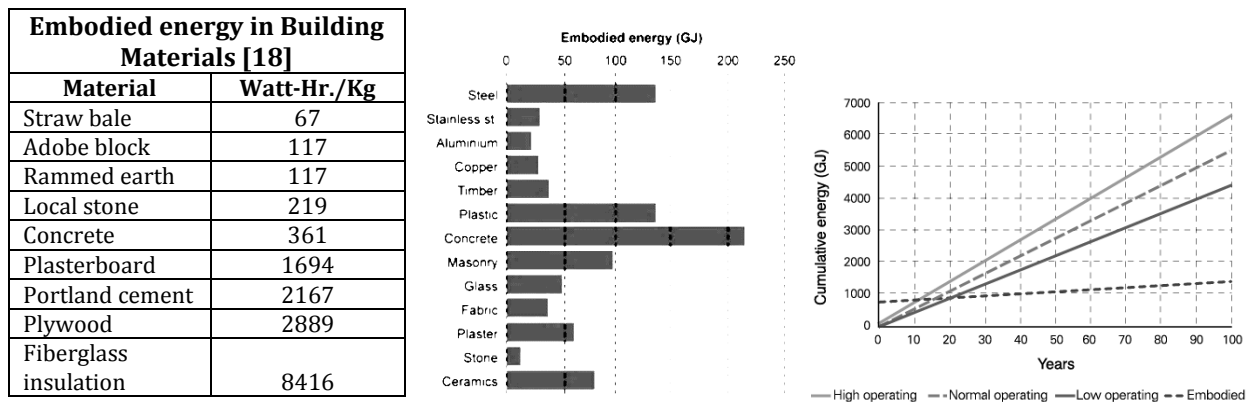


Figure 2: Embodied Energy: (a) Material Density [18]; (b) Typ. Home Construction [15]; (c) Operational Energy [22].

## 2.3. Measures for improving Concrete Sustainability

In concert with targets for overall CO<sub>2</sub> emissions [26], plans call for reduction in the cement industry by the year 2020 to 10% below a 1990 baseline through investments in equipment, improvements in formulations, and new techniques for cement and concrete that improve energy efficiency and durability [21]. These targets count on several advances with the potential to improve the carbon footprint of concrete construction, in conjunction with measures to lower the energy required in cement production [20]. The advances, in different stages of development (research, demonstration, pilot, semi-commercial), include emerging grinding and kiln technologies; alternative raw materials and cement products; carbon capture technologies and nanotechnology [27].

One key advance is the use of Supplementary Cementitious Materials (SCMs) as pozzolan replacements in the manufacture of cement. SCMs are by-products of other industrial processes and

include fly ash (coal-burning electric power plants), slag (iron blast-furnaces in steel mills), silica fume (electric arc furnaces), and calcined clays. These post-industrial recyclable materials are plentiful (~60 million tons of fly ash were produced in the U.S. in 2007) and would otherwise occupy valuable landfill space. The amount of cement used in concrete may be reduced by up to 60% through SCM substitution leading to a reduction in greenhouse gas emissions per cubic yard of concrete of 45% [21]. SCM can also modify concrete properties, e.g. fly ash reduces concrete permeability and heat of hydration, and increases strength and durability [28]. Fly ash also slows the time of set which may be offset by chemical accelerating admixtures (other admixtures can reduce water demand or intentionally entrain air). Light colored SCMs such as white silica fume or metakaolin can be used for architectural face mixes. As industrial byproducts, some SCMs may not be part of an ideal future due to lower material availability as sustainable development extends to other industries. In the meantime, SCMs offer a low-cost solution with beneficial sustainability effects on multiple industries.

More exploratory technologies exist such as carbon storage methods. For instance, Accelerated Concrete Carbonation Curing (ACC) attempts CO<sub>2</sub> sequestration. This method accelerates the curing process, improves physical properties, while storing carbon dioxide [29], and claims a potential to reduce global CO<sub>2</sub> emissions by as much as 1% [30].

### **3. PRECAST CONCRETE CONSTRUCTION**

#### *3.1. Precast Concrete*

Precast concrete is “prefabricated” at a plant and brought to the job site (See Fig. 3). It is typically prestressed at the plant using high strength steel tendons that place the concrete in compression (often placed lower in the cross-section to counteract the effects of gravity load, i.e. camber the beam upward so that gravity loads bring it back to the “zero” balance point) and thereby make the units more effective in transferring gravity loads. Prestressing provides two distinct benefits: (1) it increases stiffness because the cross-section acts as uncracked concrete; (2) it increases durability since reinforcing steel is not exposed to corrosion introduced by moisture penetrating cracks in the concrete. The primary advantages of precast/prestressed construction include [31]: (1) *Speed of Construction*: Precast unit production occurs in parallel while site work progresses; the structure is erected rapidly by lifting units off the back of a truck; and all weather construction (cold weather does not stop construction). (2) *Better Quality Control*: Precast units are produced in controlled environment (ideal humidity, temperature, etc.), using standardized modular forms by skilled, experienced workers, and are easily inspected. (3) *Light Long spans*: Greater span-to-depth ratios are achieved for prestressed members, and (4) *Durability*: Due to higher strength/quality uncracked concrete with low permeability & water/cement ratio.



Figure 3: Precast Concrete [31].

Precast/prestressed construction finds widespread use for exposed long span structures such as stadiums, parking structures, and highway bridges. In recent years, the technique has found increasing use for a wide variety of architecture, including hotels, schools, medical, governmental and office buildings [31].

### 3.2. Precast Concrete Sustainability Advantages

Precast concrete has several aspects that make it attractive as a sustainable building material [32], including those that directly address Leadership in Energy and Environmental Design (LEED™) Environmental Quality Credits [22]. These aspects pertain to its production, construction and in-service qualities [33]:

(1) Less material: The greater span-to-depth ratio possible for prestressed members leads to more slender precast members, and thus significant material savings (cement, gravel, sand) and less water use in precast construction. The lighter members lead to a lower total structure dead weight, translating into smaller foundations. These material savings all translate directly to less use of natural resources, and less embodied energy and emissions associated with mining, processing, and transporting of raw material, and manufacturing and transporting of finished product.

(2) Less waste: Raw materials, including water, are used more efficiently than normal construction because of precise mixture proportions and tighter achievable tolerances. Precast concrete generates low amounts of (low toxicity) waste (about 2% of concrete at a precast plant is waste of which nearly 95% can be recaptured to produce new panels [32]).

(3) Efficient Production: Precast concrete is made in a factory with much more efficient use of energy than in-situ construction, leading to less energy used to build precast. Most U.S. precast plants are within 300 km of a building site with raw materials obtained or extracted from sources within 300 km of the plant. The primary raw materials used to make cement and concrete are abundant all over the world. Precast concrete elements are usually shipped efficiently because of their large, repetitive sizes and the ability to preplan shipments during the normal course of a project [33].

(4) Ease of Recycling: Waste materials are more likely to be recycled in plant concrete production. For example, gray water is often recycled into future mixes; about 5% to 20% of

aggregate in precast concrete can be made of recycled concrete [33]; sand and acids for finishing surfaces are reused; and steel forms and other materials are reused.

(5) Durability: The controlled environment and lower water-cement ratio (0.36-0.38) possible at the precast plant produces higher quality concrete, which leads to a highly-durable, longer-lasting structure. The prestressing of units prevents or re-closes cracks making the structure resistant to rain penetration and repeated freeze-thaw cycles, thereby mitigating reinforcement corrosion issues. Reinforcement is placed with higher quality control in the plant than in-situ construction, greatly reducing the likelihood of inadequate cover, a common reason for surface deterioration. The longer service life for precast structures means fewer resources required for maintenance, repair and replacement.

(6) Clean Construction: Precast construction is cleaner with less noise, dust and particulates created at the jobsite as the major task is unloading precast units from the truck, ideal for urban areas with neighbors in close proximity to the site. Little waste or debris is created at the construction site (e.g. no formwork) [33]. Fewer trucks and less time are required because the concrete is made off site, particularly beneficial in urban areas where minimal traffic disruption is critical. Precast units are large components, so greater portions of the building are completed with each activity.

(7) Low End-of-Service Life Impacts: Precast concrete can be readily “de-constructed”, i.e. disassembled rather than demolished avoiding dust pollution, noise, debris and potentially dangerous demolition stages. Units from demolished structures can be reused in other applications, e.g. to protect shorelines [32]. A precast concrete shell can be left in place when the building interior is renovated.

(8) Down-cycleable: Precast concrete is readily “down-cycled” (building materials broken down and reused) with a minimum amount of energy. Examples include using crushed precast concrete units as aggregate in new concrete or as base materials for roads, sidewalks and tiles (See Fig. 4).



Figure 4: Precast Down-cycling: (a) Decks; (b) Pavers; (c) Planters [32].

Table 1 shows a comparison between typical precast and cast-in-place floors [34]. Note these benefits must be interpreted in conjunction with the material advances occurring in the wider concrete industry described in Sec. 2.3

TABLE 1: EMBODIED ENERGY COMPARISON [34].

Energy shown per m <sup>2</sup> of floor	Hollowcore	Cast-in-situ
Concrete (kg)	263.7	423.0
Reinforcement (kg)	3.2	6.1
Total mass (kg)	266.9	429.1
<hr/>		
Eutrophication (kg P <sub>04</sub> <sup>-3</sup> eq.)	0.0356	0.0410
Exhaustion (x 10 <sup>-12</sup> )	0.0468	0.0707
Ecotoxicity (x 10 <sup>3</sup> m <sup>3</sup> )	2.78	5.81
Greenhouse effect (kg CO <sub>2</sub> eq.)	55.2	53.4
Acidification (kg SO <sub>2</sub> eq.)	0.252	0.306
Summer smog (kg C <sub>2</sub> H <sub>4</sub> eq.)	0.0297	0.0460
Human toxicity (kg)	0.318	0.411
<hr/>		
Use of primary energy (MJ)	461	643
Solid waste (kg)	36.3	58.8

### 3.3. Advantages of Total Precast

Using a “total precast solution”, that is a building totally made of precast elements, provides further advantages for sustainability. In this case, the structural precast members (columns, beams, and floor units) are supplemented by architectural precast elements (wall panels, cladding). Architectural precast has many attractive qualities [35] including thermal efficiency, excellent acoustic properties and can be built integrally with structural members (See Fig. 5a) to integrate and optimize insulation levels, glazing, shading, thermal mass, air leakage control, surface color and texture. In particular, precast concrete can be used in a “sandwich panel” configuration for high efficiency in which a layer of insulation is sandwiched between the two wythes of the concrete panel, (See Fig. 5b, c).

(1) Integrated Design: Precast units can be left exposed with natural finishes of a wide range of profile, texture, and color options that require no additional treatment to achieve function and aesthetics. Polished concrete floors do not require carpeting; exposed concrete walls or ceilings do not require finish materials. This reduces the need for production, installation, and maintenance of finish materials, and eliminates products that could otherwise degrade indoor air quality, e.g. volatile organic compounds (VOCs) in interior finishings that can release gases or combine with other chemicals in the air to form ground-level ozone. Concrete itself contains low to negligible VOCs, both in lower concentrations and emission rates [33].

(2) Specified Exterior Finish: Precast exterior panels can be produced to provide reflective white surfaces to minimize urban heat island effects, and can be self-cleaning or change color [35]. Precast concrete’s controlled production allows for replication of color for all panels for a project using pigments that will not fade due to sunlight [33]. Many urban areas are 2-4 °C warmer than surrounding areas due to the heat island effect and are warming [37]. This has an impact on air quality as temperature is a major contributor to smog. A key measure is albedos, the amount of solar radiation reflected from a surface, measured from non- to fully reflective (0-1.0) [38]. Materials with higher albedos will reduce the heat island effect, thereby saving energy and improving air quality [33]. Traditional Portland cement concrete has an albedo near 0.4, but raw material ratios can be adjusted to create white Portland cement with an albedo of 0.7-0.8, and the surface emittance (ability to let go of absorbed heat [38]) of most concrete surfaces is in the range of 0.85-0.95.

(3) Efficient Building Envelope: Precast panels provide good fire resistance, significantly reduce sound penetration and are impervious to rot, termite and vermin. Properly sealed precast panels (typically large with minimal joints) have low air infiltration and are resistant to wind-driven rain, and in conjunction with continuous, edge-to-edge insulation between precast concrete layers

prevents moisture intrusion in hot and humid climates [32]. Exterior precast sandwich panels directly integrate optimal insulation that can save up to 25% on heating and cooling costs [33]. The thermal mass associated with concrete walls can significantly reduce energy demands by storing heat and delay the time it takes for a surface to heat up or cool off [22]. This thermal lag moderates daily temperature to reduce peak heating and cooling energy loads, or shift major energy usage to off-peak times (See Fig. 5d). Night-time ventilation can cool thermal mass warmed during the day [33]. Combined with insulated wall panels, the precast unit can produce high R factors and lower energy needs. These attributes can help earn LEED™ Optimize Energy Performance credits [22] and translate into lower first costs for mechanical equipment due to smaller capacity requirements.

Autoclaved aerated concrete (AAC) is a highly thermally insulating concrete-based material used in precast panels. The better thermal efficiency of AAC makes it suitable for use in areas with extreme temperature as it eliminates need for separate materials for construction and insulation leading to faster construction and savings. Installation is quick and easy because the material can be routed, sanded, or cut to size on site using standard carbon steel power tools. Due to its lower density, buildings constructed using AAC require smaller structural members and foundations. Improved thermal efficiency lowers heating and cooling loads in buildings; the porous AAC structure provides good fire resistance. The AAC industry is growing in Asia due to strong demand in housing and commercial space, with China, Central Asia, India, and the Middle-East the biggest markets for AAC manufacturing and consumption [39].

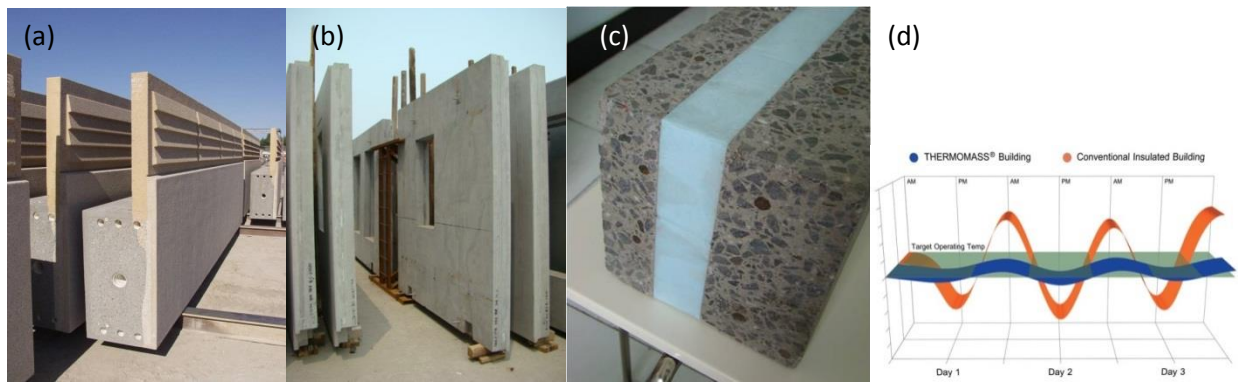


Figure 5: Precast Panels: (a) Integral Cladding [36]; Sandwich (b) Panel and (c) Insulation; (d) Heat Lag [42].

### 3.4. Future/Ongoing Precast Concrete Industry Initiatives for Sustainability

Recognizing that a 2% increase in construction costs will result in a savings of 10 times the initial investment in operating costs for utilities (energy, water, waste) in the first 20 years of a building's life [40], the Precast/Prestressed Concrete Institute (PCI) is pursuing industry-wide sustainability initiatives including [32]: Tying member certification to meeting federal, state and local green ordinances; Increased use of local aggregate resources in mixtures; Water reclamation; Use of admixtures such as hardening accelerators to eliminate applied heat in curing; Wider use of self-consolidating concrete (SCC) for quicker placement, no vibration, and less surface defects; Use of environmentally-friendly thin brick laminates in place of conventional brick; Carbon-fiber reinforcement that allows lighter, larger concrete sections with less embedded energy and no corrosion; Increased use of SCMs to reduce cement consumption (given the easier accommodation of the increased curing time associated with SCMs in a precast plant than on the jobsite [28]); Enclosed sandblasting facilities with 100% process-waste and dust control; Standardizing wood form parts for multiple (~40) reuses [32]; converting discarded forms into mulch or fuel; and, Recycling scrap steel and reinforcement. Note both the ACC and AAC techniques are more easily



introduced in precast concrete's controlled production environment. In addition, PCI recognizes and awards precast projects that exhibit excellence in sustainability (See Fig. 6).



*Figure 6: Award Winning Green Precast Projects [32].*

### *3.5. Sustainable Precast Construction Case Study: China*

As an example of the potential for the use of precast concrete in the developing world, consider recent developments in China. The modern precast industry in China was essentially nonexistent due to earlier poor seismic performance (See Sec. 4.1). However, the significant increase in China's cement production in the 21<sup>st</sup> century [41] (See Table 2) has led to a renewed interest in precast concrete. Starting around 2007, Chinese engineers, academia, contractors and developers began taking measures including inviting U.S. representatives to share knowledge on precast concrete in the form of presentations and discussions [42]. At the time, there was no widespread use of precast concrete other than bridges (a notable exception is the Dalian Xiwang Tower, a 43-story office tower employing precast/prestressed concrete beams, slab and façade cladding system, constructed in record time in 1999, ~2 floors/week [43]). The resulting increased awareness of technical advances in precast technology over the past 30 years, in particular seismic resistant construction, has led to a rebirth in the Chinese precast industry with the potential for economic savings and lessening the environmental impact of the massive China construction boom.

TABLE 2: GLOBAL CEMENT PRODUCTION [41].

<b>Main World Producers - The G-20 Group</b>							
<b>Country</b>	<b>Cement Production (Million Tonnes)</b>						
	<b>2000</b>	<b>2005</b>	<b>2006</b>	<b>2007</b>	<b>2008</b>	<b>2009</b>	<b>2010</b>
China	597.0	1068.8	1236.8	1361.2	1388.4	1650.0	1868.0
India	102.5	142.7	159.0	170.5	183.3	186.9	210.0
European Union	229.9	248.0	264.8	271.0	251.7	201.5	190.4
USA	87.8	99.3	98.2	95.5	86.3	63.9	65.5
Turkey	36.0	42.8	47.4	49.3	51.4	54.0	62.7
Brazil	39.8	38.7	41.4	45.9	51.6	51.4	58.9
Japan	83.3	68.7	69.9	67.8	63.0	54.9	51.7
Russian Federation	32.4	48.7	54.7	59.9	53.5	44.3	50.4
Korea, Rep. of	51.3	47.2	49.2	52.2	51.7	50.1	47.2
Saudia Arabia	18.2	26.1	27.0	30.3	37.4	37.8	41.0
Mexico	32.3	36.0	38.8	39.5	38.3	37.1	38.9
Indonesia	27.8	33.9	33.0	35.0	38.5	36.9	37.8
Italy	38.9	46.4	47.8	47.4	43.0	36.3	-
Germany	35.4	31.2	32.9	32.3	32.5	30.0	-
France	19.2	20.9	22.0	22.1	21.2	18.3	-
Canada	12.8	13.5	14.3	15.1	13.7	11.0	12.4
South Africa	8.2	12.1	13.1	13.7	13.4	12.0	12.0
Argentina	6.1	7.6	8.9	9.6	9.7	9.4	10.4
Australia	7.5	9.1	9.2	9.6	9.7	8.7	9.3
United Kingdom	12.5	11.6	12.1	12.6	10.5	7.8	-

Within the last half-decade more than 50 new precast manufacturing factories have been built, including joint ventures with established European companies to establish a large mainland precast technology presence [44]. Builders, including the largest developer in China, have started actively promoting precast concrete for use in their projects, introducing technology from the Japanese precast industry and physical testing of ~\$500M USD [45]. Several major precast concrete housing projects have been constructed (See Fig. 7) [45]. An additional driving factor is the cost of labor in China, which has increased dramatically over the past 5 years and will continue to increase. The labor cost per cubic meter of precast concrete is less than that of cast in-situ concrete construction because of the efficient labor use in precast concrete [42].



Figure 7: China Precast Projects [45].

On the basis of these developments, the China Ministry of Construction instructed the China Institute of Building Standard Design and Research and Academy of Building Research to develop a new precast code for all of China [42]. The precast concrete structures technical specifications [46]



are to become effective October 2014 with design aids being developed to accompany the code. In parallel, energy codes [47] are being enacted that mandate staged energy savings over time that enforce insulation requirements, and thus should further promote the use of precast concrete, in particular the insulated precast wall panels that are becoming popular to meet these requirements [42].

#### 4. EARTHQUAKE RESISTANT DESIGN

##### 4.1. Past Seismic Performance of Precast Concrete

Precast concrete construction has been shown to be one of the most efficient, durable and economical construction techniques. However, its widespread use has been hampered by its past performance in earthquakes. Fig. 8 shows several significant failures of precast structures in the past including: (a) collapse of a precast parking structure in the 2010 Baha Mexico earthquake [48]; (b) collapse of a precast parking structure in the 1994 Northridge earthquake [49]; (c) collapse of industrial buildings in the 2012 Emilio-Romagna earthquake [50]; and (d) out-of-plane failure of precast wall panels in the 2010 Chile earthquake [51]. Other than the first, where the building was under construction [48], the vulnerability of these structures is related to inadequate consideration of the panelized nature of precast structure and the needed characteristics of the connections details that unite them. As an example, consider precast construction in 1970s China.

Fig. 9a shows a typical apartment building under construction: precast exterior walls, precast floors, cast-in-place concrete interior shear walls, and brick partitions [52]. Many of these multi-family residential structures were built using a “Russian” system of flat slabs supported by load bearing panels [53] with few and brittle connections between precast units. In the M7.8 Great Tangshan Earthquake of July 28, 1976, approximately 85% of buildings in the region collapsed (See Fig. 9b) leading to approximately one-half million fatalities [52].



Figure 8: Precast concrete failures in past earthquakes.

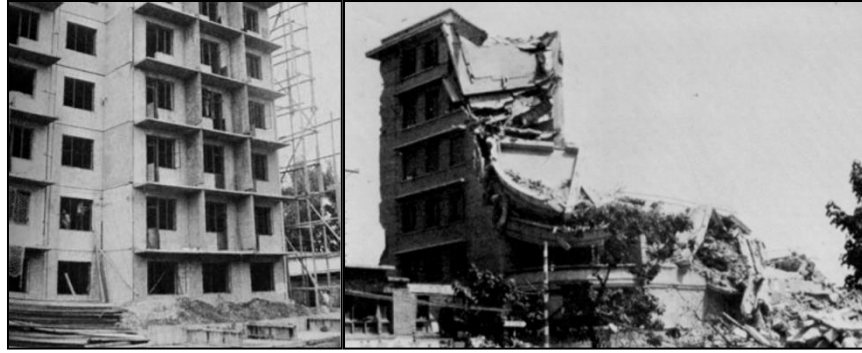


Figure 9: 1970s China: (a) Precast construction; (b) earthquake damage [52].

#### 4.2. Intent of the Seismic Design Codes and Guidelines

It is typically understood that it is not practical, reliable or economical to “out-strength” an earthquake. Thus, modern seismic codes have adopted the approach of designing building structures for strengths significantly lower than those required for elastic response to the design earthquake, but requiring special detailing of the structure so that after it reaches its strength, certain key selected regions will serve as “structural fuses”, yielding in ductile fashion, that is without fracturing or losing strength, thereby dissipating the energy of the earthquake. Typically, using the concept of “capacity design”, other portions of the structure are designed to be sufficiently stronger than the fuses to keep them elastic, and thus not requiring expensive special detailing. The measures, in conjunction with rules to avoid configurations that would be susceptible to a global collapse mechanism, form the basis of the code intent.

Existing building structures can be broadly divided into those that are properly configured, proportioned, designed and detailed for good seismic performance and those that are not. The modern earthquake engineering code was not established until the 1970’s, and important lessons have been learned in decades since. The built infrastructure may have service lives of 50-100 years, thus many existing older structures predate the modern seismic codes and thus do not conform to the best practices. Further, recent improved understanding of the geological seismic hazard worldwide has led to a reevaluation of the seismic risk for certain urban environments where strict seismic detailing has not been historically required. Buildings that do not conform to accepted seismic rules are termed “non-ductile”. Most of the precast failures (See Sec. 4.1) are due to non-ductile details or components (e.g. floor systems).

However, it is important to note that depending on the level of detailing and energy dissipation provided, a conforming structure may be designed for forces to nearly 10 times lower than would be required for elastic response. Thus a properly designed and detailed structure is intended to incur damage to itself in the design earthquake (the energy is dissipated by yielding of the structure itself). This damage, while not leading to failure, may require repair or replacement; or may produce a structure that is not adequate for an aftershock or future earthquakes. The nonstructural elements (cladding, partitions, windows, etc.) have to undergo compatible displacements with the structure and can also incur damage. Likewise the structure may not return to its original position, instead possessing residual drifts that may incur inoperability of elevators, doors or lead to penetrations in insulation or waterproof seals.

In recent years, the concept of performance based earthquake engineering (PBEE) has emerged. In this approach, an engineered asset is designed not just for adequate strength, but also to respond to the diverse needs of owner and users under common and extreme loads [54]. In parallel with advancements in PBEE, there is a recognition that minimizing or eliminating damage is an important performance requirement for seismic resilient urban communities due to an ongoing

debate on the societal expectations of building performance in rare but devastating earthquakes [55].

## 5. TWO DESIGN PHILOSOPHIES: EMULATIVES VS. JOINTED PRECAST CONCRETE SYSTEMS

The concept of accumulating vs. avoiding damage can be clearly illustrated in the two seismic design philosophies applied to precast concrete construction, so-called “emulative” and “jointed” systems. These design approaches prevent the poor detailing or construction issues that led to precast failures in previous earthquakes. Though in use in many countries, New Zealand construction practice will be highlighted since its performance was tested recently.

### 5.1. Emulative Precast Concrete Systems

The concept of emulative precast construction is to proportion the precast concrete structure to possess strong joints (relative to the elements), thereby forcing the inelastic response to the earthquake within the precast elements themselves, and to provide these precast elements with the special detailing associated with traditional seismic design of (cast-in-place) reinforced concrete (RC). Precast emulative systems are expected to perform similarly to properly designed (“conforming”) cast-in-place construction under earthquake shaking [56], or even better since the special detailing involves accurate placement of the steel reinforcement, which is better suited to the precast plant than the jobsite (Refer to Sect 3.2). In a properly detailed RC moment frame, for instance, non-ductile actions such as shear failure are precluded and the capacity design approach requires a strong-column/weak-beam design that protects against a concentration of lateral deformation termed a story mechanism. For emulative designs, the precast units are provided with: (1) ductile beam end region detailing; (2) sufficient transverse reinforcement to preclude shear failures and provide adequate confinement in plastic hinge zones; (3) proper detailing in joints to avoid anchorage, bond, or splice failures; and, (4) overstrength in the column and joint to keep these regions elastic. In New Zealand, most emulative precast moment frames systems employ small cast-in place closure pours in splice regions located between the precast units [57]. The closure pour can occur at beam mid-span (See Fig. 10) where the precast unit is erected by passing column longitudinal reinforcing through ducts. These closure joints are typically completed with pouring of the floor topping slab, including beam top reinforcing steel and diaphragm anchorage.

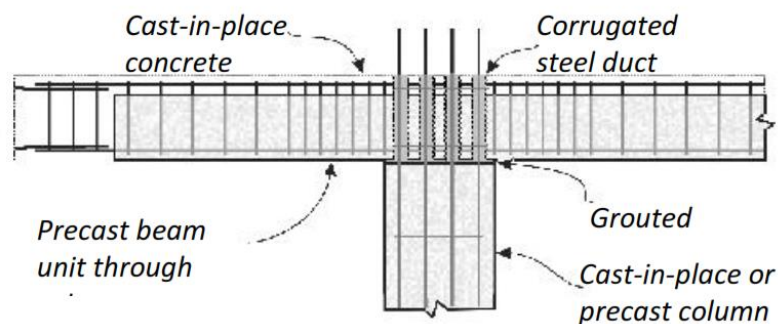


Figure 10: Emulative precast concrete system (NZ) [62].

### 5.2. Jointed Precast Concrete Systems

A more recent precast construction practice is jointed ductile construction, in which nonlinear deformation occurs not in distributed plastic hinge regions within precast units, but instead in specially detailed joints between precast units. The precast units are made stronger than the

connections between the units, and the joints provide the ductile seismic “fuses” [58]. The most developed among jointed systems are PRESSS moment frames and coupled rocking walls [59] [60] (See Fig. 11). Both systems use unbonded post-tensioning through precast elements to achieve self-centering behavior. The structural elements are maintained in the elastic range, and energy dissipation can be provided by internally grouted mild steel or replaceable external dissipators. Because of the self-centering behavior and the use of reversible joint opening (rather than the cracking and yielding of plastic hinges), such systems are referred to as low-damage or damage-control systems. The systems can be considered to provide cost-efficient alternatives to seismic design options of base-isolation and supplemental damping devices.

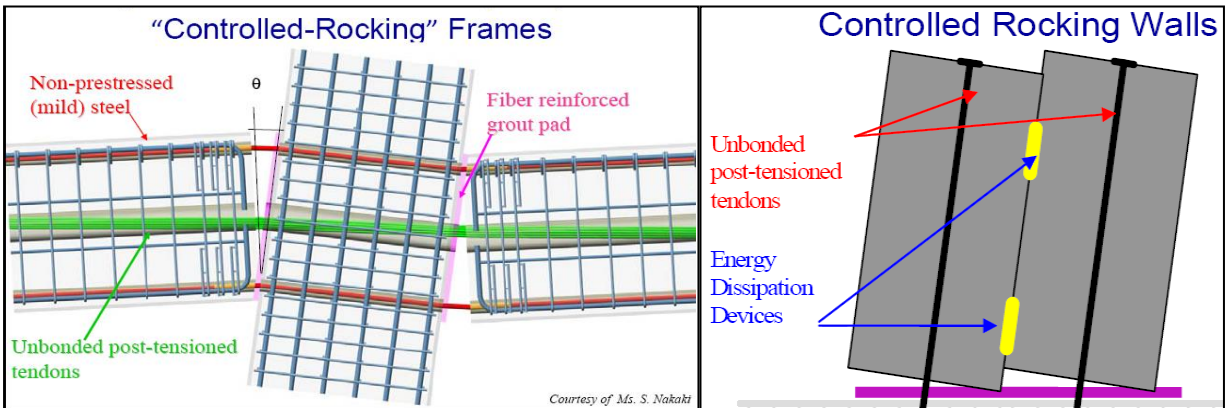


Figure 11: Jointed Precast Systems: (a) Hybrid Frame; (b) Hybrid Wall [59].

These systems have begun to be built in the U.S. and elsewhere, including a recent LEED™ Silver design [36] (See Fig. 12), which took full advantage of the thermal mass of the concrete exposing it to the interior as well as the exterior to maximize its benefits. The design team’s mechanical engineer estimated that the energy savings from using the thermal mass of concrete was approximately 15% [36].

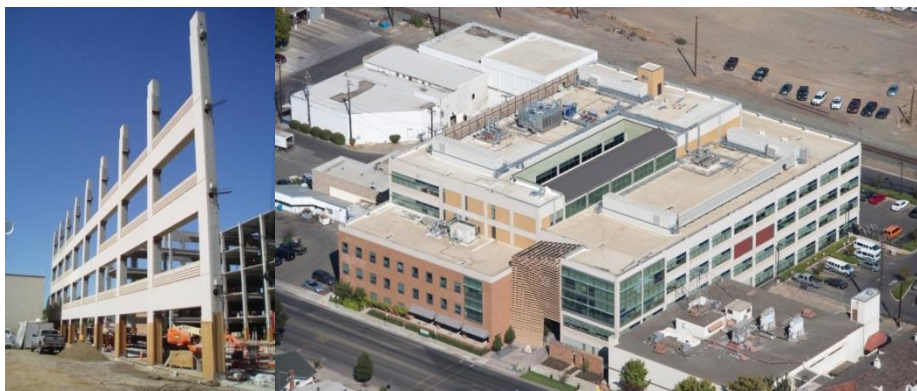


Figure 12: Recently Constructed Hybrid Precast Frame [36].

## 6. CASE STUDY: PRECAST CONCRETE PERFORMANCE IN THE 2011 NEW ZEALAND EARTHQUAKE

### 6.1. The 2011 New Zealand Earthquake

The 2011 Christchurch earthquake was roughly equivalent to the maximum considered earthquake for Los Angeles, for a region with a design seismicity roughly equivalent to Portland



[61]. Several reinforced concrete buildings collapsed or were damaged beyond repair, leading to nearly 200 fatalities. The strict seismic code and the well measured earthquake permitted a unique opportunity to evaluation building performance under strong ground shaking.

### 6.2. Performance of Emulative Systems

Figure 13a shows a 20-story Christchurch office tower built in 1988 using the system shown in Fig. 10. Note the Fig. 13a photo is post-earthquake. The moment frame possessed specially-detailed interior and corner precast beam units installed on cast-in-place columns. Fig. 13b shows a 1988 photo of one of the precast corner units being erected. Fig. 13c shows the typical damage endured by one of those units, indicating the ductile damage expected of a specially detail RC frame and little damage in the column, indicating that the emulative design met its intended behavior [62]. Nevertheless, the damage incurred by this frame, which protected the building, led to the tower being torn down (See Fig. 13d). Note that this demolition was performed using piece “deconstruction” as described in Sec. 3.2.

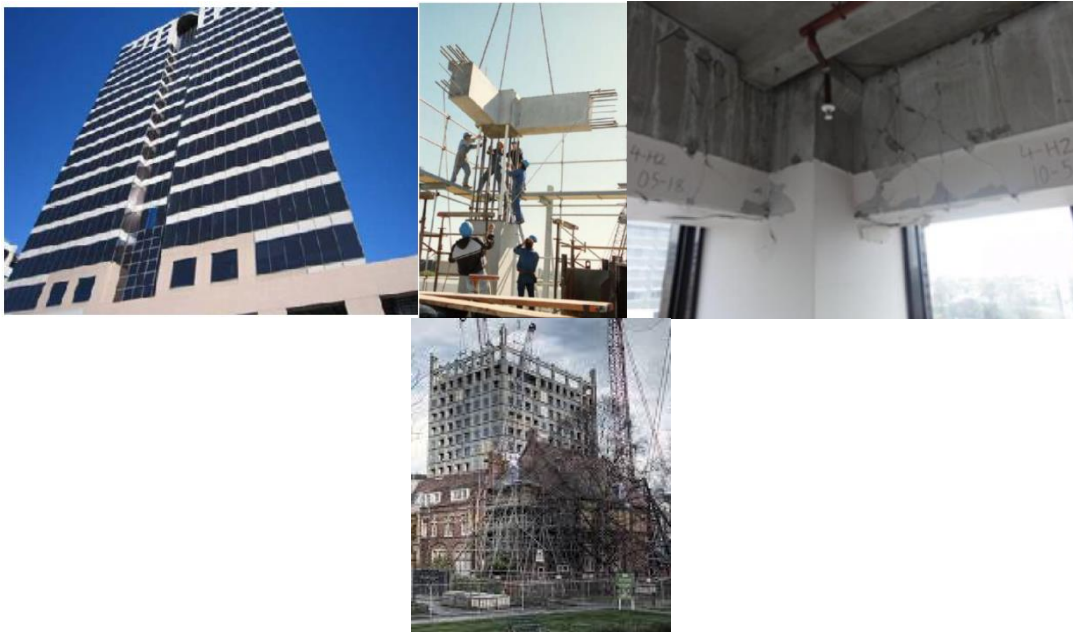


Figure 13: Precast Emulative Tower [62]: (a) Exterior; (b) Construction; (c) Typ. Seismic Damage; (d) Demolition.

### 6.3. Performance of Jointed Precast Systems

Contrast the above performance of a jointed precast structure, also located in the region of strong shaking. Fig. 14a shows the structure, a 3-story medical office building, again shown after the earthquake. The structure employed hybrid frames (i.e. Fig. 11a) in one direction and hybrid rocking walls (Fig. 11b) in the other [63]. Fig. 14b shows the extent of the damage incurred in this structure, which was limited to some drywall rubbing on the staircase. Fig. 14c shows the precast hybrid moment frame, indicating no damage and a re-centered structure [62]. Fig. 14d shows the post-earthquake state of the buildings, indicating an immediate operational state, as needed in a critical care facility.



Figure 14: Precast Hybrid Structure [62]: (a) Exterior; (b) Seismic Damage; (c) Frame; (d) Post-EQ Operational.

#### 6.4. Discussion of Performance

The emulative structure performed exactly as intended under an earthquake significantly stronger than its design earthquake. The design placed joints in the precast structure at non-critical locations and detailed the precast unit to safely dissipate the energy of the earthquake without structural distress. But the damage incurred to the structure was deemed unacceptable for repair and the structure was demolished. This indicates a difference in the expectation of the design professional/code and that of the general public [62]. Contrast this with the performance of the hybrid structure which survived the earthquake essentially damage free and immediately operational. This difference points out the benefits of using such low-damage structures for resilient communities.

## 7. CONCLUSIONS

Precast concrete construction possesses inherent characteristics that may be competitive in modern construction where an increased emphasis is placed on sustainability and earthquake resilience. The high quality control of precast concrete and the prestressing of precast concrete leads to less material required and hence less embodied energy; the piece erection leads to cleaner, quieter construction sites; and the insulation and architectural finish can be integrated directly into the precast unit, increasing energy efficiency and consolidating construction operations. The seismic performance of precast concrete, historically a liability due to non-ductile details acting at critical joints, can actually out-perform other construction forms in the modern world where damage accumulation is less tolerated by taking advantage of the jointed nature to eliminate structure damage and the use of unbonded post-tensioning to provide a re-centered structure after the earthquake. The safe, effective and efficient use of precast concrete involves an investment in technology, infrastructure and transfer of knowledge from those countries with extensive experience, but in the longer term has the potential for economic savings, less adverse environmental impact, and improved urban resilience.

## ACKNOWLEDGMENTS

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# Construction Waste Management: An Effective Approach to Sustainable Development

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### **Abstract**

It is estimated that the construction industry uses up to 25% of total raw materials and produces more than 30% of total solid wastes, even in the most developed countries. High amounts of material usage and wastage exerts several detrimental effects on economy, environment, and society. The optimization of construction material usage not only saves costs but also significantly contributes towards Sustainable Development. During recent years, growing concerns about the sustainability of construction activities has brought the issue of Construction Waste Management (CWM) to the fore. Although several studies around the globe have addressed concepts and practices of CWM, the lack of comprehensive, practical frameworks to help project managers implement those principles in construction projects, especially in developing countries where traditional construction methods are common, is still palpable. Construction Waste can be addressed in two different ways: first waste minimization, and second waste management during the project total life cycle, from initiation to demolition. The aim of the first phase of this research program was to identify the sources of waste throughout the supply chain of construction projects. In the second phase, several comprehensive studies were conducted in order to find effective ways for CWM during construction, renovation and/or demolition phases of the projects. Current research efforts are focused on the evaluation of project organization factors such as contract type on the amount of waste generated in construction projects as well as the development of appropriate guidelines that promote waste management throughout the project lifecycle.

**Keywords:** *Construction Waste Management (CWM), Sustainable Development (SD), Constructability, Construction and Demolition Waste, Construction Productivity*

## **1. INTRODUCTION**

The construction industry plays a major role in enhancing the competitiveness and prosperity of the economy. The design, construction, operation and utilization of the built environment have important economical and sustainability effects. Modern and efficient built environment is a key driver of productivity and growth in every economy. Therefore, the construction industry should focus on delivering the built environment in an effective and innovative fashion in order to maintain its share in the economy while coping with the global sustainability rules and regulations.

The construction industry has significant impact on the environment during execution of every phase of a project's life cycle. It consumes enormous amounts of raw materials and respectively

produces considerable waste during construction, renovation and/or demolition phases of projects. Studies estimate that the construction industry consumes around a quarter of all raw materials used in the economy. It also produces up to one third of total landfill wastes with a 1:2 ratio of construction to demolition waste [1-3]. Only a fraction of the produced waste is currently recycled or reclaimed.

By enhancing its efficiency in using resources, the construction industry can play a central role in the global drive to promote sustainable growth and development. Sustainable Development is defined as “Meeting the needs of the present, without compromising the needs of future generations” [4]. Construction industry, by its very nature, contributes to the economic aspect of sustainable development. However, policy makers and practitioners tend to forget the other two dimensions of sustainable development-environmental and social development-during planning and implementation of construction projects [5]. In developed countries, standards, guidelines, and regulations have been designed to address the issue of Construction Waste Management (CWM). However, despite consequence and adverse impacts that excessive production of Construction and Demolition Waste imposes on sustainable development, little care has been given to the implementation of CWM practices in undeveloped and even developing countries. As a result, the construction industry has not made satisfactory progress towards achieving sustainability. For instance, the ultimate product of today’s construction industry is the built environment designed and constructed without any consideration for dismantling and reuse at the end of its life cycle [6].

Whilst there are several articles, instructions, and manuals addressing the issue of construction waste, waste management programs in Iran are not integrated effectively in most of the construction projects. This is partly because current policies, procedures and methods do not address the issue holistically. They do not take into consideration all aspects of a project, i.e. all its phases, work resources, and activities. Lack of practical frameworks to help project managers to implement the concepts and practices of CWM in projects is a gap that has to be closed through research and development. Therefore, more holistic studies are needed to address the concepts and principals of CWM. This paper provides an overview of the research endeavors aimed at enhancing the state of knowledge and practice in devising and implementing appropriate waste minimization and management practices in the construction industry. In this context, management of waste is defined as eliminating waste to the maximum possible extent by minimizing waste where feasible, and reusing materials that might otherwise become wasted. Solid waste management practices have identified the reduction, recycling, and reuse of wastes as essential for sustainable management of resources. Studies conducted at Sharif University of Technology (SUT) during the last several years include, but are not limited to, the following topics:

## **2. CONSTRUCTION WASTE MANAGEMENT AN APPROACH TO IMPROVE CONSTRUCTION PRODUCTIVITY**

The objective of this study [7] was to enhance the understanding about CWM practices and improve construction productivity as well as promote sustainable development. Through a comprehensive literature review, concepts such as project productivity, Sustainable Development, whole life cycle paradigm, and hierarchy were analyzed. The review of literature showed that the amount of construction waste, even in most developed countries, is high. Nevertheless, it was found out that in the developed world, significant efforts have been dedicated to the development of appropriate policies and regulations as well as manuals and instruction on the CWM topic. Following the review of literature, a frame of reference to shift the current paradigm in industry to “construct with minimum waste” was developed. This paradigm identifies and discusses CWM considerations through whole project life cycle, i.e., from feasibility studies to the start-up and operation of finally-built structure.

The CWM Paradigm is the frame of reference by which project decision makers would effectively contribute to decreasing the amount of waste generated through construction activities,

which by itself will improve a project's productivity. Table 1 displays the summary of the survey. This summary table presents a mapping of CWM areas of concentration and proposed strategies to the project life cycle phases. A concentration area is a topic/issue that is of special importance when considering CWM, while proposed strategies, methods, tools, and techniques refer to special practical recommendations with regard to each concentration area.

TABLE 1: MAPPING OF CWM CONSIDERATIONS AND STRATEGIES TO PROJECT LIFE CYCLE PHASES.

Project Phases	Construction Areas	Proposed Strategies, Methods, Tools and Techniques
Feasibility Studies	Cost	Cost-Benefit Analysis, Value Engineering Life-Cycle Costing Recycled materials market analysis
	Time	Deconstruction parallel to design/engineering Proper Scheduling Work smarter, not slower (avoid complexity in workers' duties)
	Quality	Assess and estimate the quality of recycled materials Assess and estimate the quality of final products (structures)
Design and Engineering	Design/Engineering philosophy	Adoption of modern design systems e.g. modular design Use of standard, simple shapes and sizes
	Constructability analysis of design	Design construction integration Provide accurate, understandable, reliable blueprints
	Design change and modifications	Avoid frequent change Select change options with minimum demolition and rework
	Material construction	Use prefabricated members Use recycled materials
	Estimating materials requirements	Provide accurate destination of amount of material delivery Provide accurate destination of time of material delivery
	Job-site layout	Allocate adequate, appropriate space to CWM equipment Allocate adequate, appropriate space to collecting bins Allocate adequate, appropriate space to inventory Provide easy-access routes between inventory and workshop
Procurement	Materials and source selection	Use durable materials Use local resources
	Supplier selection and management	Stipulate take-back policies Require reduction of packaging materials
	Contractor's selection and management	Represent waste reduction requirements in the contract Require the contractor to submit a CWM Plan Require the contractor to document their waste reduction Incorporate the CWM plan into the contractor's QC/QA
	Equipment and machinery selection	Consider waste characteristics Consider market specifications Consider job-site space and layout
	Ordering management	Order in coordination with design/engineering unit Deliver just-in-time
	Inventory management	Allocate appropriate space and position to inventory Provide proper sheltering against weather and human factors Provide easy-access routes to inventory
	Transportation and on-site handling	Hire experienced and reliable haulers Maintain proper on-site supervision
Construction/ Execution	Construction and demolition methods	Prefabrication Deconstruction Improve efficiency of current methods
	Mistakes, errors and rework	Provide clear, reliable blueprints Maintain proper on-site supervision Use advanced, reliable technologies Perform periodic service and repair equipment Keep job-site organized and safe

	Job-site activities Plan	Construction waste management plan Construction waste management site activities plan
	Job-site supervision	Troubleshooting and on-site training/education Change requests Prepare periodic performance reports
	Training and education	Arrange and manage training sessions Provide and distribute easy-to-understand instructions Design and set job-site instructive signs and marks
	Quality control	Quality control/assurance over recycled materials Quality control/assurance over final products(structures)
<b>Start-up</b>	Job-site final clean-up	Collect unused materials after construction
<b>Operation/Utilization</b>	Renovation and repair	Deconstruction and careful dismantling Reuse and recycle used materials

It is recommended that constructors apply this frame of reference to optimize material usage. It should be noted that the implementation of this frame of reference requires no additional planning and/or resources. In addition to the introduction of the paradigm, a model based on the common lexicon provided by Project Management Body of Knowledge (PMBOK) was developed. This model is intended to serve as a standard for project managers to implement CWM program in construction projects. In the process of developing this model, first the feasibility of adding construction waste management concepts to Environmental Management knowledge area was examined. However, the scope of necessary changes as well as the importance and universality of CWM principles required that the principles of CWM would be treated as a separate knowledge area of construction extension. Ultimately, on the account of their previous studies and experience, authors suggest that this knowledge area be added to future release of construction extension to PMBOK Guide, in order to guide to maintain its inclusivity.

Construction Waste Management knowledge area includes the process required to ensure that construction projects are executed with appropriate care to reduce the waste materials headed to landfills. The proposed model recognizes seven processes in CWM Knowledge Area: Waste Identification and Analysis, Waste Management Planning, Resource Planning, Training and Educational Programs, Waste Management Plan Execution, Waste Management program Control, and Waste Management Program Administration and Records. In Table 2, these processes are mapped into five major process groups of initiating, planning, executing, controlling and closing.

TABLE 2: MAPPING OF CONSTRUCTION WASTE MANAGEMENT PROCESSES TO THE PROCESS GROUPS (FORMAT ADOPTED FROM PMBOK\* BY PROJECT MANAGEMENT INSTITUTE).

Knowledge Area	Process groups				
	Initiating	Planning	Executing	Controlling	Closing
Construction Waste Management	1. Waste Identification and Analysis	1. Waste Management Planning 2. Resource Planning	1. Training and Educational Programs 2. Waste Management Plan Execution	1. Waste Management program Control	1. Waste Management Program Administration and Records

The model is specifically developed for projects where CWM is recognized as a major program of the project portfolio similar to other programs such as the Health and Safety program. Finally, as

part of this research, a study aimed at characterizing the status of construction waste production and management in Tehran metropolitan area was conducted. The case study and the follow-up analysis led to the identification of a set of measures that can improve the current situation. Based on the findings of this analysis, in order to implement CWM principals in Iran's Construction Industry, government should set out rules and provide instructions on the issue; while constructors must design structures for minimum waste, and adopt modern construction method like prefabrication.

- Through several case studies, factors affecting construction materials waste generation during supply chain (mainly perishable like Ready-Mix Concrete (RMC) and/or Hot-Mix Asphalt (HMA) at the construction site were carefully investigated and ranked. The 10 most important ones were found to be: Wastes generated due to lack of modular or standard construction
- Wastes generated by Non-Recyclable packaging materials
- Using Low quality Building Utility Components that would require early age renovation
- Wastes generated by untrained or unskilled workforce
- Lack of CWM program in the project administration
- Using low quality construction materials
- Waste generated during transport to site or inside the site due to improper packaging
- Wastes generated by cutting due to design requirements and/or mis-orders
- Wastes due to over-stocked bulk materials at the site
- Wastes generated because of utilizing old or imprecision tools or equipment

### **3. EFFECT OF CONSTRUCTABILITY STUDIES ON CONSTRUCTION WASTE MANAGEMENT**

During the construction of high-rise buildings, project team issues may arise, such as changes, additional costs of duplication, lack of technical specifications in plans, safety, and delays. One of the most effective ways to avoid these issues is constructability evaluation at the appropriate stages of project. There are several definitions for Constructability. For instance, it has been defined as the optimal use of knowledge and practical experience in planning, design and procurement in order to achieve the overall goal of the project [8]. Numerous studies have investigated the impact of conducting constructability reviews in construction projects. A study conducted by the Construction Industry Institute [9] showed that implementation of constructability reviews in five different projects has reduced the project duration by 11 to 30 percent. In addition, analysis of data from several projects has shown that by using constructability, time is reduced without resulting in any significant costs increase [10].

The objective of this study [11] was to examine the effectiveness of constructability and productivity reviews in high-rise building projects. Interviews with experts and questionnaires were used as the main tools to gain insight about this matter. The study first investigated the opportunity to implement constructability reviews in the design phase of high-rise building projects. In the design phase, the constructability review should focus on the following areas:

- Evaluating project site and environment in terms of architectural textures
- Designing to minimize the work on levels below the surface
- Designing to simplify installation
- Encouraging standardization and increasing repetitive activities
- Designing to improve prefabricated elements
- Analyzing the access to project site
- Utilizing modeling and simulation to avoid problems during construction
- Evaluating the possible juxtaposition of different materials due to allowable tolerances
- Evaluating optimization of stages and sequence of activities

- Planning to avoid problems in sequential activities
- Considering the warehouse location due to the need of transferring materials at project site
- Studying the design effects on plant safety
- Designing to minimize repetitive traffic during construction
- Designing according to available resources and skills
- Considering appropriate designing materials
- Providing clear details and technical specifications
- Designing a general framework of construction to provide parallel work fronts
- Considering the interaction of climate on construction materials and methods

Considering the eighteen areas of constructability reviews during the design phase of high-rise buildings, a questionnaire was prepared. The aim of this questionnaire was to assess the impact of constructability reviews in the abovementioned areas on construction productivity in high-rise building projects. The responses to the questionnaire were analyzed using the average index method. Table 3 summarizes the survey results. The survey results indicated that, if conducted during the design phase, constructability reviews could enhance the productivity in high-rise building projects. It is recommended that, prior to the initiation of a project, the project management team develops appropriate guidelines and checklists for conducting constructability reviews.

TABLE 3: THE DEGREE OF INFLUENCE OF CONSTRUCTABILITY IDEAS ON PRODUCTIVITY.

No.	Criteria	Score (Out of 5)
1	Considering appropriate designing materials	4.6
2	Design to simplify installation	4.5
3	Design according to available resources and skills	4.5
4	Design to quickly create a general framework of construction to provide parallel work fronts	4.4
5	Providing clear details and technical specifications	4.3
6	Evaluation of optimization of stages and sequence of activities	4.3
7	Evaluating project site and environment	4.2
8	Analysis of access to project site	4.2
9	The use of modeling to avoid problems during construction	4.1
10	Evaluation of the possible juxtaposition of different materials due to allowable tolerances	4.1
11	Planning to avoid problems in sequential activities	4.1
12	Encourage standardization and increasing repetitive activities	4.0
13	Considering the location of the warehouse due to the need of transferring materials at project site	4.0
14	Studying the design effects on plant safety	4.0
15	Design to minimize the work on levels below the surface	4.0
16	Design to improve prefabricated	4.0
17	Considering the interaction of climate on construction materials and methods	4.0
18	Design to minimize repetitive traffic during construction	3.8

Surveys show that the two main barriers to implement correct CWM are identified as:

- Lack of culture for saving the resource and/or optimum use
- Lack of defined recycling scheme in the project administration

Experts recommended strategies should be developed in order to:

- Perform Constructability Analysis at design stage
- Use Industrial Construction and build quality to last longer
- Reuse or Recycle when demolishing

#### **4. COMPARATIVE STUDY OF GPS-INTEGRATED CONCRETE SUPPLY MANAGEMENT USING DISCRETE EVENT SIMULATION**

The Just-In-Time (JIT) delivery of critical resources needed in projects located in congested urban areas creates a unique challenge to project managers. Results of an analysis based on Analytical Hierarchy Process (AHP) confirmed the common understanding that traffic conditions, and waiting times in the unloading queue, are the most critical factors affecting both productivity and production of activities such as concrete placement. In order to study this interesting problem, a mathematical model was developed [12]. Instead of deriving explicit answers using mathematics alone, discrete event simulation was used to assess the consequences of traffic restrictions on the performance of hauling equipment. Taken together, off-site queuing did not provide significant advantages due to the lack of accurate information on the progress on site and the traffic on the last haul segment. Using the smooth stream of trucks controlled by the off-site queue can still be disrupted when, upon arrival on site, no space for unloading is available, sending the truck into “Roaming” circle.

An appropriate alternative is to create a waiting area for queuing the trucks outside the restricted area (off-site queue). The major difference between on-site and off-site waiting queues is the timing of queue entry and exit. While a full truck leaves the on-site queue immediately after the preceding truck completed its service, a truck waiting in an off-site queue exits the queue earlier with sufficient time left to finish the last segment of the delivery. However, the travel time between the off-site waiting area and the construction site fluctuates according to traffic conditions, making an accurate prediction impossible. If a truck arrives before the preceding truck has left, it has to begin cycling around the site much like an airplane arriving too early in the target airport. In this case, the truck will return to the “gate” at uncertain time intervals until the unloading space is empty. On the other hand, extending off-site waiting of the truck in order to assure immediate service at site may result in idleness of the on-site resources. Both situations contribute to wasted time despite the main function of a queue to prevent idleness of the process to be served. Discrete event simulation is an excellent tool to study the effect of an off-site waiting queue by comparing two scenarios: a) off-site waiting, and b) on-site zero-queue. In either case, a full truck arriving at the construction site when the unloading space is not empty will be sent on a short, random-duration roaming circle. This process is repeated until the truck finds an empty space. The concrete delivery process was simulated for a combination of varying fleet sizes and ‘Return’ times in order to assess the efficiency of implemented management alternatives.

Every simulation model must be tested to ensure a sufficient representation of the real world. For that purpose, data was collected during the construction of a multistory building located in Sydney Australia’s central business district (CBD). Because of space and traffic limitations only one truck could be unloaded at the one time. For this reason, an off-site waiting queue 2.4 kilometer from the site was established and the truck fleet consisted of 11 trucks.

Fig. 1 provides a graphical comparison between hauling fleets with and without off-site queues. Two curves represent each fleet size with different regimes producing a family of curves. The first regime called ‘parallel’ refers to the situation that zero-queue policy is absolutely preferable to off-site queue. Production rate tends to be constant because the concrete pump is operating continuously. Oversized fleet and shorter travel times ease development of parallel condition where zero-queue policy should be selected. Intensifying effective factors dominates parallel regime in a larger region. The ultimate situation referring to infinity ‘Return’ time is called



'identical.' Undersize fleet brings formation of 'identical' regime forward. Regardless of 'Return' time, the two approaches do not differ significantly in 'identical' regime. In this case, actually no off-site queue forms and each truck will be sent directly to construction site. 'Transition' phase describes the unsteady section between two extreme regimes and is more common in the medium size fleet with moderate 'Return' time. The two curves graphing the hourly production using 50 trucks with or without an off-site queue are parallel with the zero-queue resulting in a higher output of approximately 5 trucks/hour. This indicates that 50 units far exceed the balance point and the pump is "bottlenecking" the production. On the other hand, changing the return time for 20 trucks without an off-site queue moves the production from the left- to the right side of the balance point resulting in a large drop. Curves for 5 and 2 trucks show the effect of migrating further left while a fleet of 5 passes through all 3 phases and determines the threshold for using off-site queue. Of course the zero-queue policy performance is anticipated to be higher or at least the same as off-site queue. It is interpreted as the effect of extra uncertainty by adding a waiting time to the cycle. Simulation results confirm that an off-site queue is an uncertain component to be included in the process. In this case, separation from construction site is the main source of uncertainty. Efforts required to coordinate such a separated component with whole system reduce production rate more than what actually achieved by regulating hauling equipment. This is the reason leading to lower efficiency of an off-site waiting queue as fleet size increases. Since an off-site queue does not affect service time uncertainty, arriving trucks may find the server busy even after standing in the off-site queue. However, application of state-of-the-art communication technologies to coordinate between site, off-site queue, and hauling road is essential for the effective use of the off-site queue. It should be noted that the simulation model does not consider that the number of trucks could affect the "normal" traffic. This assumption is quite rational when the number of trucks is comparatively small. A more extensive study would be needed if the fleet itself would contribute to the congestion thus adding to the travel time.

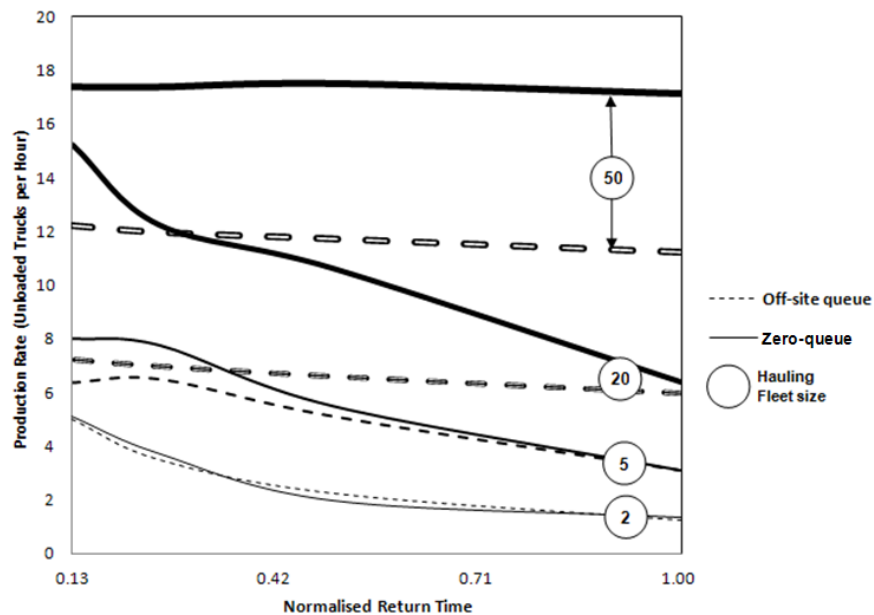


Figure 1: Comparison of normalized return times with and without offsite queues.

As part of this study, the effect of using advanced communication and real-time locating systems to reduce this uncertainty was evaluated. It was shown that the off-site waiting queue becomes very effective in regulating delivery logistics. The added accuracy of truck arrivals decreased the waiting time of the concrete pump that consequently increased the productivity of

the crew placing the concrete. GPS-integrated off-site queue management of delivery trucks in heavy traffic areas shows great promise to cut process wastes while elevating production rates.

## **5. ONGOING RESEARCH EFFORTS**

There are several ongoing research efforts focusing on CWM. An overview of these research efforts is presented below:

- a) Understanding the impact of contract type on the amount of construction waste generated in residential projects: The objective of this study is to utilize field studies and surveys in order to enhance the understanding about the impact of contract type on the amount of construction waste generated in residential projects. The study also investigates the impact of contract types on the waste minimization and management practices that practitioners adopt in residential projects. The early findings of this research indicate the contract type has an apparent effect on the amount of construction waste produced in construction project. Fig. 2 shows a comparison of the amount of waste (as a percentage of the total material consumption) generated in Lump Sum and Cost Plus projects. In the later stages of this research, the data will be statistically analyzed to determine whether the effect of contract time on the amount of waste is significant. The results will be interpreted in an effort to identify the key factors contributing to these differences.
- b) Creating appropriate guidelines to incorporate waste minimization and management considerations in project planning and permitting process: The preparation of a CWM Plan should begin in the early stages of project development to facilitate efficient and timely management of the wastes that are likely to be created during the construction process. It is essential for the parties involved in a construction project to estimate the amount waste in a construction project and accordingly plan and control the process of managing the generated waste. If developed at the early stages of a project, construction waste management plans will help project stakeholders establish goals for the management of construction waste by focusing upon waste minimization, reuse, and recycling opportunities. This will promote sustainable development, environmental protection and efficient use of resources. The objective of this study is to develop guidelines on preparation and evaluation of CWM Plans in the early stages of the permitting of construction. A model will be provided to estimate the volume of waste that is expected to be generated during the construction period. Appropriate measures will be introduced to develop and evaluate the plans that are designed to minimize and/or manage the generated waste during the construction process. The permitting agencies such as municipalities can use the outcome this research to integrate the development of an appropriate construction waste management plan as a critical part of the permitting process that all construction projects should pass.

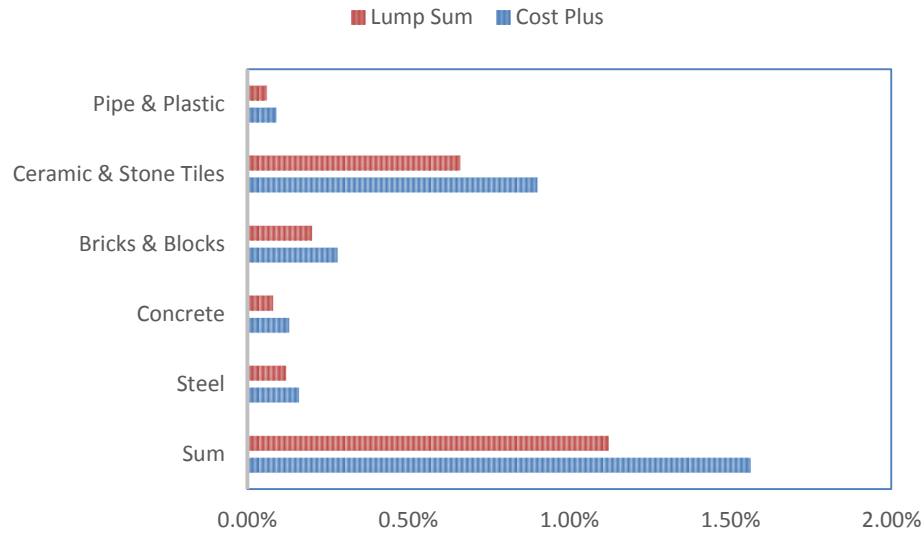


Figure 2: Comparison of the Amount of Waste Generated in Lump Sum and Cost plus Projects.

## 6. CONCLUSIONS

In this paper, an overview of the findings of a broad research program that has been undertaken over the last several years is presented. The objective of this research program is to identify and/or develop appropriate waste management procedures and practices that can be implemented throughout the construction project life cycle from planning, design and construction stage to the renovation or demolition phase.

CWM can be addressed in two different ways; first waste minimization, and second waste management during the whole project life cycle, from initiation to demolition. The aim of the first phase of this research program was to identify the sources of waste throughout the supply chain of construction projects and determine appropriate waste management practices to control the generated wastes. Several factors were carefully investigated and ranked. In the second phase, several comprehensive studies conducted in order to find effective ways for CWM during construction, renovation and/or demolition phases of the projects. The feasibility of adding Construction Waste Management concepts to Project Management Knowledge Area has been examined in this research program.

This research program has been expanded over the past few years and, at present, there are several ongoing research efforts focusing on CWM. Research is being conducted to understand the impact of project organization factors such as contract type on the amount and characteristics of waste generated in construction projects. There is another research effort focusing on creating appropriate guidelines to incorporate waste minimization and management considerations in project planning and permitting process.

It is imperative to conduct more studies on CWM. These research efforts should especially focus on the construction industry in developing economies, where construction works will remain a major economic activity. In future research projects, sophisticated modeling and simulating techniques should be used in conjunction with surveys and case studies in order to enhance the understanding about effective ways to approach CWM.

The main research recommendations are the followings:

- CWM Plan and its complementary supporting details should provide the roadmap for the execution of the CWM program;

- Achievement of CWM incentive goals should be included in the project charter;
- CWM program should require workforce to work more efficiently and neatly;
- Administration and closure should include documenting project results to formalize acceptance of the ideal final result by the Project Management, governmental authorities, and organizations approving the implement of CWM. It includes collecting program records, ensuring that they reflect final specifications, analyzing program success and effectiveness, lessons learned, and archiving that document for future use;
- Documented waste management performance should become another pillar of CWM; and
- Last but not the least, educational materials, manuals, and instructions are to be prepared and documented for extensive use.

Furthermore, CWM will remain a principle research topic at Sharif University of Technology; and issues such as human factors in CWM are the challenges that will be tackled in future research projects.

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# Urban Ecosystem Services as a Foundation for Planning and Designing Resilient Cities

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### **Abstract**

As the world becomes increasingly urbanized there is a greater need for cities to provide ecosystem services to relieve the burden put on natural systems. Cities can provide ecosystem services through green infrastructure. The supporting, regulating, provisioning, and cultural services of urban ecosystems are an important contributor to the resilience of cities. Despite this importance there are large gaps in understanding of the processes that govern ecosystem service provision in cities. Disconnections between relevant disciplines, such as ecology, planning, and landscape architecture, further compound this. Here I present a social-ecological systems approach and discuss potential connections between ecology and planning that may facilitate the use of green infrastructure to support urban resilience.

**Keywords:** *Ecosystem Services, Green Infrastructure, Ecological Resilience, Planning, Multifunctionality*

## **1. INTRODUCTION**

The majority of the world's population now lives in cities, and population growth trajectories predict even larger urban populations throughout the rest of the century [1]. Cities face complex resource and waste management challenges that affects their environmental footprints and metabolisms, as well as the provision of ecosystem services [2]. The process of urbanization also has important implications for the 'taking' of wild and productive lands as cities spread on the landscape [3]. The growth of cities in the 21<sup>st</sup> century will require investment in new infrastructure and the development of new strategies to manage these environmental challenges. Perhaps more importantly, for urban dwellers, the growth of cities poses significant challenges for well-being and health [4].

Urban ecology has developed in the past few decades partially in response to these challenges [2]. Ecologists have largely and historically ignored the ecological importance of cities [5]. During much of the last century, ecologists have instead tended to focus their studies on what would be considered relatively pristine and undisturbed locations. This occurred despite the recognition by key developers of ecological thought and approaches that humans have a central role shaping ecological processes and are in fact a part of nature [6,7]. An ecological school of thought is emerging that recognizes the central role people play as mediators and creators of the environment [8-10]. This trend has been described by Emma Marris (a popular science writer) by contrasting early and present ecological views of humans and nature: "we must temper our romantic notion of

untrammled wilderness and find room next to it for the more nuanced notion of a global half-wild rambunctious garden, tended by us [11].” A discipline is developing that reflects the growing understanding that ecological systems, especially urban landscapes are novel systems and that recognizes the role of people as managers, stewards, and consumers of nature.

The majority of urban spaces will be newly created or remade in the coming decades [12], presenting a significant opportunity to affect the environmental sustainability of cities. Urban ecology and environmental planning will play critical roles in this transition [13]. These fields are connected through their relationship to the ecosystem services (the benefits we receive from nature) of green infrastructure (Fig. 1) [14]. Planning and design seek to bring the benefits and values of ecosystem services to landscapes through the implementation of green infrastructure. Urban ecology uses assessment and monitoring to connect the design, characteristics, and functioning of green infrastructure to its ecosystem services. The relationship between ecology and planning are important for urban sustainability, but there are many barriers to interdisciplinary connections and collaborations [15].

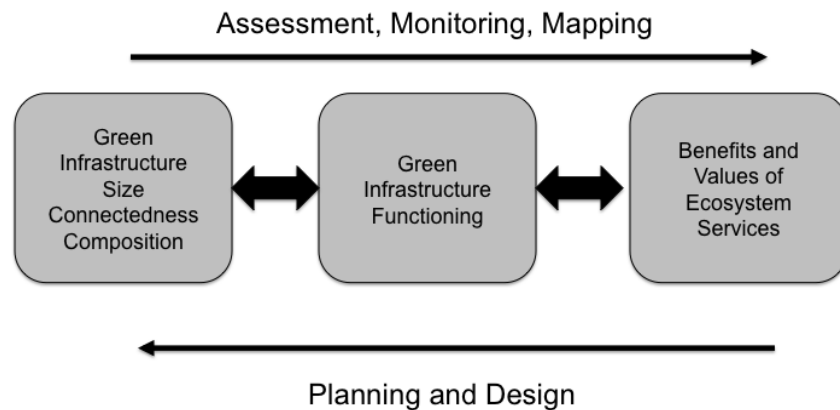


Figure 1: Connecting urban ecology and ecological planning and design (Modified from Opdam 2013 [14]).

The goal of this paper is to present a framework for linking urban ecology and urban planning through the lens of ecosystem services of green infrastructure. I contrast and compare the way these two disciplines define and approach the concepts of ecosystem services and green infrastructure to identify ways for the fields to unify in approach to work towards what are often shared goals, even if the definition of concepts seems divergent.

## 2. HOW ECOLOGISTS THINK ABOUT CITIES

Cities have an important role in global change, both as local drivers of climate change and strong global change force in and of themselves [16]. Moreover, cities are important harbingers of the future environmental conditions anticipated from climate change [16,17]. Urban ecology has emerged a discipline in the last 2-3 decades in recognition of this critical role that cities play in shaping ecological dynamics and environmental patterns. Ecologists have recognized several approaches to studying urban ecology: ecology in the city and ecology of the city [18]. Ecology in the city refers to the study of a city as another form of habitat within which to explore ecological pattern and process. Urban gradient approaches have characterized how forests, soils, biodiversity, and nutrient cycling processes vary across urbanized landscapes [17,19-22]. Ecology of the city expands this approach to treat the city itself as the object of investigation, applying theoretical frameworks and approaches to study a city as an ecosystem. Here, an emphasis is on characterizing the fluxes of materials and energy in, out, and within the urban ecosystem [23,24]. There has been a great deal of progress in understanding urban ecology by applying both these approaches across

the globe. It is impossible to ignore the potential application of the ecological knowledge generated by studying cities. Recognizing this, Wu suggests 'sustainability of the city ' as a third approach that exists within the field of urban ecology [25].

Urban sustainability perspectives integrate understandings of drivers of ecological process, spatial patterns of urban development, and drivers of social patterns and processes [25]. A social-ecological systems perspective recently emerged in the ecological sciences to address the connections between social and ecological drivers and processes [26-28]. Cities can be viewed as social-ecological systems as they are hybrids of natural and human systems with important feedbacks between people and nature that give an urban system its character, structure, and function (Fig. 2). The factors that either enhance or lessen the resilience of social-ecological systems is a core focus of applications of the SES framework [29,30].

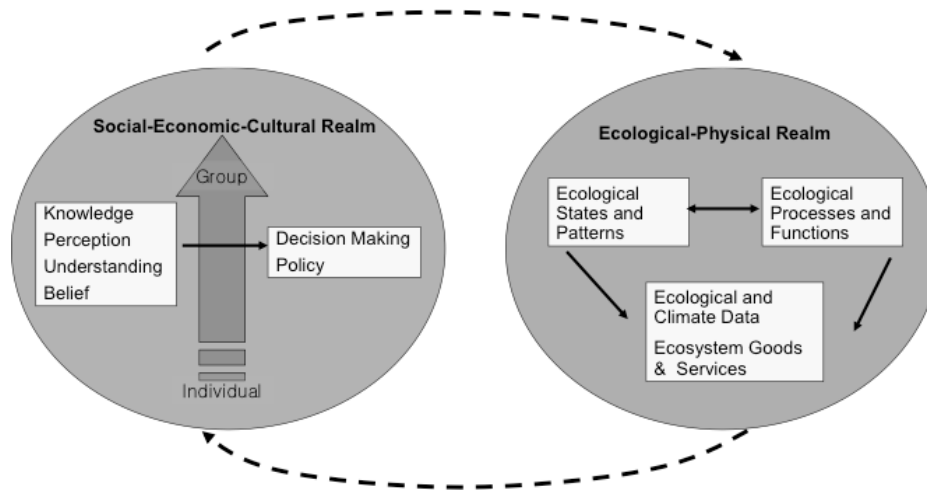


Figure 2: The city as a social-ecological system (SES). Social-ecological systems integrate the dynamics of ecological and social subsystems. Here they are shown linked through the flow of information (dashed lines) which may represent decision-making, perception, design, planning, and other forms of management.

### 3. HOW ECOLOGISTS THINK ABOUT RESILIENCE

#### 3.1. Ecological vs. Engineering Resilience

Resilience is an emerging concept in environmental management and planning [31]. There are disciplinary notions of what resilience means in theory and practice, with two main resilience concepts relevant for urban systems: engineering resilience and ecological resilience [32,33]. Engineering resilience applies to how a system responds to disturbances with an eye to how the system is stable with respect to an equilibrium steady state [32-34]. Engineering resilience derives from notions of resistance to and recovery from disturbances and focuses on the ability and speed of a system to bounce back to its initial, equilibrium conditions following a disturbance event [32,34]. Ecological resilience diverges from engineering resilience due to observed dynamics of ecosystems that suggest that ecological systems (including those that are managed) do not have single stable equilibrium points and exhibit episodic and sudden change [33,35]. Ecological resilience derives from the ability of a system to tolerate stress and reorganize in the face of disturbance and recognizes that systems may shift from one equilibrium state to another. Ecological resilience is the amount of disturbance that a system can absorb before it changes structure and switches to an alternative stable state [27,32,33].

The engineering and ecological concepts of resilience are connected in several ways. Holling suggests that there may be tradeoffs between the two, where an increase in ecological resilience

may come at the expense of engineering resilience, and vice-versa [27,33]. Liao [32] suggests that when the object of study is a 'hybrid system,' one that links humans with environmental, physical, and technical systems, ecological and engineering resiliencies are linked [26,28]. In cities, this may occur through processes that contribute to "community resilience" [24]. Liao [24] suggests that while notions of community resilience are commonly aligned with that of engineering resilience, that is, how a community may prevent and recover from disaster; there is also space for more ecological notions of resilience, where focus is on building resilience. Accepting the variability and surprise that comes from disturbance and building capacity to adapt, absorb, and reorganize in face of shocks are critical components of this form of ecological community resilience. Tidball and Krasny [36,37] describe this ecological perspective well for cities following natural disasters such as hurricanes, highlighting the role that a participatory and "civic" ecology plays in community resilience. Wang and Blackmore [34] identify three aspects of resilience: (1) related to crossing a performance threshold (ecological), (2) related to the response and recovery of a system following disturbance (engineering), and (3) focusing on adaptive capacity and management of a system (social-ecological). They propose that these engineering and ecological perspectives on resilience are complementary, not conflicting, and thus propose a framework to bridge these perspectives for the purpose of planning and management of systems. Again, adaptive capacity is described from a social-ecological perspective on system resilience. Following Wang and Blackmore [34], adaptive capacity is a system property that can support and enhance resilience from both engineering and ecological perspective. In other words this adaptive capacity describes the pace of recovery after disturbance and also how much disturbance can be absorbed before a system moves into an alternative state.

### 3.2. Adaptive Capacity

Adaptive capacity is thus a critical system component that underlies the resilience of urban systems to stresses and disturbance regimes. Resilience can be thought of as the inverse of vulnerability, in that approaches that will enhance the resilience of a city to a form of disturbance will also reduce its vulnerability to the disturbance [38]. Vulnerability to disturbance is derived both from the exposure or sensitivity of a system to disturbance, as well as the adaptive capacity of a system in face of disturbance and change [38]. Adaptive capacity operates at multiple scales and derives from characteristics of both components of the social-ecological system. To highlight how to enhance resilience at multiple scales, Adger et al. [38] provide a matrix describing how to either decreasing risk or increasing adaptive capacity at both local and regional scales (Table 1). These approaches are applicable for urban ecosystems and green infrastructure, as both local (lot, yard, parcel) and regional (planning, greenways, greenbelt) approaches are both needed to ensure ecosystem service provision from functioning green infrastructure.

TABLE 1: ENHANCING RESILIENCE IS LINKED TO REDUCING VULNERABILITY (ADAPTED FROM ADGER ET AL. 2005 [38]).

<b>Element of Resilience</b>	<b>Local Actions</b>	<b>Regional Actions</b>
Exposure to Hazard	Maintain ecosystem functions of GI	Mitigation of drivers of change
	Enhance ecosystem functions of GI	Enhanced Responsiveness
Adaptive Capacity	Ecological Diversity	
	Economic Diversity	Integration response organizations
	Cultural Diversity	Networks to promote learning
	Inclusive and Flexible Governance	

Cities are vulnerable to multiple sources of environmental and resource stress and disturbance that affect resilience. Water resources are a critical element of urban vulnerability both from the perspective of abundance (flooding) and scarcity in arid lands, as well as through impacts on water quality [39]. Cities exhibit urban heat islands (elevation in air and surface temperatures in built



environments), and this shift in temperature can impact the rates of ecological processes and pose significant health risks by exacerbating heat waves [40]. In semi-arid cities there are clear connections between water and energy consumption, plant ecology, and attempts to mitigate urban heat islands [41,42]. The provision of ecosystem services is an important element of urban resilience, impacting both a city's ability to limit exposure to environmental stresses and also to enhance the adaptive capacity of a city to environmental, political, and economic stressors.

### *3.3. Ecosystem Services and Urban Resilience*

Ecosystem services are the benefits and goods that people gain from ecosystems [43], and are a way of translating ecosystem structures and functions into tangible ways of describing how ecosystems contribute to human well-being [44]. The Millennium Ecosystem Assessment [43] classifies ecosystem services as supporting, provisioning, regulating, and cultural services. It is common to combine supporting and regulating services as they often correlate strongly in spatial analyses, or to ignore supporting services as they are implicit in the production of regulating, provisioning, and cultural services [45]. A hierarchical classification approach has been suggested as a way to move forward from concept to operation to facilitate using the ecosystem service concept in assessments and evaluation across spatial scales [46,47]. Such hierarchical classifications categorize ecosystem services at the most general level as sets of themes: provisioning, regulation and maintenance, and cultural [46,47].

As ecologists have turned their attention to cities as objects of study, they have also begun to recognize the ecosystem services that cities provide [48,49]. This may at first seem to be oxymoronic, considering that the ecosystem service concept originated in part as a way to describe the value of ecosystems that were lost due to land use change and urbanization. However, the parks, designed landscapes, remnant patches of ecosystems, and greenspace within cities provide many important ecosystem services [48-50]. These services are important for the health and well-being of urban residents [51]. The ecosystem services that cities provide may also be an important contributor to regional ecological function and ecosystem service budgets that extend beyond city boundaries [52].

Ecosystem services play critical roles in contributing to the resilience and sustainability of urban social-ecological systems. The stewardship and social contexts of urban green areas play important roles in the social memory and ecological management, further contributing to the resilience of urban communities and places [53]. From a social-ecological perspective, the generation of ecosystem services is dependent on both ecological properties of an ecosystem and also social characteristics of the system [54-57]. While the role of planning and formal management have been recognized to be important for the provision of ecosystem services, informal management, through local knowledge, networks, and institutions, may be equally important for the resilient provision of urban ecosystem services [14,54,58]. Linking different perspectives on the management of urban ecosystem services may contribute to more adaptive approaches that capitalize on a diversity of goals, perspectives, and approaches [54,59].

Environmental planners recognize ecosystem service provision and conservation and they are now identified as a target and goal. This has occurred as the spatial scale and complexity of environmental planning expands. Planners classify ecosystem services as abiotic, biotic, and cultural, perhaps to reflect the ways that these services are produced in a more utilitarian sense, linked to the practice that is inherent in the planning discipline [58,60]. From this perspective it becomes apparent how design alterations that are driven by an object-oriented approach might tweak an ecosystem component to yield a desired service. This differs slightly from the more process-oriented approaches used in the fields emerging from ecology and environmental economics.

## **4. THE ROLE OF GREEN INFRASTRUCTURE IN URBAN RESILIENCE**

### *4.1. Defining Green Infrastructure*

Green infrastructure has strong potential to affect ecosystem functions in cities and to support the provision and restoration of ecosystem services for urban residents. Despite this promise, the term "green infrastructure" has several uses in relevant disciplines of ecology, planning, design, and conservation. The definition of green infrastructure reflects the scale of implementation and the environmental goals. The differences in definitions of green infrastructure also reflect an object versus process-oriented classification that is discussed above. In the planning field, green infrastructure is considered "an interconnected network of green space that conserves natural ecosystem values and functions and provides associated benefits to human populations [61]." Planners also define green infrastructure as "the fine-grained network of both terrestrial and aquatic landscape elements [14]." Ecological definitions of green infrastructure are less focused on concepts of networks and have less explicit focus on landscape ecology principles (such as connectivity and patch size). Many implementations by ecologists are more focused on types and objects, rather than a relational or systems oriented notion. For example, Pataki et al. calls green infrastructure, simply, "designed urban green space [62]." While there is variation between disciplines, there is also variability within fields that often reflects some intersection of local physical-environmental conditions and local goals for green infrastructure.

### *4.2. Green Infrastructure Ecosystem Services*

Green infrastructure, however it is defined, is designed to provide ecosystem services. These ecosystem services contribute to resilience and sustainability of urban ecosystems. Green infrastructure is thought to reduce dependence of urban dwellers on more expensive and 'brittle' grey infrastructure, as well as reduce the externalities of consuming ecosystem services from distances far away. Green infrastructure alters storm water flows and enhances ecological functions in ways that enhance infiltration and mitigate surface water pollution [63,64]. Urban forests and trees can reduce the heat loads on buildings and shift urban heat islands [41,65]. Several calculator tools (such as UFORE, iTree) exist to assess ecosystem service provision by existing urban plant covers. However, it is important to note that many actual benefits of green infrastructure have yet to be documented and quantified in real-world urban settings, particularly in a way that accounts for the great variability in urban form and location of cities [62]. Moreover, there is little understanding of how benefits of green infrastructure compare to costs of providing those benefits [62].

## **5. LINKING ECOLOGY AND PLANNING THROUGH ECOSYSTEM SERVICES**

Environmental planning recognizes that, "issues of human-nature interaction are central to the very process of human settlement, urbanization, and well-being [66]." This matches the goals of many urban ecology and ecosystem service approaches [2,25]. Despite the long history of environment and human-nature relationships in the planning discipline, it has seen a limited focus on the implications of ecological principles and interactions as the primary concern in planning theory and practice [66]. Conservation planning has evolved through time to incorporate a larger focus on the landscape scale, and corresponding objectives and goals have increasingly incorporated more complex and process-centered targets [67,68]. As the spatial scale of planning has expanded, so has the focus on targeting multiple goals, including ecosystem services [69].

There is a disconnection between ecology and environmental planning that could be bridged with a focus on green infrastructure [15,70-72]. The ecological and engineering approach to green infrastructure begins to explore structure and function at fine scales. Focusing on the operation

and physiological ecology and biogeochemical cycling in individual installations and how these operate at scale as they expand in implementation. A critical link between ecological and planning perspectives is to bridge the top down and bottom up - or the patch vs. landscape scales - that are the focal points in each discipline [14]. This hierarchical approach would yield great insights into urban function and sustainability and is already seen as the center point for facilitating resilience in social-ecological systems.

There is a need to better connect scientific knowledge about and decision-making and landscape design practice regarding ecosystem services [72]. The role of science in planning and design has been addressed from three interacting perspectives: (1) design is an intentional landscape change that recognizes the needs and values of society with the purpose of providing ecosystem services, (2) collaborative partnerships between designers, planners, and scientists can create experiments in the landscape to "balance ecological goals with context, esthetics, amenity, and safety;" (3) adaptive design informed by ecological knowledge can investigate innovative approaches [58]. The common thread is that bridging ecology and design to meet ecosystem service goals requires respecting the knowledge base and approach of the ecological sciences and the ways in which design approaches context, aesthetics, and societal values.

There are critical gaps in our understanding of the functionality of green infrastructure that would be alleviated by better integration between ecological sciences and planning disciplines. There are great uncertainties in the ability of green infrastructure to provide ecosystem services, particularly as this concept is applied in different regional contexts [62]. This gap is largely due to a lack of monitoring and assessment of ecosystem service provision by green infrastructure after the planning and installation phases of design [15]. Ahern [60] suggests that the ecosystem service concept provides a tool for assessment because it can be used to derive benchmarks and indices of performance in a spatially explicit manner. There are important limitations from the ecological sciences that also lead to gaps in understanding. Most ecosystem service assessment tools that take a spatially explicit approach lack the grain to appropriately address the landscape heterogeneity that green infrastructure would introduce in urban land cover assessments [73], as well as the contribution of cities to regional service budgets [52]. Recognizing this need, ecologists have begun modifying mapping and assessment approaches to account for the scales needed to properly incorporate green infrastructure into ecosystem service assessments [74].

Proper assessment and monitoring of the ecosystem services of green infrastructure is critical to adopting approaches that address urban resilience. A resilience approach puts sustainability into a non-equilibrium framework where the critical feature is the ability for cities to build an adaptive capacity to respond to disturbance. Monitoring and assessment programs are needed in order to assess this adaptive capacity and the contribution of green infrastructure. Ahern [58,68] suggests five strategies for building capacity for resilience in cities: biodiversity, multifunctionality, multiscale networks, modularity, and adaptive/experimental design. A key to implementing this is a transdisciplinary approach that also operated in a co-productive process that is both iterative and adaptive; what Ahern [58] calls 'safe to fail.' There is great resonance between this approach from the design disciplines and adaptive management approaches that stem from a social-ecological systems approach to resilience [28,29]. Social-ecological system approaches to ecosystem services demonstrate the need to assess multifunctionality at broader scales [75]. This is another point of intersection that could bring ecological and planning approaches to cities closer together.

Connecting science of cities and landscape design would also support assessment and monitoring of the ecosystem services of green infrastructure by accelerating our knowledge of the function of urban landscapes. The city itself can be used as an experiment [68,70,76] to try out new methods for design and implementation. A city-wide approach that links safe-to-fail and adaptive management approaches across urban scales is the urban transition lab approach [76]. Urban transition labs are a model of co-production, where research needs and priorities are set by discussions between interdisciplinary academics, practitioners, and stakeholders. These priorities

are then implemented in the urban landscape in an experimental setting, and coupled with monitoring and assessment that allows the community to analyze how goals are being met. This approach could be adopted to explore the conditions that facilitate and constrain green infrastructure implementation and function in particular cities. The built environment could be explored as a nexus in a cycle of drivers and responses [77], where through the iterative process of the urban design and monitoring, the implications for ecological function and societal acceptance and governance of green infrastructure can be assessed. This understanding in turn becomes a driver for further changes in the built environment and urban landscape under this urban transition lab approach [76].

## 6. SUMMARY

The ecology of cities becomes increasingly important as our populations become more and more urbanized. Ecosystem services, the benefits and goods that we all rely on from nature, is a framework that can help bridge scientific and planning perspectives on cities to improve the well-being of urban residents. An understanding of the provision of ecosystem services in cities is just beginning to be explored, but is greatly needed to adequately address urban concerns through green infrastructure approaches [62]. Most importantly, there is presently a disconnect between disciplines that focus on the ecosystem services of green infrastructure in cities [15]. While the tools to address the ecosystem services of green infrastructure in cities are not yet adequate for the task of addressing urban resilience, there is great potential for the disciplines of ecology, planning, design, and landscape architecture to integrate to address these needs [15,71,72]. A social-ecological systems perspective puts the role of design and landscape creation at the center of how urban ecosystems function and can guide the integration of these fields. With this unifying framework the contribution of the ecosystem services of green infrastructure to urban resilience can be better assessed and implemented.

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# Application of Resilience Thinking to Evaluate the Urban Environments (A Case Study of Tehran, Iran)

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### **Abstract**

Resilience thinking has been recently proposed as a different way of understanding the world and a new approach to managing urban environments. It embraces human and natural systems as the complex entities continually adapt through cycles of change, and it seeks to understand the qualities of a system that must be maintained or enhanced in order to achieve sustainability. This research aims to evaluate the environmental quality of metropolitan Tehran – Iran using some resilience criteria. Based on the comparative analysis of the current related theories we have extracted and classified some of the resilience criteria into four dimensions: pattern and Process of social-economic in urban landscape, Responses of human society in urban landscape, Pattern of Biophysical Structure in urban landscape, and Urban Ecosystem dynamic and Function. We have focused on the last two criteria; the composition and configuration of urban green spaces as the most important component of ecosystems and the biophysical variables such as air, water resources and impervious surfaces are considered the basic factors of urban ecosystem services. The results obtained show that the composition and configuration of urban green spaces of Tehran and consequently its ecosystem quality does not fulfill the requirements of a resilient urban landscape. Assessment of Tehran air quality shows that the number of unhealthy days has increased over the last decade. Also, Tehran has heavily relied on outer water basins. In addition, the proportion of impervious surfaces within a period of 22 years (1988-2010) has increased by more than two times. These results support the resilience criterion as a more realistic approach to demonstrating both the urban environments situation and the directions of future urban plans.

**Keywords:** *Resilience Thinking, Urban Environment, Ecosystem and Ecosystem Services, Urban Landscape*

## **1. INTRODUCTION**

Resilience is a flexible concept which is currently used as an approach in different fields of study [1]. The concept of resilience was originally suggested as a descriptive ecological term [2]. Resilience is referred to as a basic capacity of an ecosystem to maintain desirable services of the ecosystem confronting environmental changes and human exploitation [3]. In another definition resilience is presented as the capacity of ecological-social systems to attract disorders and also to

maintain the feedbacks, processes, necessary and inherent structures of the system [4]. Resilience thinking, through the concept of multi-scale and selection of appropriate temporal and spatial scales, provides an insight to consider unpredictable future, inevitability of change, and vulnerability of such systems [5], [6]. Resilience thinking provides a structured method for taking into account the complexities, uncertainties, and interdependence of systems, processes and it also paves the way for new methods of planning and more efficient application of assessment and sustainability thinking [7].

One of the most important concepts considered in resilience thinking is the social-ecological system. Scholars, within the realm of resilience, have created the term of social-ecological system which includes cities. The term of social-ecological system elaborates on interdependence between human and nature emphasizing the concept of humans-in-nature. Social-ecological systems include the integration of nature and human society with mutual feedbacks and interdependence. Although we cannot find a recognizable social or ecological portion in such system, we cannot separate them for the purpose of analysis [8,9]. Influenced by the resilience thinking, new sources introduce urban ecosystems as the production of natural and social processes within which structure and performance are very closely related [10-13]. In cities and urban regions, with regard to the decisions made related to land use, we experience things such as structure changing, fragmentation, isolation of natural habitats [14], Hydrological system failure [15] and changes of energy flow and food cycle [10] all of which lead to a reduction in resilience in different spatial scales making urban systems increasingly vulnerable. So it can be concluded that we can improve the ecological performances and consequently resilience in urban habitats through establishing a reform in the urban structure).

In the assessment of urban resilience, the system is regarded as a whole and not a specific kind of disorder or specific aspect of the system that might be affected [16]; instead the general performance of the system will be evaluated with regard to the resilience criterion. Different criteria have been developed to determine the general resilience of the system. Van Oudenhoven et al. presented a list of social-ecological indices (criteria) for landscape resilience; however, their indices (criteria) concentrate more on agricultural landscapes [17]. In addition, some studies have been performed on the assessment of resilience in social-ecological systems with rural nature. Walker and Salt developed some criteria presented in their book entitled "Resilience Thinking" [7]. Nine criteria were suggested for assessment of resilience including ecological diversity, ecological variability, modularity, economic-social system diversity, social capital, overlap in different levels of governance, tight feedbacks, political, social, economic, and environmental conditions, unpriced ecosystem services, diversity of such services, acknowledging slow variables, and innovation. Resilience World Alliance as well as some researchers developed some other criteria including diversity, openness, inter relationship of feedbacks, reserves, and modularity [6,7,16].

In the present study, based on the characteristics of urban systems and interaction of subsystems in urban regions indicated in these references [10-13,18,19], we classified these criteria into four groups including Pattern of Biophysical Structure in urban landscape, Pattern and Process of social-economic in urban landscape, Urban Ecosystem dynamic and Function, and Responses of human society in urban landscape. Resilience criteria and their application in urban environment, with regard to the literature related to general resilience criteria in urban environment, are all shown in Table 1.

The current study addresses an emphasis on the general resilience of the city of Tehran, Iran taking into consideration that there are actually a lot of resilience criteria basically; the criteria considered include pattern of Biophysical Structure in urban landscape and Urban Ecosystem dynamic and Function. The composition and configuration of urban green spaces as the most important component of urban ecosystems and also the biophysical variables such as air, water resources and impervious surfaces are considered the basic factors of urban ecosystem services.

## 2. METHOD

The current study selected Tehran as a case study; in addition, its resilience was assessed. Based on Statistical Centre of Iran, the population of Tehran was more than 8 million in 2011, the first most populous in Iran. According to the results of the public census in 2011, the population of the province of Tehran was about 12,183,391 which showed an average annual growth rate of about 1.44% [20]. Based on the suggestions made by the Resilience World Alliance for the assessment of resilience [16], the following steps were taken for assessment of Tehran resilience:

1. Defining appropriate measures to assess the criterion (landscape metrics). Table 2 shows appropriate measures for each criterion
2. Mapping measures
3. Description of the main system with regard to the resilience assessment criteria
4. Interpretation of Tehran's resilience based on the results achieved through metrics

TABLE 1: SUMMARY OF CRITERIA OF ASSESSMENT OF GENERAL RESILIENCE IN URBAN LANDSCAPE.

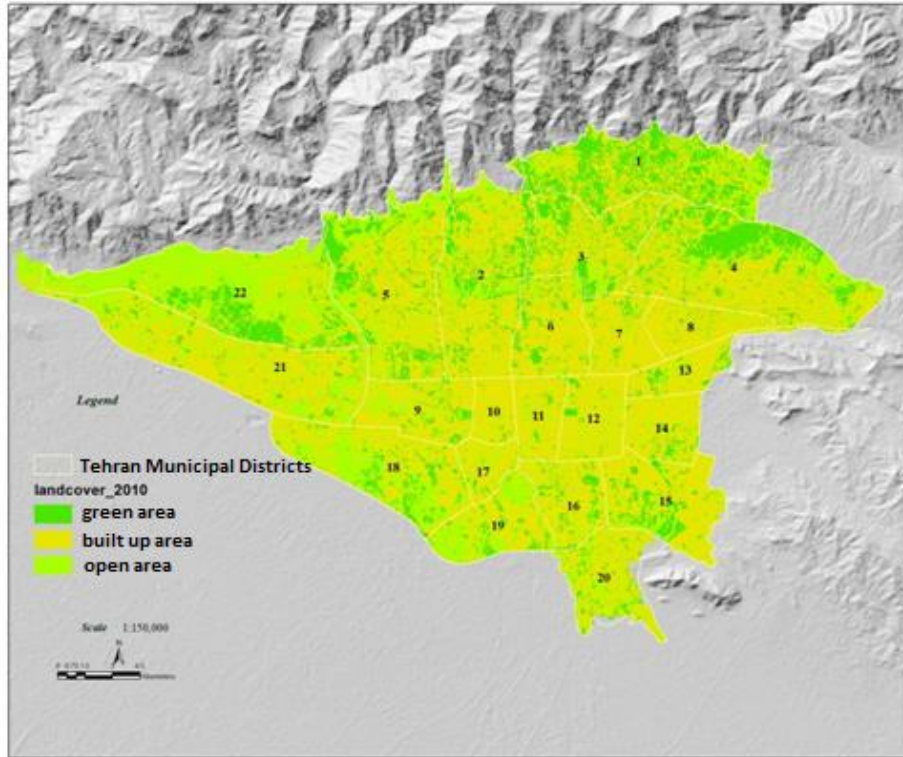
Criteria Category	Criteria	Feature of Criteria with urban landscape
Pattern of Biophysical Structure in urban landscape	Diversity of structure pattern	Spatial diversity in habitat patches that are source of supply of ecosystem services in urban landscape
	Modularity of structure pattern	Spatial and temporal configuration of structure that are source of supply of ecosystem services in urban landscape
	Connectivity of structure pattern	The Presence of ecological networks (greenways, green belt)
Pattern and Process of social-economic in urban landscape	Diversity	Diversity of urban land uses Presence of institutions and social networks Diversity of social interactions Diversity of economic opportunities Diversity of economic resources
	Social capital	Presence of strong social networks in urban locals
	Different Levels of Governance	Diversity of governmental structures and executive levels of urban management
	Modularity	Flexibility and diversity in institution structures
	Openness	Reasonable openness of society to respond to changes
Urban Ecosystem dynamic and Function	Diversity of the main kinds of Ecosystem Services	Diversity of the types of ecosystem services or slow variables that are good for urban landscape Regulating services Supporting services
	Tight Feedbacks	Long term policies and local solutions to improve ecosystem services and reserves
	Unpriced Ecosystem Services	To be aware of costs for monitoring and active management of Un priced Ecosystem Services Internalizing external costs of loss of Ecosystem Services
Responses of human society in urban landscape	Ecological Variability	Preparation for and knowledge of society for the origin of internal and external disturbances
	Innovation	Providing the context for experiences. new priorities of the stakeholders in urban local area

TABLE 2: LANDSCAPE METRICS OF ASSESSING TEHRAN RESILIENCE BASED ON PATTERN OF BIOPHYSICAL STRUCTURE AND URBAN ECOSYSTEM DYNAMIC AND FUNCTION.

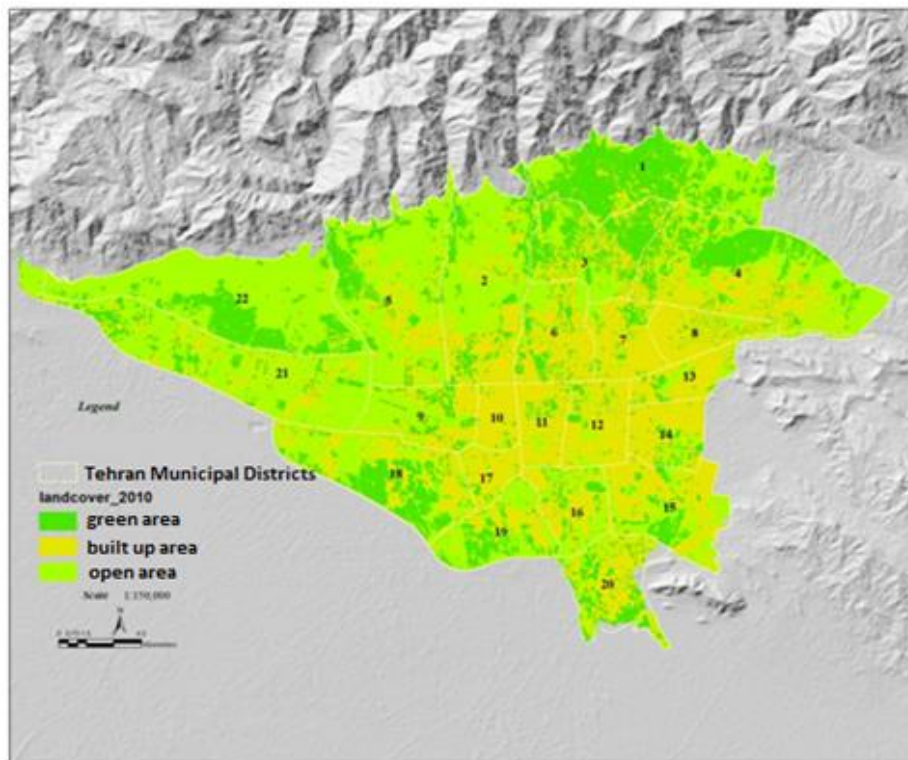
Dimensions of urban resilience	Criteria	Measurable variables or data	Metric
Pattern of Biophysical Structure criteria	Diversity or spatial heterogeneity	The amount of green and open patches coverage	Patch richness density (PRD)
		Number of green and open patches	Percentage of Landscape (PLAND)
		Richness of green and open patches	Euclidean Nearest-Neighbor Distance (ENN)
	Connectivity	Mean distance between each class of patches	Radius of Gyration (GYRATE)
		Modularity	Amounts of heterogeneity or homogeneity of urban green and open patches
	Urban Ecosystem dynamic and Function	Unpriced Ecosystem Services	Air quality
Water resources			The quantity of water resources
Change of impervious surfaces			Change in Ratio of impervious surfaces

For measuring the landscape metrics or appropriate measures for the criteria FRAGSTAT 4.1 software was used. This software makes it possible to calculate landscape metrics [15]. In the present study, FRAGSTAT 4.1 software was used to calculate landscape metrics. Using this technique can reduce the errors resulted from the calculation of the metrics through the software. In addition, it makes it easier to interpret the metrics because it shows the results of the metrics calculation as zoning map.

In this study, land cover maps in three classes of green, open, and built were taken from images from Land Sat (January 4, 2010 and 1988) through TM sensor. The following steps were taken in order to achieve land cover maps: after getting satellite images, the process of geometric match and also making coordination for the images through vector road maps of Tehran were performed to prepare data for the purpose of processing and exploiting information. The second sampling was done using the Nearest Neighbor interpolation (NN) method. All the bands used here were geometrically matched using the above method with RMSE 0.47. Spectral modification of the images was aimed to highlight the phenomena and also to improve the quality of the images. Then, using a combination of the bands 432, we did the supervised classification through maximum likelihood method. Validity assessment was done after classification using a ground truth map, therefore, the general validity index of 85% and Kappa index 89% were achieved. The results were considered satisfactory. In the interpretation of data, the land use maps with 1:2000 scale and personal experiences of field surveys were used. Map 1 and 2 show land coverage in the three classes of open, green, and built.



Map 1: Land coverage map of Tehran-Iran from Landsat satellite 2010.



Map 2: Land coverage map of Tehran-Iran from Landsat satellite 1988.

### 3. RESULTS

As mentioned above, the present study aims to analyze Tehran resilience according to Pattern of Biophysical Structure and Urban Ecosystem dynamic and function criteria.

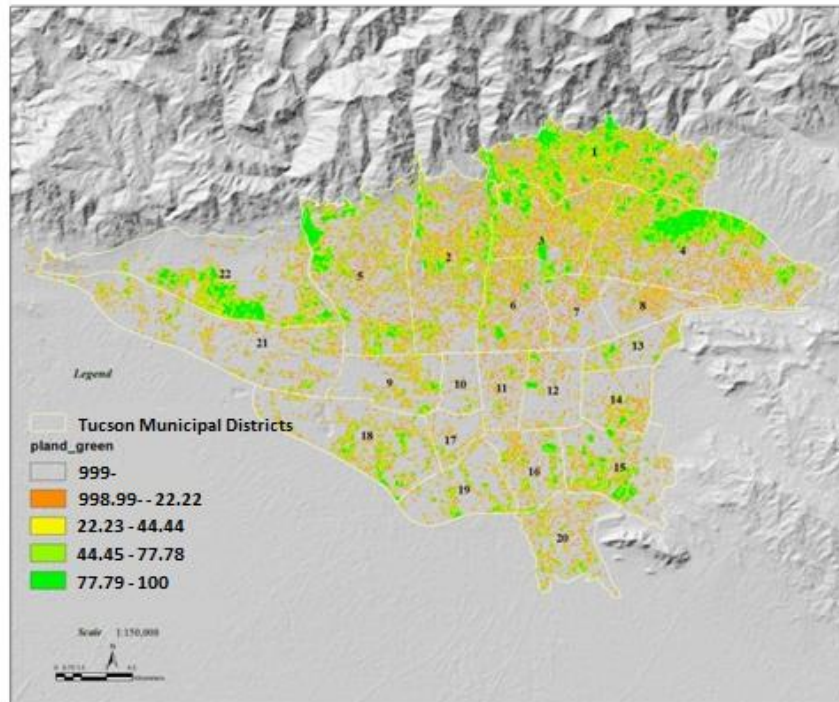
The Pattern of Biophysical Structure are related to patches originated from environmental services. Therefore, our analysis was based on green patches with environmental service origin. Our criteria included diversity, connectivity, and modularity. The results are presented in three parts according to these criteria:

#### 3.1. Diversity (Spatial Heterogeneity) of the Green Patches in Tehran

Diversity (spatial heterogeneity) of green patches in Tehran was assessed with the two metrics of patch area (PLAND) and patch richness density (PRD).

##### 3.1.1. The ratio of green patch areas in Tehran

Patch area is one of the most important metrics to measure landscape composition specifically to show how much of the target patch type (green patches) exists within the landscape (Tehran). Map 3 shows the area of green and open patches and their distribution. As shown in Map 3, in few parts of Tehran the ratio of green and open patch areas is 50% or more.



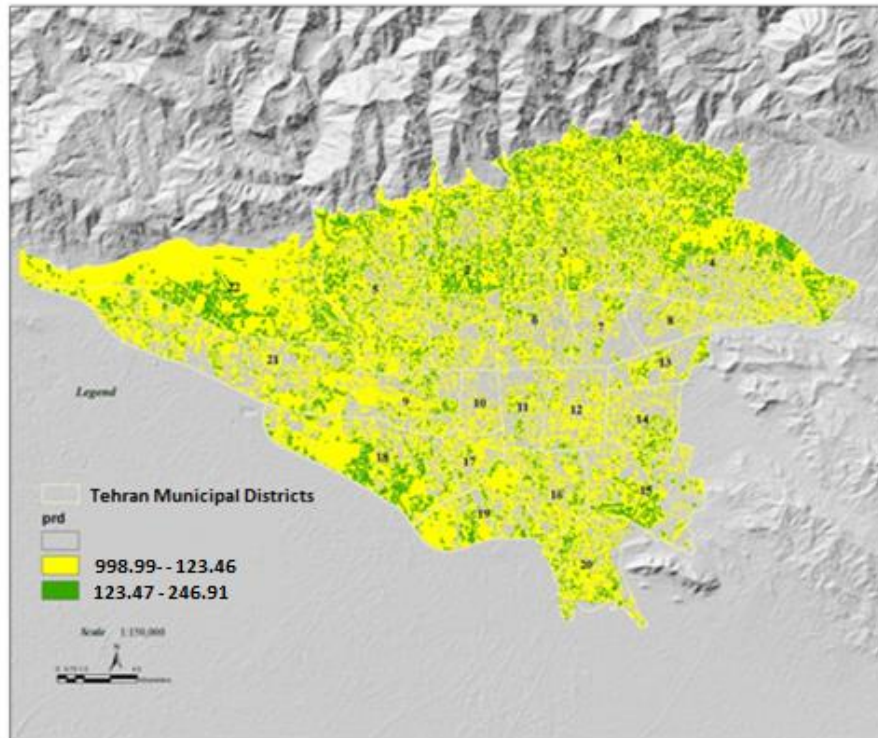
Map 3: The ratio of green patch areas in Tehran.

##### 3.1.2. Density of richness of green patches in Tehran

In this metric, we divided the number of all kinds of patches in the city to the whole area of the landscape. The unit of this metric is the number of patch type in 100ha. This metric concerning a particular patch type (for example: green patches in urban landscape) may affect a variety of ecological processes in this landscape, such as biodiversity. The number or density of patches is probably mostly valuable as the basis of computing other more interpretable metrics. Through this



metric we can compare different landscapes. As shown in Map 4, the higher the result of this metric, the richer is that area with regard to green patches.



Map 4: Density of richness of green patches in Tehran.

### 3.2. Connectivity of Green Patches in Tehran

Connectivity of green and open patches Tehran was assessed using Euclidean distance to nearest neighbor (ENN) metric and intensity of the patch (GYRATE) metric.

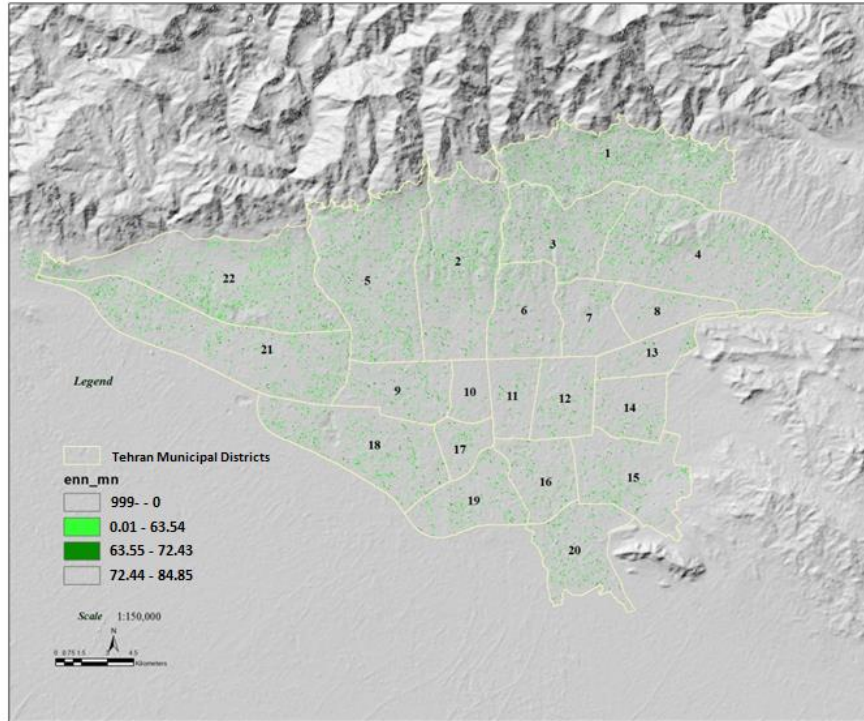
#### 3.2.1. Euclidean distance to nearest neighbor of green patches

This metric shows the mean nearest neighbor distance between one types of patch. This metric computes the shortest straight-line distance between the focal patch and its nearest neighbor of the same class. The unit of this metric is meter. This metric was summarized for all the patches of the same type (green patches of Tehran) as Simple arithmetic mean or the average weight of the nearest distance neighborhood. In Map 5, you can see the average distance of Euclidean neighborhood of green patches in Tehran. As can be seen in Map 5, the average neighborhood distance of green and open patches in Tehran is more than 63 meters.

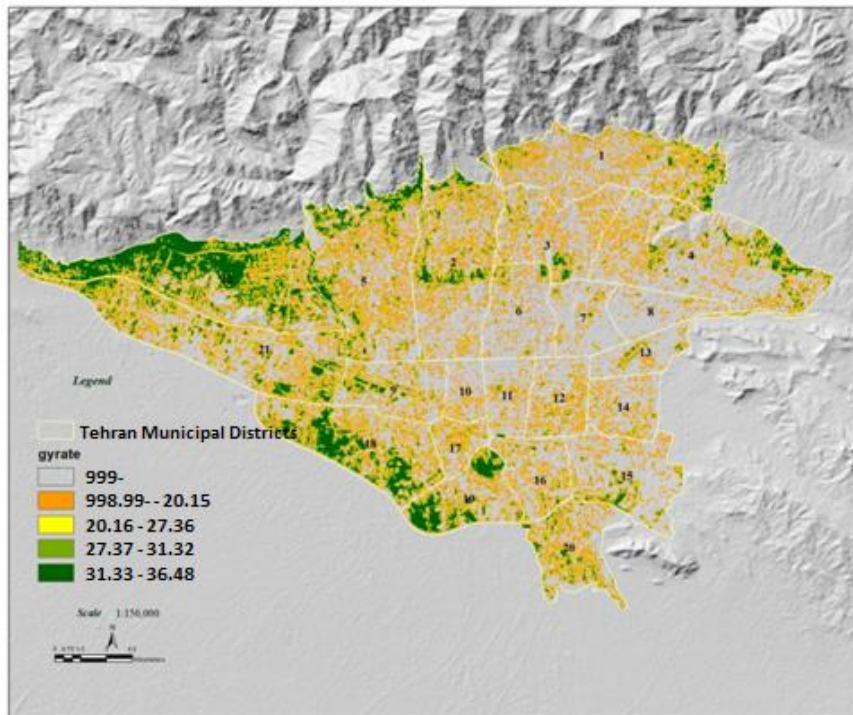
#### 3.2.2. Intensity of green patches in Tehran

Intensity of the patch (GYRAT) is a technique to measure the extended area of patches (or their intensity). It shows how far across the landscape a patch can extend its reach. This metric, for each patch, is calculated as the average distance, in meters, between each cell in the patch to the center of the patch. Then it was summarized for all the patches or patches of the landscape, as the average of the weighted area. When aggregated at the class or landscape level, radius of gyration provides a measure of landscape connectivity. This metric is considered to be zero (or more?) in scattered areas. In Map 6, the intensity of green patches in Tehran is shown. As can be seen, the area of

patches is mostly less than 28 meters. In only a few locations, such as in Region 1 or 22 and some parts in the south including agricultural lands, was the patch intensity 28-36 meters.



Map 5: Euclidean distance to nearest neighbor of green and open patches.



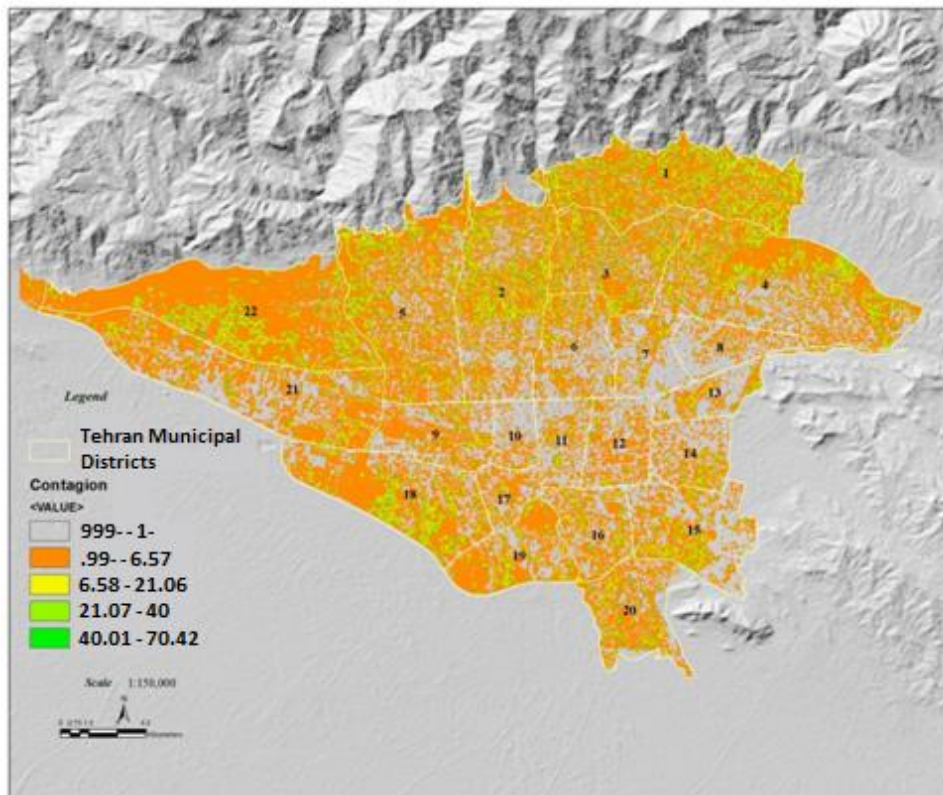
Map 6: Intensity of green patches in Tehran.



### 3.3. Modularity of Green Patches in Tehran

The metric of contagion was used to analyze modularity in Tehran. This metric shows the composition and texture of land cover. Contagion metric measures both patch type interspersion and patch dispersion at the landscape level. Based on the result obtained from this metric we recognized the extent to which patch types are aggregated or clumped. The unit of this metric is percentage. The metric of contagion is a measure showing green patches in Tehran which is contagion in a cluster-like manner in a cumulative way or is scattered around the city as smaller patches. Higher values of contagion may result from landscapes with a few large, contiguous patches, whereas lower values generally characterize landscapes with many small and dispersed patches [21]. In other words, if the result is close to zero, it indicates that the green patches are small and scattered and if it is close to 100, it shows that the patches are accumulated in one place and they don't have a congruent distribution in the urban landscape of the city. As can be observed in Map 7, there is no 100 as a result of contagion metric, the places with 40-70 have acceptable contagion and there is a balance, in these places, between connectivity and contagion. Areas with a contagion of less than 20 are the places suffering from lack of connectivity, as well.

Urban Ecosystem dynamic and Function is about diversity of types of ecosystem services or slow variables that are good for urban landscape. The biophysical variables such as air, water resources and impervious surfaces are considered as the basic factors of urban ecosystem services.



Map 7: Modularity of green patches in Tehran.

### 3.4. Air Quality of Tehran

Air pollution is a serious problem in Tehran. The numbers of clean days from 2007 to 2011 were 23, 13, 32 and 14 days, respectively. Within each of these years, healthy conditions were

observed on 327, 293, 291 and 247 days, respectively. The numbers of days in these years considered as unhealthy were 15, 59, 40 and 103 days, respectively. The very unhealthy conditions did not occur in 2007; however, in years spanning from 2008 till 2010, there was experienced only one day with dangerous and unhealthy condition. Generally, concerning the PSI index in 2007 till 2009, the pollution States had a trend showing the conditions as becoming unhealthy [20].

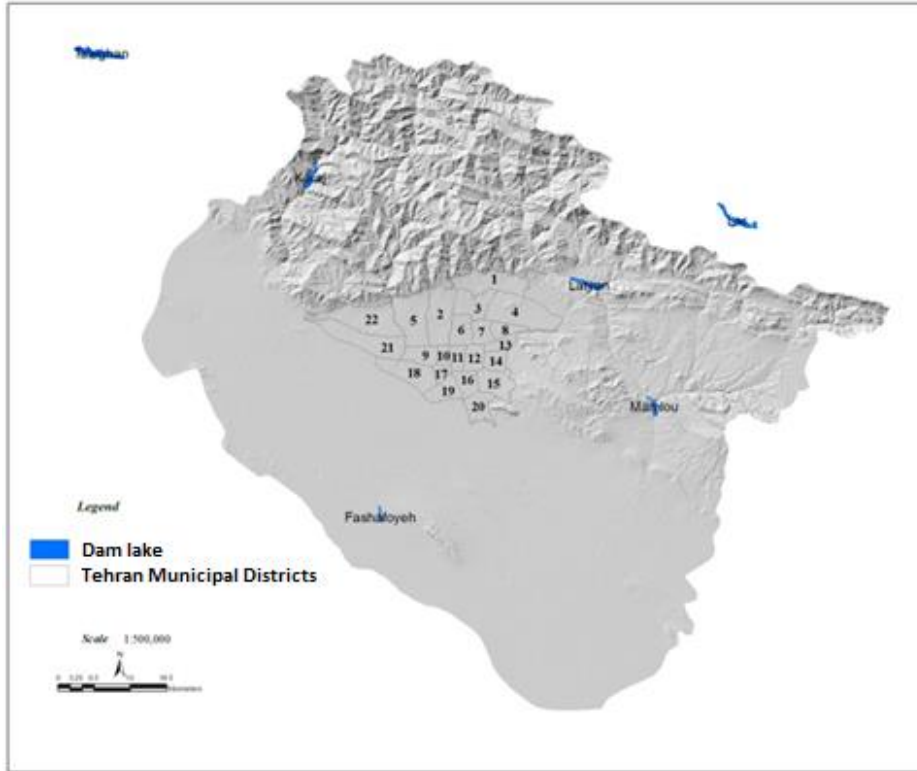
### *3.5. Water Resources*

An unsustainable situation of water resources in Tehran has occurred due to the dry hydrologic conditions in the region due to average precipitation of about 250 millimeters per year accompanied with high population density, changing climate, and an imbalance between water supply and demand. The trend and associated changes in total water consumption in Tehran has been upward and incremental with annual consumption rising from 886 million cubic meters to 1,033 million cubic meters from 1998 to 2010, an average annual increase of 0.74% per year [20]. In order to provide a fresh water supply for urban and agricultural consumption in Tehran, several dams were constructed on the flowing rivers including Karaj (Amir Kabir dam), Lar Dam, Latian, and Taleghan Dams. It is significant to note that Tehran has heavily relied on the outer water basins. Map 8 shows the situation of Tehran dams. Lar Dam and Taleghan belong to other basins.

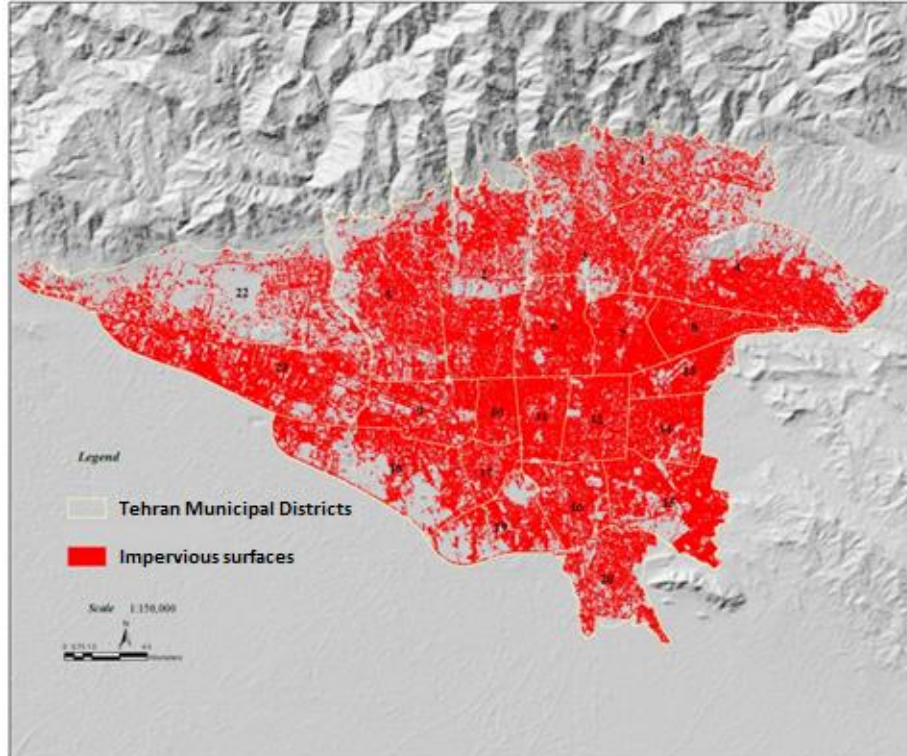
The ground water aquifers are considered strategic resources in the arid regions. In the case of Tehran, the importance of ground water, due to water shortages from the surface water, has increased substantially. The drop in annual average water level in the Tehran aquifer plain is about 18 centimeters per year [20].

### *3.6. Change in Ratio of Impervious Surfaces*

This is based on the interpretation of Landsat images taken from the city in the two mentioned years. The green land area and open space areas have been constantly and gradually decreased and the area has been taken by construction of buildings. In 1988, only 37% of the present area of Tehran was built on and constructed while in 2010, this was increased to 61%. Map 9 shows the impervious surfaces in 2010.



Map 8: The situation of Tehran dams.



Map 9: The impervious surfaces in Tehran in 2010.

#### 4. CONCLUSION

Survival of the cities as social-ecological systems depends on natural and ecosystem services. As a result, getting to know resilience in urban environment needs interdisciplinary understanding and an analysis in different scales. Among the criteria defined for assessment of resilience of urban ecosystems we can refer to diversity, connectivity, and modularity of structural elements with ecological performance (green patches), also the main ecosystem services can be regarded as some other criteria. Based on the results obtained from metrics of distribution diversity of open and green patches (PRD & PLAND) in Tehran the ratio of green and open patches areas are more than 50 only in few regions and have appropriate intensity. These regions are mostly on the north part of the city or the south where agricultural lands exist. The results obtained from connectivity metric (GYRATE & ENN) indicate that only in few regions the edge to edge distance between the patches is inconsiderable. The results achieved from CONTAG metric focusing on spatial distribution of green and open patches (modularity) show that in most of the region we experience low contagion due to low connectivity. In few regions, where the connectivity is considerable, the percentage of contagion is high. From the results achieved from three criteria of diversity, connectivity and modularity –that in its own turn shows Tehran resilience with regard to ecosystem criteria- we can conclude that combination and spatial distribution of the green patches are not resilient in Tehran. The state of ecosystem services (air, water and the ratio of impervious surfaces) does not fulfill the requirements for a healthy urban structure to support a resilient landscape. Assessment of resilience in urban environments based on the above mentioned criteria is a guideline for authorities and decision makers to use flexible and modern approaches in urban management. Consequently, the current study indicates that Tehran is not a resilient city regarding the Pattern of Biophysical Structure and ecosystem services criteria which means that Tehran Municipality's proceedings with regard to the green space, air, water and urban development management have not been efficient so far and it cannot guarantee their performance. Achieving resilience needs cooperation between and within organization matching the organizations responsible for making decisions with ecological scale of the recognized source to prevent one sided views.

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# Resilient Cities, A Key Solution to Safeguard the Environment

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### **Abstract**

In the 21st century, the world population is growing at a spiraling pace. Much of this growth is occurring in developing countries, where access to food, sanitary water, education, and health is severely limited. The ever increasing urbanization highlights the need for sustainable development based on human-environment interaction, concurrently focusing on economic development, social justice, and environmental preservation. The excessive and unplanned expansion of cities has resulted in numerous environmental predicaments due to clearly emphasized economic issues at the expense of social and environmental concerns.

The most significant features of megacities are population density, dynamism of growth, settlement, infrastructures, land ownership, socio-economic inequalities, hazards and vulnerability, and urban governance. The factors related to each feature are indicated in this paper. To reach sustainability and resiliency in a megacity there are different criteria related to various categories, namely environmental, social, physical, and economical amongst which the environmental aspects are discussed.

To examine the practical use of these criteria, extensive studies and field activities were carried out on the District 14 of Tehran municipality concerning the environmental category. The study indicated the desire of authority to move toward sustainable development as their activities showed much environmental status improvements between the years 2009 to 2014. At the end some recommendations were made, according to obtained results, to speed up the move toward sustainability and resiliency.

**Keywords:** *Megacities, Resilient City, Sustainable City, Safe Environment*

\* Corresponding author

## **1. INTRODUCTION**

Today, more than half of the human population resides in cities and by 2030; about 60% of the world population will live in mega cities, which are urban areas with more than five million

residents. Meanwhile, 95% of future urbanization will take place in developing countries. Cities across the globe occupy only 2% of the land area; however, they consume 60% to 80% of the energy and cause 20% of the total carbon emissions. The rapid development of cities depletes the freshwater resources, endangers the biota, and strains the public health. On the other hand, cities could play an essential role in the global green economy through transportation improvement, building construction, energy conservation, water sanitation, sewage treatment, and the facilitation of a wide range of socio-economic issues [1].

All over the world, megacities have destructive environmental effects that may necessitate the role of governments to manage the cities essentials. This calls for revision of the urban management principles by governments and metropolitan authorities. Urban areas in developed and developing countries will be under influence of the growing unpleasant impacts of climate change, depletion of resources, lack of food security and economic instability in the near future. These factors will significantly alter the status of urban and suburban areas in the coming century. These issues must be addressed promptly and effectively in order to achieve resilient cities, signified by the safe environment, productive economy, and active community. Otherwise, the rapid growth of urbanization in many of the developed countries cannot be sustainable.

Since more than half of the global population now live in urban areas, there is no doubt that the issue of urban management has become a priority for any given government in the world [2]. Urbanization as phase transition from rural to urban population is growing rapidly in the coming decades, and will continue especially in developing countries [3].

Urbanization in the developing countries has a higher rate of growth compared to the industrial countries which will continue for years to come. Asia and Africa, where more than half of the population are now living in rural areas expected to become new urban areas resident by 2050 [4]. Of the 29 megacities in the world in 2014, Tokyo-Yokohama in Japan with 37,555,000 population has the first place, London with 10,149,000 is ranked 29<sup>th</sup> and Tehran the capital of Iran with population of 13,429,000 is ranked 22<sup>nd</sup> [5].

The rapid urbanization development and increase in the number of megacities has resulted in serious environmental and socio-economic predicaments and has created various challenges in urban strategic planning and policy making [4]. There is international concern of urban overpopulation and resultant impacts to the global environment, including excessive exploitation of resources, air pollution, lack of food security, poverty, social discrimination, and vulnerability of the lower social classes. Also the challenges for urban policies and urban planning strategies are to optimize urbanization while managing the development in a sustainable and resilient way. Studies conducted by various national and international networks indicate that there is an urgent need for the development of well-defined strategies for expansion of cities, long term land-use strategies, and effective urban management [6].

This paper discusses different aspects and elements of megacities then presents a case study of District 14 in the Tehran Municipality to highlight some steps that have been taken toward sustainability and resiliency in Iran.

## **2. MEGACITIES FEATURES AND CHALLENGES**

The following specifications are the characteristics of megacities that draw scientific, economic, and political attention in order to address their potential threats and opportunities at national, regional, and international levels. Based on the major characteristics of the mega cities, the most significant factors are as shown in Table 1 [4].

The increase in number of megacities is considered as the driving force of the global economy that effectively influences the flow of goods, people, culture, and knowledge. Megacities potentially provide unique concentrations of skills and technical resources to improve the quality of life for large numbers of people. On the other hand, most cities face various challenges such as



overcrowding, higher levels of pollution, as well as security threats, lack of services and excessive demand. According to the United Nations reports, megacities are struggling to reach a balance between quality of life, economic competition, and the environment.

Megacities are 21st century phenomena; their size, unique complexity, and essential role as global economic gateways have created many challenges for sustainable urban development [1]. It is important to point out that only the environmental challenges are being addressed in this article.

TABLE 1: MAJOR CHARACTERISTICS OF MEGACITIES.

<b>Megacities features</b>	<b>Factors</b>
Population density	Concentration of the human population in reference to space
Dynamism of growth	Society: Population growth rate Economy: Real growth rate of the Gross Domestic Product (GDP) Land: Suburbanization rate, land sealing rate.
Settlement, infrastructures, and land ownership	Number and the size of unofficial urban settlements Land use alteration Quality and the quantity of the urban infrastructures
Socio-economic inequalities	Poverty rate Unemployment rate Mortality rate
Hazards and vulnerability	Mortality risk Economic risk Level of vulnerability determined for each risk
Urban governance	Participation, rule of law, transparency, responsiveness, consensus orientation, equity, effectiveness, efficiency, and accountability Indicators: i.e. corruption index

Regardless of Megacities positive aspects, they have a long list of environmental problems. The accumulations of water and air pollution, lack of proper management of waste, and soil erosion are familiar issues for most cities worldwide, especially the megacities. Thus, the sustainable expansion of megacities is to be promoted. The main challenges of megacities include the followings [1]:

- Lack of public awareness
- Lack of proper social behaviour
- Inadequate/insufficient technical knowledge
- Lack of adequate infrastructures
- Lack of compatibility between the college curriculum and the actual socio-economic needs
- Lack of guidelines for effective public participation

### 3. SUSTAINABLE AND RESILIENT CITY

Sustainable development is a broad term emphasizing on the proper long term use of resources. Sustainability refers to procedure that could be repeated over and over again without affecting other aspect of environment and be cost effective. Therefore, “sustainability” simply means to satisfy the needs of the present generation without endangering the wellbeing of the future generations [7].

Also, cities should have certain characteristics to be resilient toward potential risks and natural disasters without incurring irreparable damages [8]. Table 2 presents four categories of resilient and sustainable cities which has 12 criteria.



TABLE 2: CONSIDERED ENVIRONMENTAL, SOCIAL, PHYSICAL AND ECONOMIC CRITERIAS.

Categories	Criteria
Environmental	Conservation of the environment
	Protection and expansion of green space
	Optimized use of resources
Social	Providing continuous education and training at schools and local communities to increase public awareness
	Interaction with the social media
	Communication with various communities and institutions
Physical	Establishment and improvement of infrastructures, monitoring the construction process
	Risk assessment and determining the potential dangers and planning for their mitigation and implementing action plans
	Define and determine the organizational structure and the responsibilities for the management of crisis
Economical	Determine and allocate the requires budget for the establishment and development of infrastructures and other effective steps to increase city resilience
	Providing loans for the modernization of old buildings and the reinforcement of weak structures or those located in high risk areas
	Ability to allocate the required budget in a crisis

### 3.1. Environmental Categories

This paper reviews environmental features of a resilient and sustainable city; elements are listed in Table 3.

- *Environment conservation*

Protection of the urban environment plays a significant role in sustainability. For example, reduction of air pollution or greenhouse gases could mitigate climate change and its adverse consequences [9-14].

- *Protection and expansion of green space*

Green spaces not only reduce greenhouse gases and improve climate, but also reduce runoff and risk of flooding because most cities with asphalt stress are vulnerable to flooding. Therefore, protection and expansion of green landscape has effective impact on prevention and mitigation of risks thereby reducing financial damages [8-10,14].

- *Optimized use of resources*

Reduction in consumption of resources and increase in use of clean or renewable resources and energy could mitigate damage during a crisis; this will help the sustainability and resiliency of the city [8,11,14]

TABLE 3: ENVIRONMENTAL ELEMENTS OF A RESILIENT & SUSTAINABLE CITY [15].

Topic	Factors determining sustainability & resiliency of Mega cities	Issues influencing factors
Air	Urban environmental quality	Air quality in urban areas
	Environmental air management	Density of stationary control sites
		Number of supervised pollutants
		Number of polluted days

Energy	Energy usage	Energy consumption per person Energy consumption in each sector (household, industrial, agricultural, commercial, services, etc.)
	Urban action plan	Amount of natural gas consumption per person Implementation of Environment and Energy plan
Green Space	Urban environmental quality	Density of public green spaces Density of various green centers (urban parks, historical green areas, local parks, green belts, children playgrounds, gardens, etc.)
	Environmental management of green spaces	Annual construction of new green spaces Annual statistics of green spaces Implementation of urban green plans
Noise	Environmental management of noise	Number of noise measurement stationary sites Installation of noise barriers Number of noise supervision camps Number of public protests due to noise pollution from industrial, traffic and repair sources
	Urban action plan	Number of activities conducted by the municipality causing noise pollution (festivals, sports events, vehicles, etc.) Number of driving tickets for noise pollution Implementation of noise zoning plan Implementation of noise reduction plans
Transportation	Infrastructural equipment	Length of railroad infrastructures Density of railroads Density of railroad lines per type (conventional railroad, monorail, subway, etc.)
	Density of vehicles	Density of personal cars Density of transportation vehicles Density of taxis Number of urban vehicles per type (personal cars, buses, motorcycles, trucks, etc.) and fuel type (regular gasoline, unleaded gasoline, diesel, etc.) and their average age
	Environmental management of transportation	Number of sidewalks Length of bicycle paths Number of traffic limitation zones Number of free public parking Number of pay public parking
	Passengers of transportation fleet	Number of passengers riding on buses, monorails, subway, ...
Wastes	Production and management of wastes	Implementation of urban traffic plan Traffic control innovative plans
	Environmental management of wastes	Collection of urban wastes Separated collection of wastes based on their type (paper, glass, plastic, aluminum, metal, wood, organic, etc.) Number of sanitary land fills Number of garbage bins Number of camps promoting separation of wastes from the origin The amount of fine for illegal disposal of wastes
Water	Water resources	Water consumption per capita Household consumption per capita Consumption per capita (household, industrial, agricultural, commercial, etc.)
	Environmental management of water	Number of sewage treatment facilities % of sewage network subscribers
Demographic land information	Public indicators	Lands across the urban area Population density Number of housing units

#### 4. TEHRAN MUNICIPALITY DISTRICT 14: SOME ENVIRONMENTAL ACTIVITIES TOWARD SUSTAINABILITY AND RESILIENCY

District 14 has an area of 22.04 km<sup>2</sup> and is located in the eastern part of Iran's capital Tehran which is a megacity, and covers about 3.2% of its area. A small district with high population density, District 14 has 6 regions and 26 neighborhoods with a population of 483,833. Fig. 1 shows the location of District 14 alongside the other districts in Tehran [16].

The following is a brief description of District 14 activities during the 2009 – 2014 period that were reviewed and the status with respect to each environmental criterion was determined.

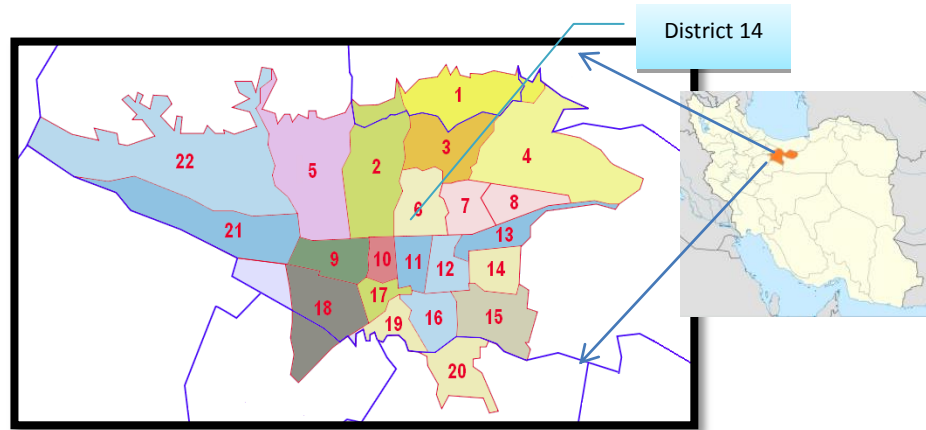


Figure 1: Location of District 14 in Tehran City's municipal divisions.

##### 4.1. Environmental Protection

District 14 of Tehran Municipality has conducted measurements for air, ground water, and noise pollutants which were afterwards managed and mitigated accordingly. These actions have been in line with the conservation of the environment. The status of the district in terms of air, noise and ground water pollution and the managerial actions are explained below; these studies started in 2011.

##### 4.1.1. Air pollution in District 14

Air pollution is a serious problem in megacity of Tehran. Due to lack of proper and modernized model of urbanization, high concentration of population, and heavy traffic, District 14 is one of the polluted districts of Tehran. So with the goal of air pollution reduction, District 14 developed a crisis map of air pollution in 2011. To this end, a lengthy study at 25 selected monitoring stations was conducted; PM<sub>2.5</sub> pollutants were measured at the aforesaid stations during the second week of the second month of the season for three days, in 24 hours. The results indicate that District 14 has PM<sub>2.5</sub> concentrations above the permissible standards of the Iranian Department of the Environment during every season [16]. Since the air pollution is above the permissible limits, actions were taken to mitigate pollution and improve air quality of the district in recent years as a priority in its urban planning. Amongst these actions were the use of less polluting vehicles and regular technical inspection, promotion of the use of bicycles in order to reduce fossil fuel consumption, and emphasis on development of green spaces to reduce air pollution. Fig. 2 illustrates a typical distribution of PM<sub>2.5</sub> pollution in District 14.

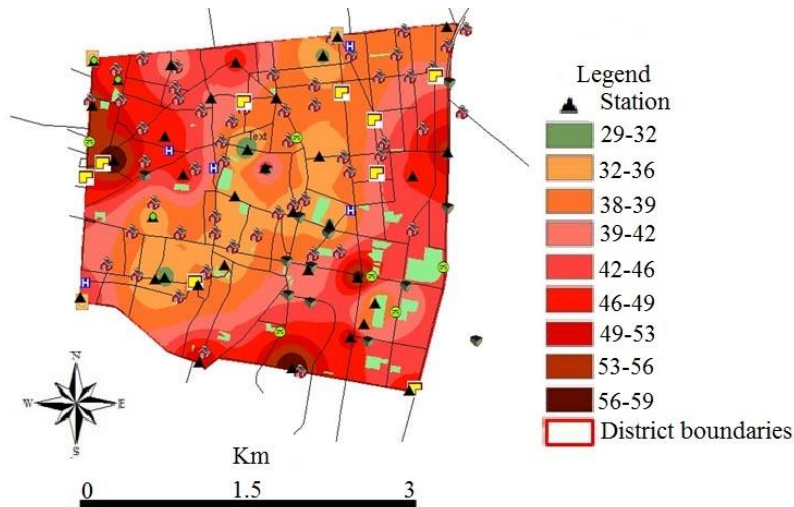


Figure 2: A sample of PM<sub>2.5</sub> distributing in District 14 [16].

#### 4.1.2. Noise pollution in District 14

The measurement of noise pollutants in District 14 was conducted in 2011 and specific steps are envisioned to reduce noise pollution until 2014. Thus, 91 stations were selected and noise equivalent levels were measured three times on Saturdays to Wednesdays in the morning (7-9), noon (12-3) and afternoon (5-8). Based on the results of this research, noise equivalent levels in all stations were above the permissible standards [17]. Due to high levels of noise pollution, some recommended measures for control and mitigation were put on the district agenda. Fig. 3 illustrates the recommended steps. Some of these actions included increasing the highway green spaces through plantation a dense combination of broad leaf and needle leaf vegetation, construction of noise absorbing levees covered with vegetation, and use of acoustic walls based on technical specifications and proper density which is shown with dark lines in Fig. 3. Also, some of the streets were widened that are indicated with red lines in Fig. 3.

With respect to the potential impacts of high noise levels on certain residential areas, engineering measures are being implemented during building construction which include the use of double-layered windows, thick glass, insulation of walls bordering two neighboring buildings, insulation of ceilings and floors, and the use of noise absorbing building materials. All of these measures are being implemented in this district to mitigate noise pollution.

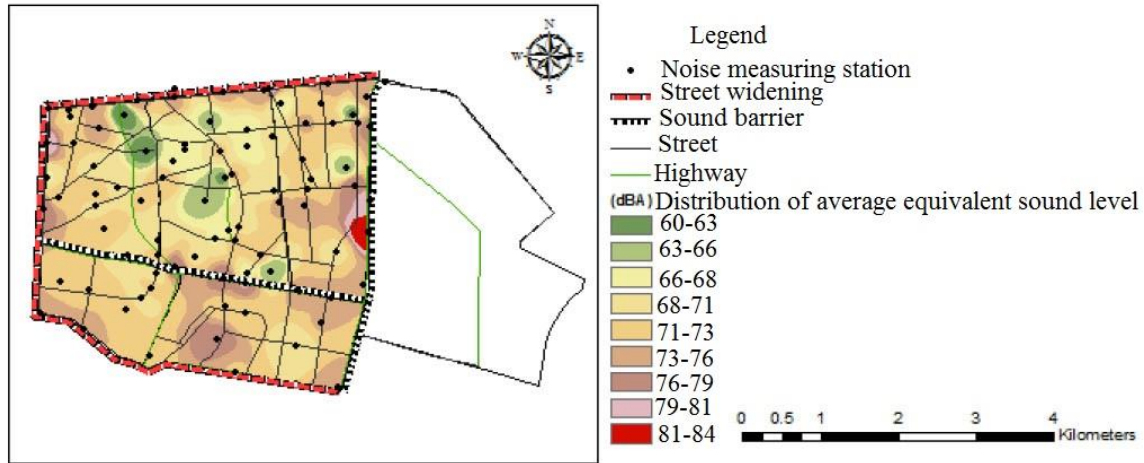


Figure 3: Recommended actions to mitigate noise pollution in District 14 [17].

#### 4.1.3. Ground water contamination in District 14

Since the use of ground water for various consumptions was on District 14 agenda, as an environmental concern, the assessment of water pollution and prevention of its contamination were essential. Sampling of 16 wells (Fig. 4 shows the well locations), which are managed by the municipality and used for green spaces irrigation, was conducted in order to identify the qualitative status of ground waters and the factors threatening its quality. The measured factors were physical parameters (temperature, color, and odor), chemical parameters (pH, EC, TSS, TDS), anions ( $\text{NO}_2^-$ ,  $\text{NO}_3^-$ ,  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{CO}_3^{2-}$ ,  $\text{HCO}_3^-$ ), cations (Mg, K, Na), heavy metals (Pb, Ag, Cd,) and MTBE. Comparison of the 19 measured parameters with the standard levels (the chemical parameters and the anion concentrations were compared with FAO standards, the heavy metal concentrations were compared with Australian Water Quality Guidelines) revealed these wells were suitable for agricultural purposes and most of them were within the accepted limits. Use of wells for irrigation is not problematic and based on the Wilcox classification, it belong to the medium category [18]. Reduction in use of pesticides, chemical fertilizers, as well as practicing environmental protection measures throughout painting and washing of urban structures are on the agenda of the municipality. Comparison of ground water measured values with international standards showed that all of the parameters were within standard limits; Table 4 lists concentration data and acceptable limits for dissolved ions measured in ground water in this district.

TABLE 4: MINIMUM, MAXIMUM AND AVERAGE DISSOLVED ION CONCENTRATIONS IN GROUND WATER IN THE REGION [18].

Analysis / Parameter	Nitrate $\text{NO}_3^-$ (mg/L)	$\text{NO}_2^-$ (mg/L)	$\text{SO}_4^{2-}$ (meq/L)	$\text{CO}_3^{2-}$ (meq/L)	$\text{HCO}_3^-$ (meq/L)	$\text{Cl}^-$ (meq/L)	$\text{Na}^+$ (meq/L)	$\text{K}^+$ (meq/L)	$\text{Mg}^{2+}$ (meq/L)
Average	5.5	0.26	2.69	0	4.85	4.23	5.87	0.055	2.25
Maximum	15.2	3.1	5.95	0	6.96	9.94	12.21	0.117	2.95
Minimum	1.7	0.06	1.66	0	2.95	2.99	3.08	0.033	1.63
Median	5.2	0.06	2.35	0	4.91	3.97	4.95	0.049	2.21
Acceptable max. <sup>[19]</sup>	10	5	20	1	10	30	40	0.051	5
Acceptable min. <sup>[20]</sup>	0	0	0	0	0	0	0	0	0

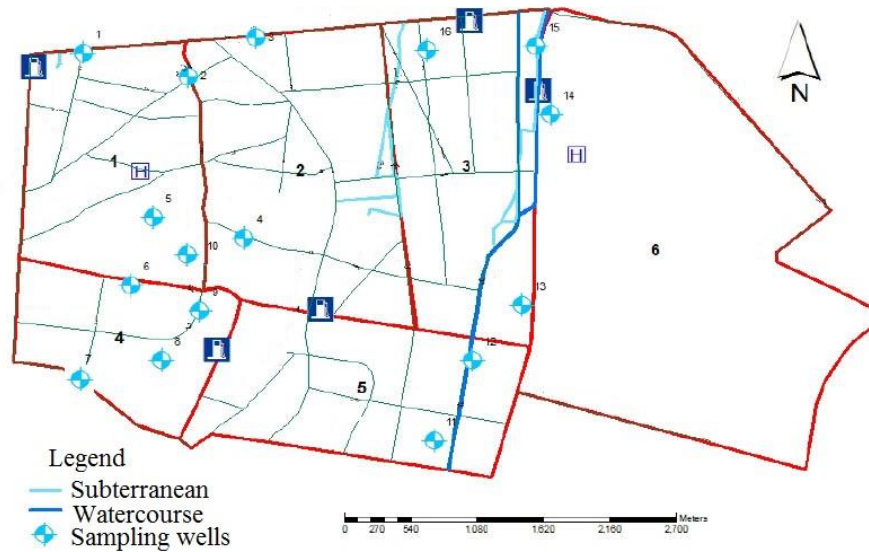


Figure 4: Location of groundwater sampling wells in District 14 [18].

#### 4.2. Protection and Expansion of Green Space

The green space area of District 14 has increased from 2,430,000 m<sup>2</sup> in 2009 to 2,857,600 m<sup>2</sup> in 2014. Also, the nearby Forest called Ghasr-e-Firouzeh has been expanded from 355 hectares in 2009 to 369 hectares in 2014. Although the green landscape expansion is considerable and the district appreciates a suitable status in this regard, there is still potential to expand and reclaim more land. With the aid of proper planning, the green space per capita in the district could reach more than 6.08 square meters in the future.

#### 4.3. Optimized Use of Resources

Steps taken in District 14 to optimize resource use include utilizing sustainable energies, reducing social waste and recycling techniques starting from the collection locations. The lack of optimized use of rain water and local water resources and lack of ability to suitably exploit solar and wind energies are the deficiencies in this field. Certain measures are to be made to attain the optimized use of resources and energy. The overall measures taken by District 14 of Tehran Municipality in regard to the environmental criteria are listed in Table 5.

According to the present study it is indicated that the status of environmental criteria such as Environmental conservation, expansion of green land space and optimal use of resources have been improved up to 2 times from 2009 to 2014.

TABLE 5: ENVIRONMENTAL CRITERIA AS THE CITY RESILIENCE INDEX AND ACTIONS BY TEHRAN MUNICIPALITY DISTRICT 14.

Classification	Criteria	Actions taken by Tehran Municipality District 14
Environmental	Environmental conservation	Attainment of ISO 14001 certificate in 2009 and its extension for 5 consecutive years
		Study the pollution sources (air – ground water and noise pollutions) and existing pollutions in the region, eventually provide an action plan to remove or control them
	Conservation and expansion of green landscape	Expand the green landscape from 2430000 m <sup>2</sup> in 2009 to 2857600 m <sup>2</sup> in 2014, expansion of Ghaser-e- Firouzeh Forest from 355 hectares in 2009 to 369 hectares in 2014
	Optimal use of resources	Use of renewable energies like solar through installation of 7 solar water heaters and 64 solar light stands in parks
Use of local water resources and wells for the irrigation of green spaces. Increase the separation and recycling of urban wastes from 19.15% to 22.1% with potential for future activities.		

## 5. CONCLUSION FOR THE ATTAINMENT OF RESILIENT CITY AND SAFE ENVIRONMENT

In order to reduce the cost of urbanization, it is essential to coordinate the implementation of the mentioned steps with the relevant organizations. Megacities require natural and human resources to provide energy, industry, construction, urban infrastructures and maintenance, in a scale that will have local and global impacts or in other words, they will have ecological footprint. An accomplished megacity can be recognized in terms of economic production, social justice, and its biodiversity protection, which taken together indicate a stable megacity that has the potential to attract more residents. The expansion of cities has increased the population density, created various types of environmental pollutions, raised energy consumption, and produced greater amounts of waste. Therefore, there has been great environmental impact at local and global levels that require profound urban management and planning.

This paper evaluated the sustainability and resiliency of Tehran Municipality District 14 from environmental point of view as a pilot. Outcomes of this research showed that from 2009 to 2014 it has improved significantly. This was achieved by senior management commitment to environmental conservation, green space development, obtaining ISO 14001 as well as HSE management system certificates, conduction of detailed studies on different aspects of environment such as air, noise and water, etc. then taking the measures to mitigate the diverse effects of environmental pollution and setting an annual environmental auditing program.

The activities as indicated in this paper by the authorities of municipality of Tehran District 14 indicated their tendency to move towards resiliency and sustainability not only for the safeguard of the environment but also in other social and economic aspects and resistive to natural disasters. The study indicated that in spite of some success on this matter there is still a long way to go in all different aspects including optimized utilization of water and energy resources. Overall, the resilient status of District 14 was enhanced during the past five years. Ultimately, benefits of resilient and sustainable cities will outweigh the initial investments by national and local governments. The long-term goal is to establish a network of resilient cities.

Although more economic activities results in better individual and collective wellbeing of citizens, it usually instigates individual, social and environmental tensions. It is important to point out that economic recessions in large populated areas initiate unemployment, weaken social cohesion, disturb social security and neglect environmental issues. Sustainability of cities requires public awareness and strong commitment to conduct the envisioned tasks including:

- Development of new plans and/or revision of the present plans
- Establishment of new priorities
- Utilization of resources for sustainable causes
- Cooperation with other legal entities in the regions to attain sustainability [7]

## 6. THE SUSTAINABLE SOLUTIONS

- Promote the use of alternative energy resources
- Construct energy efficient buildings
- Use higher energy efficiency vehicles
- Take actions to combat the emission of Green House Gases (GHG), especially CO<sub>2</sub>
- Recycle water and waste
- Utilize vegetation coverage to filter pollution and absorb atmospheric carbon dioxide
- Cooperate with governmental institutions and municipalities
- Cooperate with higher education institutions and executive organization
- Conduct urban repair and maintenance plans
- Reduce air pollution caused by urban transportation vehicles
- Promote green construction and sale
- Take actions to mitigate the emission of GHG gases [4]
- Decrease the use of pesticides in urban areas
- Promote environmental preservation
- Encourage use of public transportation
- Improve and optimize the transportation infrastructures
- Improve and expand the infrastructures of the green city
- Participate in the local, national and international meetings and share the attained experiences with them and eventually join the global network of sustainable cities
- Use endemic knowledge alongside the scientific studies in order to find ways to combat the potential risks by recognizing the intrinsic value of local know-how

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# Resilient Approach Toward Urban Development in Lake Catchments, Case of Urmia Lake

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### Abstract

Climate change and human development in lake catchments have placed these habitats in drying conditions such as Aral Sea in Asia, Lake Chad in Africa, Lake Mead in USA, Lake Urmia, etc. These ecosystems play an important role in social, ecological and economical activities. In the case of Lake Urmia, recognized as an international wetland in 1973, it is located at the northwestern corner of Iran and is the second largest hyper saline lake in the world and the largest lake in the Middle East. Lake Urmia is one of the most biologically and ecologically interesting places in the world. Bacteria, algae and even a shrimp called *Artemia urmiana* live in it. This lake is a winter habitat for various wildlife species. The lake's surface has shrunken from 6,000 km<sup>2</sup> to 900 km<sup>2</sup> in 2013. The statistics indicates the local human population has increased by 13% during this period. This shows that in addition to natural causes such as climate change and global warming, human-related issues like population growth, urban development, and construction have the most important role on the lake's status. Construction of 76 dams on rivers leading to the lake has jeopardized Urmia Lake's life in all economic, social and ecological aspects. This paper presents an innovative method for quantifying wetland status based on health, safety & loss, and environmental (HSE) factors, to make preventive measures and bring an acceptable coexistence of lakes with all their ecological and environmental features and nearby urban areas as sustainable and resilient cities.

**Keywords:** *Lake Urmia, Drying Out, Urban Development, Resilient City, Wetland HSE Index (WHSEI)*

## 1. INTRODUCTION

Climate change and human development in lake catchments have placed these habitats in drying conditions. Prominent examples include the Aral Sea in Asia, Lake Chad in Africa, Lake Mead in USA, and Lake Urmia in Iran. These ecosystems play an important role in social, ecological and economical activities and also contribute greatly to human and wild life well-being by climate regulation, water supply, water purification, providing nutrition, etc.

The Aral Sea, previously the fourth largest lake in the world, is located between Kazakhstan in the north and Uzbekistan in the south [1]. In the 1950s, the Soviet Union decided to increase cotton production by implementing considerable irrigation projects [2]. This led to a decrease of 23m in

Lake Urmia water level, a 90% reduction in lake volume and an increase in salinity from 10 g/l to more than 100 g/l; overall, it caused negative changes in human health, ecology, economy and society [3].

Lake Chad, which is the largest freshwater lake of Africa, is a vital source of water near the Sahara Desert, and holds a large area of wetlands with significant size and ecological values [4]. Droughts in the past three decades have reduced the lake by 90% which has resulted in decreased groundwater level, disappearance of specific plant species, loss of wildlife populations, increased soil erosion and loss of its fertility, and reduction in rain fed and irrigated crops [5].

Lake Mead is the largest reservoir in the United States and is a national recreation area with substantial biodiversity. Human development activities have caused considerable diverse impacts on the region economy and wildlife [6].

As it was mentioned, wetland shrinkage or disappearance has a growing trend. Lake Urmia in the northwestern part of Iran has had a similar trend and is the motive behind the definition of Wetland HSE Index (WHSEI) that is proposed and discussed in this paper. This index can be implemented for any wetland globally.

## 2. CASE OF URMIA

Urmia Lake is second largest hyper saline lake in the world which has an active food chain. It supports green and blue-green algae that nourishes the endemic brine shrimp *Artemia urmiana* that has an important part in feeding *Pelecanus onocrotalus*, *Egretta garzetta*, *Plegadis falcinellus*, *Platalea leucorodia*, *Phoenicopterus ruber*, *Tadorna ferruginea*, *Tadorna*, *Himantopus*, *Recurvirostra avosetta*, *Tringa tetanus*, *Larus cachinnans armenicus*, *Larus genei*, etc. [7,8,9].

There are around 102 rocky Islands in the lake which create a winter habitat for migrating water birds to feed and breed. They are also home to endangered mammals such as *Dama mesopotamica* and *Ovis orientalis gmelini*. The lake is also valuable in terms of tourism and therapeutic benefit because of its salinity. Urmia Lake is an important natural asset, with considerable cultural, economic, aesthetic, recreational, scientific, conservation and ecological value. It has been declared as a Wetland of International Importance in the Ramsar Convention and in 1976 UNESCO designated it as a Biosphere Reserve [9-11].

Prime geographical and climate specifications of Urmia Lake are shown in Tables 1 and 2, respectively. Many of these parameters have decreased due to climate change and human activities [12].

Wetlands features contribute to human welfare, which makes them vital ecosystems not only for wildlife but also for mankind; in the case of Lake Urmia, it provides salt production, food for animals, *Artemia* harvesting, ground water salinity control, water-bird habitat, therapeutically used herbs, hunting, tourism, recreation, etc. Urmia basin is surrounded by mountains, foothills and savannas divided between three provinces: 51% West Azerbaijan, 39% East Azerbaijan and 10% Kurdistan provinces [9,13,14]. There are more than 55 cities and 3,026 villages in Lake Urmia's catchment and around 6 million people live in this area; most of them are farmers and ranchers [12,14]. More than 76 dams on rivers leading to the lake are collecting about 2,068 million cubic meters of water per year from the catchment; 88.9% of this water is used for agricultural purposes [14]. The surface elevation of Lake Urmia has declined significantly, falling almost 7 meters compared to previous years and the water volume has decreased from 42 million cubic meters in 1995 to 22 million cubic meters in 2010 [8].

TABLE 1: URMIA LAKE PRIME GEOGRAPHICAL SPECIFICATIONS.

<b>Title</b>	<b>Description</b>
Geographical coordinates	36, 45-38, 20 N – 44, 50- 46, 10 E
Area	5,000-6,000 km <sup>2</sup>
Length	130-146 km
Width	15-58 km
Altitude	1,276 m. amsl
The average water volume	32 million cubic meters
North Basin	Aras river
South Basin	Sefid rod & Sirvan Rivers
West Basin	Zab River
East Basin	Sefid rod River
Rivers leading into the lake	Zarineh rod, Simineh rod, Godar chai, Aji chai, Barandazo chai, Nazlou chai, Shahr chai, Zola chai, Sofi chai, Azar shahr, leilan chai, Mardogh chai, Ghale chai, Mahabad chai, etc.
Most important islands	Kabodan National Park, Ashk, Azro and Espiro

TABLE 2: PRIME CLIMATE SPECIFICATIONS.

<b>Parameter</b>	<b>Description</b>
Basin precipitation	Mediterranean and in some areas of the like-Mediterranean
Average rainfall	317 mm
Average annual temperature	From 11 to 13 °C
Average humidity during the cold months	63 %
Climate	Semi-humid, with cold winters and mild summers and semi-arid central area

The present state of Urmia Lake is the result of global climate change, increased evaporation, development of non-mechanized agriculture in the Lake Catchment, surface flow diversions, groundwater extraction, lack of efficient water management, dams in the watershed, and the Shahid Kalantary causeway which crosses the Lake.

Lake Urmia holds an estimated 8 million metric tons of salt [9]. Input efficiency caused an increase in the amount of salt in its 40 years average which resulted in huge salt deposits. If the lake were to completely dry out, a vast amount of salt in form of particulate matter would be released into the regional atmosphere resulting in an ecological, agricultural, and social catastrophe not only in Iran, but also in neighboring countries such as Azerbaijan, Turkey and Iraq. It will force many people to abandon their villages and towns around the lake and the immense majority of flora and fauna will be lost permanently [11].

These changes jeopardized Urmia Lake's life which designates that even though urban development has aimed toward welfare of citizens, but in long term the consequences of these actions could result in unpredictable negative impacts.

### 2.1. *Aftermath of Lake Urmia Dryout*

- Desertification in National Park of Urmia Lake
- Threatening farmlands around the Lake
- Loss of income security for the catchment population
- Urmia Islands Wildlife threatened
- Loss of valuable and rare source of Artemia in Urmia
- Decline in the number of local and migratory birds Branch
- Jeopardizing tourism economy in the area of Urmia
- Disappearance of lake's therapeutic values
- Presence of huge amount of salt on the dried lake bed
- The potential of salt particular matter spreading all over the region
- Loss of biological value of the Lake
- Remaining saline water of the lake has become super saturated saline water

The critical conditions at Lake Urmia and some other wetlands in the world were an inspiration to introduce an innovative method for quantifying wetland status using an index based on health, safety & loss, and environmental factors (HSE) to make preventive measures to help promote resilient cities in the wetland catchments.

### 3. **WETLAND HSE INDEX (WHSEI)**

Health, safety & loss, and environmental issues are major concerns for wellbeing of wetlands. This paper introduces some factors to provide certain enabling tools for experts to monitor a wetland's status. The quantitative measures of these indices can provide decision makers with enough information to follow the development progress in a resilient manner. These factors can be divided in three categories: health, safety & loss, and environment: their changes can be followed regularly (e.g. annually):

#### 3.1. *Health Factors*

Changes in:

1. The number of people visiting the lake for treatment and water therapy (%)  $I_{wt}$
2. The number of patients admitted to medical centers for respiratory diseases associated with changes in wetland status (%)  $I_{rd}$
3. The number of patients admitted to medical centers for skin diseases related with changes in wetland status (%)  $I_{sd}$
4. The number of patients admitted to medical centers for eye diseases associated with changes in wetland status (%)  $I_{ed}$
5. The number of patients admitted to medical centers with diseases related to heavy metals in consumed salt (%)  $I_{hm}$
6. The number of patients admitted to medical centers for thyroid gland diseases (%)  $I_{ed}$

#### 3.2. *Safety & Loss Factors*

Changes in:

1. Recreation activities revenue (%)  $I_{inc}$
2. The cost of producing Agricultural yields (%)  $I_{agr}$
3. Tonnage of agriculture products (%)  $I_{tp}$
4. The related health care costs, such as respiratory and skin problems (%)  $I_{me}$

5. Immigration rate as a result of changes in wetland status (%)  $I_{ie}$

### 3.3. Environmental Factors

Changes in:

1. Regional climate due to humidity level variations of the wetland (%)  $I_h$
2. Regional climate due to precipitation variations (%)  $I_p$
3. Regional climate due to temperature changes in wetland catchment (%)  $I_t$
4. Biodiversity (wildlife, birds, fish, vegetation, etc. population) (%)  $I_{bio}$
5. Physical status of the wetlands (%)  $I_{TDS}$ : Total Dissolved Solid
6. Chemical status of the wetlands (%)  $I_{DO}$ : Dissolved Oxygen
7. Wetland water pH (%)  $I_{pH}$
8. Temperature of wetland water (%)  $I_{wt}$
9. Groundwater quality of the catchment (according to local standards) (%)  $I_{wq}$
10. Area of land under cultivation (%)  $I_{lc}$
11. Soil quality of the catchment (%)  $I_{sq}$
12. Air Quality Risk Index (%)  $I_{AQRI}$  [15]

To evaluate the Wetland HSE Index (WHSEI), the following steps should be taken:

- I. Identifying existing status for all defined factors of the wetland.
- II. Setting an auditing program, in order to monitor changes of the selected factors on annual basis.
- III. Executing necessary actions to keep these factors within a satisfactory range.

### 3.4. Calculation of WHSEI

Each of the factors is quantified according to experts' opinions and the regional standards definition. Scoring is based on the range of acceptable 10 (green), moderate 5 (yellow) and critical 0 (red); values are then compiled and summed as shown in Table 3.

TABLE 3: WHSEI EVALUATION TABLE.

Code	Factors	Acceptable (10)	Moderate (5)	Critical (0)
1	$I_{wt}$			
2	$I_{rd}$			
3	$I_{sd}$			
⋮	⋮			
21	$I_{lc}$			
22	$I_{sq}$			
23	$I_{AQRI}$			
Sum of factors		$N_a$	$N_m$	$N_c$

According to equation (1), total scores will be recorded. The sum of total scores will be divided by number of measured parameters then results will be multiplied by 10 (in equation 2) to obtain an accumulated range number for Wetland Health, Safety & loss, and Environment Index (WHSEI).

$$N_F = 10 N_{F_a} + 5 N_{F_m} + 0 N_{F_c} \quad (1)$$

$$\Sigma F_s = N_{F_a} + N_{F_m} + N_{F_c}$$

Where:

$N_F$ : Number of Factors  
 $N_{F_a}$ : Number of Acceptable Factors  
 $N_{F_m}$ : Number of Moderate Factors  
 $N_{F_c}$ : Number of Critical Factors  
 $\Sigma F_s$ : The sum of Factors Score

$$\text{Wetland HSE Index (WHSEI)} = \frac{\Sigma F_s}{N_F} \times 10 \quad (2)$$

According to results of the WHSEI, the status of the wetland can be estimated (Table 4).

TABLE 4: INDEX EVALUATION.

Score	WHSEI
Acceptable (A)	75 to 100
Moderate (M)	40 to < 75
Critical (C)	0 to < 40

#### 4. RESULTS AND RECOMMENDATIONS

Resiliency for cities in catchment areas will not be achieved if bilateral effects of human development and lakes or wetlands wellbeing are not taken seriously; WHSEI can be used to make these activities to be in accordance with sustainable and resilient concepts.

Implementation of the Wetland HSE Index can assist decision makers and authorities in several ways including:

- The general status of wetland will be determined.
- Factors threatening the wetland will be identified by degree of importance.
- With the knowledge of WHSEI status there will be comprehensive information on wetland catchment which can be used for EIA (Environmental Impact Assessment) and other related activities for executing any development projects.
- WHSEI can be used as a tool to find the status of each factor within three categories of A, M, and C which as a result will encourage decision makers to take the improving steps.
- WHSEI can help to introduce new means for development plan on the catchment area with least diverse effects on the human health and the environment.
- Implementing WHSEI and other indices like Air Quality Risk Index, etc. can be used as tools for comparative survey of cities' resiliency at national or international levels.
- WHSEI can be implemented for any lake or wetland around the world which will enable authorities to audit the wellbeing of these water bodies.

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# Consideration of Climate Uncertainties in Urban Planning: Challenges in Predicting Future Trends and Hydrologic Extremes

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### ***Abstract***

This paper will provide a summary of both the progress and the related challenges in the field of water management in a changing climate. Among the issues discussed will be the strength and limitations of remote-sensing observations, downscaled modeling products, assimilated and re-analysis information. Furthermore, the authors encourage further discussion about the recent proposed strategies to advance the development and application of hydroclimatological models for water management in a changing climate.

### ***Keywords:***

## **1. INTRODUCTION**

The need for more efficient use and effective management of water resources is a critical global issue facing the 21<sup>st</sup> century. At least three factors place special stresses and additional uncertainties on water resources planning, development and system operation strategies. First, rapid population growth is occurring in many regions of the developing world. Second, growth in economic prosperity and access to modern amenities over the last few decades has impacted per capita water consumption rates and shifted demands in most regions, especially in countries that have experienced rapid population growth and urbanization. Third, complication arises from the additional regional uncertainty resulting from global climate change and the resulting intensification of the hydrologic cycle and occurrence of more hydrologic extremes (severe floods and droughts). The key issue in managing water resources is to have reliable information. In the next few sections, after reviewing the recent hydroclimatological observations and conditions over Iran in the past several decades, we introduce some of the commonly used hydroclimate related data and models, the gaps and shortcomings of observations and forecasts are presented. Finally, suggestions for increasing the resiliency of the system are discussed.

## 2. REVIEW OF THE HYDROCLIMATOLOGICAL OBSERVATIONS AND ANALYSIS OVER IRAN

Over the past several decades the Middle East region including Iran has experienced more sustained drought conditions. Fig. 1 represents the drought analysis over the Northwestern and Southeastern Iran covering the period of 1948-2010 by Dai [1,2] of the National Center for Atmospheric Research (NCAR) in Boulder Colorado. The graph represents a historical account of the meteorological conditions based on the Palmer Drought Index (PDI). As evident from the figure, the drought conditions seem to have been relatively more persistent and largest since 1948 in most of the region.

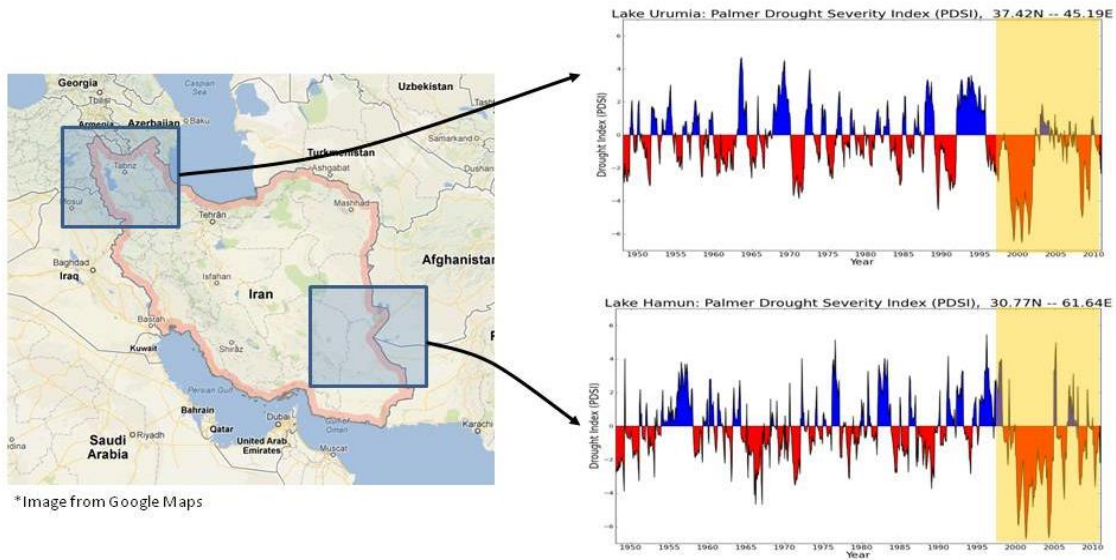


Figure 1: Palmer Drought Index analysis for the period 1948-2010 for Northwestern (top right) and Southeastern (bottom right) Iran.

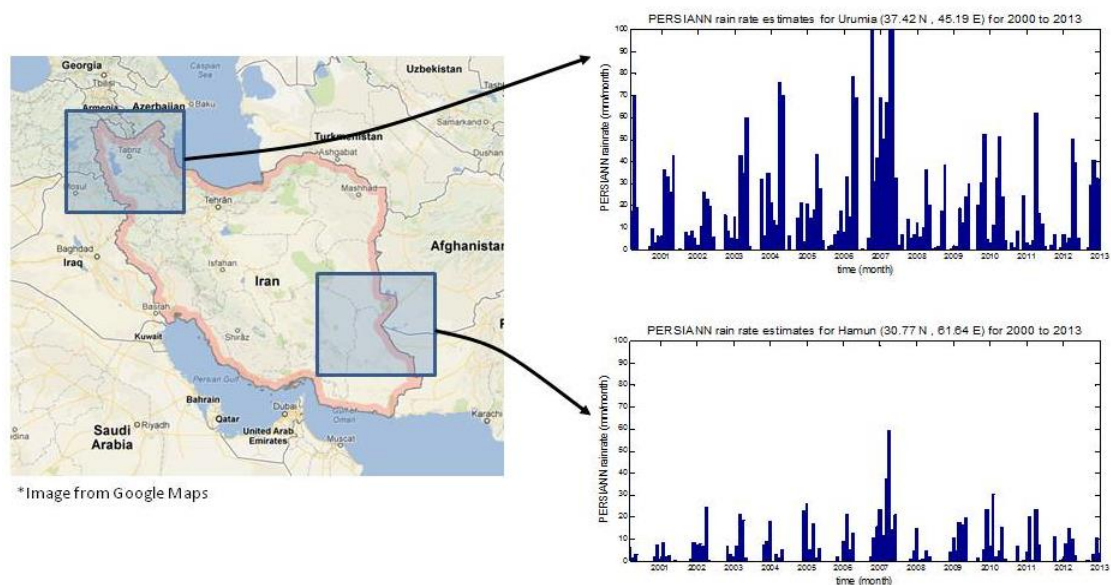


Figure 2: Satellite Precipitation Estimates from PERSIANN System (2000-2013) for Northwestern (top right) and Southeastern (bottom right) Iran.

Fig. 2 shows the histogram of monthly precipitation estimates from remotely sensed observation based on the University of California-Irvine (UCI) PERSIANN System [3], over the period of 2000-2013 and over the Northwestern and Southeastern Iran. Compared to the average long-term historical precipitation information over these regions, it is evident that past decades precipitation amounts are below what would be expected as normal.

### 3. GAPS IN OBSERVATIONS AND MONITORING

To be responsive to the need for more effective tools to address hydrologic hazards and manage water resources systems, engineers and scientists have become more reliant on the use of predictive models and stochastic methods. Depending on the problem, the hydrometeorological information needed may range from hourly forecasts (i.e., in the case of flash floods) to seasonal to inter-annual (i.e., in the case of reservoirs and other water resources system operations), and to decadal to century (i.e., in the case of long range water supply planning and structural designs).

Responding to the desired timescale and spatial resolution, varieties of mathematical models have been developed and are continuously being refined. Regional climate models are used with longer time scales, ranging from seasons to decades while information from Numerical Weather Prediction (NWP) models are often employed to help with shorter time scale forecasts (days to weeks). On the daily to seasonal forecast, the International Research Institute (IRI) for Climate and Society provides a real time multi-model probability seasonal forecast dataset available online (<http://iri.columbia.edu/our-expertise/climate/forecasts/seasonal-climate-forecasts/>). This model demonstrates the probability of precipitation above normal or below normal and also validation maps for past events that shows the regional performance of their model.

Considering the long term water resource management, the future projections of global climate models are available to the community. Based on the recommendations of the Intergovernmental Panel on Climate Change (IPCC), the general circulation model (GCM) data are available in different concentration trajectories (Representative Concentration Pathways, RCPs) ranging from stabilization to mitigation and baseline emission scenarios [4]. Commonly, a set of future projections based on climate model simulations will be considered to account for uncertainty in the models and predictions. The GCMs are usually available in coarse resolution and therefore, the majority of regional hydrometeorological models rely on downscaling of these coarse resolution datasets. The downscaled outputs of such models are then used as input to hydrologic models for a variety of applications, including flood forecasting. While there is a rich body of literature reporting on progress related to both, “weather-scale” and “climate-scale” hydrologic predictions, many challenges face the research community attempting to extend the lead-time and accuracy of both types of predictions. More specifically, despite the progress in each of the three pillars (models, observations and parameterization) of hydrometeorological prediction system over the past several decades, the improvements in the overall forecast quality is yet to reach the users expectations.

One of the issues related to GCMs is that the agreement between different models on future trends of precipitation is not very strong in many regions of the world. Fig. 3 presents an example of discrepancies among four different model simulations (CNRM-CM5, CSIRO-ML-3.6.0, GISS-E2-R, HadGEM2-ES). The figure shows the rate of decadal precipitation change (mm/month/decade) based on the RCP2.6 scenario by 2100 over the Middle East is not consistent among different models. While the French GCM (CN-CM5) projects more rain over the region, the Australian and U.K. models demonstrate a drying pattern over most parts of the area. The GISS-E2-R model displays a wetting trend on the eastern side and drying trend on the western part of Iran. These discrepancies among different models and the lack of reference points to assess the skills of future predictions are real challenges that the management community faces.

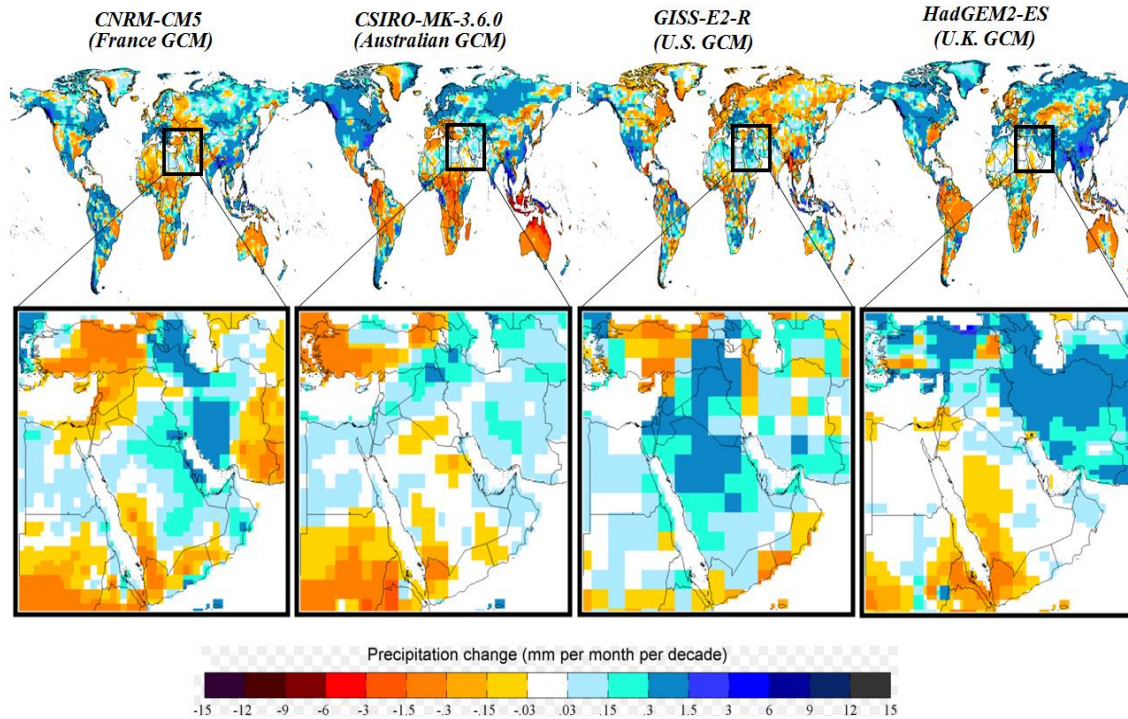


Figure 3: Rate of change of precipitation (mm/month/decade) in 4 different GCM models over the Middle East based on the RCP2.6 scenario.

#### 4. SOLUTIONS TO IMPROVE SCIENCE COMMUNITY, DECISION MAKERS, USERS AND STAKEHOLDERS

The best approach to understand the future changes of our system is to identify the best models that have better agreements with current and historical observation data. Measuring precipitation from space has been a very promising approach to provide high resolution data over large regions and also over the oceans. The TRMM Multi-satellite Precipitation Analysis (TMPA) [5], the NOAA CPC Morphing Technique (CMORPH) [6], the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN) algorithm [3,7], and PERSIANN cloud classification system (PERSIANN-CCS) [8] are some of the different near real-time precipitation products that are very useful in hydrometeorological studies.

In addition to near real-time precipitation data, long term historical data are also very valuable in assessing the climatology of the region. The PERSIANN-CDR dataset [9] (available from <http://www.ncdc.noaa.gov/cdr/operationalcdrs.html>) provides a long term high resolution (0.25 degree) daily scale precipitation data available from 1980. This unique satellite based precipitation data is very valuable especially over remote or data sparse regions. With a greater focus on extreme events, the PERSIANN-CONNECTED precipitation object (PERSIANN CONNECT) [10] dataset facilitates a search platform to look at the changes of characteristics and also path of all heavy storms globally. The users can search the objects that pass through a geographic region of interest and find all the storms in the region. The data that is currently populating the object-oriented database is the nearly global precipitation estimated by the PERSIANN algorithm for the period 1st March 2000 to 1st January 2011, hourly, 0.25-degree resolution. The database is publically available and can be searched using simple web search queries through: <http://chrs.web.uci.edu/research/voxel/index.html>.



The above mentioned datasets are just a subset of global observations that are available to the community. The future satellite missions, as well as recently launched NASA Global Precipitation Measurement (GPM) mission, will provide additional datasets that help us to better understand the current state of the weather and climate systems [11].

In addition to all these different datasets, the traditional statistical methods with probabilistic approach are a good alternative that can be used to evaluate the system based on historical data. Fig. 4 shows an example of a probabilistic model that demonstrates the trend in precipitation or runoff observations (e.g. wetting or drying) to the hydrologic variability (e.g. magnitude, severity, duration). These types of traditional probabilistic models are useful tools while considering the variability and changes in the systems and make decisions based on the uncertainty of the system and the risk level.

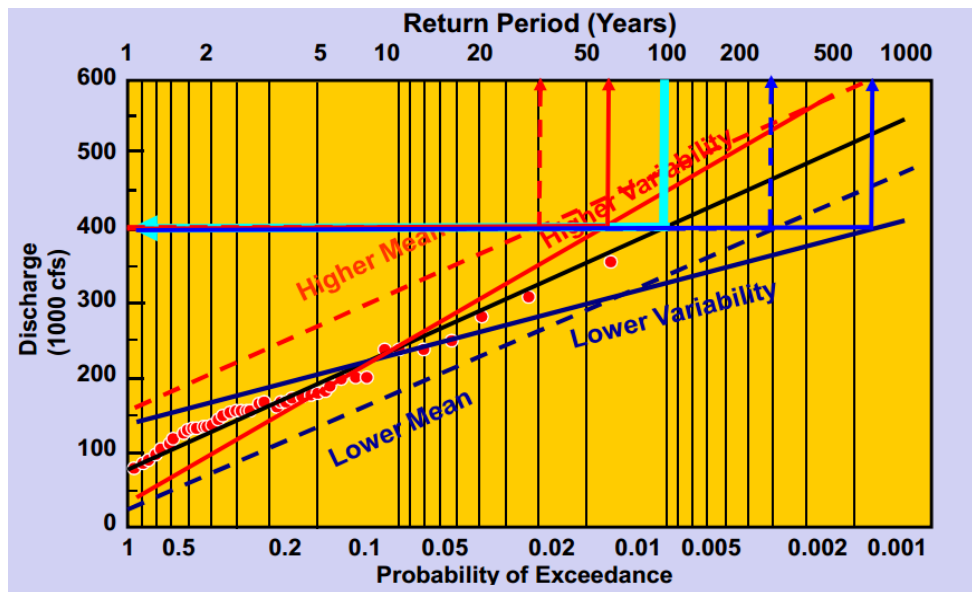


Figure 4: A probabilistic model representing the changes in the discharge and return period based on different hydrologic scenarios.

Population growth, climate variability, increase in water consumption and urbanization are some of the factors that increase future water use. Meeting water needs of large urban areas requires taking advantage of all the available resources. Water recycling is one of the options to provide clean water and many communities are moving toward using recycled water. One of the very successful cases of using recycled water is Orange County, California. Recent droughts, snowpack reduction and high water demand in the area are some of the challenges that Southern California faces. Orange County's Groundwater Replenishment (GWR) system is a great example of increasing the resiliency of the system. GWR has been operating since 2008 with an average production of ~60 million gallons per day (mgd). Reusing treated wastewater is a reliable source of water that can be used for groundwater recharge as well as other purposes.

## 5. CONCLUSION

Presently, the accuracy of Hydroclimate model predictions falls short of meeting the requirements of water resources planning. By considering different projections of future changes in climate, or using different global climate models, one can estimate the projection of the future changes in the hydroclimate variables. However, various models do not necessarily agree with each

other in their trend and variability on regional scales. These differences among models and concentration scenarios make it very challenging for decision makers and water resource managers. Therefore, factoring in resiliency in water resources system's design and planning is still the safest approach. Building reservoir to control floods and store water for dry periods, also transferring water from reservoirs to water scarce regions are some of the engineering solutions to mitigate water resource risks and challenges. Moreover, meeting water needs of urban areas requires consideration of all possible sources and their conjunctive use. Recycling and reuse of wastewater generated by urban areas must be part of the planning process – technological advances make this feasible if there is a will to do it.

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# A Case Analysis of Air Quality in Tehran and Considerations for City Sustainability and Resilience

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### **Abstract**

Cities adapting to population growth, climate change, and other societally-relevant pressures face challenges associated with both local and transported air pollution that impact public health and welfare, visibility, regional climate, and the spatiotemporal distribution of precipitation. Tehran, Iran represents a metropolitan area vulnerable to these changes with far-reaching effects rooted in emissions of gases and particulate matter with unknown spatiotemporal profiles, physicochemical properties, and impacts on over 12 million inhabitants. We examined multiple data sources to build a decadal climatology of particulate matter characteristics in this region. The use of satellite remote sensing data in combination with surface measurements and transport modeling clearly illustrate the far-reaching effects of dust and also transported biomass burning pollution from upwind regions superimposed on significant local emissions within the city. The effects of a shallower boundary layer in the winter, weekday-weekend differences in human activity, and precipitation are explored and point to importance of considering temporal patterns in air pollution. These results have major implications for the future sustainability and well-being of this and other megacities.

**Keywords:** *Aerosol, Clouds, Precipitation, Tehran*

## **1. INTRODUCTION**

According to the United States Environmental Protection Agency (EPA), the goal of sustainability is to “create and maintain conditions, under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic, and other requirements of present and future generations.” As cities experience population growth and land use change, the spatiotemporal profile of emissions from natural and anthropogenic sources will change and impact city sustainability from the perspective of aerosol (i.e. particulate matter) effects on public health, air quality, climate, and the hydrologic cycle. Particulate matter has been extensively monitored in several major urban centers of the world such as Beijing, Mexico City, and Los Angeles, but one area that has received disproportionately less attention is the arid Middle East. Crosbie et al. [1] recently conducted an extensive characterization of air pollution in the greater Tehran area, and the discussion hereinafter is adopted from that work.

The capital city of Iran is Tehran (Fig. 1) and the metropolitan area covers an area over 2,300 square kilometers in the northern part of the country. The population of the Tehran metropolitan area has grown from 11.3 million in 2006 to 12.2 million in 2011 (United Nations Population Fund; <http://iran.unfpa.org/>). Air pollution problems are exacerbated in this major metropolitan area due to surrounding mountains, which extend to over 5000 m and inhibit ventilation of pollutants, especially during wintertime. The Alborz Mountains provide a more prominent meteorological barrier to many other urban regions, which suffer topographical blockage in the presence of a subsidence inversion (e.g., San Gabriel and San Bernardino Mountains/Los Angeles, Wasach Mountains/Salt Lake City and Cordillera Neovolcánica/Mexico City). The growing population and extensive anthropogenic emissions result in major air quality issues and uncertain effects on the region's microclimate and hydrological cycle. Visibility data from the last 50 years indicate a long-term trend in visibility reduction and suggest that worsening air quality is attributable to emissions rather than meteorological factors [2]. Vehicular emissions are of particular concern in the region owing to more than two million vehicles, many of which are more than two decades old [3]. Dust has a substantial impact on the region owing to internal sources [4–6], including numerous dry lakes (e.g., Hamun-e Jaz Murian, Hamun-i-Mashkel, Daryacheh-ye Mamak) and the larger Dasht-e Kavir Desert, and external sources due to its location near the Arabian Peninsula to the south and the Euphrates and Tigris Basins to the west [6–9]. PM<sub>10</sub> concentrations in parts of Iran can reach more than 5 mg·m<sup>-3</sup>, which consequently contribute to enhanced mortality [8]. It was reported that in the city of Zanjan, just to the northeast of Tehran, the dominant aerosol type was dust and that only 20% of all particles were smaller than 1 μm [10]. Dust has also been shown to be more abundant in parts of Iran during spring and summer, while motor vehicles are more influential during fall and winter and during weekdays [11].



Figure 1: Geographic locations of the ground-based meteorological monitoring stations.

Owing to limited surface measurements of particulate matter in the Tehran metropolitan area, satellite remote sensing data are highly valuable in examining spatiotemporal patterns of air pollution in this area [12]. Concerted efforts to combine satellite data with available surface measurements, air mass back-trajectory data, and chemical transport model results do not exist for the Tehran area and its surroundings, a fact that motivates the current study. The goal of this work is to report a multi-year (2000–2009) aerosol characterization for metropolitan Tehran and surrounding areas with an aim to extend upon previous studies examining air pollution characteristics in Iran. This work addresses the following questions: (i) what are monthly trends in aerosol-related parameters and others that potentially influence them such as meteorology and air mass source regions?; (ii) What is the role of precipitation in modulating aerosol-related



parameters?; and (iii) can the datasets provide any indication of the weekly aerosol cycles and the relative strength of dust *versus* other aerosol types? In addressing these questions, we will determine the degree of correspondence between satellite data, chemical transport modeling, and surface measurements of visibility. Direct surface measurement data for aerosol particles are not publicly available for Tehran during the study period. In light of this limitation this study leverages a combination of remotely-sensed data, local meteorological observations and model data, the details of which are summarized by Crosbie et al. [1].

## 2. RESULTS

### 2.1. Local Meteorology

The local meteorology is examined using surface station data at Tehran (Mehrabad) and compared with data from the nearby stations at Gharakhil and Semnan to understand the impact of local microclimatic variability within the context of the region (locations shown in Fig. 1). A summary of the monthly average surface station data at Mehrabad, Gharakhil and Semnan is shown in Fig. 2a–e. The region is characterized by a semi-arid climate, with hot and dry summers, cold winters, and mild conditions in the spring and fall. The annual cycle of ambient surface temperature is expectedly very similar at Mehrabad and Semnan ranging from as low as 3.7 °C in January to 32.2 °C in July and with monthly averages deviating by approximately 1 °C between the sites. Gharakhil has a slightly lower seasonal variability, because of its proximity to the Caspian Sea, with temperatures ranging from 7.2 °C in January to 26.6 °C in August. At Mehrabad, wind speeds at the surface are lowest in the winter months and peak in the spring and early summer. Semnan has comparable wind speeds during the summer but in the other seasons the wind speed is lower. Gharakhil has lower wind speeds overall with minimal seasonal variability. Precipitation accumulation at Mehrabad and Semnan is generally low throughout the year with minimal rainfall from May to October. April is the wettest month for both stations with 45 mm at Mehrabad and 30 mm at Semnan. Both of these stations receive 80% of their annual precipitation between November and April. Gharakhil experiences a markedly different precipitation regime with comparable totals during the early part of the year followed by a large upswing starting late summer and extending through the fall to early winter with precipitation peaking at 132 mm in November. The surface RH at Mehrabad and Semnan follows a very similar seasonal pattern with the driest conditions found during the summer months because of the high ambient temperatures. Gharakhil is humid throughout the year with little seasonal variability.

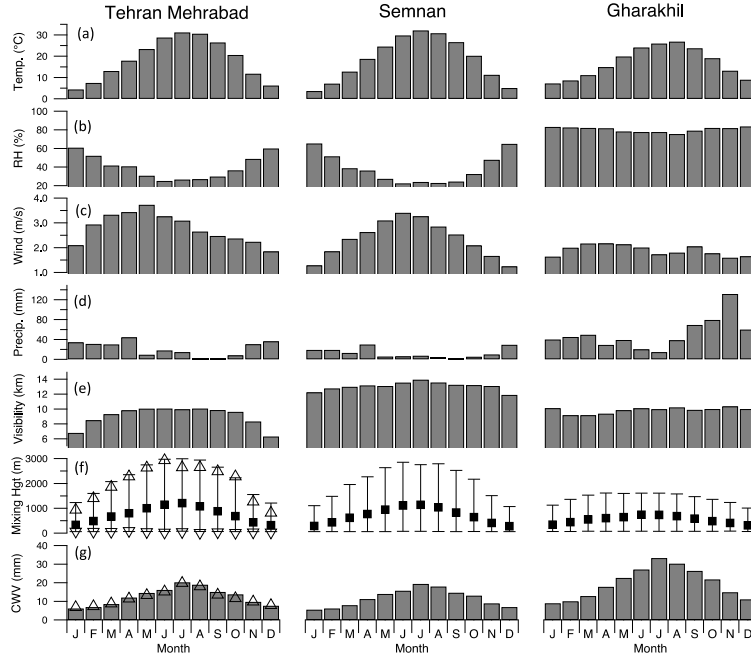


Figure 2: Monthly summary of surface meteorological data at three sites near Tehran (see Fig. 1 for locations) between 2000 and 2009 for (a) dry bulb temperature ( $T$ ), (b) relative humidity ( $RH$ ), (c) wind speed, (d) accumulated precipitation, and (e) visibility. Monthly summary of upper air data for the same sites: (f) mixed layer height derived from Mehrabad radiosonde data (1980–2012; 00Z and 12Z soundings shown as triangle markers) and MERRA reanalysis data (2000–2009; square markers represent daily mean and whiskers represent average daily range) at grid points near Tehran ( $35.50^{\circ}N$ ,  $51.33^{\circ}E$ ), Semnan ( $35.50^{\circ}N$ ,  $53.33^{\circ}E$ ) and Gharakhil ( $36.50^{\circ}N$ ,  $52.67^{\circ}E$ ); (g) Same as (f) except for average total column water vapor (CWV).

Monthly patterns in mixing layer height (Fig. 2f) and columnar water vapor (CWV) (Fig. 2g) were calculated using the radiosonde data at Mehrabad in conjunction with the values derived from the NASA MERRA dataset at grid points near Tehran ( $35.50^{\circ}N$ ,  $51.33^{\circ}E$ ), Semnan ( $35.50^{\circ}N$ ,  $53.33^{\circ}E$ ) and Gharakhil ( $36.50^{\circ}N$ ,  $52.67^{\circ}E$ ). There is a noticeable increase in the daily maximum mixing layer height during the summer compared with the winter and increased mixing layer heights are found on the south side of the mountains (Tehran and Semnan) consistent with expectations for a semi-arid sub-tropical climate. The diurnal cycle of the mixing layer (not shown) shows the characteristic maximum in the afternoon driven by solar heating at the surface and overnight surface inversion typical of desert environments. Gharakhil shows a similar diurnal pattern with slightly less variation and has the signature of the influence of afternoon sea breezes. CWV (Fig. 2g) is at a maximum during the summer at all locations, consistent with higher temperatures and hence higher saturation vapor pressures. The peak monthly values occur in July for all three locations reaching 20 mm at Tehran, 19 mm at Semnan, and 33 mm at Gharakhil.

The average visibility (Fig. 2e) at Semnan is highest in July at 13.9 km with a moderate reduction observed during the winter, reaching a minimum of 11.9 km in December. Mehrabad also follows the same annual pattern; however, the visibilities are systematically lower for all months with a considerable reduction during the winter with minima of 6.3 km in December and 6.8 km in January. In both cases, local aerosol emissions are trapped within the surface layer leading to higher surface concentrations and lower visibility in the winter. The contrast between the two stations highlights the magnitude of the local aerosol sources in Tehran, which strongly affect the Mehrabad data but have a smaller effect on Semnan. In complete contrast, the annual visibility profile at Gharakhil follows a different pattern with minimal variability throughout the year (range  $\sim 1.2$  km *versus*  $\sim 3.8$  km at Mehrabad). This is likely due to the different meteorological conditions

north of the Alborz Mountains where reduced visibility may be associated with phenomena other than an increase in aerosol concentration, such as fog or rain.

## 2.2. Air Mass Source Origin

An important factor governing aerosol characteristics in the greater Tehran area is the seasonal air mass transport pathways ending at this location. To determine air mass source origins impacting Tehran, five-day back-trajectories were computed using the NOAA HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) model [13], which was run using the NCAR/NCEP reanalysis data with the isentropic vertical velocity method. Six-hourly trajectories from 2000 to 2009 were obtained ending at Tehran (35.70°N, 51.42°E) at 500, 1000, and 3000 m above the surface. The HYSPLIT data were used to construct seasonal (DJF, MAM, JJA, SON) trajectory frequency maps for the 2000–2009 period, which present the most frequent transport pathways of air ending in Tehran. Trajectories are also classified by source region denoted by regions A–E (Fig. 3): A = desert region southwest of Tehran; B = Europe; C = Siberia/Russia; D = countries which are east of Iran; E = representation of local sources near Tehran.

Trajectories ending below 1000 m show qualitatively similar patterns with altitude (Fig. 3) and during the majority of the year, the most dominant source region is found to be in the desert regions to the west and southwest (Region A). In summer the circulation pattern of the region is significantly different and trajectories from Region C prevail at low levels. Low-level trajectories in winter (DJF) included a significant contribution from Region E (34%), which is indicative of stagnant low-level air. While HYSPLIT may not resolve these features entirely, the stagnation at the surface would be further enhanced by shallow mixing heights with stable air aloft which would trap air below the mountain tops. The least important source regions were from Regions B (northwest) and D (east). The importance of trajectories originating from the dust-rich region between the west and south of Tehran increased for the upper levels. At an ending altitude of 3000 m AGL, the air mass origins were in Region A for 57% of trajectories annually and reached a peak fraction during the spring (MAM) of 73%. For trajectories ending below 1000 m, there was no significant change in the attribution of source region when only surface influenced (<500 m) fractions of the trajectory were considered (not shown). Low-level (ending altitude 500 m AGL) trajectory density is presented as an average residence time (hours per trajectory) within each cell in a  $0.5^\circ \times 0.5^\circ$  grid to supplement the apportionment of source regions (Fig. 4). Consistent with Fig. 3, all seasons except summer (Fig. 4c) exhibit similar trajectory maps with air mass source regions in a quadrant from the south through to the west and a secondary source region to the northeast, although many of these trajectories were likely classified as Region E. The summer source region is predominantly to the north and northeast, which accounts for the abundance of Region C trajectories during these months.

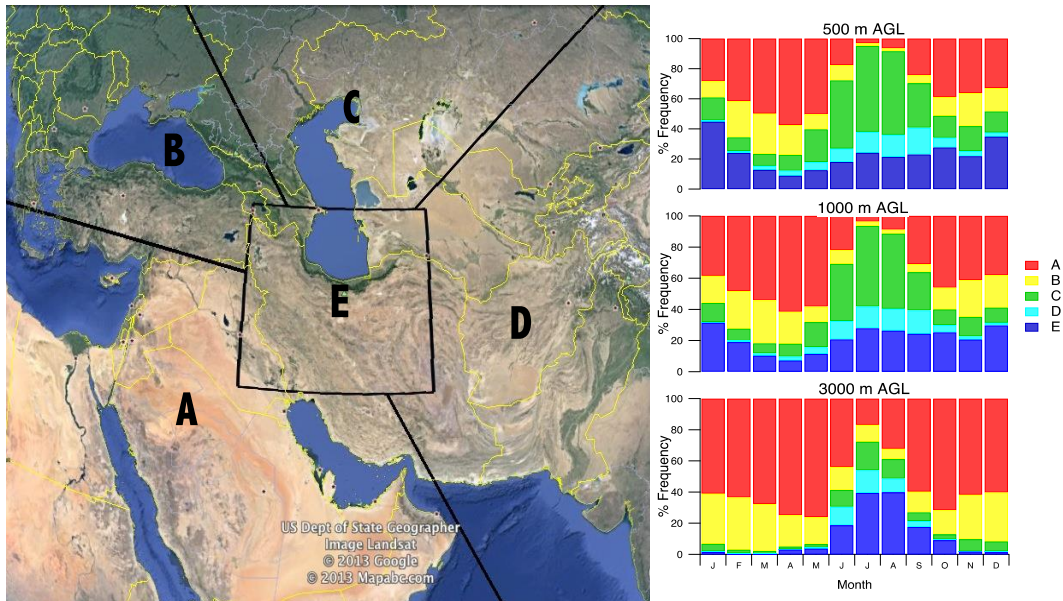


Figure 3: Monthly pattern in air mass source region as determined by analysis of daily HYSPLIT data between 2000 and 2009. Back-trajectories are classified by time spent in each region. The region totals are shown, by month, for end points at 500 m, 1000 m and 3000 m above ground level (AGL) (Right).

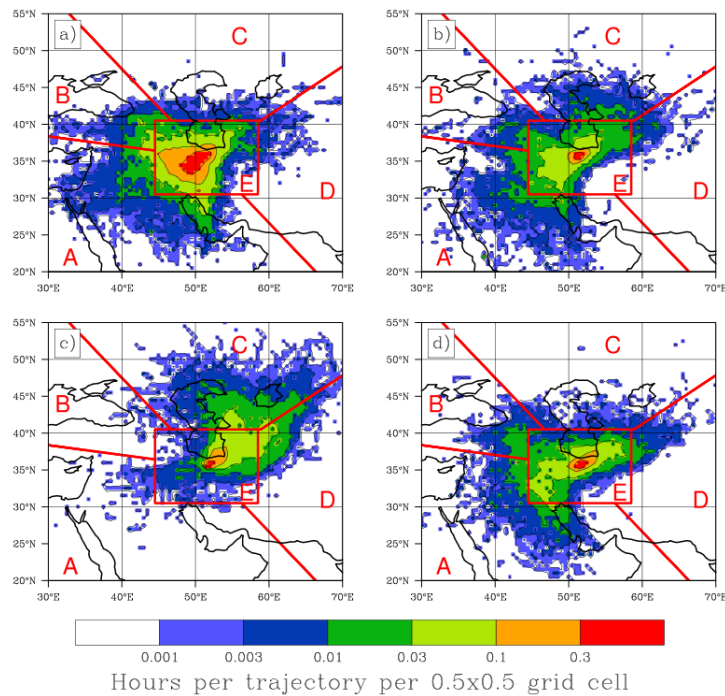


Figure 4: Decadal (2000–2009) summary of seasonal HYSPLIT five-day back-trajectory frequencies, ending at 500m above Tehran (35.70°N, 51.42°E) for (a) winter (DJF), (b) spring (MAM), (c) summer (JJA), and (d) fall (SON). Frequency is defined as the number of trajectory-hours spent in each  $0.5^\circ \times 0.5^\circ$  grid box divided by the total number of trajectories analyzed. Source regions, as illustrated in Fig. 3, are overlaid.

### 2.3. Regional Fire Patterns

Using the Moderate Resolution Imaging Spectroradiometer (MODIS) Fire Information for Resource Management System (FIRMS) data from 2000 to 2009, a fire radiative power (FRP) climatology has been developed for four seasons for a region spanning eastern Europe, central Asia and the Middle East (Fig. 5); FRP is related to the burn intensity of the fire pixel and is provided for each identified fire per overpass. FRP across the region increases in spring and summer. In particular, the region to the north of the Caucasus Mountains extending into Ukraine, southwest Russia and further northeast into Kazakhstan experiences a substantial number of fires during the summer. The fires in Ukraine and southwest Russia are predominantly associated with agricultural burning. During spring, there is a maximum in fire density shifted farther east into Kazakhstan. The number of fires during fall and winter is significantly lower than other seasons and is likely to have little impact on aerosol concentrations in the study region.

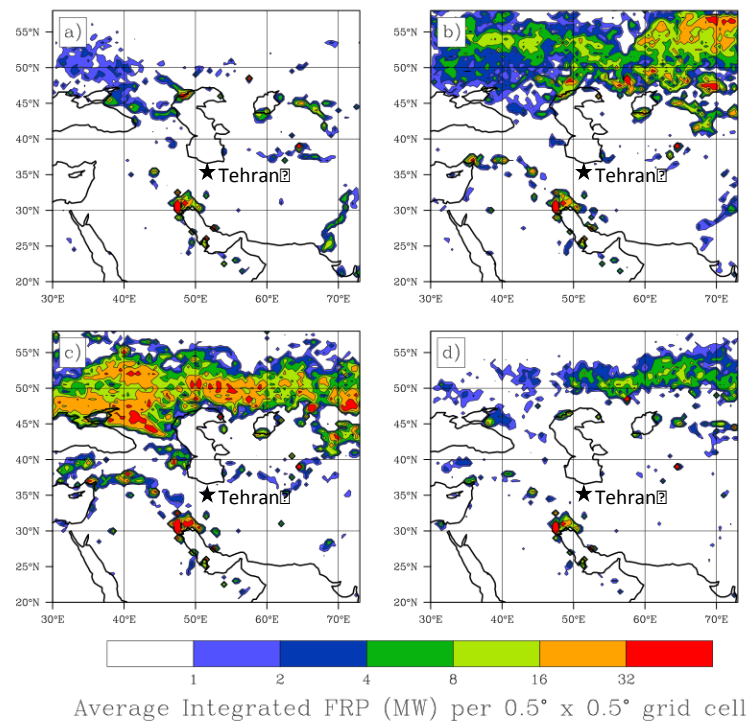


Figure 5: Seasonal patterns in Fire Radiative Power (FRP) derived from Moderate Resolution Imaging Spectroradiometer (MODIS) Fire Information for Resource Management System (FIRMS) data from 2000 to 2009. FRP is shown as integrated seasonal average power (megawatts per  $0.5^\circ \times 0.5^\circ$  grid box) for (a) winter (DJF), (b) spring (MAM), (c) summer (JJA), and (d) fall (SON).

### 2.4. Remotely-Sensed Aerosol Data

MODIS Deep Blue (Terra and Aqua) and Multi-angle Imaging Spectroradiometer (MISR) all show that aerosol optical depth (AOD) is largest between April and August (Fig. 6a). Although not presented quantitatively, the MODIS Angstrom Exponent (AE) monthly averages were also considered as a qualitative method of assessing coarse mode *versus* fine mode aerosol. Lower AE values are generally found in the spring and summer months, which suggests a shift towards coarser aerosol such as dust. This point is further supported by Fig. 6c where it is shown that the highest ultraviolet (UV) aerosol index (AI) values are observed in the spring and summer (May–

July), especially for the Total Ozone Mapping Spectrometer (TOMS) sensor; note that UV AI is a representation of the relative abundance of absorbing aerosols (e.g. smoke and dust). However, there are two possible mechanisms for the significant upswing of UV AI levels during the summer: an increase in the abundance of absorbing aerosol (*i.e.*, dust and smoke) or a change in the column distribution of the absorbing aerosol. While an increase in overall dust concentration is the likely contributor to the increase in UV AI, it may also be driven by an increase in elevated dust and/or smoke layers. Some caution must be employed when considering the mean AOD and UV AI values during the winter, since during this time of year there were fewer data points available, because of cloud contamination. To qualitatively assess the significance of the seasonal cycle we evaluate monthly mean values against the standard deviation of interannual variability (shown as error bars on Fig. 6). Winter AOD is generally more variable than summer; however, in summer the range of variability is amplified, particularly for the TOMS data, in part due to extreme dust events, which occur in some years and not in others.

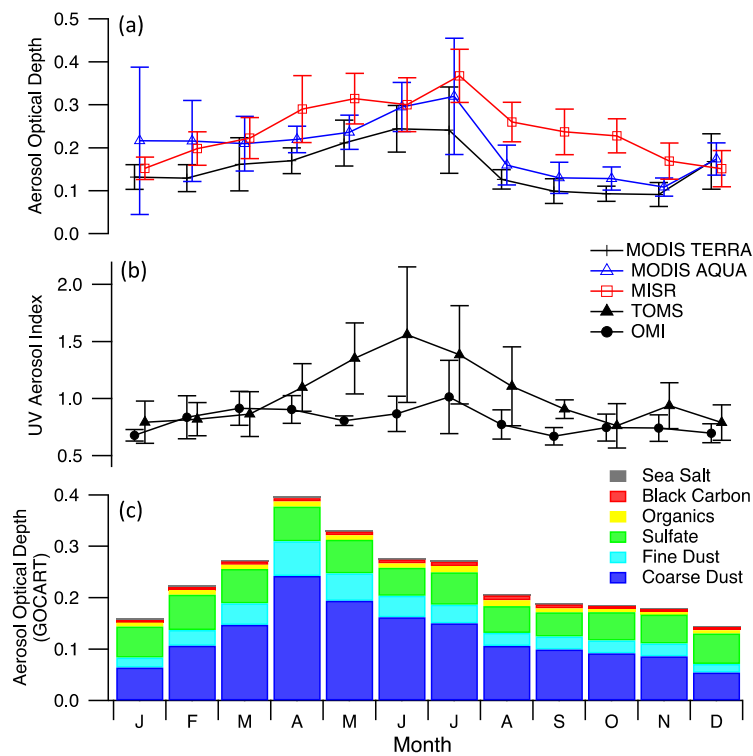


Figure 6: Monthly summary of remotely-sensed and model data for the greater Tehran area (see Table 1) for different satellite products (a and b): (a) aerosol optical depth (AOD) from MODIS Deep Blue (Terra and Aqua) and Multi-angle Imaging Spectroradiometer (MISR); (b) Total Ozone Mapping Spectrometer (TOMS) and Ozone Monitoring Instrument (OMI) ultraviolet aerosol index; (c) monthly summary of fractional AOD from Goddard Ozone Chemistry Aerosol Radiation and Transport (GOCART).

## 2.5. Goddard Ozone Chemistry Aerosol Radiation and Transport (GOCART) Model

Data from GOCART [14] simulations were used to quantify the relative importance of different aerosol constituents. The monthly average fractional AOD for fine and coarse dust, black carbon, organics, sulfate, and sea salt are shown in Fig. 6d. In examining these data, we focus on the relative fraction of the constituents and their seasonal trends instead of considering the absolute values to reduce sensitivity to model limitations.

Throughout the entire annual cycle, dust optical depth (which includes coarse and fine dust), accounts for the largest fraction of the total optical depth at 68% of the average annual aerosol with highest levels during April. Sulfate contributes the next highest fraction with an annual average of 25% with little variability through the year. Black carbon and organics are responsible for a relatively small fraction of the total AOD at 2.8% and 3.6%, respectively; however, the peak occurs during July and August and is suggestive of a biomass-burning source due to wildfires mainly in Ukraine, Russia and Kazakhstan. The peak AOD from GOCART occurs during spring, which is consistent with the influx of regional and local dust; however, the model may be under predicting the role of black carbon and organics associated with biomass burning due to uncertainties in the emissions inventory. In addition, GOCART does not include gas phase chemistry and hence cannot suitably model secondary production of aerosol that is not approximated at the source. Sea salt is also a very low impact contributor to the total AOD (approximately 0.6% annual average) with the peak occurring during winter and early spring where upper air trajectories are from the west and southwest. The HYSPLIT trajectories suggest that sea salt aerosol sources include the Gulf and the Mediterranean Sea and perhaps the Caspian Sea, although its salinity is far lower. The high terrain and lack of local sea salt sources suggests that marine air intrusions do not affect the lower troposphere and this is confirmed by the contrast in meteorology at Mehrabad and Semnan as compared to Gharakhil and justifies the lack of sea salt aerosol.

### **3. DISCUSSION**

#### *3.1. Seasonal Climatology*

Many of the patterns found in the surface data conform to the expected seasonal variability, which is characteristic of a sub-tropical desert environment such as temperature, humidity, and visibility. The observed meteorology at Mehrabad, Gharakhil and Semnan can be explained by the influence of local topography, land surface, urbanization, and large-scale atmospheric circulation pattern of the region. Further analysis of the data suggests mechanisms for variability in aerosol quantified using satellite-derived AOD and surface visibility. Since satellite AOD was available only on days with low cloud fraction, there was a potential sampling bias associated with the comparison of seasonal visibility and AOD cycles. However, the difference between the visibility statistics derived on days when satellite data were available and the entire dataset was found to be negligible, and so this bias was not relevant to this study.

Using the visibility data at Mehrabad as a proxy for surface-layer aerosol concentration reveals that the reduced visibility during winter is aligned well with recurring reports of hazardous air quality within the city being more prevalent during this season. MODIS Deep Blue and MISR data indicate that AOD is lowest during winter. For this to happen the distribution of aerosol through the column is more weighted towards the near-surface layer. The local meteorology supports this conclusion, since average mixing layer heights are far lower in winter and stable air above the mixing layer traps air below the mountains causing a high incidence of stagnant air at the surface, which is infrequently ventilated. In contrast, the summer exhibits a maximum in the satellite-derived AOD and the highest visibilities at Mehrabad. Mixing heights are highest mainly due to the high incident solar radiation, which vigorously mixes aerosol in the lower troposphere and helps to relieve the accumulation of aerosol near the surface. The AOD is highest during this season, which suggests a higher columnar aerosol concentration, and is likely attributed to dust transport in the mid- to upper-troposphere from source regions in the deserts to the west of Iran (Arabia, North Africa, and the Levant), although it is unclear exactly which dust source regions are most influential for Tehran. While data for AOD and perhaps TOMS and OMI UV AI indicate that dust is most important during spring and summer, the trajectory analysis only supports the argument for regional dust transport during spring. Nonetheless, there is evidence from individual cases that



regional dust transport can contribute to extreme events during the summer. In addition, there is an abundance of local sources of dust within Iran, in relative proximity to Tehran, and these sources may be most impactful during summer due to higher surface wind speeds and potentially lower soil moisture. One possible method for isolating local and regional dust sources is the ratio of  $PM_{2.5}$  to  $PM_{10}$ , with lower ratios suggestive of greater influence from local dust sources [15]; that study suggested 0.35 as a threshold value, above which data are contaminated by non-local dust sources. Results from [8] for  $PM_{2.5}$  and  $PM_{10}$  concentrations measured at a site in western Iran during 2010, suggest a range of  $PM_{2.5}:PM_{10}$  between 0.18 and 0.32 (based on ratios of monthly-averaged values) indicating that local dust sources make a significant contribution.

Another mechanism for the enhancement of satellite-derived AOD during the summer may be the swelling of aerosol due to uptake of water vapor (*i.e.*, hygroscopic growth). Higher CWV in the summer (Fig. 2g) supports the occurrence of hygroscopic growth, and even though surface relative humidity values are suppressed (Fig. 2b), the relative humidity in the upper parts of the (deep) mixing layer (not shown) is sufficient for significant water vapor uptake. Later in the summer, upper air trajectories imply that air mass origins from the north are prevalent, which may indicate a contribution from biomass burning sources due to smoke from wildfires in Ukraine and Russia. Although the magnitudes are too small to be of major significance, if taken in a relative sense, GOCART generally supports this with an increase in black carbon optical depth during the summer.

### 3.2. Precipitation

The discussion above suggests that the combination of local and regional aerosol sources is stronger during the summer; however, the mechanism for the removal of aerosol can be equally as important. An essential mechanism for modulation of aerosol loading is the scavenging of aerosol by precipitation. Summer (JJA) rain in Tehran is rare, and the average interval between rain events at Mehrabad during 2000–2009 is 23.5 days compared with 4.5 days for winter (DJF), 5.0 days for spring (MAM), and 8.2 days for fall (SON). To understand the importance of this interaction for the climatology of Tehran, we investigate the difference in aerosol immediately before and after rainy days, which are defined as days with observed rainfall at Mehrabad. We focus only on the winter months, since this is the season with the most rain days and also is the most critical season in terms of aerosol effects on public health owing to a shallower mixing layer accumulating a higher concentration of pollutants near the surface. Fig. 7a shows the composite average change in visibility at Mehrabad between the mean visibility during the two days before and two days after rainfall stratified by the severity of the rainfall event and Fig. 7b shows the same comparison for AOD. Since the number of rain events is small and there is considerable loss of AOD data surrounding rain events due to cloud contamination, a “consolidated” AOD is generated using the three satellite products used in this study (MODIS Deep Blue (Terra and Aqua) and MISR). We take the available data from the three products, and for instances where more than one measurement exists, we take the (unweighted) mean. Consequently this alleviates the fact that each product is not available for the entire study period. There is a significant increase in visibility and concurrent reduction in AOD at all rain rates and furthermore, there is a general trend showing that the magnitude of the change in visibility and AOD increases as the severity of the rainfall increases. Overall, this finding suggests that rainfall events tend to have a beneficial impact on the extreme aerosol concentrations found in Tehran during the winter.



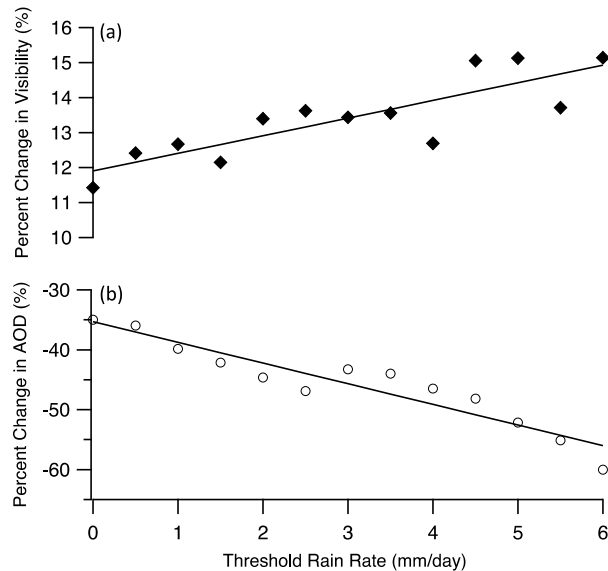


Figure 7: Change in (a) visibility and (b) satellite-derived AOD immediately before and after rain days. The plots show the composite average difference between the mean visibility/AOD during the two days after rain and the two days before rain. The composite is taken for rain events, which exceed the given threshold daily rainfall rate and is presented as a percentage with respect to the mean visibility/AOD before the rain.

### 3.3. Trajectory Analysis of Extremes

The spring season exhibits a significant increase in AOD, and it is of interest to investigate the mechanisms responsible for this. The effect of precipitation washout is certainly in favor of this trend since monthly-accumulated precipitation at Mehrabad decreases rapidly from April into May. Trajectory analysis shows that the prevailing upper air origins are the deserts to the west of Iran (Region A) during the winter and spring; however, there is a more preferential bias for Region A against Region B (Europe) during spring compared to winter. This result would indicate that there was the potential for increased long-range dust transport into Tehran and the surrounding areas during spring. The distribution of air mass origin during this season was further refined by considering a subset of trajectories corresponding to the extremes of the consolidated AOD data. The top and bottom 10% of observed daily AOD were analyzed to identify if there was a change in the distribution of upper air origins for “high” versus “low” AOD days (Fig. 8a). It is clear that there is a higher-than-average fraction of back-trajectories that originate in the dust-rich Region A during high AOD days compared with low AOD days.

A similar analysis is also performed for surface trajectories during the winter and is also shown in Fig. 8b. The main finding is that the “high” AOD days contain an abundance of stagnant trajectories (Region E) compared with low AOD days, which show a higher prevalence of trajectories from the west (Regions A and B). Whilst this result may appear to conflict with the postulation that regional dust transport from Region A at higher levels leads to an increase in AOD during spring and summer, the presence of westerly winds near the surface has the beneficial effect of ventilating the lower atmosphere, which is typically plagued by stagnation during the winter. Additionally, the advection of dust from Region A is dependent on surface emission within the source region, which is reduced during winter because of increased soil moisture. Finally, the scenario of low-level westerlies in the winter is typical during the passage of a mid-latitude system, which may promote precipitation and vertical mixing and hence act as an aerosol sink.

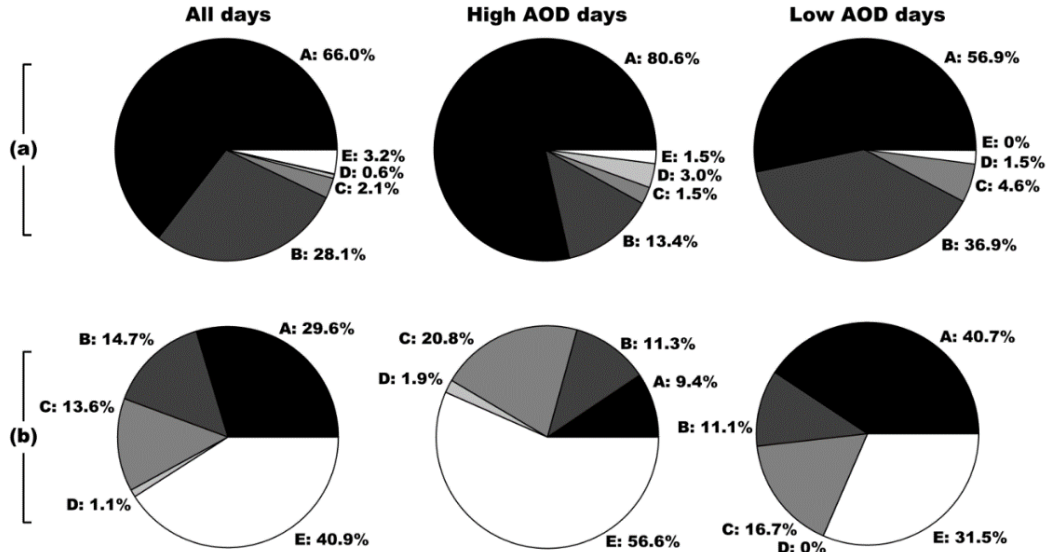


Figure 8: Air mass source origin for all days, high AOD days (>90th percentile) and low AOD days (<10th percentile) for (a) spring upper air trajectories (ending altitude of 3000 m AGL) and (b) winter low level (500 m AGL) trajectories. High and low AOD days were identified using the consolidated MODIS Deep Blue (Terra and Aqua) and MISR AOD data.

### 3.4. Weekly Cycle of Visibility

Another potentially important modulator of local aerosol concentrations is the weekly cycle of human activity, since anthropogenic emissions are expected to vary between workdays and weekends. It should be clarified that typically only Friday is the weekend in Iran; for some industries Thursday is also a reduced working day. Fig. 9 shows the average visibility anomaly at Mehrabad for each day of the week. The anomaly is calculated as the average deviation from the seasonal mean visibility for each of the four seasons, which allows an independent comparison of the weekly cycle to be made without incorporating the significant seasonal variability in visibility. In all seasons, Friday exhibits a strong increase in visibility, which is aligned with an expected reduction in anthropogenic emissions. In addition, the visibility on Thursday is also anomalously high which would be supported by reduced working hours. With minor exceptions, the other days show broadly consistent visibilities. Another notable feature in these data is that the increased visibility on Friday is stronger in winter and fall compared with spring and summer. If the weekly cycle were used as an indicator of the relative importance of local (anthropogenic) sources compared to regional and meteorologically driven sources (e.g., dust), then this result would support the conclusion that local sources are more important in winter and fall for modulating aerosol concentrations. Conversely, during the spring and summer, regional dust transport, local dust sources and possibly biomass burning overshadow local anthropogenic emissions, which are strongly mixed in the deep summer mixing layer and so the apparent importance of the weekly cycle is reduced. The weekly cycle was also analyzed for the satellite AOD data (not shown) and no significant pattern emerged. This further supports the argument that urban sources play a secondary role to regional transport and meteorology in modulating the column aerosol properties, even though they are an important local influence for conditions at the surface.

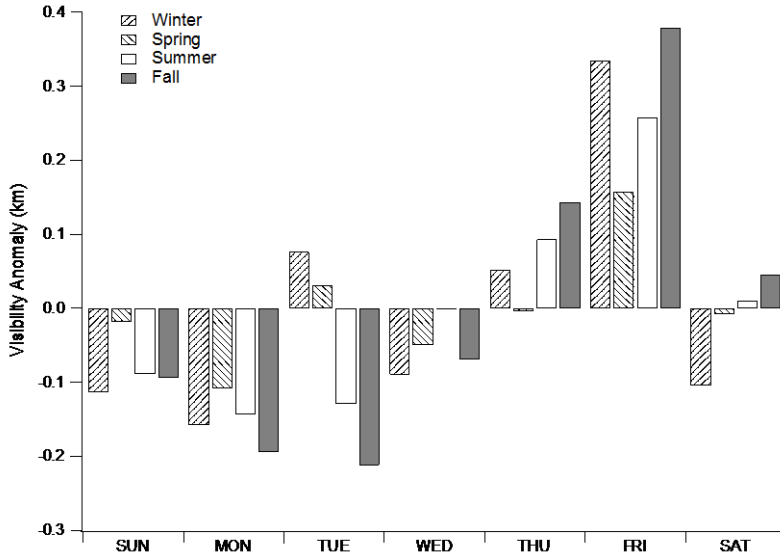


Figure 9: Average visibility anomaly in Tehran (Mehrabad) filtered by day-of-week for each season of the year. The visibility anomaly is calculated as the average deviation for each day-of-week from the climatological mean for each season. Note that the weekend in the study region is Friday, although some industries also observe Thursday as a reduced working day.

#### 4. IMPLICATIONS FOR CITY SUSTAINABILITY AND RESILIENCE

Efforts rooted in improving the sustainability of Tehran and other megacities should involve plans to reduce emissions of pollutants as this can improve public health and minimize significant financial losses due to stoppages in daily activities such as school and work on very polluted days (especially in wintertime). Aside from controlling surface emissions in the region, which would greatly help in winter time, another challenging issue is long-range transport of pollutants such as dust and biomass burning aerosol particles from upwind regions; while these pollutants may not necessarily impact the boundary layer and thus public health and welfare, they can impact the regional climate due to their effects at higher altitudes on solar radiation transmission, cloud formation, and precipitation. To better adapt to transported emissions and their impact on microclimate, process-level understanding and thus predictive capabilities need to improve.

#### ACKNOWLEDGMENT

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# Some Climate/Meteorological Aspects of Air Pollution and Its Mitigation in Tehran, Iran

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### **Abstract**

Urban areas accommodate most of the world population that is still increasing. Hence effects of climate factors on urban problems such as air pollution, heat island and urban hydrology become increasing important in mitigation and adaptation issues. The control of some air pollutants and heat island effect are still challenging problems. In the present paper we discuss some climate/meteorological factors affecting air pollution in Tehran, Iran.

Tehran is a unique megacity geographically, being non-coastal, mountainous and an ever expanding urban area; hence suffering from acute air pollution and heat waves episodes. For about the last half a century the mean annual temperature in Tehran has increased by about four to five times of the background climate temperature trend. Recent records of air pollutants also show increased trends with some low frequency variability. Apart from the increase in pollutant emissions as a result of the city expansion, the wind speed has also decreased as a result of the aerodynamic surface roughness increase and probably the decrease in the passage of cyclones over the area. The northern mountain also plays an important role in local air circulation and air pollution distributions. Mixed layer height over the city, due to higher surface heat fluxes, is expected to have increased. That is favorable for some air pollutants reduction such as CO, but not so for ozone or particle matters. Finally, an integrated framework for actions regarding impacts, developments, emissions, urban climate change and monitoring including adaptation and mitigation towards climate change resilient city is proposed.

**Keywords:** *Climate Records, Air Pollution, Resilient City, Tehran*

## **1. INTRODUCTION**

Chemical imbalance of the atmosphere, produced by anthropogenic activities, has had a wide range of effects on climate and air quality at small to large scales [1]. Urban environments as evermore expanding areas with much of economical and industrial activities nowadays are suffering from air pollution problems as well as being large emitters of greenhouse gases, especially CO<sub>2</sub> [2]. Hence, sustainability and resiliency to weather and climate changes of urban areas leading to poor air quality, urban heat island and hydrological problems, are becoming governance challenges for cities [3]. In order for cities to develop effective and resource-efficient integrated

strategies for climate change adaptation and disaster risk reduction, the two efforts need to be connected wherever possible with ongoing policies and actions that link the two from both directions. Disaster risk reduction strategies and/or adaptation strategies can contribute to reduction of poverty levels and vulnerability, and promote economic development and resilience in an era of increasing climate change [4].

Increasing built up areas, anthropogenic heat and air pollutant emissions and change of surface albedo in urban environments modify the weather and climate over these regions [e.g. 5, 6 and 7]. Emerging climate change risks identified globally create new vulnerabilities for cities [3]. Global climate change has modified the wind and temperature fields of the atmosphere especially in the mid-latitudes, shifting the storm tracks further northwards, leading to decreasing frequency of mid-latitude cyclones, hence, less ventilation of the cities in these latitudes. For example, in North America, Leibensperger et al. [8] have shown that the effect of such climate change can cancel partially the benefit of emission reduction of air pollutants such as ozone. Christensen et al. [9]), for an ensemble of about 20 GCM (General circulation model) predictions for 21st century of world climate, have shown a temperature rise and reduction of precipitation for most of the mid-latitudes as well as the Middle East. Jacob and Winner [10] have reviewed some recent works on the effect of climate change on air quality using GCM results. They show that as a result of weakening global circulations and decreasing number of cyclones in mid-latitudes due to climate warm up, ozone and to some extent PM10 will increase especially in more polluted urban areas in mid-latitudes regions. Spatial data that link greenhouse gas emissions with urban form and city growth would be useful for efficient planning. This information will strengthen locally relevant policy decisions and build support by the public [11].

Tehran, a fast growing city (grown since 1950, especially with a faster rate since 1970s), has a unique setting, being a non-costal capital city of about 570 km<sup>2</sup> and at the shadow of the Alborz Mountain range in the north and east and adjacent to the arid region known as Kavir. These two features create local winds known as mountain and country breezes which only circulate the urban air within this rather poor ventilated city. Hence more acute air pollution episodes and hot summers are a serious problem to the habitants. Tehran has many orbital towns and some of them have also grown since the 1980s. In a short period the economic base of the city has changed from agricultural to an industrial-commercial one. The population of the city is more than 10 million; total number of vehicles was about 1.5 million [12] and now being about twice that. Direction of the streets in the city is mainly west-east, parallel to the Alborz Range, with some of them in north to south direction along the slope of the mountains. Central and southern parts of the city have short buildings with older structure compared to buildings in northern part. Built up areas are not uniform with some parts, especially the northern area, being covered by more recent and taller buildings. The average height of the buildings is usually less than that of the other large cities of the world (often 4-5 story buildings). The sky view factor [13] for the built up areas of the city on average is about 0.5, corresponding to a height/width ratio of about one.

During the year for about 300 days, the city is under dominant ridge condition, a synoptic calm condition. In wintertime often an extension of Siberian cold high (and to some extent middle latitude westerlies) dominates, and in summer time south easterlies related to Asian monsoon affect the weather (e.g. [14]). Sadatabadi and Bidokhti [15] have shown that the temperature of the city (Mehrabad) with respect of that of Varamin, a small city southeast of Tehran, has increased dramatically as a result of urban warming.

Such setting, climate condition and growth rate make the city prone to climate adverse effect regarding air pollution and heat waves. In this paper we present some long-term records of climate and meteorological parameters and some recent records of air pollutant trends. We speculate on the causes of the observed trends and try to indicate the way we can counteract the adverse effects in terms of sustainability and resiliency in such environment.



precipitation, but under calm conditions it produces thermally induced winds known as katabatic and anabatic winds, namely northerly at night and southerly during the daytime (Fig. 2), with daytime winds being much higher due to a stability effect of atmospheric surface layer at night. Kavir affects Tehran climate as a source of heat and dust haze. More details of these effects can be found in [15].

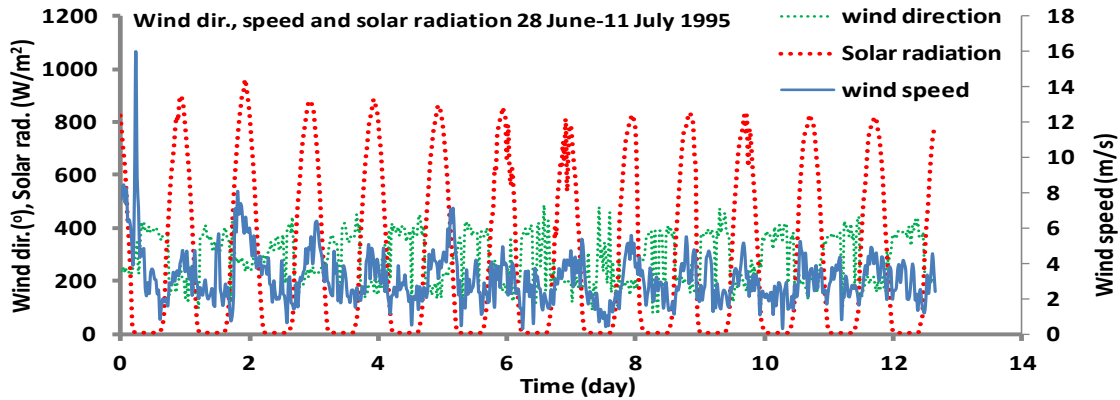


Figure 2: Typical wind direction, solar radiation and wind speed at the geophysics station for calm condition, at 2m above ground. Notice the regular flipping of wind direction from northerly (katabatic, nighttime) to southerly (ababatic, daytime). Day time wind speed is also higher than those at nights.

### 3. RESULTS AND DISCUSSION

#### 3.1. Short Long-term Climate Trends

First, we present some long-term trends of temperature and wind for the last 50 years to show signs of climate change in Tehran area. Fig. 3 shows trends of annual mean summer temperature for periods of 1950-2013 for Mehrabad and the mean maximum summer temperature for the last ten years (2003-2013) for Geophysics stations. The mean summer temperature has increased at a rate of 0.04 °C/year, while the summer mean maximum temperature has a steeper rise of 0.0832 °C/year for the recent years. The annual mean temperature has a typical rate of increase of about  $0.0654 \pm 0.018$  °C/year (graph not shown). As much as about 0.01°C/year can be due to regional warming in this area [16]. Hence urban warming in Tehran appears to be imminent that should be of concern and appropriate steps should be taken to curb such trends. These records are from two off center stations in the city, so the central parts are bound to have steeper warming. As the city buildup areas are rather patchy, especially in the northern areas, there might be a few heat island centers needing to be explored. More details of seasonal and daily variations have been reported by Sadatabadi and Bidokhti [15] who also showed the correlation of such temperature (the annual minima) increase in comparison with that of Varamin (as a rather non-urban site) as a function of population of Tehran, as is shown in Fig. 4. They fitted a relation as

$$\Delta T = 3.185 \log(\text{pop}) - 16.86 \quad (1)$$

where  $\Delta T$  is the temperature difference between Tehran and Varamin. They called this a climatic kind of heat island intensity (although different from actual recorded relation for urban heat island, UHI) which is rather similar to that of North American cities UHI-population relationship [17].



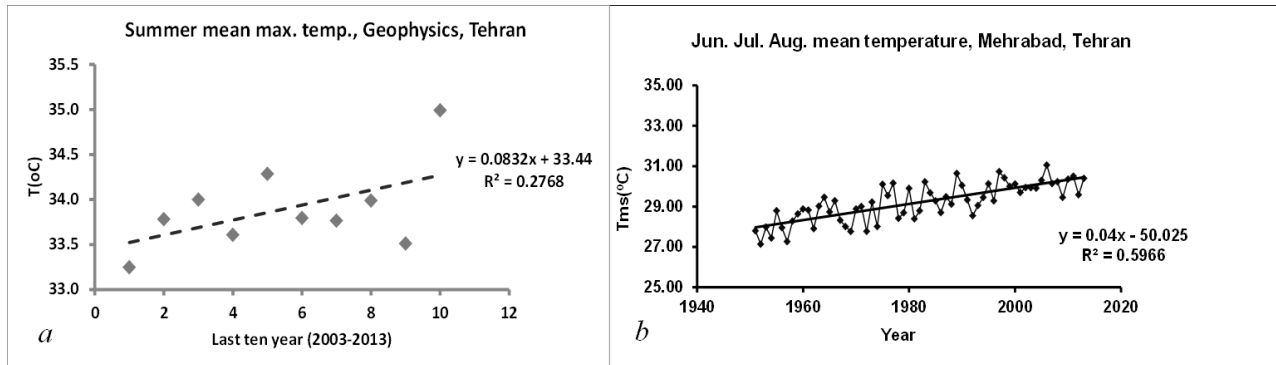


Figure 3: Mean summer maximum temperature for Geophysics station (a), and annual mean summer temperature for Mehrabad station, Tehran (b).

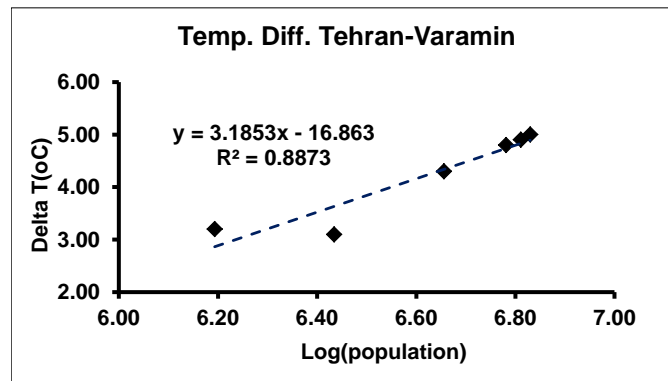


Figure 4: The annual mean temperature difference of Tehran (Mehrabad) and Veramin, against the population of Tehran for 1950-2000, for the years data are available [15].

The wind records also show changes indicating a slowing down of wind over the city, especially its northerly component (katabatic wind) as shown in Fig. 5. The mean annual winter wind speed has not only decreased but it is smaller than that of the annual mean, as the spring time wind speed is usually larger. Such slow winds in this populated area cannot ventilate this area efficiently, leading to strong adverse effect on air pollution. This factor can lead to strong episodic air pollution periods, especially when the mid latitude jet stream is far from this area [18] in cold seasons. It should be mentioned that the upper air (above atmospheric boundary layer) winds, known as synoptic winds are still the main driving force of the near surface air, responsible for sweeping polluted air from this urban areas.

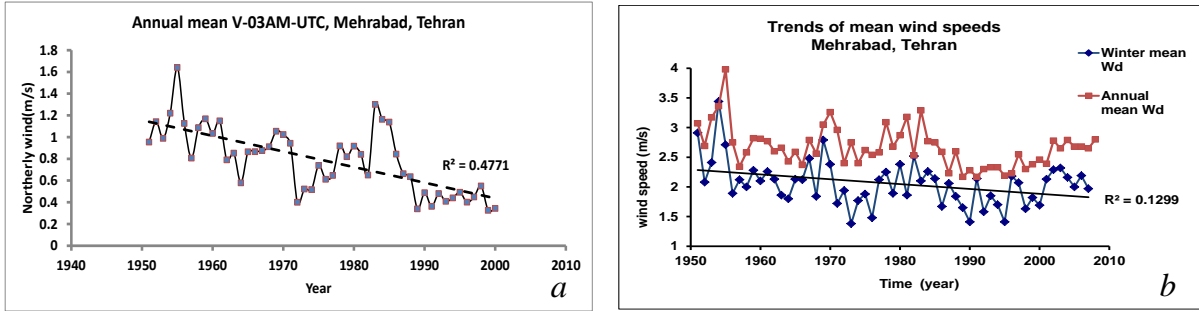


Figure 5: Long term records of early morning northerly component of annual mean wind speed (a), and mean annual wind speed (b).

Fig. 6 shows the long-term trend of the number of winter low pressure centers, usually associated with frontal systems that can sweep the near surface air passing over Tehran, indicating a slight reduction of these systems over the area during the last sixty years. Hence part of the near surface wind reduction can be due to this factor as Leibensperger et al. [8] have also shown that atmospheric global circulation has weakened leading to a decreasing frequency of mid-latitude cyclones. Soltanzadeh et al. [19] have also shown by numerical study that urban heat island can induce circulation over cities such as Tehran that can interact with mountain led circulation, enhancing the daytime anabatic wind and weakening nighttime katabatic winds as Fig. 5 shows.

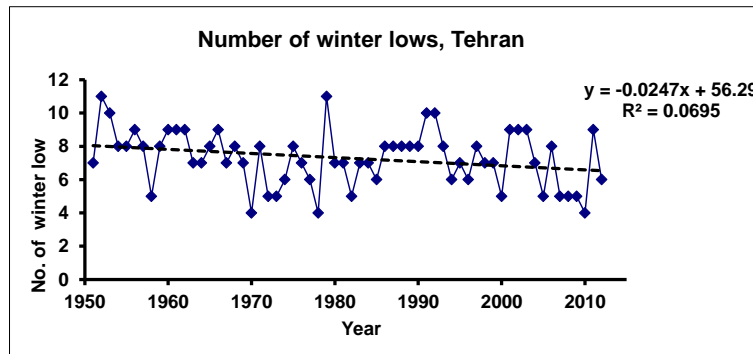


Figure 6: Number of winter lows passing over Tehran from 1950 through 2010.

Surface roughness length ( $z_0$ ) increase, as a result of building taller structures, has also occurred in this period. This can also be partially responsible for the observed slowing down wind trends. The surface wind stress  $\tau_0$  is given by

$$\tau_0 = \rho C_d U_{10}^2 \quad (2)$$

where  $\rho$  is the air density,  $U_{10}$  is the wind speed at 10 m above ground and  $C_d$  is the drag coefficient and is given by (using logarithmic law for surface layer wind profile near ground,  $U(z)/u_* = (1/k)\ln(z/z_0)$  for nearly neutral condition)

$$C_d = k / (\ln(z_r / z_0)) \quad (3)$$

where  $k$  is the von Karman constant (about 0.4) and  $z_r=10$  m and  $z_0$  is surface roughness that is about  $0.1h$ , where  $h$  is about the mean height of the buildings in the area. Hence as  $h$  increases  $C_d$  is expected to increase and moving air over this area would lose more momentum, leading to further near surface stagnations. The city planners for Tehran hence should consider arranging buildup

areas so that the newly built structures have appropriate spacing and orientations for dominant winds (often westerly) to ventilate the area more efficiently.

### 3.2. Some Air Pollution Trends

Air pollution data only exist for the last 10 to 15 years for Tehran. Before we show such records, some long records of visibility, which are usually measured at synoptic station, as other meteorological parameters, are presented. Fig. 7a shows annual mean daytime visibility trends for Mehrabad. Deterioration of visibility is an unfavorable consequence of urbanization of this area, which is related to particulate matter in the atmosphere. In fact urban (and occasional dust) aerosols as haze in Tehran area is related to visibility (Fig. 7b) and such aerosol loading is responsible for the poor visibility. The variations of visibility in Tehran are related to the meteorological parameters that have been studied by Sabetghadam et al. [20]. They showed that winter visibility has deteriorated worst and that relative humidity can worsen visibility due to growth of fine urban aerosols known as swelling by water vapor absorption.

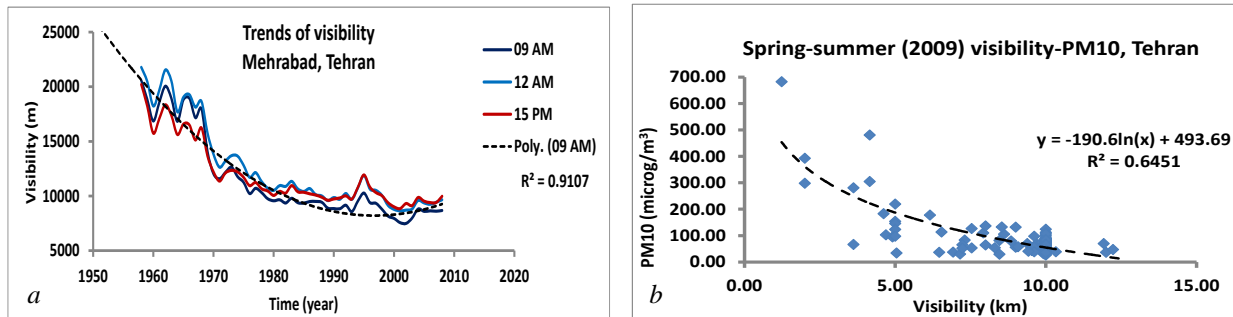


Figure 7: Visibility trends for three daytime's hours (local time) at Mehrabad for the last 50 years (a), spring-summer time visibility versus PM10 in Tehran (b). Note that the large PM10 concentrations are associated with dust events, being more frequent in recent years.

It is clear that the atmospheric aerosols concentration in Tehran has increased leading to poor visibility. The origin of the urban aerosols is often due to automobile emissions which enhance the nitrate and sulfate gases that can form fine secondary urban aerosols. Occasional fugitive dust from the Middle Eastern dry areas, especially Iraq and Saudi Arabia, in recent years has led to occasional dust events over the western parts of Iran, from which some also reach Tehran. One of the dust events that reached Tehran created very poor visibility and its PM10 was about 700 microg/m<sup>3</sup> (Fig. 7b, leftmost point in the figure). Such events have led to temporary closures of the main institutions and organizations in recent years.

Typical records of air pollutants for Tehran using some of the existing data are now presented. Fig. 8a shows a decreasing trend of mean November CO concentration for a station northeast of Tehran, indicating an improvement of its emission in recent years as the quality of cars has improved and also the highway networks over the city have expanded. It may also be partly due to increased use of liquefied natural gas (LNG) as fuel for vehicles and domestic needs. Similar trends for gaseous primary pollutants at other air monitoring stations are also observed. However the trends for PM10 and ozone (O<sub>3</sub>), as secondary pollutants, are on the rise (see below). Similar trends have been reported by Jacob and Winner [10] for some of the cities in the U.S. Tropospheric ozone is also on the rise for cities in Iran [21] as seen in Fig. 8b. The origin of this increase appears to be mainly due to industrial activities as well as urbanization, although part of it is transported from upwind sources as well as from the stratosphere.

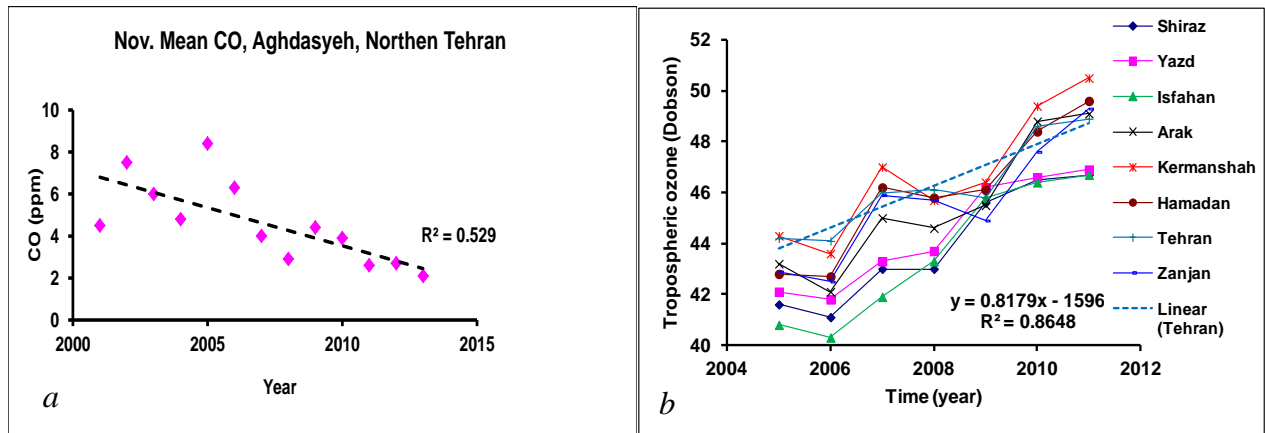


Figure 8: A record of mean November CO concentration for a station in the north of Tehran (a), and records of tropospheric ozone in some cities of Iran, including Tehran (b).

In Fig. 9, daily variations of CO (a) and O<sub>3</sub> (b) in Tehran for 2001 and 2011 indicate that a reduction of CO, a primary pollutant, but an increase in O<sub>3</sub> occurred during this decade in rather warm periods of the year. Larger day-to-day variation of CO has also occurred in cold months indicating the role of cold front passage and residence of subsequent high pressure weather systems, while variation of ozone is more pronounced in spring and summer as its concentration is also much higher at those times of year.

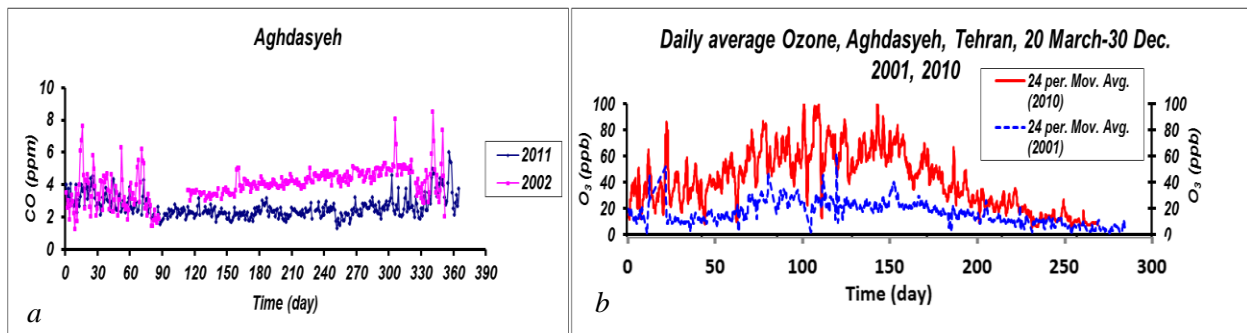


Figure 9: Variations of CO (a), and O<sub>3</sub> (b) for 2001 and 2011.

Typical trends for PM<sub>10</sub> (November average) and O<sub>3</sub> (summer average) for the Aghdasieh station, northeast of Tehran, are shown in Fig. 10a and 10b, respectively. Annual variability is rather large but the trends are on the rise. November mean values of PM<sub>10</sub> also have strong annual variability due to the more frequent dust events in the area in recent years. November data were chosen as this month, or December, due to more predominant stagnant weather conditions and stronger near surface inversions (Fig. 11), have higher air pollution episodes.

Ozone is also on the rise that can be due to more emission of precursor gases as VOCs (volatile organic compounds) and particularly warmer urban area [10]. Water vapor can destroy ozone; hence lower humidity may also contribute to this increase. Stronger urban heat island effect as shown in Fig.3a may be responsible for ozone increase in summer. Warming of the area can enhance the growth of atmospheric mixed layer which could reduce the concentration of primary pollutants such as CO (Fig.8) as they disperse in larger volume of air over the city, especially in summer.

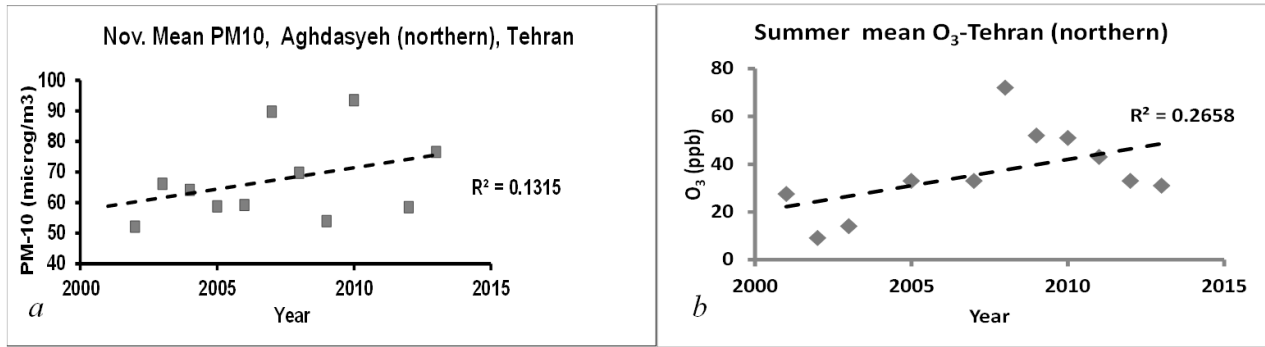


Figure 10: Trends of November average PM10 (a) and summer average ozone (b) for Aghdasyeh, Tehran.

As the sources of air pollutants are near the surface, near surface stability (temperature inversion, or temperature difference between 20m and 10m or 2m above ground here) and hence wind can be important for air pollution concentrations. Fig. 11 for example shows near surface wind at 10m and number of days with inversion for 2001-2010; showing again more days with inversion and lower winds.

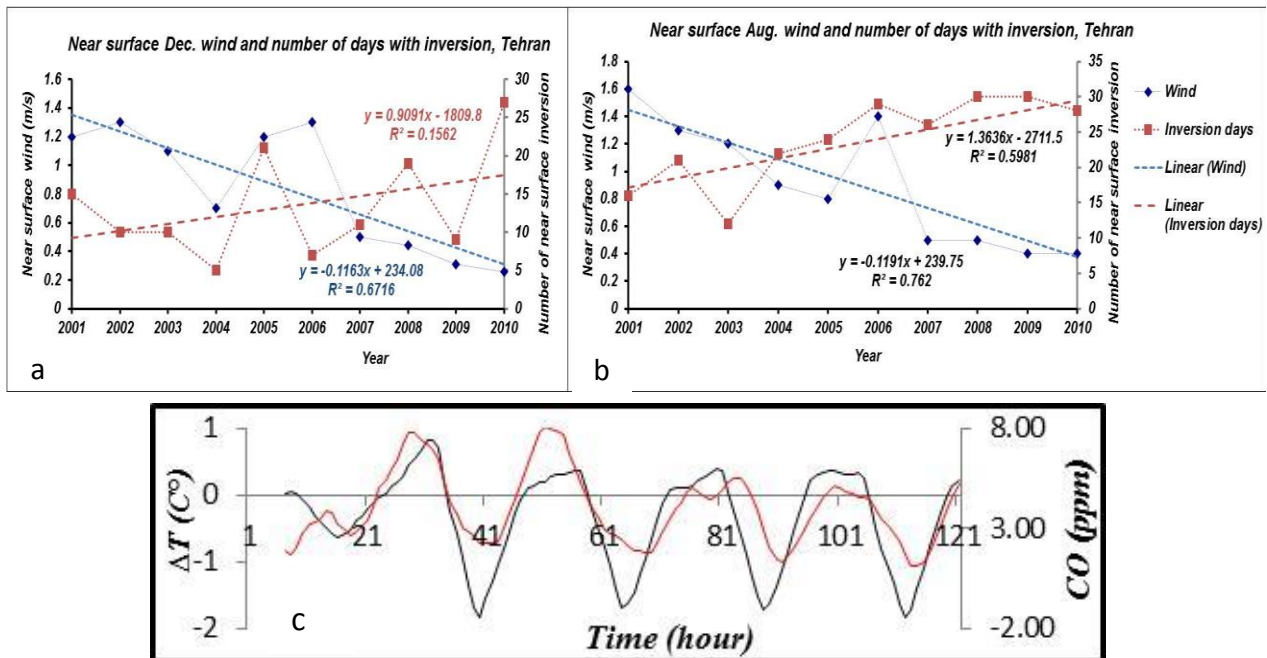


Figure 11: Near-surface average wind speed and number of days with temperature inversion for Dec. (a), and Aug. (b) for the period 2001-2010, for a station east of Tehran (Resalat Tower); typical variations of near surface temperature differences between 20 m and 10 m and CO (c), positive  $\Delta T$  corresponds to stability and vice versa.

Daily variations of air pollutants for the Aghdasyeh station (northeastern part of Tehran, not shown) indicate that the overall average CO concentration is higher in December than in July, while NO<sub>2</sub> and SO<sub>2</sub> are larger in July and ozone, a secondary pollutant, is much higher in summer, as expected since the temperature is much higher. For primary pollutant CO, the increases in morning and again later in the afternoon are due to traffic peak hours, while the mid-day reduction is mainly due to the increase of mixed layer height due to thermal convective processes over the city especially in summer months. This has also been shown by Bidokhti and Banihashem [22] using a

model based on turbulence kinetic energy for variations of the urban mixed layer growth.  $\text{NO}_2$  and  $\text{SO}_2$  have more complicated behaviors as their sources are tied up to the formation of ozone and local circulation over the city respectively.  $\text{PM}_{2.5}$ , which is being measured in recent years, has a similar behavior as CO daily variation.

Occasional periods of high air pollution have occurred, particularly in recent years. Such episodes have led to the closure of major activity in the city and to public health problems. Fig. 12 shows a typical record of P index (number observations with concentration 1.5 times greater than the mean seasonal value from three monitoring stations to the total number of observations) for winter period of 2007-2008. In Jan. 2008 we had such a city activity closure; this can be regarded as an extreme event of air pollution that requires evaluations of risks and vulnerabilities. Action planning (at the local scale over a short time period) of coordinated intensive actions for a limited area over a short period should be taken in such an acute air pollution episode.

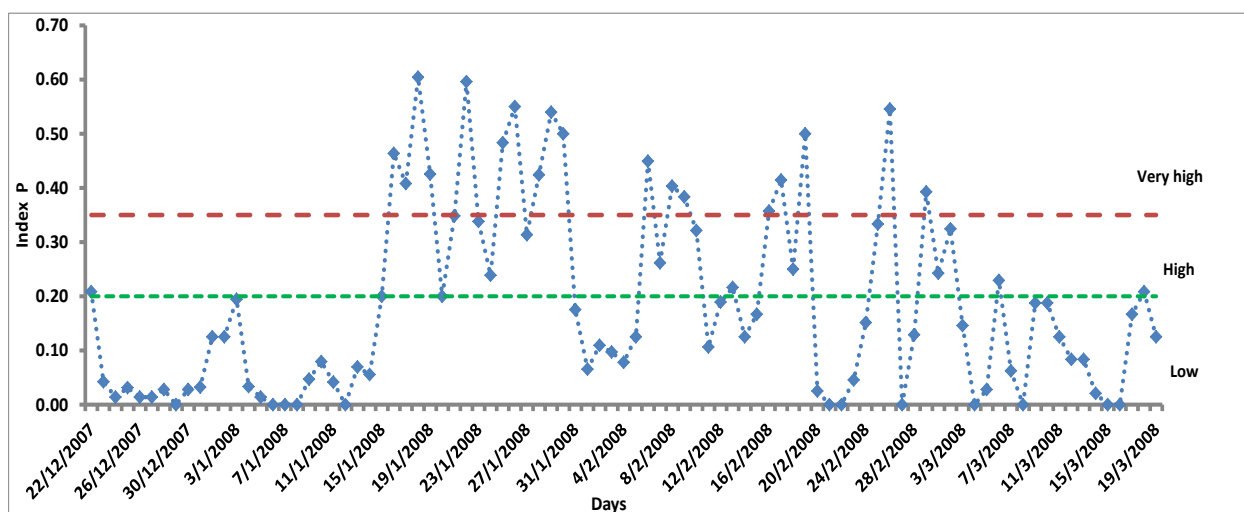


Figure 12: An example of air pollution record in winter 2007-2008 for Tehran. Broken lines show levels of low, high and very high air pollution (this is based on CO, other gaseous primary pollutants such as  $\text{NO}_x$  also show the same behavior).

Unfortunately such conditions have increased in recent years, making the city more vulnerable to air pollution episodes. The behaviors of long term climate trends (as shown in Fig. 11) are likely to cause them. We are trying to find weather indices that could be used in prediction of onset of such periods. These indices can include characteristics of large-scale atmospheric circulation over this region, for example geopotential height anomalies related to large-scale atmospheric flows and pressure patterns that determine vertical motions (high pressures are related to providing calm conditions with more frequent inversions). We have found that there can be some relation between such large-scale indices and air pollution in Tehran, especially for the stations farther away from mountains in the north. The near mountain air pollution station data show that the northern parts of Tehran are much more affected by the local circulations due to mountain rather than upper air weather conditions. The correlations between air pollutant concentrations for the stations near mountains (as Aghdasyeh and Ponak in the north of Tehran) and those further away from mountains (as Ray and Bazar) in the south are good but those between south stations and north stations are poor as shown in Fig. 13.

It is clear that the processes (sources, local circulations, large scale circulations, chemical) affecting the northern or southern stations may act similarly in air pollution variations, however differently for those locations near the mountain and those away from it, requiring more investigation.

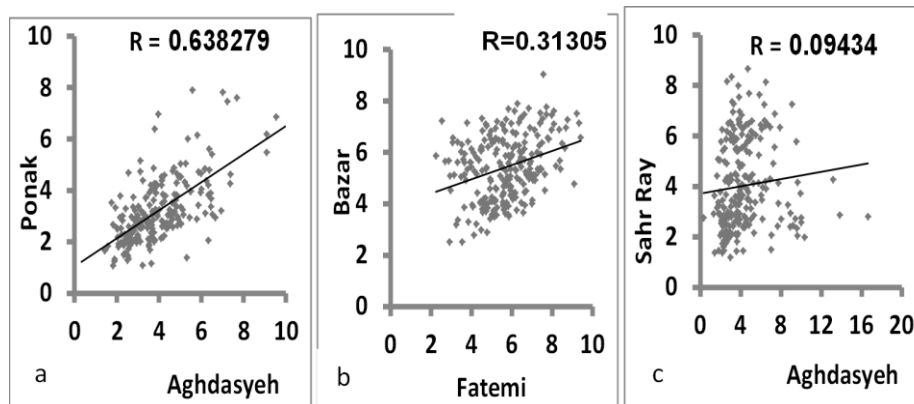


Figure 13: The correlations between CO concentrations of a: Ponak and Aghdasyeh (north, near mountain), b: Bazar and Fatemi (further south, away from mountain) and c: Ahdasyeh and Shahr Ray (One north and other south respectively). Data available is for daily winter values of CO for years 2002-2007.

#### 4. DISCUSSION

Based on this and other studies of temperature rise, climate change in urban areas is particularly marked especially for higher latitudes and altitudes that would lead to stronger heating, hence deteriorating the heat island effect for city as Tehran and also less snow (more related to global climate) which is a major source of water over this mountainous area, leading to water supply problem. In order to combat such thermal effects in this city, building materials should have larger albedo (whiter), having less heat storage capacity, as well as having more green areas in between, reduction of the emission of greenhouse gases especially CO<sub>2</sub> due to fossil fuel burning to combat more warming.

Regarding pollutants especially ozone and aerosols, more trees and green spaces are required which in turn can also be effective in reducing heat. In order to reduce emissions, better non-polluting transports, creation of more walkable areas in order to encourage less use of cars and taxing for car user (polluters pay more), more efficient use of energy for systems that use fossil fuels or even use of renewables especially solar energy should be considered. Reductions of pollutant emissions from cars, especially VOCs that lead to ozone production in warm season (summer smog) also depend on quality of cars that should all be equipped with catalytic converters (used for CO and VOC filtering from car emissions). Such devices are not often used in cars in Tehran and the use of them should be mandatory. Hotter temperatures could cause more emission of VOCs from asphalt surfaces as well as even parked cars. It should be mentioned that ceiled car parks in the city are rather scarce and should be expanded in order to reduce such emissions. Use of higher quality brake pads in cars is also important for reducing PM10 emissions, especially of more harmful ones.

Knowledge of climate change impacts should be transferred to inhabitants as well as decision makers to create stronger infrastructures, policies and human resource response capabilities in order to have a climate resilient city. Less resilient cities (called hot cities) on the other hand would be less flexible, having deteriorating air, water and soil pollution problems as well as being less prepared to combat climate change causes (mitigation) and effects (adaptation). As the time scale of climate change is long, no policy of “wait and see” should be considered and actions should be taken now. All such actions (strategic planning at the city-wide scale over a long time period with multispectral coordination of sectorial planning, sectorial investment plan, financial resources, and institutional frameworks) can be integrated into a comprehensive plan to work for a resilient city. Fig. 14 shows an example with some of the components for an integrated framework leading to city resiliency (a quasi-steady state condition) in terms of urban climate and air quality factors that



have been discussed in this paper. In a clockwise direction in this diagram, emissions lead to changes in atmospheric pollutant concentrations as well as greenhouse (GH) gases that change the energy balance of urban climate and increase certain pollutants that impact both humans and natural and anthropogenic systems. These affect natural resources and human health and life that in turn affect all aspects of human developments.

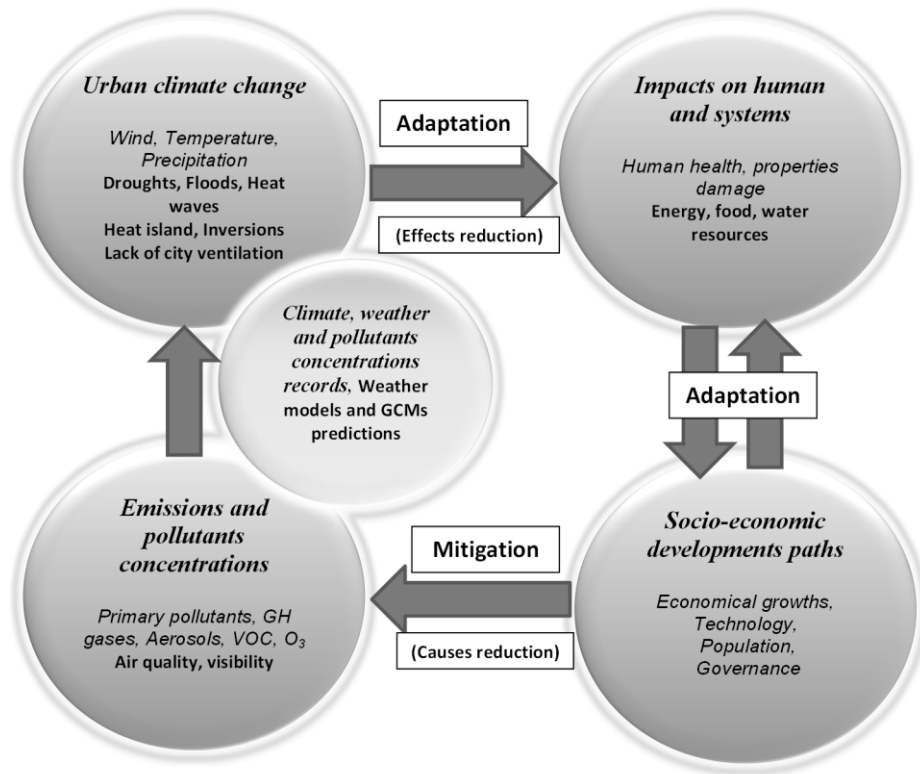


Figure 14: An integrated framework for urban climate change, impacts and developments through adaptation and mitigation that can lead to steady state conditions or resiliency of urban environments. Monitoring climate and pollutant changes are done using data records and numerical model predictions (shown in gray circle) for various scenarios (Partly adapted from Houghton [23]).

Adaptations (effects reduction as opposed to cause reduction by mitigation) between the impacts and developments can go both ways. As for example, urbanization can lead to deforestation and loss of resources. Urban climate and pollutant concentrations are monitored by atmospheric data records, as presented in this study.

## 5. CONCLUSION AND OUTLOOK

Here we have presented some climate, weather, and air quality records for Tehran. Clearly the records show that temperature related to urban heat island in such a growing city is on the rise. Climate change as greenhouse warming could have aggravated the warm up condition for Tehran. The warming trends have led to an increase of near surface ozone concentration, a potential hazard to public health and properties. Winds have also been slowing down due to weakening large-scale atmospheric circulation as well as the increase of surface roughness over this urban area. Built up areas as well as the locations of some industrial sites (often upstream of the prevailing winds) appear to have often been expanded irrespective of weather and climate conditions, hence ventilation of the city is becoming an ever increasing problem. Emissions of gas pollutants as well



as particulate matter seem to have increased PM10 concentrations and resulted in poorer visibility over the city. Fugitive dust has also become frequent due to the transport of dust from long distance sources. Such events could increase particulate matter in the atmosphere by a substantial amount and have led to the closure of city activities at an increasing rate that could be due to long-term trend of climate change and emissions, affecting air quality conditions. Episodes of acute air pollution periods have also increased, leading to the more frequent hampering of the city activities.

It was also shown that occasional stagnation periods have led to the increase of air pollutants to alarming levels, leading to closure of major institutions in Tehran that has become more frequent in recent years. It is also interesting that the air pollution concentrations appear to be more correlated between either the northern (near mountain) or southern stations (further away from it) of the city and not between those of the north and those of the south, indicating that the northern mountain has a strong influence on the air pollution distributions over the city. As the city is not in a horizontally homogenous terrain, spatial variations in distributions of pollutant concentrations are also marked (recent unpublished results) indicating that mitigation concerning control of emissions should not be holistic.

The climate, meteorological and air pollution records demonstrate the challenges that this city could face. Part of air pollution regulation is by emission control; however such control can be modulated by weather and climate factors, as have been shown in this paper. Tehran is the commercial and industrial hub of Iran, requiring more effective coordination among different departments, and government levels to become adaptive as well as having resiliency in the face of natural hazards such as those associated with climate change with adverse effects on air quality, heat waves and drought. Although it is a non-coastal city, other natural hazards such as earthquakes are also a major threat, as a disaster risk reduction management has been setup in recent years for such hazards. Some mitigation and adaptation methods can be as follows:

- Control of emissions (presently done by traffic restrictions, activities closure, under the supervisions of DOE and AQCC);
- Using less emitting cars (presently done by car emission checks: part of JIKA project instructions (2004) and AQCC); using cleaner fuels, possibly using hybrid cars;
- Faster expansion of metro subway;
- Creations of greener areas (“green fingers”), water bodies (as in District 22 of Tehran);
- Using brighter construction materials to more reflect daytime heating;
- Use of more ceiled car parks as well as better quality asphalts for surfaces to reduce VOCs emission;
- More nocturnal cooling by less emission of greenhouse gas such as CO<sub>2</sub>;
- Planning according to dominant winds;
- Creating more public awareness on AP and HI hazards.

At present we are planning to do some numerical simulations regarding various scenarios of urban modifications on wind and temperature fields over this expanding urban area.

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## U.S.-Iran Symposium on Resilient Cities

June 16-18, 2014

Irvine, California



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# Global Earthquake Model for Forecasting Seismic Risk in Urban Regions

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### ***Abstract***

The Global Earthquake Model project, organized by the GEM foundation (<http://www.globalquakemodel.org/>), seeks to build a heightened public understanding and awareness of seismic risk, leading to increased earthquake resilience worldwide. This is accomplished by a GEM community that: - shares data, models, and knowledge through an OpenQuake platform used for risk calculations - applies GEM tools and software to inform decision-making for risk mitigation and management - expands the science and understanding of earthquakes.

A critical component of GEM is the prediction of ground shaking intensity using predictive models known as ground-motion prediction equations (GMPEs). GMPEs relate ground-motion intensity measures to variables describing earthquake source, path, and site effects. We select from many available GMPEs those models recommended for use in seismic hazard assessments in the Global Earthquake Model. We present a GMPE selection procedure that evaluates multi-dimensional ground motion trends (e.g., with respect to magnitude, distance and structural period), examines functional forms, and evaluates published quantitative tests of GMPE performance against independent data. Our recommendations include: four models, based principally on simulations, for stable continental regions (SCRs); three empirical models for interface and in-slab subduction zone (SZ) events; and three empirical models for active shallow crustal regions (ACRs). To approximately incorporate epistemic uncertainties, the selection process accounts for alternate representations of key GMPE attributes, such as the rate of distance attenuation, which are defensible from available data. Recommended models for each domain will change over time as additional GMPEs are developed.

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# Effect of Geotechnical Works on Sustainable and Resilient Cities

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### **Abstract**

The geotechnical works in the cities have great impact on life and prosperity of the people, thus greatly affecting the sustainability and resiliency of the cities. The excavation for utilities, including gas, electricity, telephone lines, fiber optic lines, sanitary and storm sewers, are usually done in separate trenches, and hinder people and traffic and are vulnerable to heavy rains, snow falls and freezing temperatures. Sustainable and resilient cities should have proper planning for unique utility tunnels with redundancy. The excavation for underground metro tunnels, freeways, new intersections and interchanges and street widening have tremendous impact on comfort and prosperity of the people, and new insights and methods should be implemented to improve the situation for sustainable and resilient cities. The excavations for high rise buildings sometimes are up to 40 meter deep and 100 m by 100 m wide. Traditional excavation methods of soil nailing and anchoring etc. are used to save land adjacent to neighbors and city streets and cause discomfort to the cities. Innovative methods should be applied for sustainable and resilient cities. In this paper examples of traditional and improved methods are presented and guide lines are offered so that the geotechnical works have positive outcome for sustainable and resilient cities.

**Keywords:** *Resilient and Sustainable Cities, Geotechnical Works, Utilities, Infrastructure, Excavation*

## **1. INTRODUCTION**

The future urbanization of the world will be unprecedented; by 2050 three-quarters of the world's 9 billion population will live in the urban environment. The definitions of resilient and sustainable cities are presented by many authors. The definition presented by "Resilient Sustainable Cities, a Future" [1] is quoted here: "*resilience* concerns the capacity of an urban system – including its natural, built, social and economic elements – to manage change, learn from difficult situations and be in a position to rebound after experiencing significant stress or shock, while *sustainability* questions whether or not certain aspects of our daily activities, and systems within which they operate, can be continued indefinitely into the future, again from a social, economic and environmental perspective." For infrastructures, including geotechnical works in the cities, three horizons are presented by Newton [2] as shown in Fig. 1. Detailed explanation is given in Table 1, presented by Newton [3].

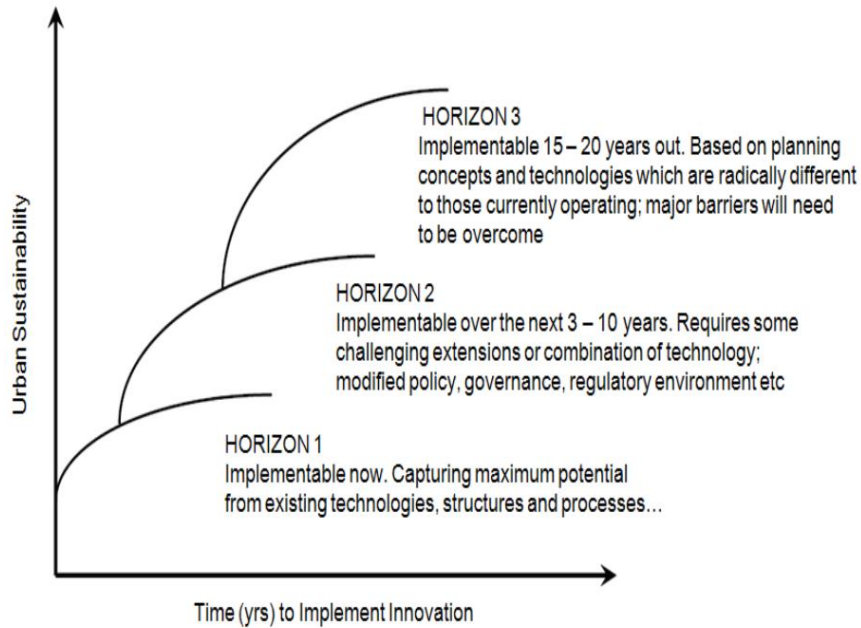


Figure 1: Three horizons of urban development [2].

TABLE 1: THREE HORIZONS OF URBAN INNOVATION.

**3 HORIZONS OF URBAN INNOVATION** (Source: Newton, 2010)

Urban Environmental Domain	H1	H2	H3
<b>Energy</b>	Energy efficiencies in housing and industry; dwelling energy rating; appliance rating etc	Distributed renewable energy and low emission energy generation systems; methane bridge (substitution of gas for coal)	Renewables-based solar-hydrogen economy
<b>Water</b>	Water-smart appliances; domestic rainwater tanks; desalination	Sewer mining; water sensitive urban design	Integrated urban water systems (recycled stormwater, wastewater)
<b>Waste</b>	Product stewardship; waste separation and recycling; domestic composting	Extensive cradle to cradle manufacturing based around single enterprises (e.g. motor vehicles, computers, building products etc.)	Eco-industrial clusters based on utilisation of multiple waste streams

TABLE 1: THREE HORIZONS OF URBAN INNOVATION (CONTINUED).

3 HORIZONS OF URBAN INNOVATION (cont'd)			
Urban Environmental Domain	H1	H2	H3
Transport & Communications	Road pricing; high speed rail; telepresence via broadband internet communications	Hybrid / electric vehicles; telecommuting, teleshopping, telebanking etc.	Integrated transport and landuse; intelligent transport systems; green transport
Buildings	Check-box system for green building design; tall buildings	Real-time life cycle sustainability performance assessment during design; building information models; hybrid buildings	Ultra-smart building and linked infrastructures; green building materials with embedded intelligence
Urban Development	Smart Greenfield development	Brownfield development	Comprehensive Greyfield regeneration

It is clear from above that Geotechnical works have great impact on life and prosperity of the people in the city, thus greatly affecting the sustainability and resiliency of the cities. In this paper the excavation for utilities, excavation for transportation development and excavation for high rise buildings are presented and innovative methods are discussed.

## 2. EXCAVATION FOR UTILITIES

The excavation for utilities including gas, electricity, telephone lines, fiber optic lines, sanitary and storm sewers in most cities are carried out after the asphalt pavement is built and they are usually done in separate trenches. Fig. 2 shows an example of such utility construction being carried out in one of the Shiraz Boulevards at the same time on two sides of the boulevard.



Figure 2: Utility construction on two sides of a Shiraz Boulevards at the same time.

The separate trenching hinders people and traffic and is vulnerable to heavy rains, snow falls and freezing temperatures. It is estimated that up to 7 kilometers of trench are carried out in these



streets per kilometer of street length. Thus the enormous carbon imprint and inconvenience for people are evident. Sustainable and resilient cities should have proper planning for unique utility tunnels with redundancy. An example of proper utility construction is shown in Fig. 3 for city of Mashhad, Iran. These utility constructions should be carried out in modern cities for resilience and sustainability.

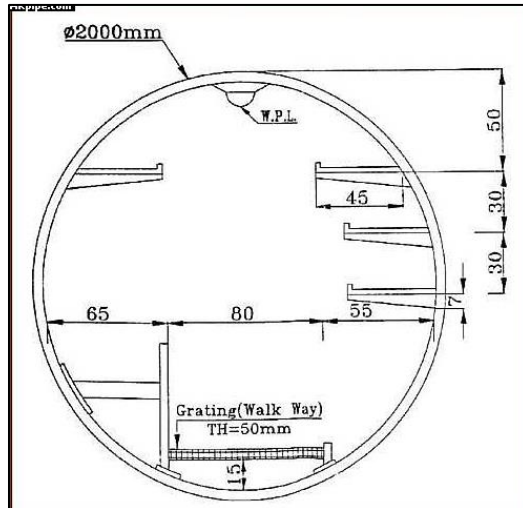


Figure 3: Examples of proper utility construction in city of Mashhad, Iran

### 3. EXCAVATIONS FOR TRANSPORTATION NETWORKS

The excavation for underground metro tunnels, freeways, new intersections and interchanges and street widening have tremendous impact on comfort and prosperity of the people, and new insights and methods should be implemented to improve the situation for sustainable and resilient cities. Underground metro tunnels carried out with tunnel boring machines have small carbon imprint. City of Tehran, Iran is an excellent example of such public metro transportation. It is inconceivable now to imagine Tehran without metro transportation. Other cities in Iran such as Mashhad, Tabriz, Isfahan and Shiraz are completing metro construction and are planning for future expansion.

Other nations have adopted metro and rail construction. Eighty-two Chinese cities are building metros Dingding, [4]. Beijing and Shanghai have metros. In India fourteen cities are building metros [5]. Figs. 4-6 show examples of Metros in the Iranian cities of Tehran Piroozi, Mashhad, and Shiraz.



Figure 4: An example of Tehran Piroozi metro, Iran.



Figure 5: Mashhad metro, Iran.





*Figure 6: Shiraz metro, Iran.*

Public transportation is an important step in making cities resilient and sustainable. Metro, bus lines and trains are important steps. Another trend which is confronting many Iranian cities is to widen and make new streets. Then start making intersections and interchanges and then burst into making freeways, all of which will not relieve the traffic in our developing cities. Adding new cities around the main city is another trend which will not eventually solve the problem of expansion of the city and traffic. As far as the emphasis is on private passenger cars the problem will worsen and the eventual end is air pollution and devastated environment and the cities will not be loveable and in many instances will not be livable. In such cities you will not find bicycles and pedestrian pathways and the concept of café city is completely forgotten. Parking spaces become unavailable and traffic congestion becomes daily routine. The whole city looks then like a huge parking space and hours of city occupant are spent in traffic and in bad and polluted air. Because of job attraction, migration to these cities is another serious problem with under developed and unsuitable neighborhoods. Strategies like even and odd day traffic and city center traffic plan often will inconvenience the people and if the strategies do not change into emphasis on public transport the problem persists. Fig. 7 shows the comparison of green spaces in part of Shiraz between 2003 and 2014. Fig. 8 shows beautiful rotary turned into huge interchange at Maaliabada, Shiraz between 2003 and 2014.



*Figure 7: The comparison of green spaces in part of Shiraz between 2003 and 2014.*



*Figure 8: Beautiful rotary turned into huge interchange at Maaliabada, Shiraz between 2003 and 2014.*

Another development in our cities for relieving traffic is to construct intercity tunnels and double deck freeways. Again if the public transport is not developed, these measures will not in the long run relieve the traffic. Fig. 9 shows the intercity tunnel Resalat in Tehran and Fig. 10 shows the double deck freeway in Isfahan.



*Figure 9: Intercity tunnel Resalat, Tehran, Iran.*



*Figure 10: Double deck freeway in Isfahan, Iran.*



#### 4. EXCAVATION FOR HIGH RISE BUILDINGS

The excavation for high rise buildings, which sometimes are up to 40 meter deep and 100 m by 100 m wide with traditional methods of soil nailing and anchoring etc. are basically used to save land adjacent to neighbors and city streets and cause discomfort to the cities. Innovative methods should be applied for sustainable and resilient cities. Fig. 11 shows examples of such excavations. Fig. 12 shows the examples of collapse of such excavation. The top down excavation process should be implemented to bypass such problems.



Figure 11: Examples of excavations in Tehran, Iran for high rise building construction.



Figure 12: Examples of collapse of such excavations, from lecture by Prof. Fakher of Teheran University [6].

The following is taken from Engineer Ali Chaboki's [7] LinkedIn page about top down construction:

*“Top Down (or Cover-cut) Construction is used in packed plans and is used in Metro Station and Tall buildings as a rapid and effective construction method. In this construction method, the structure and the required retaining structure are connected. These can be installed in close proximity to existing structure with minimal loss of support to existing foundations. In addition, construction dewatering is not required, so there is no associated subsidence. Top Down Construction are practically suited in the construction of deep basements, Metro Railway Projects. The “Top Down” method of construction is designated to enable above ground construction work to be carried out simultaneously with the excavation of the basement resulting in significant saving of time on a project.”*

*“The main characteristic of this method is time saving in construction, you can divide the construction in two different parts: 1) upper structure and 2) underground that each can be*

*constructed separately. Of course the main element of this method is diaphragm walls as support and foundation. Last year, we carried out a comprehensive analysis for construction a tall building in Tehran (with 40 story above and 11 underground), finally and we found out the best method and cheaper method is "top-down method with diaphragm walls".*

Two methods for excavation considered:

1: Traditional excavation (stabilization the walls with ground anchor and shotcrete)

2: The diaphragm walls and top down method (first diaphragm walls and the ground floor slab and then upper structure and the cost was almost equal however; the second method was one year faster, because the upper structure could start right after ground floor slab, (as its foundation). In addition, the settlement of the neighbors (for 45 meter excavation was less) and the underground water issue solved by this method."

## **5. SUMMARY AND CONCLUSIONS**

The effect of geotechnical work for resilient and sustainable cities is explained in this paper. The normal utility construction with separate trenches for each utility that sometimes incorporates 7 kilometer of utility trench for each kilometer of street length should be abandoned and tunnel utility construction with redundancy is recommended. The transportation network for resilient cities is emphasized and it is shown that metro and train construction and double deck and city tunnels are promising for resilient and sustainable cities. The deep excavation for tall buildings with normal method of soil anchoring, nailing is explained and it is recommended that the method of top down construction should be planned for these deep excavations for resilient and sustainable cities.

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# Upcoming Challenges of Future Electric Power Systems: Sustainability and Resiliency

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### **Abstract**

Going back and taking a quick glance at the history of the most developed countries in the world prove the fact that prosperity of any society is tightly intertwined with resiliency and sustainability of its primary infrastructures. Surely, in any modern society, electricity is one of the most important infrastructures whose resiliency and sustainability can be a key driving force toward development of the society. This can be verified by considering the fact that, since the industrial revolution, per capita electricity consumption was/is taken as a key index showing the level of economic development and standard of living in a country. This paper intends to focus on the concept of resiliency and sustainability of electric power systems. The paper, initially, introduces the concept and evaluation procedure of resiliency in power systems. Then it strives to introduce the most challenging issues faced by the power utilities towards achieving a resilient and sustainable power grid. The challenging issues are electricity load growth, energy crisis, environmental emissions and climate changes, unexpected events including both natural disasters such as floods and earthquakes and power system components malfunctions, aging infrastructures and cyber challenges. Following the challenges, the most effective solutions which were recently proposed by power industry scientists and engineers are discussed. The solutions are asset management, renewable energy resources, demand response, controlled islanding and micro grids, advanced automation systems, self-healing systems, and monitoring systems. Finally, a typical sustainable and resilient power system which is established according to the solutions is described.

**Keywords:** *Power Industry Challenges, Power Industry Solutions, Future Power Systems, Resilient Power Systems, Sustainable Power Systems*

## 1. INTRODUCTION

The concept of resiliency, which was stimulated by environmentalism, focuses upon the requirements to counter with occurrence and impact of catastrophic events against urban areas. In particular, the concept of resiliency is used to describe the ability of cities and regions in moving toward more 'safe' and 'sustainable' communities [1]. As electric power infrastructures have contributed a lot to the safety and sustainability of communities, upgrading the current infrastructure to a resilient one is one of the major goals which portray the future resilient urban areas.

Electric power system, with its humble beginning in the 1880s, has been matured into a large-scale industry. Taking the role of a basic necessity for modern societies, the electricity consumption around the world experiences a fast growing trend. In response, the electricity production worldwide nowadays has reached near 21 billion kilowatt-hours per year (see Fig. 1). As new gears and machines have been made based on electricity, human life quality has intertwined more and more to continuity and quality of electricity services. The proliferation of electric devices in human life has obliged the power industry to pay a greater attention to the service reliability.

On the other hand, electricity industry encounters a great deal of challenging issues in meeting reliability requirements of the society. Electric power systems are among the most complicated man-made structures through the history with a large number of components scattered in vast areas. This beside aging infrastructures, growing loads, natural disasters, energy crisis, and proliferation of renewable energies makes meeting the reliability requirements a very difficult task. On the other hand, huge and almost always growing needs for capital intensive reinforcements in power systems are in an obvious contradiction with tightly limited budgets in this industry. These all force the industry to explore some innovative ideas useful for utilizing existing electricity infrastructures in a more effective manner thereby guaranteeing a sustainable and resilient system. Asset management, self-healing systems, precise monitoring and visualization systems, prompt automation systems, controlled islanding and micro grids, demand response, and renewable energy sources are among the most effective ideas which were proposed by power engineers to propel the industry towards a more sustainable and resilient power system.

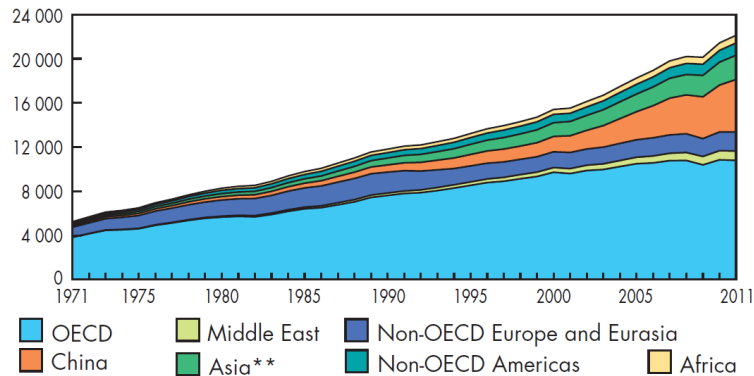


Figure 1: Electricity production around the world (TWh) [2].

A sustainable power system should be able to tolerate against unexpected events such as equipment outages, severe weather conditions, natural disasters, and fuel shortages to name just a few. Synonymously, in a sustainable system, customer service continuity and reliability should be preserved during such events. A resilient system is able to effectively and promptly recover the likely load interruptions following an unexpected event such as equipment outages and natural disasters. The concept of asset management is a cost effective way to efficiently manage asset related procedures, i.e. procurement, operation, maintenance and disposal of assets and help system owners to satisfy their financial goals while meeting benchmarked reliability and resiliency standpoints. Advanced monitoring infrastructures provide system operators with more precise situational awareness and allow them take more effective remedial actions. Automated power systems enable system operators with remote control actions which in turn result in prompt remedial actions. The controlled islanding and micro grids by isolating autonomous areas of the system intends to serve electricity needs of end users which are located in healthy areas. Demand response is an effective load shaping tool which can be utilized to alleviate operational limits such as network overloads and under voltages. Finally, renewable energy sources by declining the share

of fossil fuel fired generating units in load procurement can be an effective solution for energy crisis. Therefore, moving toward a sustainable power system not only calls for changes in the way electrical energy is supplied, but also in the way it is consumed.

Based on the above discussions, one can come to this point that power industry faces with several challenging issues that should be properly addressed to promise a bright future for the system. Also, as mentioned heretofore, a great deal of efficient as well as economical solutions have been found to counter with the critical issues. As a complementary to the published works in this area, this paper describes the major challenges encountered by the industry to move towards a resilient and sustainable power system. In addition, this paper reviews the most effective ways available to enhance the system resiliency and sustainability following unpredicted events including both of endogenous and exogenous failures. A brief explanation on how the ways cover concerns about resiliency and sustainability of power systems is the other goal of this paper. Discussing about the challenges and solutions, an envisioned power system which is equipped with effective tools to reach an appropriate level of resiliency and sustainability is also introduced.

## **2. RESILIENCY CONCEPT AND EVALUATION IN POWER SYSTEMS**

As mentioned in the previous section, over the past decades, the international society and specifically power utility managers have paid a great attention towards preventing catastrophic losses and managing disruptive impacts of both manmade and naturally happening threats and hazards. To this end, there exist several different definitions for a resilient system which is immune against both manmade and naturally occurring threats. In the following, a few of the most relevant definitions for “resilience” are given [3]:

- Resilience is “a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables” [4]
- Resilience is “the capacity to cope with unanticipated dangers after they have become manifest, learning to bounce back” [5]
- Resilience is “the capacity to adapt existing resources and skills to new situations and operating conditions” [6]
- Resilience is the “ability to resist, absorb, recover from or successfully adapt to adversity or a change in conditions.” [7]

Resiliency is a system concept which is related to some other system concepts such as reliability or survivability. Actually, in an electrical engineering literature, resiliency and reliability have almost the same meaning. The term reliability is the probability of a device or system performing its purpose adequately for the period of time intended under the operating conditions encountered. When it comes to the power grid, reliability can be defined as the ability of the grid to perform its intended function which is serving electricity needs of consumers and other preliminary infrastructures in a continuous and of course economic manner. In the electric utility industry, system reliability has two fundamental aspects of adequacy and security. Adequacy refers to the existence of sufficient generation, transmission and distribution facilities to produce and transport electrical energy to end users taking into account specified outage events. Security, however, refers to the ability of a system to withstand any disturbances arising within the system. These include both local and widespread disturbances and unexpected sudden loss of generators, network components, or loads resulting in system instability and cascading outages. Needless to mention that, a reliable power system refers to a system which is both adequate and secure.

In order to recognize adequacy and security, power system conditions can be described by several operating states in terms of the degree to which adequacy and security considerations are satisfied. These operating states are designated as normal, alert, emergency, extreme emergency, and restorative as shown in Fig. 2. These states are determined in terms of the degree to which

security margins are satisfied. In the normal state, the system is capable to serve the existing total load. In this state, sufficient margin is available such that any likely disturbance, specified by some criteria, can be tolerated. The criterion such as the loss of any single component depends on the planning and operating philosophy of the service provider. The system is in the alert state if all the constraints are within limits but there exist some disturbances which cannot be tolerated by the system and following which electricity service interruption is not avoidable. In the emergency state, some of the system operational constraints are violated. In this state, the system is still intact but appropriate remedial actions must be taken into account to restore the system to at least the alert state; otherwise, the system will transfer from the emergency state to the extreme emergency state. In the extreme emergency state, system operational constraints are violated and some load points experience electricity service interruption.

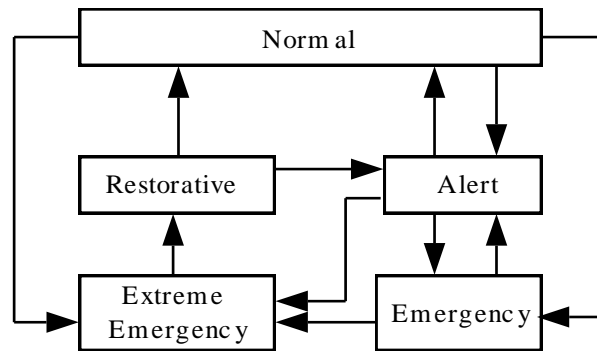


Figure 2: System operating states diagram [8].

According to the above model, for a system, probability of being in the fivefold operating states illustrates the degree of system well-being. In order to estimate the states probabilities, a three step procedure which is shown in Fig. 3 must be performed. As can be seen, in the first step, likely events including both manmade and naturally happening disturbances and hazards are selected. In the next step, the selected events are analyzed and their circumstances are obtained. Clearly, some of the selected events lead to violations in operational constraints which can be mitigated by appropriate remedial actions and some result in service interruptions. The achieved consequences associated with the selected events are combined with their occurrence probability to form state probabilities as reliability indices in the third step.

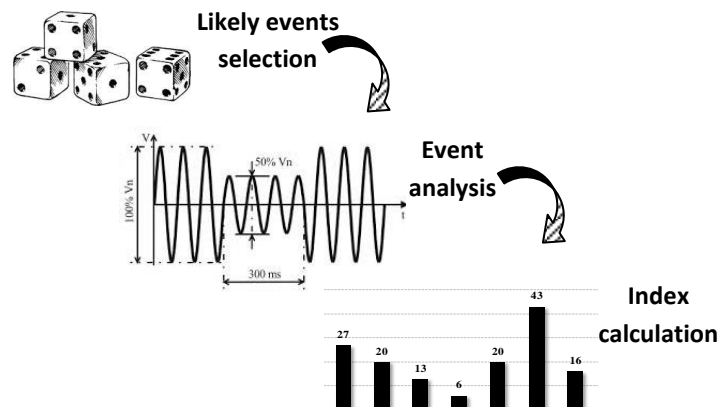


Figure 3: Three steps of reliability assessment procedure for a power system.



The reliability evaluation procedure, although seems to be straight, is a very challenging process mainly due to the required data and the huge number of likely events. The former origin of difficulty goes back to the fact that almost all of manmade and naturally happening disturbances are stochastic in nature and their occurrence highly depends on several affecting parameters such as weather condition. For example, failure rate associated with power system components usually increases during severe weather conditions. In order for an analysis to lead to reasonable and accurate results, likely events and their occurrence probabilities must be determined through comprehensive analyses of historical recorded data of the system during different conditions (e.g., different weather conditions). The later origin of difficulty in reliability assessment procedures goes back to the enormous number of power system components which are scattered in vast areas with different weather conditions. This substantially increases the number of likely events which can occur in the system. Note that analyzing a huge number of events is exhaustive and computationally expensive. For these reasons, there have been developed sorts of commercially available software packages for both data collection and reliability analyses. The Iran Grid Management Company (IGMC) which is in charge of the Iranian power system, under the umbrella of a project with Sharif University of Technology (SUT), studied almost all of available worldwide power system reliability assessment software packages and, based on their pros and cons, is going to develop a comprehensive software package for the national grid.

It can be concluded from the above discussion that the system must be able to resist against likely disturbances as well as to recover to its normal condition following any disturbances. Even though resiliency is a more comprehensive concept, both resiliency and reliability include some aspects of resistance against disturbances and recovering from them. Both aspects become more meaningful when deal with very large scale and complex systems such as power grid.

### **3. CHALLENGES**

This section describes the major challenging issues which may be encountered while the power industry intends to move toward a resilient and sustainable system. The issues are load growth, energy crisis, emissions and climate changes, unexpected events, aging infrastructure and cyber challenges.

#### *3.1. Load Growth*

Electricity load growth is a challenging issue which should be considered by the power industry. The system load increases as new customers are added to the grid or existing customers add new appliances or replace their existing equipment with devices that require more power. Load growth is influenced by many factors including the national economy, income per capita, power management, prices, policies, and conservation. The Annual Energy Outlook 2007 (AEO2007) [9], prepared by the Energy Information Administration (EIA), presents long-term projections of energy supply, demand, and prices through 2030. According to this report, the mean incremental growth rate of annual electricity consumption will be 1.55%, due to new uses of electricity. This may vary in different countries. For instance, Fig. 4 shows the load demand variation in Iran from 1979 to 2013, where the load growth on average is 7%.

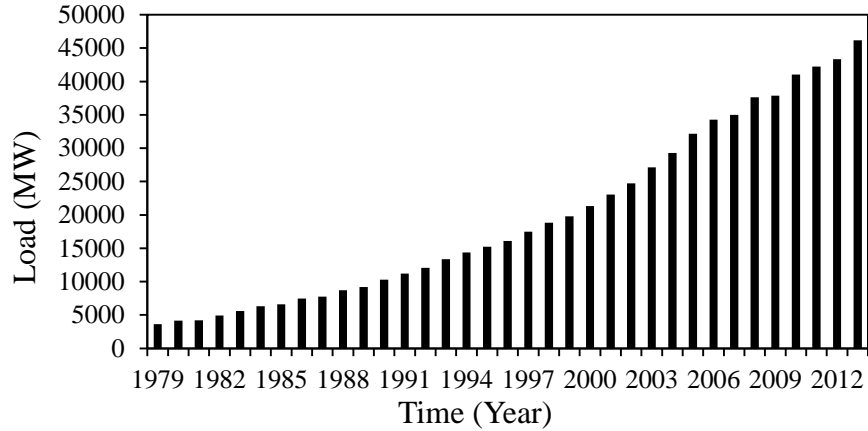


Figure 4: Annual peak load variation in Iran from 1979 to 2013 [10].

Besides the mentioned load growth, proliferation of electric vehicles which is triggered by environmental concerns will add a significant load to the power industry. A typical plug-in electric vehicle requires 0.2–0.3 kWh of charging power for a mile of driving. Assuming average daily trip with 30–40 miles length, electric vehicles need 7–10 kWh of electrical energy daily. These load growths, if they are not managed effectively may degrade power systems reliability. In addition, unbalanced load growths, resulting from unequal single-phase and double-phase loads such as plug-in vehicles, could result in degradation of power quality, increased harmonics and voltage problems, and increasing line losses.

### 3.2. Energy Crisis

Secure and price consistent sources of primary energies are among critical prerequisites for modern societies. Primary energy is referred to as an original energy form which can be found in the nature and has not been subjected to any transformation process. The major sources of primary energies are fossil fuels (coal, oil, and natural gas), biofuels-wood, wooden wastes, agricultural wastes, etc. Fig. 5 demonstrates the share of different primary energy forms in worldwide energy consumption. As can be seen, oil, coal, and natural gas made up almost 78% of primary energy production.

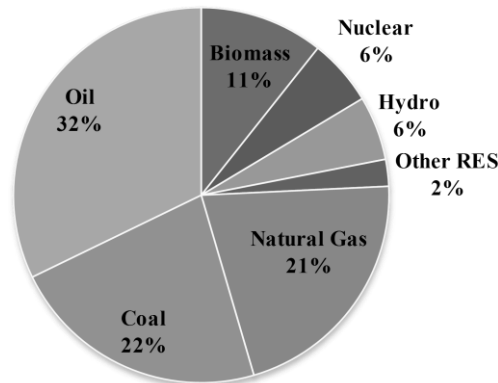


Figure 5: Worldwide Consumption of primary energy sources [11].

As mentioned earlier, fossil fuels have the largest share in the sources to produce electricity worldwide. However, fossil fuel reserves are not uniformly distributed over the earth. Tables 1, 2, and 3 respectively give the share of different countries from the remaining resources of natural gas,

coal, and crude oil. As can be seen, a great deal of the primary energy reserves is owned by a few countries. Therefore, countries with inadequate reserves of fossil fuels face serious concerns about primary energy availability since functionality of their power systems is highly dependent on others. Besides, according to the most optimistic forecasts done, the reserves of fossil fuels last for 109 years for coal, 56 years for natural gas, and 53 years for crude oil. Based on the above discussions, power industries whose main sources of primary energy depend on fossil fuels will encounter the challenging issue of energy crisis.

TABLE 1: WORLD RESERVES OF NATURAL GAS [12].

	<b>Proved Reserves (Trillion Cubic Meters)</b>	<b>Percent of World Reserve</b>	<b>Years of Extraction Remaining</b>
World	187	100	56
Iran	34	18	209
Russian Federation	33	18	56
Qatar	25	13	160
Turkmenistan	18	9	272
U.S.	8	5	12
Saudi Arabia	8	4	80
United Arab Emirates	6	3	118
Venezuela	6	3	170
Nigeria	5	3	119
Algeria	5	2	55

TABLE 2: WORLD RESERVES OF COAL [12].

	<b>Proved Reserves (Trillion Cubic Meters)</b>	<b>Percent of World Reserve</b>	<b>Years of Extraction Remaining</b>
World	860,938	100	109
U.S.	237,295	28	257
Russian Federation	157,010	18	443
China	114,500	13	31
Australia	76,400	9	177
India	60,600	7	100
Germany	40,699	5	207
Ukraine	33,873	4	384
Kazakhstan	33,600	4	289
South Africa	30,156	4	116
Colombia	6,746	1	76

TABLE 3: WORLD RESERVES OF CRUDE OIL [12].

	Proved Reserves (Trillion Cubic Meters)	Percent of World Reserve	Years of Extraction Remaining
World	1,669	100	53
Venezuela	298	18	299
Saudi Arabia	266	16	63
Canada	174	10	127
Iran	157	9	117
Iraq	150	9	132
Kuwait	102	6	89
United Arab Emirates	98	6	79
Russian Federation	87	5	22
Libya	48	3	87
Nigeria	37	2	42

### 3.3. Emissions and Climate Change

A power system must be environmentally friendly to support a sustainable society. Therefore, alleviating climate changes and environmental concerns are among challenging issues which are encountered by the power industry. Moreover, since greenhouse gases generating by electric power plants are much easier to be monitored and controlled than emissions from other sources such as vehicles, the electricity sector has always been considered as a primary target in emission control programs. Fossil fuels burning to supply the global electricity demand account for release annually over 7,700 million tons of carbon dioxide (CO<sub>2</sub>) which is equivalent to 37.5% of total CO<sub>2</sub> emissions. It has been predicted that the annual CO<sub>2</sub> emission will surpass 15,000 million tons by 2020 [11]. Nowadays, in worldwide electricity production, coal continues to have the largest share at 38%, which provides electricity with high greenhouse gases and emissions.

### 3.4. Unexpected Events

Unexpected events are the major contributor in jeopardizing power systems resiliency and sustainability. As mentioned heretofore, power systems have been designed and operated to withstand a great majority of disturbances while being able to supply the customers. However, despite the arduous efforts to build a resilient and sustainable system, unexpected disturbances always threat the system security and functionality. In addition, interconnected nature of the system increases the probability of fault propagation which can interrupt the service to a large number of customers. In the next paragraph, main roots of system events are initially categorized followed by a brief discussion on the expected consequences of outages and blackouts.

In the electrical engineering context, faults are categorized based on their electrical nature and duration. Accordingly, faults are generally divided into two major groups of open and short circuit faults which can be further classified based on the number of involved electrical phases [13]. Following an event, repair/replacement expenses, likely service provider's losses, and likely customers' damage costs are the three main contributors of the overall damage cost. It's clear that, damaged components must be repaired/replaced to fully restore the system functionality. This procedure incurs maintenance or replacement costs to the service provider. Besides, since the system is unable to supply customers whose electricity service is interrupted, the revenue from selling electricity to the customers is lost as well. At last, customers who experience service interruptions are imposed to monetary damages and loss of comforts. Among the three terms, since

prosperity of customers activities are highly intertwined to electrical energy, any interruption in the services paralyzes customers and as a consequence, customers' interruption costs is much more than the maintenance and service providers' losses [14]. In fact, customers' type and outage duration are the two important factors that determine the customers' damage. To delineate the subject, Table 4 lists the estimated customer interruption costs for different outage durations and customer types [15].

TABLE 4: ESTIMATED AVERAGE ELECTRIC CUSTOMER INTERRUPTION COSTS IN 2008 US DOLLARS.

Interruption Cost	Interruption Duration				
	<5 min	30 min	1hr	4hr	8hr
<b>Medium and Large C&amp;I</b>					
Cost Per Event	6,558	9,217	12,487	42,506	69,284
Cost Per Average kW	8.0	11.3	15.3	52.1	85.0
Cost Per Un-served kWh	96.5	22.6	15.3	13.0	10.6
<b>Small C&amp;I</b>					
Cost Per Event	293	435	619	2,623	5,195
Cost Per Average kW	133.7	198.1	282.0	1,195	2,368
Cost Per Un-served kWh	1,604	396.3	282.0	298.9	296.1
<b>Residential</b>					
Cost Per Event	2.1	2.7	3.3	7.4	10.6
Cost Per Average kW	1.4	1.8	2.2	4.9	6.9
Cost Per Un-served kWh	16.8	3.5	2.2	1.2	0.9

Blackouts or large outage events are the most catastrophic events that can happen in a power system. These catastrophic events are usually originated by either natural disasters such as floods and earthquakes or propagation of component outages through power systems. Cascading outages which are defined as a sequence of dependent failures, lead to power system weakness, may spread through the system and cause blackouts. A propagation sequence can be due to the fact that power systems are weakened following an outage as well as due to protection system malfunctions or system operator errors. In such catastrophic events, extensive interrupted areas along with usually long restoration time worsen the situation and exacerbate their monetary losses and social consequences compared to events with limited affected areas and short durations. To demonstrate both the vulnerability of modern power systems and also the catastrophic consequences of service disruption, Table 5 lists the ten most severe blackouts concerning affected population and duration [16]. Cascading outages have been reported as the most important cause of recent major blackouts.

TABLE 5: TEN MOST SEVERE BLACKOUTS.

	Country	Year	Affected population	Duration
1	New Zealand	1998	70,000	4 week
2	Brazil	1999	97,000,000 (70% of the territory)	5 hour
3	India	2001	226,000,000	12 hour
4	U.S. & Canada	2003	50,000,000	4 days
5	Italy	2003	56,000,000	18 hour
6	Spain	2004	2,000,000	5 blackouts within 10 days
7	Indonesia	2005	100,000,000	7 hour
8	South West Europe	2006	15,000,000	2 hour
9	Brazil + Paraguay	2009	87,000,000	25 min to 7 hour
10	Brazil	2011	53,000,000	16 hour

### *3.5. Aging Infrastructures*

A great deal of components in the existing power systems was designed and installed decades ago. As a matter of fact, by passing the time, failure rates of these components have increased significantly which degrades the grid ability to handle unexpected events. This is due to the fact that failure frequency of an old component is much more than that of a similar but new component. Aging power system components, in order to properly perform their functionality with reasonable failure rates, need regular costly maintenance and even replacement actions. These actions however seem very difficult considering number and geographical disparity of the components and also tightly limited budgets of the industry. Therefore, the power industry faces the key challenging issue of aging infrastructures which must be overcome to achieve a resilient and sustainable power system.

### *3.6. Cyber Challenges*

While modern communication, control, and computing technologies offer tremendous opportunities to improve electric power system response and resilience to failure, they also render the grid vulnerable to intentional attacks from internal or external parties. This in fact increases the risk of compromising reliable and secure power system operation. In general, security attacks against the electricity infrastructure can be classified into physical and cyber threats. In case of physical threats, although the attacks may be troublesome and incur extra cost to the local grid owner, they are likely to affect only a small portion of the overall grid. On the other hand, the number of documented cyber-attacks and intrusions worldwide has been rising very rapidly in recent years. Due to the increasingly sophisticated nature and speed of malicious code, intrusions, and attacks, human responses may be inadequate. In addition, adversaries often have the potential to initiate attacks from nearly any location in the world. While the direct physical destruction may be the most obvious strategy for causing blackouts, cyber-attacks could also disrupt the system, cause blackouts, and in some cases result in physical damage to key system components. As a result, cyber security is just as important as physical security and according to the abovementioned facts, special attention should be paid to this subject.

## **4. SOLUTIONS**

The previous section provides a brief description over the most challenging issues which are faced by the electricity industry intending to achieve a resilient and sustainable system. This section gives the most effective solutions which have been proposed by power industry scientists and engineers. The solutions are asset management, renewable energy resources, demand response, controlled islanding and micro grids, advanced automation systems, self-healing systems, and monitoring systems.

### *4.1. Asset Management*

Power systems are constituted by a large number of components which are subjected to different types of tensions ranging from corrosion, fatigue, and severe weather conditions to natural disasters and terrorist attacks. The resistance of the components against the tensions and their capacity to endure extreme conditions directly affect power systems overall resiliency and sustainability. Therefore, enhancing components ability to tolerate harsh conditions is a way to move towards a more resilient and sustainable power system. However, managing a large number of highly scattered components that have different types, ages, manufacturers, priorities, physical conditions, and required maintenance procedures is a challenging task. Asset management is the knowledge that strives to propel the physical assets capabilities toward desired goals while

observing technical and financial restrictions [17]. Recent practices of asset management in different industries and also in power systems proved that asset management techniques are effective approaches that can greatly influence on the system resiliency and sustainability while coping with limited budget and resources [18].

In asset management, service provider systematically looks to find the best strategies to acquire, upgrade, operate, maintain and also dispose assets. It is worthwhile to mention that the best strategies have the ability to satisfy benchmarked resiliency and sustainability indexes while meet budget restrictions. The first step of asset management is to develop a few strategic plans for the service provider considering consumers' needs, legislations, investors, and the business environment. Then, the risk associated with the developed strategic plans is assessed by taking into account available assets and scheduled asset related procedures. Thereafter, final decision making is done based on the risks, organizational objectives, and available resources to determine physical asset-related strategies (i.e. acquirance, operation, maintenance, and disposal).

#### 4.2. *Renewable Energy Resources*

As discussed earlier, energy crisis and environmental issues, nowadays, have become among the major concerns of humankind around the world. The first oil crisis in the early 1970s was a wakeup call for human societies about the limited sources of fossil fuels and as a consequence, the need for sustainable sources of energy. To handle the issue, a few ideas has been proposed amongst were applying new technologies with higher efficiencies as well as moving towards so called 'clean energies' as promising alternatives for fossil fuels. Development and presence of renewable energies in energy markets can bring diversity to energy consumption and play a role in supplying energy services in a more sustainable manner. On the other hand, all the traditional energy sources pollute the environment while renewable energies are pollution free and devoid of the negative effect.

The most popular and accepted technologies of renewable energies are wind energy, solar energy (direct, photovoltaic, and thermal), hydraulic (employing potential and kinetic energy of water), geothermal, bio-energy, etc [19]. Based on data published around the world, it is estimated that renewable energies supplied 12.9% of the total primary energy (492 EJ) in 2008 [11]. In 2008, the contribution of renewable energies was almost 19% of global electricity supply. Although the share of the energies is still relatively small, their capacities are growing rapidly. In 2012, total installed renewable power capacity worldwide exceeded 1,470 GW. This means, in 2012, renewable energies comprised more than 26% of global generating capacity and supplied an estimated 21.7% of global electricity demand [20].

Renewable energy sources are usually available everywhere in the world. Furthermore, technologies which can harness these energies are also available and are improving rapidly. Therefore, they can play an important role in stepping towards a sustainable and resilient power system from the following aspects:

- **Social and economic development:** The economic development of a society is mainly correlated with per capita energy use. Therefore, one can come to this conclusion that electricity services with a higher quality are prerequisites for development. In this regard, renewable energies taking into account their decentralized nature can improve electricity service sustainability and resiliency in far and especially rural areas and as a consequence, play an important role in fostering rural developments.
- **Energy access:** In 2009, more than 1.4 billion people had no access to electricity. In addition, by 2015, it has been forecasted that almost 1.2 billion people will request for electricity. As renewable energies are dispersed around the world, these energies can be a proper candidate for supplying the upcoming demand of energy. In particular, in rural regions, reliance on

renewable energies will allow to attain universal access to modern energy services. Small size of renewable-based units such as photovoltaic, hydropower, and bio-energy can often meet energy needs of rural regions more cheaply than conventional distributed generation technologies.

- Climate change mitigation and environmental concerns: As a key driving force, climate change mitigation can be achieved by growing usage of renewable energies. In addition to decreasing greenhouse gas emissions, renewable energies also offer benefits with respect to air pollutions.
- Energy crisis concerns: Proliferation of renewable energy sources in power systems can alleviate dependence of the power industry to foreign fossil fuel markets, thereby mitigating energy crisis concerns.

#### *4.3. Demand Response*

In the past, power system planners have been responsible to predict future electricity consumption and make optimal reinforcement plans in order to serve the load. In such a way, the system is equipped with no driving force to motivate/force consumers to react in response to what is happening in the power industry. Having no active role in the power industry, consumers are passive players who plug in their electric devices, consume electricity, and pay bills. However, in recent decades, power industry researchers understood the value of demand response programs and the significant opportunity they offer to enhance sustainability and resiliency of the system while decreasing costs. They found out that even a small portion of demand which is flexible can be an effective remedy to mitigate/alleviate the negative impact of several technical and financial issues. Demand response is referred to any voluntary effort to change normal consumption pattern with the objective of individual and/or social benefits. Demand response can be invoked when either power system resiliency or sustainability is jeopardized or electricity procurement cost is substantially raised. As found by engineers, a great portion of power industry issues can be mitigated by demand response potentials. For instance, a faint increment in electricity demand during peak periods might be translated to a significant increase in electricity procurement costs. Demand response can be used to decrease the peak load and thus, the procurement cost. Moreover, due to severe peak loads, a significant portion of power system facilities are installed to be utilized a limited number of hours a year. This for sure imposes significant monetary losses to the power industry. Demand response can be used to flatten the system load profile, therefore, postpone a great deal of power system reinforcements. Also, any unexpected outage in key generation or transmission system components during peak periods may impose significant risks to power system resiliency and sustainability. In such a situation, demand response, by reducing load, can increase safety margins of the system, thereby, propelling it towards a more resilient and sustainable system.

In order to realize demand response potentials in a power system, there exist sort of approaches which can be grouped into two categories. These two categories are price based and incentive based programs. In a price based program, electricity service provider releases time varying electricity prices by which consumers are motivated to alter their normal consumption pattern such that some savings in electricity bills are obtained as well as power system sustainability are enhanced. In an incentive based program, however, a contract is signed between consumers and the service provider. The contract obliges the consumers to modify their consumption pattern upon receiving a signal from the service provider in exchange for some predefined monetary incentives.

#### *4.4. Controlled Islanding and Micro-Grid*

As mentioned heretofore, power systems have been faced with catastrophic events such as the Aug. 14, 2003, blackout [21]. The power industry in order to prevent such events needs to develop



new infrastructures and operational concepts. A recently developed operational concept is *controlled islanding*. The main idea behind the concept of controlled islanding goes back to preventing from propagation of faults through the whole system. In controlled islanding, the power system is divided into a few sub-systems which are able to be operated autonomously. The sub-systems capable to be operated autonomously if they are connected to each other via weak boundary lines and active and reactive power balance conditions are met within each of the sub-systems. According to the concept, following a severe fault in a sub-system, boundary lines are mandatorily opened and healthy sub-systems will be operated autonomously. Fig. 6 shows an example of an extra-large power system which is constituted of four sub-systems. As can be seen, the sub-systems are connected to each other via three tie-lines.

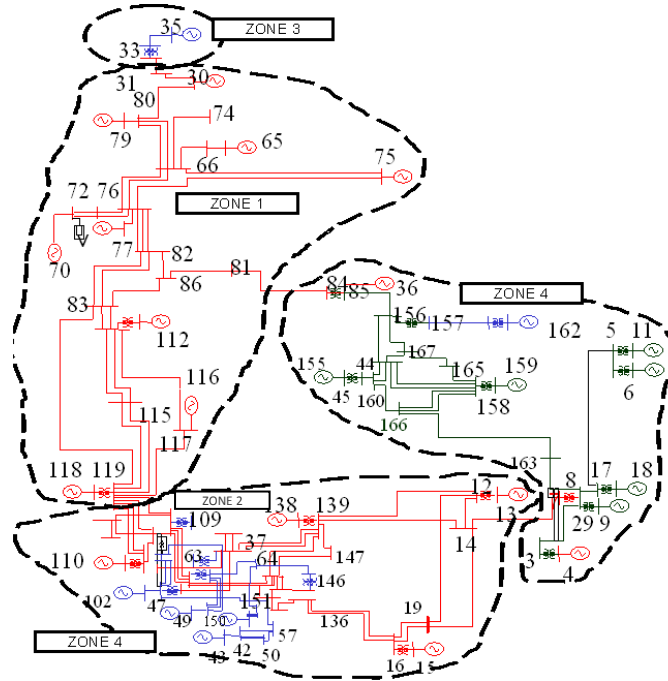


Figure 6: An extra large power system constituting four sub-systems [22].

Besides the concept of controlled islanding which focuses on sub-systems in the transmission level, the concept of microgrid is another recently proposed idea which focuses on sub-systems in the distribution level. Microgrid refers to a group of interconnected loads and generation units constituting a subsystem [23]. In fact, a microgrid can be considered as a very small vertically integrated electric utility in which there is no transmission component. In other words, generation and distribution components are the fundamental elements of a microgrid. A microgrid can operate in both grid-connected and islanding modes, since it has the ability to independently serve its loads with the power generated by its generation units. Thanks to this capability, following an event in the main grid, a microgrid can disconnect its loads and generation units from the grid and continues to serve its loads with the power generated by local generation. Consequently, microgrids, by serving loads even when the main grid is de-energized, have the potential to effectively improve resiliency and sustainability of power systems. Besides, they are equipped by additional control facilities which allow more distributed energy units to be connected to distribution networks thereby alleviating environmental concerns and energy crisis issues.

#### 4.5. *Advanced Automation*

Power system automation is an effective tool by which system operators can promptly react in response to any unexpected event. In [24], advanced distribution automation is described as the “Heart of the Smart Power Delivery System.” Automation will play a central role in providing enhanced levels of security, quality, reliability, and availability that are characteristics of a resilient and sustainable power system. Advanced automation systems are concerned with complete automation of all the controllable equipment and functions in the distribution level to improve its strategic operation. The growing and changing role of electricity in our society, availability and need to use of distributed generation resources, along with the growing importance of service resiliency and sustainability are all drivers behind advanced automation systems. The potential benefits of an advanced automation system include:

- Improve reliability and performance of distribution systems
- Reduce operating costs
- Enhance contingency responses
- Improve power quality
- Increase customer service options
- Prevent and mitigate outages
- Aid in outage recovery operations
- Support distributed energy resources integration into distribution operations
- Make customer systems part of the system performance equation

#### 4.6. *Advanced Monitoring Systems*

Monitoring systems provide power system control centers with an insight over the system current status. Based on the system status, the online security analysis of power systems is performed in power system control centers to help system operators in operating power systems in a more resilient and sustainable manner. In recent decades, great efforts have been devoted in increasing accuracy of monitoring systems. Advanced monitoring systems are the result of the efforts. In the past, monitoring systems update status of the system every 3-5 seconds while advanced monitoring systems update the system status several times a second. Measurements from conventional monitoring systems were asynchronous which results inaccuracies. However, measurements from advanced monitoring systems are equipped with an accurate time tagging system (which is based on the global positioning system) and as a result, their resulted system insight is much more accurate.

The more accurate insight over the system status, which can be obtained using advanced monitoring systems, the more benefits to resiliency and sustainability of power systems. Accurate system insight enables operators to more effectively take both preventive and corrective actions in case unexpected events are likely. As noted earlier, efficient and secure communications are the prerequisite of an efficient monitoring infrastructure. Cyber-attacks may block or delay the delivery of the associated messages or even modify or falsify their contents. In this regard, strict authentication and authorization procedures should be implemented in the monitoring systems to ensure their security and dependability.

#### 4.7. *Self-Healing*

Traditionally, following an event, power system operators were informed about service interruptions by calls from affected consumers complying from the curtailed supply. Upon receiving an interruption call, system operators by looking at the network topology and protection system settings approximately determine the interrupted area. Then, after the rough detection and

localization of the interruption causes, a repair crew team is sent to patrol the area and manually fix the problem. However, this manual problem diagnosing and repairing process may take a long time which can be translated to much more significant monetary losses and customers' dissatisfaction. In order to solve the issue, the idea of self-healing systems was proposed by power industry researchers. A self-healing system is expected to respond to threats, material failures, and other destabilizing influences by preventing or containing the spread of disturbances [25]. In a self-healing system, thanks to monitoring and control technologies, system operators are informed about unexpected events by monitoring of network switches status. Any sudden change in status of network switches can be a signal from an event. Then, following the event detection, available remedial activities are utilized to restore electricity services to the interrupted customers. A self-healing system has to provide non-stop services in terms of:

- Providing situational awareness throughout the system
- Predicting, preventing, and containing problems
- Enforcing operational plans and required margins
- Supporting system restoration

In order to realize a self-healing system, a high performance IT infrastructure is needed to address gaps in the geographical and temporal coordination of power system monitoring and control. It is also essential to address a comprehensive set of operating concerns (in normal and abnormal conditions) that are associated with performance enhancement, adequacy of resources, and equipment and system operating limits, as well as primary and back-up protection of systems and components. In a self-healing system, not only the existing on-line analytical capabilities are envisioned to continue playing their role, but current off-line capabilities must also be integrated into the on-line environment. All these surely require the use of on-line decision support tools with intensive computational and communication requirements.

## 5. SUMMARY

This paper focused on the topic of resiliency and sustainability in the electricity industry. In this regard, the most challenging issues encountered by the power industry as well as the most effective solutions proposed by the field researchers were thoroughly discussed. The challenges are load growth, energy crisis, emissions and climate changes, unexpected events, aging infrastructure and cyber challenges. The set of solutions includes asset management, renewable energy resources, demand response, controlled islanding and micro grids, advanced automation systems, self-healing systems, and monitoring systems. It is worthwhile to mention that the solutions are based on the degree of smartness in the system and can generally be categorized into two major groups. The first group contains those solutions which are on the basis of new advanced technologies such as monitoring and automation systems. On the other hand, the second group is devoted to solutions which are based on the existing procedures but with more systematic routines and in a more effective manner. Asset management is an example for the second group of solutions.

According to the existing literature, an electricity system in which the pointed solutions are realized is referred to as a smart grid or grid of the future. This coincidence goes back to the fact that resiliency and sustainability of electricity services constituted as the main criteria in developing a roadmap for electricity systems in the future. A typical smart grid is shown in Fig. 7. In the following, effectiveness of the solutions in the electricity system is briefly described.

- **Asset management:** The system has a great deal of elements including wind turbines, photovoltaic panels, circuit elements, and switches each of which has a failure rate. As mentioned earlier in this paper, failure rate of a typical component usually increases substantially through the time. In the considered system, the operator attacks to the issue using

effective asset management strategies by which optimal candidate elements for maintenance or replacement actions are identified. This is a positive step towards achieving a sustainable and resilient system in a cost-effective manner.

- **Renewable energy resources:** As can be observed in Fig. 7, the system contains a great deal of renewable-based generating units (wind turbines and photovoltaic panels). The green power produced by the units does not only alleviate environmental concerns but also, reduces dependency of the system to diminishing sources of fossil fuels. These sustainable energy resources can propel the system towards more resiliency and sustainability as well.
- **Demand response:** As can be observed in Fig. 7, demand response potential of some flexible loads is activated in the system. Operation of the flexible loads can be postponed to a later time whenever any violation in operating conditions experiences. Doing so, service interruptions which were conventionally invoked to alleviate the violations are avoided and so, the system resiliency and sustainability are enhanced.
- **Controlled Islanding and Micro grids:** The system contains central power plants as the conventional way of energy procurement as well as some smaller generating units dispersed almost all over the territory. In three cases (pointed by smaller network loops), a group of loads and generating units have established micro grids. The micro grids, although are connected to the main grid during the normal condition, can serve their loads autonomously in an isolated manner. This can be counted as a step towards a more sustainable and resilient system since the loads connected to the micro grids can be supplied even when the main grid experiences supply interruptions.
- **Advanced Automation:** As can be seen in Fig. 7, the system is equipped with a few remote controlled switches embedded in the shown detectors. These switches, following an unexpected event, can be used to isolate the faulted area and restore energy supply to likely interrupted loads. Owing to the fast switching actions which are possible thanks to the automatic remote switches, the load restoration can be done promptly thereby improving the system resiliency and sustainability and so, customers' convenience.
- **Advanced monitoring system:** The at hand smart system is equipped with an advanced monitoring system by which the operators sitting in the control center can trace the current state of the system and predict occurrence probability of any likely event. Therefore, decide about the most appropriate remedial actions which should be invoked to minimize possible unpleasant effects of the events. Besides, the system can be operated under lower security margins which in turn can be translated to a more resilient and sustainable situation even with lower operating costs.
- **Self-healing:** As can be seen in Fig. 7, a few detectors and switches are embedded in the system. Moreover, the system is designed such that loads can be supplied at least from two independent parallel routes. Accordingly, once an unexpected event occurs, the faulted area can be detected based on the status of the detectors. Then, appropriate switching actions can be performed to isolate the detected area and serve loads from an alternative route. In this system, the fault detection and isolation as well as service restoration to affected loads can be done automatically in a very short time. Self-healing systems with automatic and prompt responses to events can result in a more resilient and sustainable electricity system.

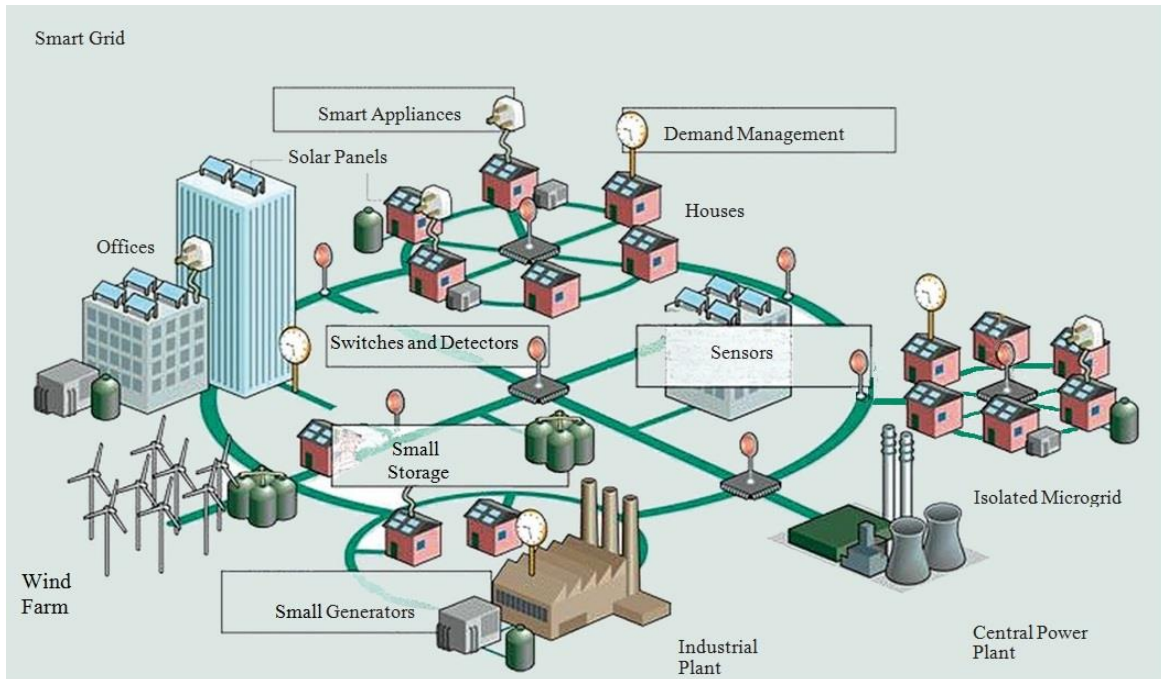


Figure 7: A typical resilient and sustainable electric power system [26].

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# Reimagining Electric Power to Enhance Urban Resilience

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### ***Abstract***

Reliable electricity is increasingly indispensable to urban life. As the world urbanizes and personal affluence grows, the demand for electricity has grown apace. A corollary is that electricity demand growth is low in slow-growing, advanced industrial economies like the United States, which reduces opportunities to incorporate new technologies into power systems. Regardless of the growth in demand for commodity electricity, the increasing presence of information, computing and telecommunication technologies in every aspect of urban life has highlighted reliability concerns. New metrics have been developed to capture better the end user's perspective on electric reliability, and there is increasing investment in reliability enhancements on the customer side of the meter. Parallel pressures to reduce the environmental impacts and economic cost of electricity have combined to encourage significant experimentation with new technologies and institutional arrangements for this industry. This paper uses the experience of New York City with Hurricane Sandy in late 2012 to consider links between electric power system reliability, urban resilience, and the structure of this essential infrastructure sector. Key findings include recognition that the sector needs to re-invest at a high level to upgrade reliability, there are synergies between some but not all sustainability and resiliency solutions, and end users will continue to hold major responsibilities for ensuring their capacity to adapt during urban disasters, with attendant equity implications.

***Keywords:*** *Electric Power, Resiliency, Cities, Sandy*

## **1. INTRODUCTION**

The electric power sector has urban origins, beginning in 1881 with street lighting in a single British neighborhood, and evolving since then into networks that span continents and serve myriad uses. As electricity has shifted from an expensive local novelty into a cheap and widely available commodity, it has become an essential determinant of urban resilience. This paper presents a user-centered framework for assessing infrastructure services. It investigates how well the modern electric power sector meets performance criteria for urban resilience, drawing on New York City's experience of Hurricane Sandy in 2012. The paper then considers the potential and limits for future electric power sector configurations that might perform better.

## 2. ELECTRIC POWER SYSTEMS

City dwellers increasingly want and need electricity. Access to electricity is a key metric for economic development, and correlations are strong between per capita values of gross domestic product (GDP) and electricity consumption ( $r = 0.89$  across countries in 2011), and their annual growth rates ( $r = 0.78$  for worldwide growth from 1981 to 2011) based on data from the World Bank [1] and EIA [2]. These data sets also confirm that electricity consumption per capita tracks urbanization, most likely because GDP per capita does too.

Modern, large-scale electric power systems include generation, transmission, and distribution assets that are spatially dispersed and often owned by different parties even though they are physically interconnected and synchronously operated. Just as cities depend on their hinterlands for food and water, they also depend on distant power plants and robust transmission networks to deliver reliable electricity to urban customers. A supply chain view captures the key relationships, shown in Fig. 1. Distribution and consumption will always occur locally, but the upstream stages involve a mix of local and distant facilities.



*Figure 1: Traditional electricity supply chain*

Starting in the 1980s, regulators in many countries forced mature electric power systems to restructure, changing ownership patterns and contractual relationships among stages in the supply chain. Common patterns have been to encourage competition among primary fuel providers and generators, while treating transmission as a regulated common carrier and distribution as a regulated local monopoly [3]. This has had the effect of placing more market risk (and opportunity) on generators, thereby discouraging capital-intensive nuclear and even coal-based technologies, while encouraging natural gas-fired generation [4]. An unintended consequence was to discourage reinvestment in regulated, less lucrative transmission and distribution systems in countries such as the United States for several years, a trend that has been reversed [5]. Although difficult to prove conclusively, many serious analysts believe that U.S. system reliability has suffered [6,7].

Fig. 2 shows the pattern of major electric power outage events reported by the U.S. Department of Energy during 2011-2013. The distribution of events has a long tail, so that there are many fewer large events than small events. Event frequencies suggest a seasonal pattern; indeed, the four most impactful events (Hurricanes Irene and Sandy, an early winter snow storm, and a summer thunderstorm system) are all weather-related and affect the densely populated northeastern states.



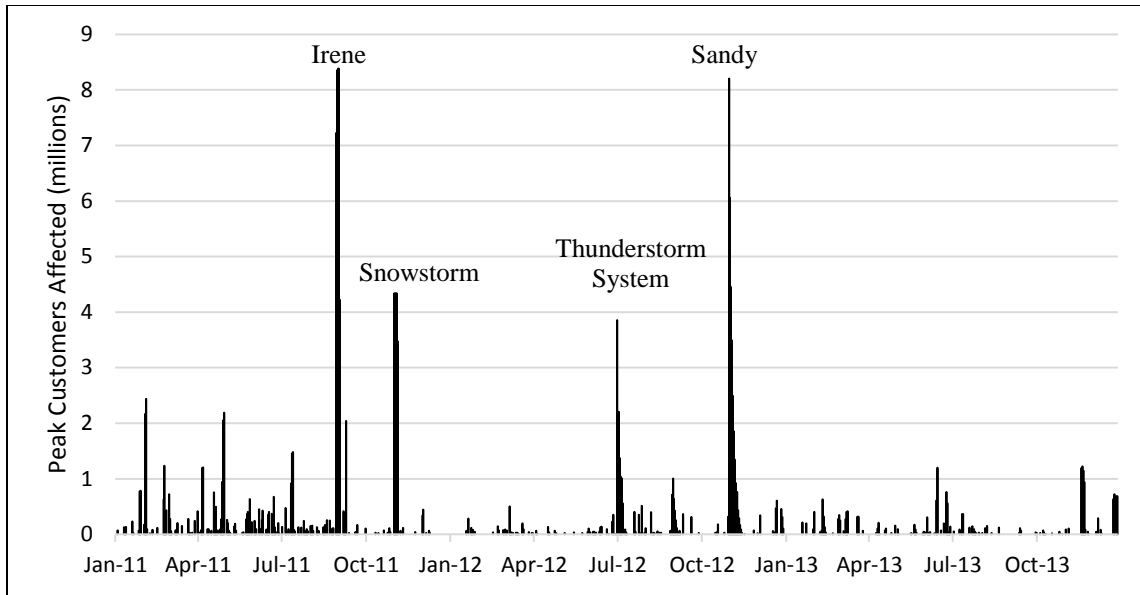


Figure 2: Major U.S. power outage events 2011-2013. Source: Compiled from OEDER Energy Assurance Daily reports 2011-2013 [8].

Fig. 3 confirms that the most frequent proximate cause of major outage events is weather, and that accidents and human error generally have relatively localized impacts. The U.S. Department of Energy data summarized in Figs. 2 and 3 show only major outage events affecting at least 10,000 customers. A more complete accounting of electric power system reliability would consider minor events too, that is, it would bring in a fuller set of localized, distribution-level events. It would also address the multiple dimensions of reliability including the *magnitude*, *frequency*, and *duration* of adverse events. Metrics that the industry commonly uses to assess progress and allow cross-system comparisons of reliability include the following:

SAIFI – System Average Interruption Frequency Index (interruptions per customer)  
 = Total number of customer interruptions / Total number of customers served

SAIDI – System Average Interruption Duration Index (minutes)  
 = Sum of customer interruption durations / Total number of customer interruptions

In international comparisons of electric power system reliability, the sprawling U.S. system does poorly relative to European peers. SAIFI and SAIDI for the United States are 1.5 and 240, respectively, which is worse than Austria (0.9, 72), Denmark (0.5, 24), France (1.0, 62), Germany (0.5, 23), Netherlands (0.3, 33), and the UK (0.8, 90) [9].

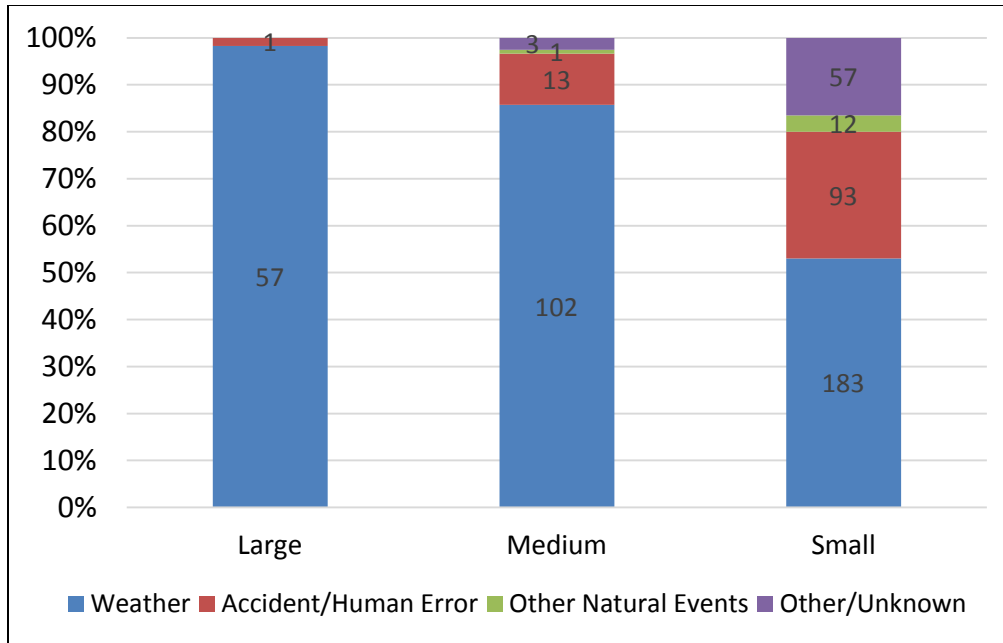


Figure 3: Causes of major U.S. power outage events 2011-2013. Large = 250,000+ customers, Medium = 50,000 – 249,999 customers, Small = 10,000 – 49,999 customers. Sources: Compiled from OEDER Year in Review (2011-2013) [10].

The metrics vary across U.S. utilities and regions, with SAIFI ranging in the same year from 1.22 in the Mountain States to 1.99 in the Pacific States, and SAIDI ranging from 118 in the Mountain States to 498 in the East North Central States [11]. Important for the urban context is relative contribution of bulk power (generation and transmission) and distribution to the metrics. Typical SAIFI values for transmission and distribution in a well-managed system are 0.117 and 0.915, respectively, yielding an overall value of 1.059; and for SAIDI they are 9.9, 102.4, and 115.4 overall [12].

### 3. USER-CENTERED FRAMEWORK

Industry analysts focus on financial metrics including capacity utilization and returns to capital when assessing the power business. Policy analysts assess the performance of electric power systems using metrics of reliability, cost, and environmental impacts. In the United States, the industry pursues reliability criteria largely with self-regulation, although in recent years the Federal Energy Regulatory Commission has acquired authority to backstop the industry efforts. State and federal regulators seek to ensure reasonable electricity prices by adjudicating whether the costs of regulated electricity services (transmission and distribution) are prudent, and establishing clear rules for competitive generation markets. Environmental regulation follows federal rules as implemented by states, and air quality regulations especially have had dramatic impacts on costs and technology choices in the electric power sector.

An alternative perspective that helps for discussing urban resilience is to focus on the end user’s experience. By viewing the electricity supply chain from the customer’s point of view, it becomes easier to see what each stage adds to a “value chain” [13] and to imagine alternative cost-effective means to achieve a customer’s objectives [14]. In recent years, the industry has developed corresponding metrics:

CAIDI – Customer Average Interruption Duration Index (minutes)  
 = Sum of customer interruption durations / Total number of customers served

MAIFI – Momentary Average Interruption Frequency Index (brief interruptions per customer)  
= Total Number of Customer Momentary Interruptions / Total number of customers served

Typical CAIDI values for transmission and distribution in a well-managed system are 84.7 and 111.9, respectively, yielding an overall value of 109 [12]. The overall MAIFI value for Pacific Gas & Electric (PG&E) is 1.636 for this metric and is of increasing interest in the digital age [12].

The end use perspective additionally requires the definition of end-use services, since no-one consumes electricity directly but rather uses it to power lights, computers, and other equipment that in turn deliver a desired functionality. Baccini and Brunner [15] offer a parsimonious set of categories that encompass essentially all urban human activities: Nourishing, Cleaning, Residing & Working, and Transporting & Communicating. Further subdivision of these categories identifies how electric power touches urban dwellers, as shown in Table 1.

Table 1 shows that electricity has become the type of network infrastructure upon which the most activities depend. This illustrates why reliable electricity supply has become so important in the urban context—without it, normal life cannot continue. However, a closer look somewhat mitigates these concerns, because alternative ways to perform many of these activities exist if the end user has done advance planning and has the capacity for improvisation. For example, candles or battery-powered flashlights can provide temporary lighting services, citizens can postpone laundering clothes or performing work, and they can amuse themselves with face-to-face socializing rather than on the Internet. Economists bundle these adaptive responses into an elasticity of demand concept to help predict how the aggregate demand profile for electricity varies. However, to understand better how electric reliability affects urban resilience it is useful to keep the end-use specific adaptive responses disaggregated.

#### 4. “SUPERSTORM” SANDY

A strong test of a modern city’s resilience came at the end of October 2012, when the tropical storm Sandy scored a direct hit on New York City (NYC) and New Jersey. The storm surge inundated densely populated, low-lying areas, and hundreds of thousands of residents of NYC lost electric power. The peak flood level for New York City (at The Battery) was 14.1 feet (4.3 m) above mean sea level, almost 5 feet (1.4 m) higher than the previous year’s Hurricane Irene; some 141 human lives were lost, and property damage exceeded \$20 billion [17] (p. 1). The official scorekeeper rated October 29, 2012, the day Sandy made landfall, as the highest stress day of the year for the North American grid, assigning it a severity risk index (SRI) of 27.89, where a value greater than 5.0 is “high stress” [18]. SRI includes three components: generation (1.95), transmission (1.78), and load loss (24.16); and the relative contributions of these three components supports a conclusion that the bulk power system was not strongly affected; instead, the major problems involved the distribution system and the end users of electricity [18].

The official 2012 SAIFI (0.36), SAIDI (44), and CAIDI (121) statistics for Consolidated Edison, the primary utility serving New York City, are bland, characterizing 2012 as being no different than the previous four [19]. However, these metrics do not capture well the per-customer performance of the city’s highly networked distribution system; hence the company also tracks frequency of interruptions per 1000 customers and average interruption duration in a year. Those metrics in 2012 were much worse than in previous years, at 3.66 and 58.49, respectively [19].

TABLE 1: ACTIVITIES AND RESOURCE NEEDS.

	Activity	Resource Requirement					Absence Tolerance
		Electric	Water	Gas	Sewer	Telecom	
Nourishing	Procurement of food						1 week
	Food storage	x					2 days
	Food preparation	*	x	*			1 day
	Fresh water for consumption	x	x				< 1 day
	Circulation of clean air	*					< 1 day
Cleaning	Bathing/showering	x	x	*	x		variable
	Toilet use		x		x		< 1 day
	Brushing teeth		x		x		1 day
	Laundering clothes	x	x	*	x		> 1 week
	Washing dishes	x	x	*	x		variable
	Solid waste removal						1 week
	Cleaning room surfaces	*	x	*			> 1 week
Residing & Working	Sleeping						< 1 day
	Working	**				**	1 week
	Entertainment/time-passing	**				**	variable
	Maintaining a comfortable ambient temperature	* ^		* ^			variable
	Repairs/maintenance in personally controlled space	**					indefinite
	Repairs/maintenance in common spaces	**					indefinite
Transporting & Communicating	Mobile phone use (voice and data)	x				x	variable
	Land line phone use					x	variable
	Connecting to the internet	x				x	variable
	Modes of egress and ingress: getting from personal space to/from building entrance	*					variable

Source: Hewitt, Oberg, Coronado & Andrews [16]

\* Depends on building design

\*\* Depends on specific activity

^ Depends on season

TABLE 2: CAUSES OF NEW YORK CITY ELECTRIC SYSTEM OUTAGES AND CUSTOMER IMPACTS FROM SANDY.

Outage Cause	Customers Impacted*
Overhead distribution damage	390,000
Substation flooding	345,000
Transmission system overload	140,000
Pre-emptive shutdown of networks	35,000
Customer equipment flooding	54,000

\* Overlaps of customer counts exist between categories

Source: NYC [20] (p. 115)

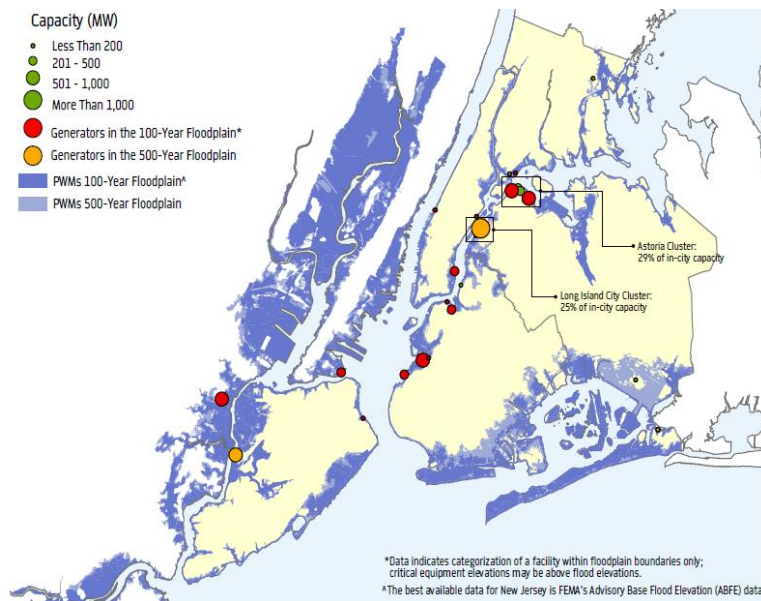


Figure 4: In-city electric generating facilities in the floodplain [20].

New York City typically has 62% of the generating capacity it needs within the city and relies on imports for the rest, but immediately post-Sandy the available capacity shrank by one third, mostly within the city, leaving the city more dependent than usual on transmission imports, although still well positioned to meet bulk demand [20] (p. 114). Of the in-city generation capacity, 53% sits in the current 100-year floodplain and 86% is in the 500-year floodplain; for transmission substation capacity the numbers are 37% and 63%, respectively; and for distribution substation capacity the numbers are only 12% and 18%, respectively [20] (p. 118). Critical equipment elevations at those sites luckily are often above flood elevations. However, as sea level continues to rise and larger storm surges become more frequent, these coastal assets (see Fig. 4) are at increasing risk.

Some 805,000 customers lost power in New York City during Sandy, with outage causes as shown in Table 2. The wind-related failure of overhead distribution lines was the single largest problem, and substation flooding was second. However, the bulk power network-related problems (substation flooding, transmission system overload, and pre-emptive shut down) were mostly resolved within four days, as shown in Fig. 5. Fixing overhead distribution lines dominated the next week, and thereafter the delays were primarily on the customer side of the meter. As Fig. 6 shows, power restoration following Sandy in 2012 took more than twice as long as it did following Irene in 2011, mainly because the storm surge flooded a greater number of customers, and overhead line repair crews were hampered by a subsequent Nor-easter (extra-tropical winter storm).

A vignette illustrates what happened on the customer side of the meter during Sandy. Wealthier residents of neighborhoods in lower Manhattan that lost power simply went uptown to regain their comforts, albeit at a cost. This was not an option for many poorer residents such as those living in public housing. The New York City Housing Authority (NYCHA) is the largest public housing agency in North America, with 2,596 residential buildings containing 178,914 apartments that house 403,736 legal residents, plus a voucher program that provides subsidized private-sector housing to another 225,000 people [21]. Public housing was built disproportionately in flood-prone waterfront areas during the 1930s-1960s because land was cheap, shoreline areas were under-utilized, and there were systematic efforts to replace derelict 19th century buildings containing worker housing [22,23]. Twenty-six multi-building developments housing 45,000 people were located in the mandatory evacuation zone, but only half of residents actually evacuated by the time

the storm hit, including 70% of a special needs population which totaled 3,296 mobility-impaired residents and 140 requiring life-sustaining equipment in those buildings [24].

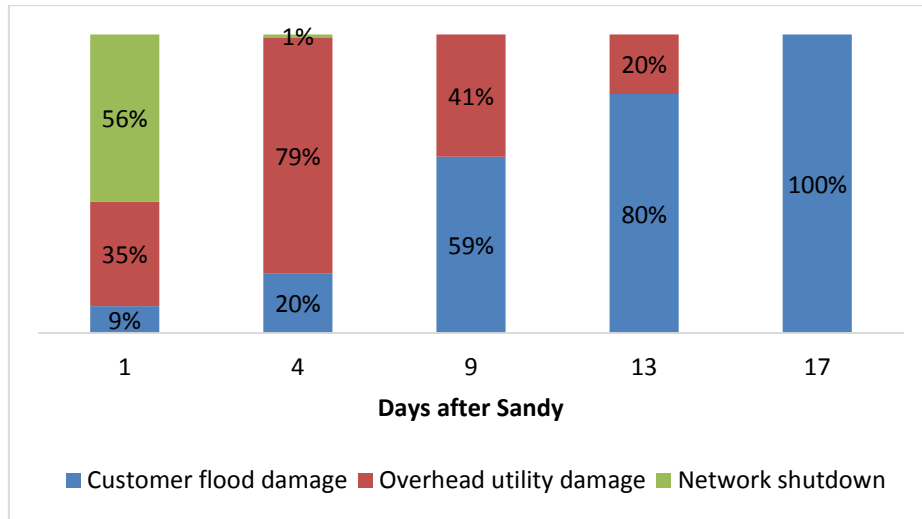


Figure 5: Customer outages by outage cause (% of daily total). Source: NYC [20] p. 115

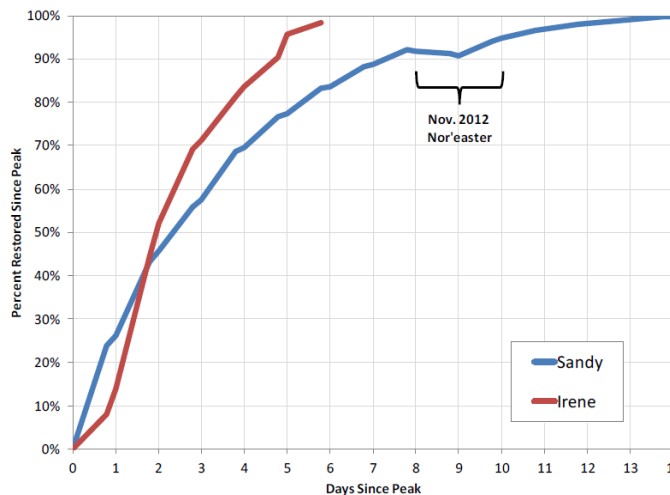


Figure 6: Comparison of power outage restoration percentages by storm. Source: OEDER [17], p 11

The suffering of NYCHA residents extended beyond the flood zone because of utility outages. The day after Sandy made landfall, 402 NYCHA buildings with 35,476 apartments housing nearly 80,000 residents had lost electric power. This knocked out elevator, lights, and often heat in the buildings. More acutely, right after the storm, 386 NYCHA buildings housing 76,817 residents lacked heat and hot water because 26 basement boiler rooms with 85 separate boilers were flooded [24]. A week after the storm, 114 buildings housing 21,000 people were still without electricity, and 162 buildings housing 33,583 residents lacked heat and hot water [24]. Two weeks after the storm, power was finally restored to all NYCHA buildings, although in some cases from portable generators instead of the electric power grid; and 94 buildings housing 18,019 residents still lacked heat and hot water [24]. Heat and hot water were not restored to all NYCHA buildings until almost three weeks after the storm, well after the first snows of winter had fallen [24].

## 5. REIMAGING THE ELECTRIC POWER SECTOR

It may be tempting to assert that if we simply pursue a sustainable vision for the electric power sector, then resilience will naturally follow, but New York City's recent experience leads to somewhat different conclusions. The Sandy case study suggests several lessons for making electric power systems and the cities they serve more resilient.

Advanced industrial countries are well able to manage their bulk power systems for high reliability. Aggregate outage statistics show that weather-related events are the immediate cause of most reliability problems in the electric power sector. These data also confirm that the distribution and customer links in the electricity supply chain cause the largest fraction of reliability problems. Thus, the choice of whether we generate electricity from coal or wind—an important distinction in sustainability terms—is largely irrelevant to the electric power sector's contribution to urban resilience. A vision for a grid powered by solar or wind energy could work well, especially as energy storage technologies improve, but the decentralized version depending rooftop solar, for example, will only thrive in a land-rich exurban or suburban context, but not in densely crowded cities with high-rise buildings. Most of the solar panels and wind turbines will still need to be outside the city limits and therefore dependent on vulnerable transmission and distribution networks to deliver power to customers.

There are two technological strategies that offer great potential for aligning sustainability and resiliency objectives. The first is **energy efficiency**, because more efficient buildings and end-uses reduce the burden on infrastructure services and make back-up supplies more affordable. The second is the use of **combined heat and power (CHP)** systems that locally transform natural gas (among other fuels) into heat and electricity. New York University's new CHP system made it an island of comfort in Manhattan's darkened downtown during Sandy [20].

Strategies that focus primarily on enhancing urban resilience span the regulatory, technological, and social arenas of action. NYC [20] provides the following useful list:

- **Redesign the regulatory framework to support resiliency** (develop a cost-effective system upgrade plan to address climate risks, reflect these in system design and equipment standards, establish performance metrics).
- **Harden existing infrastructure to withstand extreme events** (protect key generators, transmission assets, and distribution infrastructure from flooding; harden overhead lines against winds; protect natural gas and district heating infrastructures from flooding).
- **Reconfigure utility networks to be redundant and resilient** (repower and upgrade older downtown power plants, add transmission lines to facilitate power imports including offshore wind, require more in-city plants to be able to restart quickly after blackouts, disinvest in distribution to flood prone areas, relieve transmission limitations to large load pockets in central areas, reconfigure networks and switching to allow more precise pre-emptive shutdowns prior to storm events and better preservation of service to critical customers such as hospitals, implement smart grid technology to improve real-time assessment of system status, establish pre-connections for mobile substations).
- **Reduce energy demand** (expand demand-response programs, expand energy efficiency in buildings).
- **Diversify customer options in case of utility outage** (scale up distributed generation and microgrids, experiment with electric vehicles and local energy storage, improve backup generation for critical customers).

The most cost-effective items on this list are the most prosaic: submersible network protectors, tree clearing, generation levees, sensing, substation hardening, distribution system hardening, overhead line sectionalizing, flood sectionalizing, and mobile substations [20](p. 124). Given the demonstrated vulnerability of overhead distribution, it may make sense to put more of the system

underground. **Undergrounding** of distribution networks is expensive and is quite rare in the U.S. context, and New York City's resiliency report considered it to be a less cost-effective strategy. However, a multi-country comparative analysis of European electric power industry practices confirms that (1) undergrounding correlates with population density, (2) undergrounding improves system reliability on both the SAIFI and SAIDI metrics, and (3) it brings aesthetic and other non-reliability benefits [25]. Cost multipliers for underground relative to overhead distribution links have dropped from 20x in the 1970s to 4x-10x today [26]. Undergrounding could become a standard part of coordinated efforts to co-locate urban service corridors in "joint trenches" (Tallahassee), "common utility ducts" (Bremen), "common services tunnels" (Singapore), and "utilidors" (Taipei) [27].

The final bullet on New York City's list (customer-side options) deserves amplification. Urban dwellers can do a great deal to prepare better for adverse events including power outages. Most New York City residents who lived in the city during the "9/11" attack in 2001 have learned to pack a "go bag" of essential items in case evacuation becomes necessary, and almost every urban household in the world has a flashlight or candle handy in case of an electricity outage. More and more digital devices include batteries to assuage the effects of momentary outages. Where electricity is less reliable and people can afford the cost, backups may be more extensive. The storms Irene and Sandy have encouraged many homeowners in the leafy suburbs (where overhead distribution lines frequently fail) to install backup generators. These range from small portable, gasoline-burning units to large, permanent installations powered by natural gas, demonstrating that some customers are willing to pay thousands of dollars for improved electric reliability. Those who cannot afford such backups are left in the dark, as we saw for the NYCHA residents. There is clearly a common-sense level of preparation that all city dwellers should achieve, but it is also clearly inequitable to allow the electric power system to deteriorate to the point where only rich enjoy reliable service.

In conclusion, urban resilience depends on having reliable electric power infrastructure, and this sector, especially the distribution component, needs continued investment at a higher level than is currently typical in the United States. Energy efficiency and combined heat and power represent win-win solutions for sustainability and resiliency, but many other valuable actions only advance one or the other of these objectives. Customers have responsibilities too to prepare for outages, but infrastructure providers have a moral obligation to ensure that inequities between those who can and cannot afford to pay for extra preparedness do not become excessive.

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# Role of Smart Vision in Creating Intelligent and Resilient Cities

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### **Abstract**

The intelligent traffic surveillance system as an important part of a smart resilient city is reviewed. The superiority of the multi-camera vision in more accurate extraction of traffic data compared to single camera imaging is explained. The smart traffic control system is not only important in improving the lifestyle by decreasing the traffic density and air pollution, it is also vital in preparing for and rescuing from the emergency conditions such as earthquakes and floods. Still, multi-camera vision is more helpful in dealing with different disasters. Apart from its superior features, existing multi-camera surveillance systems suffer from computational complexity and degraded accuracy. To overcome this shortage, three-dimensional (3D) optical techniques for fusing the multi-camera images and extracting 3D vehicle locations are proposed in this paper. The result of 3D image reconstruction from these techniques shows their dominance in providing the 3D object location.

**Keywords:** *Earthquake Engineering, Value Based Seismic Design, Structural Assessment, Endurance Time Method, Nonlinear Dynamic Analysis*

## 1. INTRODUCTION

The role of information and communication technology (ICT) in creating a resilient city is to create a smart city infrastructure system which is cost and resource efficient. Monitoring and management of water cycle, energy usage, transportation and traffic, and air pollution, are among the main issues to be considered in a smart city infrastructure.

The history of human beings is closely tied to water. Fresh water has been a key factor in the emergence of civilizations, not only for direct human consumption but also for agriculture and animal husbandry. Mankind has been clever and creative with respect to the use of water, but also the cause of its contamination and shrinking availability. Worldwide falling groundwater levels, disastrous droughts and calamitous floods are increasingly attributable to human activity, and deteriorating water quality is directly so. Integrated water cycle management is a way for local water utilities to sustainably manage their water systems to maximize benefits to the community and environment. Water cycle is vital for any city so it must be monitored in order to assure a perfect system performance. The network of sanitary sewers of a city manages the disposal and storm water harvesting, and the transport, control and treatment of waste water. This system must work perfectly and it must be able to react against unexpected situations in order to minimize the

economic losses produced by natural disasters such as floods. Thus, sensors could be integrated throughout the city's sewerage infrastructure to monitor and regulate sewage flows on a mathematically optimized basis. They might also monitor and detect leakages, which can then be fixed early to avoid costly structural damage.

The other important issue of a smart city infrastructure is the natural resource management. Worldwide global water consumption has tripled since 1950 [1]. Smart cities must monitor water supply to ensure that there is sufficient access for citizen and industry. Wireless sensor networks provide the technology for cities to more accurately monitor their water pipe systems and identify their greatest water loss risks. Cities that are addressing water leakages with sensor technology are generating high savings from their investment. Sensors can be used to help cities constantly monitor water use across their local area. These sensors can measure water consumption, detect water leakages, prevent water loss problems and reduce a city's water and electricity costs. Existing and future civic buildings in the city could be equipped with a network of sensors to monitor and control water usage in these buildings. Additionally, they could be incorporated with a building management system, which controls their heating, ventilation and air conditioning for optimal thermal comfort and energy savings.

Another important part of a smart city infrastructure is closely related to the intelligent transportation system. An intelligent transportation system could be established in the city by integrating wireless sensors into its road infrastructure. The sensors might monitor traffic and adaptively control traffic signals in real time. The system can lead to reduction in traffic congestion and carbon emissions, thus enhancing public health. Furthermore, the data collected from the sensors could be invaluable for future transportation planning projects. This system might be designed to facilitate priority routes for emergency vehicles, to be detected in real-time. Vehicle traffic can also be monitored in order to modify the city traffic lights in a dynamic and adaptive way. Processing the images captured with the cameras installed at the crossroads helps in automatic estimation of the traffic congestion on each side. This way, the length of green and red signals could be set accordingly. Traffic control and monitoring could also be performed through multi-camera vision and three-dimensional (3D) imaging. In this way, a more precise tracking and detection could be performed via captured 3D images instead of two-dimensional images of only one camera. Understanding the flow and congestion of vehicular traffic is essential for efficient road systems in cities. Smooth vehicle flows reduce journey times, reduce emissions and save energy. Similarly the efficient flow of pedestrians in an airport, stadium or shopping center saves time and can make the difference between a good and a bad visit. Monitoring traffic - whether road vehicles or people - is useful for operators of roads, and transport hubs. The monitoring system can also be used to calculate the average speed of the vehicles which transit over a roadway by taking the time mark at two different points. This platform can help drivers to avoid congested roads through provision of real time warnings on electronic displays or via smart-phone applications. Similarly, pedestrian monitoring enables improvements to be made in the operation of airports, shopping centers, tourist attractions and sports stadiums. Such data can even be used to assess the suitability of emergency evacuation plans.

A smart city infrastructure can also help in solving atmospheric pollution. The quality of city life across the world is negatively impacted by atmospheric pollution and congested roads. Road congestion results in lost time for motorists, wasted fuel and is a major cause of air pollution. A significant contribution to congestion arises from motorists searching for available parking spaces - often requiring a considerable time before they are successful - and is a major cause of driver frustration. Providing accurate information to drivers on where to find available parking spaces helps traffic flow better and allows the deployment of applications to book parking spaces directly from the car. Motorists get timely information so they can locate a free parking slot quickly, saving time and fuel. The sensors may then track the vehicles' length of stay and charge parking fines if the vehicles exceed their parking limits. This information can reduce traffic jams and atmospheric

pollution, improving the quality of life. It has also been recently asserted that, due to the revenue-generating nature of parking, smart parking systems could be the ideal foundation for building municipal wireless networks. These sensing networks could later be extended to include other types of sensing such as adding road surface temperature and noise sensing capabilities to its smart parking portfolio. Among mentioned branches of a smart resilient city, smart transportation system, natural resource management and controlled air pollution could all be managed through a smart surveillance system. Traffic control is of great importance in Iran and especially in Tehran as of the problem of air pollution and traffic congestion. The existing smart traffic control systems in Tehran mainly include the systems for automatic traffic congestion estimation and speed control. The Automatic congestion estimation is performed through radar systems called remote traffic microwave sensors (RTMS) and inductive loops. Through using these structures, the number of passed vehicles, the type of vehicles and their speed is measured automatically. From the estimated traffic volume the traffic signals' duration are set automatically at cross-roads. Ground magnetic loop detectors are accurate but are expensive and difficult to maintain, requiring significant work, such as the excavation of road surfaces, while providing limited information, since their data is only for a point in space. Video monitoring systems, however, are easy to install and maintain, making them significantly more flexible, since changes can easily be implemented. They also have the potential to provide more information than can be obtained from point detectors as they capture information over a wide area. In recent years, the use of camera vision in traffic control systems used in Iran is growing. The automatic speed control system, red light enforcement system, emergency green road and traffic restricted zone management system, are examples of using smart traffic surveillance system in Iran. An example of an image processed for red light enforcement at a cross-section in Tehran, is shown in Fig. 1. Still, broad aspects of an intelligent traffic control system could be implemented through camera vision and image processing including traffic congestion estimation and traffic signal timer control. These aspects of camera vision are presently utilized in some smart cities such as Seoul, Singapore and New York.



Figure 1: Red light enforcement through image processing at a cross-road in Tehran [Tehran traffic control center].

Therefore, in this paper, different approaches proposed till now for smart vision traffic control in a resilient city have been investigated. Among these methods, the specific focus of this paper is on intelligent multi-camera surveillance used for automatic traffic control. Multi-camera vision and

its necessity and application in traffic control are reviewed in Section 2. Section 3, explains different applications of single camera and multi-camera smart vision in emergency conditions. Section 4 covers our proposed solution for improved smart traffic control system through improved multi-camera vision based on stereo 3D imaging. Finally, section 5, concludes this paper.

## **2. SMART TRAFFIC SURVEILLANCE THROUGH MULTI-CAMERA VISION**

Intelligent video surveillance has been one of the most active research areas in computer vision. The goal is to efficiently extract useful information from a huge amount of videos collected by surveillance cameras by automatically detecting, tracking and recognizing objects of interest, and understanding and analyzing their activities. Video surveillance has a wide variety of applications including traffic control. There is an increasing interest in video surveillance due to the growing availability of cheap sensors and processors, and also a growing need for safety and security from the public. Nowadays there are tens of thousands of cameras in the road network of a city, collecting a huge amount of data on a daily basis. Researchers are urged to develop intelligent systems to efficiently extract information from large scale data.

The view of a single camera is finite and limited by scene structures. In order to monitor a wide area, such as tracking a vehicle traveling through the road network of a city or analyzing the global filled and empty locations in a parking lot, video streams from multiple cameras have to be used. Many intelligent multi-camera video surveillance systems have been developed [2-4]. It is a multidisciplinary field related to computer vision, pattern recognition, signal processing, communication, embedded computing and image sensors. Some key computer vision technologies used in multi-camera surveillance systems are as follows:

1. Multi-camera calibration which maps different camera views to a single coordinate system. In many surveillance systems, it is a key pre-step for other multi-camera based analysis [5-8].
2. The topology of a camera network identifies whether camera views are overlapped or spatially adjacent and describes the transition time of objects between camera views [9-15].
3. Object re-identification is to match two image regions observed in different camera views and recognize whether they belong to the same object or not. This technique is purely based on the appearance information without using spatial-temporal reasoning.
4. Multi-camera tracking is to track objects across camera views [16,17].
5. Multi-camera activity analysis is to automatically recognize activities of different categories and detect abnormal activities in a large area by fusing information from multiple camera views.

Multi-camera tracking requires matching tracks obtained from different camera views according to their visual and spatio-temporal similarities. Matching the appearance of image regions is studied in object re-identification. The spatio-temporal reasoning requires camera calibration and the knowledge of topology. Some studies show that the complete trajectories across camera views can be used to calibrate cameras and to compute the topology. Therefore, multi-camera tracking can be jointly solved with camera calibration and inference of the topology. Multi-camera tracking is often a pre-step for multi-camera activity analysis, which uses the complete tracks of objects over the camera network as features. It is also possible to directly model activities in multiple camera views without tracking object across camera views. Once the models of activities are learned, they can provide useful information for multi-camera tracking, since if two tracks are classified as the same activity category, it is more likely for them to be the same object. A good understanding of the relationship of these modules helps to design optimal multi-camera video surveillance meeting the requirements of different applications. Still, intelligent multi-camera video surveillance faces many challenges with the fast growth of camera networks. A few of them are briefly mentioned below.

- A multi-camera video surveillance system may be applied to many different scenes and have various configurations. As the scales of camera networks increase, multi-camera surveillance systems should self-adapt to a variety of scenes with less human intervention. For example, it is very time consuming to manually calibrate all the cameras on a large network and the human effort has to be repeated when the configuration of the camera network changes. Therefore, automatic calibration is preferred. Object re-identification and multi-camera activity analysis prefer unsupervised approaches in order to avoid manually labeling new training samples scenes and camera views change.
- The topology of a large camera network could be complex and the fields of views of cameras are limited by scene structures. Some camera views are disjointed and may cover multiple ground planes. These bring great challenges for camera calibration, inference of topology and multi-camera tracking.
- There are often large changes of viewpoints, illumination conditions and camera settings between different camera views. It is difficult to match the appearance of objects across camera views.
- Many scenes of high security interest, such as street intersections are very crowded. It is difficult to track objects over long distances without failures because of frequent occlusions among objects in such scenes. Although some existing surveillance systems work well in sparse scenes, there are many challenges unsolved in their applications to crowded environments.
- In order to monitor a wide area with a small number of cameras and to acquire high resolution images from optimal viewpoints, some surveillance systems employ both static cameras and active cameras, whose panning, tilting and zooming (PTZ) parameters are automatically and dynamically controlled by the system. Calibration, motion detection, object tracking and activity analysis with hybrid cameras face many new challenges compared with only using static cameras.

A more thorough investigation of these problems reveals a common reason behind most of them, and that is the complicated and random nature of image processing. Automatic self-adaptation of camera views for different scenes, camera calibration, topology estimation, vehicle tracking and activity analysis are mainly relying on object re-identification. Object recognition is completely done through image processing which is in turn sensible to different parameters such as illumination condition, occlusion, rotation and other transformations. In other words, the main goal of an automatic traffic monitoring system which is to detect different still and moving vehicles is mainly influenced by itself. Topology estimation, camera view adjustment and activity analysis are all used to help in better object detection and tracking while are all influenced by the accuracy of the object detection procedure itself. Accordingly, to follow a more systematic approach in a smart traffic surveillance system, different arrangements such as topology estimation, activity analysis, camera view setting and occlusion concealment should be performed upon another concept other than object recognition and image processing. In this paper multi-camera image fusion is done through the concepts of optical three-dimensional (3D) imaging which is completely based on the geometrical and diffractive optical principals other than image processing. Afterward, image processing is used for detection and tracking of still and moving vehicles in reconstructed 3D images. The concept of the major incoherent multi-camera 3D imaging systems named as integral imaging and incoherent holography will be reviewed in the following section while their usage in improving the multi-camera traffic surveillance systems is explained subsequently.

### **3. THE ROLE OF SMART VISION IN EMERGENCY CONDITIONS**

A city will not always experience the normal conditions. If a disaster does occur, for example a cyclone, earthquake, tsunami or mass transport accident, then the ability to respond quickly and

effectively is paramount. Smartness could be effective in all related processes including predicting, responding to and recovering from a range of natural and man-made disasters. Thus, in this section we will mainly focus on different implemented and potential usage of a smart traffic control system based on smart vision in appropriate handling the emergency conditions.

### *3.1. Different Usage of Smart Vision in Emergency Management*

Perhaps the mildest emergency conditions that may occur in a city are the air pollution and traffic saturation which could be managed and diminished through smart surveillance traffic control systems. They can control the traffic flow in a limited area and provide traffic information to vehicle drivers to take other route for traffic flow dissemination. The aim is to prevent traffic congestion and to decrease environmental pollution, thereby protecting the health of pedestrians and residents along roads.

Fatal chain accidents are the other case of small size miseries. Police agencies have been struggling to improve this situation by shorting the time lag between occurrences of an accident and calling of rescue, with a wish to help as many lives as possible. When a traffic accident occurs, the location data obtained by the global positioning system (GPS) is sent automatically or manually from the in-vehicle terminal to the rescue center. The example of such system is working in Euro: When in-vehicle push-button is pressed, or when sensor signal for airbag expansion etc. is detected, the in-vehicle GSM cellular phone automatically calls Service Operation Center (SOC) to notify an emergency. When SOC answers, the system provides SOC with the user identification number as well as the vehicle location detected by the in-vehicle GPS terminal. Still, the location of the accident and the degree of aroused damages could be detected through the smart surveillance system and transferred to the nearest police station and hospital. In this way, a more complete data would be transferred to the police station and more precise reaction could be performed consequently.

When large scale disasters such as earthquakes and floods occur, information can also be collected promptly on the disaster status through the network of smart vision systems. The cameras can collect and process the 2D and 3D images from different regions in the ruined area. Different useful information such as the location of important catastrophes including injured persons, probable occurred conflagrations, broken water pipes, car crashes and so on, could be extracted through processing of these images. The other vital information to be extracted from the captured images is the location of rescue centers such as hospitals, fire-fighting centers and police offices. It also becomes possible to carry out traffic regulations of general vehicles, guidance of rescue vehicles, and priority passage control. Of course the communication of these networks of cameras is done through the existing communication services in the city such as VSAT (satellite communications), wireless communications in UHF and VHF bands and fiber optics networks. When information communication facilities are damaged in the disaster area, their backup system will be substituted. These backup systems should be more robust in emergency conditions than others. From flexibility point of view, satellite communication networks are more robust in emergency conditions than optical fibers and radio communications. Optical fibers may be broken in earthquakes and floods and radio base stations may fall down or become misaligned in disasters. Using cellular networks data communication can be possible as long as the transmitters are powered. The power supply at the transmitter and repeater stations are critical factors in case of major earthquakes.

In all mentioned emergency conditions, the common role of smart surveillance system is to collect images from the critical locations and extract the required information about the injured persons and damaged locations. Notwithstanding with this fact, these information could be extracted more accurately from 3D images instead of 2D ones, as they provide three-dimensional spatial information. Furthermore, from the previously gathered 3D spatial information, the city

could be simulated in different emergency conditions and appropriate emergency preparedness could be performed.

### *3.2. Role of 3D Spatial Information in Emergency Management*

Three-dimensional spatial information extracted from captured 3D images could be of superior help in making the city more disaster resilient. A good example of this system could be found in Seoul. Since 2001, Seoul metropolitan government has been increasing the capabilities of its 3-dimensional (3D) spatial information system: a mapping application providing 3D street information and enabling the provision of new smart services [18]. In April 2008, the system supported the launch of three new services: 1) “Geographical Information”, which allows users to view streets as if standing upon them; 2) “Tour with a Theme Information”, which highlights tourist attractions, offering its users a virtual tour of Seoul; and 3) “Urban Planning”, an application allowing city planners to simulate infrastructure development or renovation. Improved further by high-quality photographs and video clips in 2009, 3D spatial information will be very useful in monitoring the environment, preventing disasters and constructing disaster-resilient infrastructure. For example, flood simulations developed in 2012 aid in predicting which areas will be worst affected by floods, thereby enabling the development of preemptive flood-response mechanisms.

The other examples of using 3D spatial information for emergency handling could be found in New York City, USA [19]. In part of their strategic plan a framework is described for how the City will leverage spatial data in the years ahead to improve New Yorkers’ lives. The interactive city map of New York provides information on transportation, education, public safety, resident service and city life. The office of Emergency Management operates a GIS, which maps and accesses data - from flood zones and local infrastructure to population density and blocked roads - before, during, and after an emergency case.

In general, crisis-management systems can be founded on three columns, the Crisis Preparedness Plan, the Early Warning System, and Rescue and Management Action [20]. A good crisis preparedness plan is the turnkey for any operational crisis management system and needs highly interdisciplinary work. Usually an inventory of natural and artificial structures and their potential for risk is obligatory and builds its basis. The natural disaster potential must be evaluated by geological and hydrological research. In case of an earthquake, the geological structure transports the various waves. Geological and hydrological data build the basic layers in a geo-database. This information can also be part of an early warning system. Aerial surveys use airborne cameras and/or airborne LIDAR sensors and are able to deliver a high-density DTM (digital terrain models) and DSM (digital surface models). The better the input data the more precise the final model and the results it produces.

As part of the crisis-management system, they are dependent on data other disciplines produce. Photogrammetry and remote sensing contribute to the GIS application; 3D data and animation in a virtual reality environment contribute to understanding sustainable city development. To simulate different scenarios in 3D helps all involved getting a better understanding of the need for changing existing structures to produce a safer city. Infrastructural objects such as roads, bridges, pipelines, and dams must be part of a master plan that aims to reduce the risk and show ways to access areas in case of a disaster. Dealing with such amounts of various data needs a powerful server or a server farm with a spatial database. A centralized data server is needed for modeling data and for managing crises. Spatial information sciences use geo-data servers to store these data and to give access to specialists for analyzing, modeling, and to produce new data sets. Such data collection enables one to set up an early warning system and to organize a disaster management plan.

The crisis preparedness plan must contribute to the rescue planning. Crisis preparedness means to simulate the disaster and to adjust the rescue plans. The geoscientific data deliver models



e.g. estimation of possible destroyed infrastructure by shock waves. Other simulations might deliver run-up simulations and their efficiency on the urban structure. Results are maps that points out where help is needed. The geo-database can then assist in planning the best access to these areas. Where are the roads to access these places, which hospital is the closest, how to get machines and other material there? Where will people go when in panic? What infrastructures can create additional disasters? This extremely interdisciplinary cooperation might result in a “rescue plan” which also can be used to manipulate input variables to improve the city planning and to define rules. Finally, a good rescue plan must include the population. Interactive maps, oblique images and 3D city models with virtual reality simulations assist in training people for the emergency conditions.

With respect to the important role of 3D vision in making the city more resilient in ordinary and emergency conditions, improvement in 3D vision is of major significance in this field. Therefore, in this paper an improved 3D vision through multiple cameras is proposed and compared with the commonly in use multi-camera surveillance systems. The proposed smart surveillance system based on 3D imaging is explained in the next section.

#### **4. IMPROVED SMART TRAFFIC SURVEILLANCE SYSTEM THROUGH 3D VISION**

In commonly in use smart traffic surveillance systems via multi-camera vision, image fusion is completely performed through image processing techniques. The calibration and registration of the different images, taken from variant view-points of a scene is performed through extracting different image features and mathematically matching them. The most commonly used for merging multi-camera images and extracting the depth information is line-path triangulation. However, inferring the visible surface depth from two or more images using light-path triangulation is an ill-posed problem due to the multiplicity of ways in establishing point correspondences in the input images. To alleviate this problem of ambiguity, different rectification algorithms [21,22] have been proposed to rearrange image pixels so that the corresponding points (that result from the projection of the same 3D point) will lay on the same image scan line. Even with this powerful constraint in hand, identifying stereo correspondences is still a very challenging problem. A great number of stereo algorithms have been proposed in the past few decades and many of them are surveyed in [23,24]. Among all these algorithms, dynamic programming (DP)-based optimization techniques are often used due to its simplicity and efficiency. DP is an efficient algorithm that constructs globally optimal solutions by reuse and pruning. One common way to achieve global optimality and stabilize the DP-based stereo matching results is to impose the continuity (or smoothing) constraint. That is, neighboring pixels (most likely) view 3D points that lie closely together, and hence, should have similar stereo disparity values. However, this constraint is only applicable to a single or a few neighboring scan lines, and applying this constraint often results in undesired striking effects. Furthermore without using any ground control points (GCPs), or reliable anchor points, as guidance, DP is very sensitive to the parameters chosen for the continuity constraint [25]. In other multi-view fusion methods used in video surveillance, different view images are registered and fused through geometric constraints of the roads [26]. Among these methods, single plane probability fusion map (PFM) is more successful [27,28]. However, since the co-planarity of image points is not strictly true, the single plane PFM is subject to distortions, which lead to less accurate measurement of target positions and dimensions. More other works have been done in terms of 3D model matching for tracking and vehicle classification [29,30]. However, in these approaches it is important that there be no occlusion in the first few frames for correct matches to be established. Otherwise, any subsequent tracking is suspect. Therefore, all image processing based approaches for multi-camera image fusion are error prone to a high extent as of different reasons such as occlusion, anchor point misidentification and non co-planarity of corresponding image points, to name a few. In other words, for a growing number of cameras the

existing methods become infeasible for two reasons: (a) The number of required camera-to-camera homographies increases dramatically which gives rise to the computational complexity and (b) the information fusion becomes more and more complicated requiring more processing utilities and taking more time. An example of 3D urban image reconstructed from multi-camera views is shown in Fig. 2.

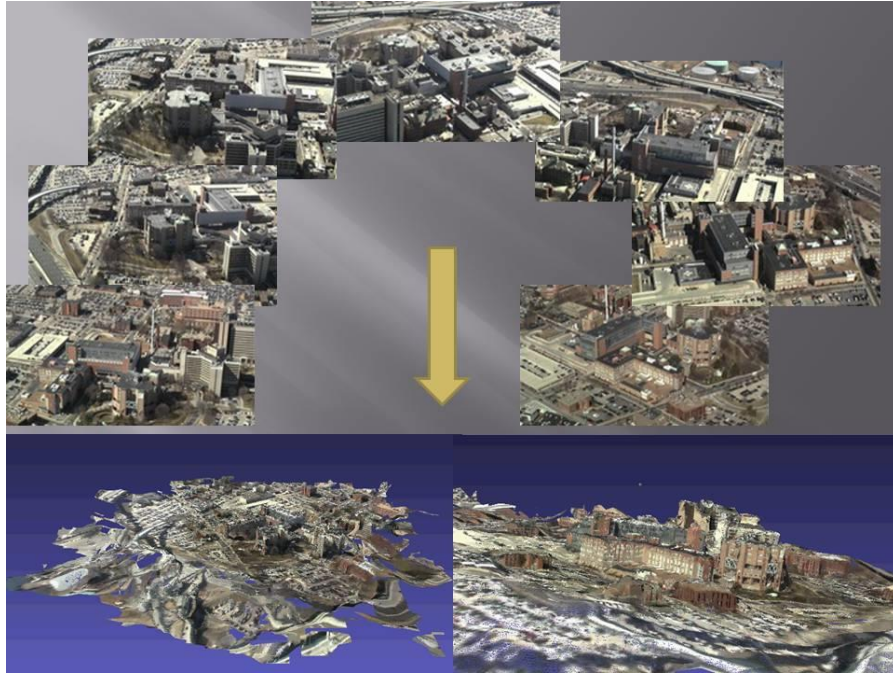
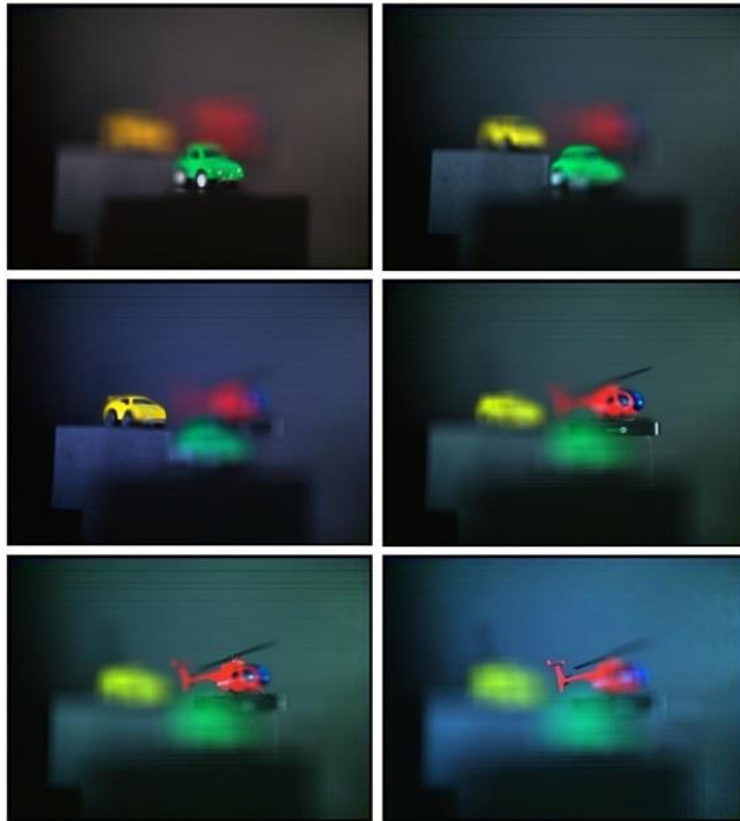


Figure 2: Multi camera images (upper part) and reconstructed 3D images (lower part) of an urban region based on image processing [<http://excelsior.cs.ucsb.edu/lab>].

On the other side, optical three-dimensional (3D) imaging techniques are able to extract the 3D image information and thus 3D objects location through the principles of geometrical and diffractive optics from the same set of multi-camera images. The main advantage of using 3D imaging concepts in addition to image processing techniques fusing images and extracting the location of vehicles in still and video images is to make use of optical concepts when image processing fails to give accurate response, due to non-dependent nature of these processes on the image contents. Furthermore, image fusion techniques do not depend on image contents making the process much faster. Integral imaging and incoherent holography are the main 3D imaging systems based on multi-camera vision. In integral imaging the 3D image information could be extracted from the array of 2D images captured with a set of cameras from different view-points, computationally [31]. In this structure, the 3D information is extracted from the recorded intensities in different directions through the principles of geometrical optics. Given that the captured image of each camera gives the information of a different viewing angle of the 3D object, the information of the third dimension – depth information – would be available in the captured images. An example of multi-camera images and the resulted fused images in different depths are shown in Fig. 3.a and b respectively.



(a)



(b)

Figure 3: (a) Set of multi-camera images and (b) the fused images in different depths based on geometrical optics (integral imaging).

The second 3D imaging technique, incoherent holography, is based on mapping each view image captured by each camera to a spatial frequency coefficient of the object's reflectivity pattern [32]. Each view point image captured from a different camera brings the information of a specific spatial frequency vector,  $(k_x, k_y, k_z)$ , in 3D space based on the rules of wave optics. In this way, the

object's Fourier hologram could be extracted from the set of 2D images captured from multiple cameras which in turn will yield the 3D object's reflectivity pattern. The set of multi-view images together with the reconstructed 3D image in different depth based on incoherent holography are shown in Fig. 4a and b, respectively.

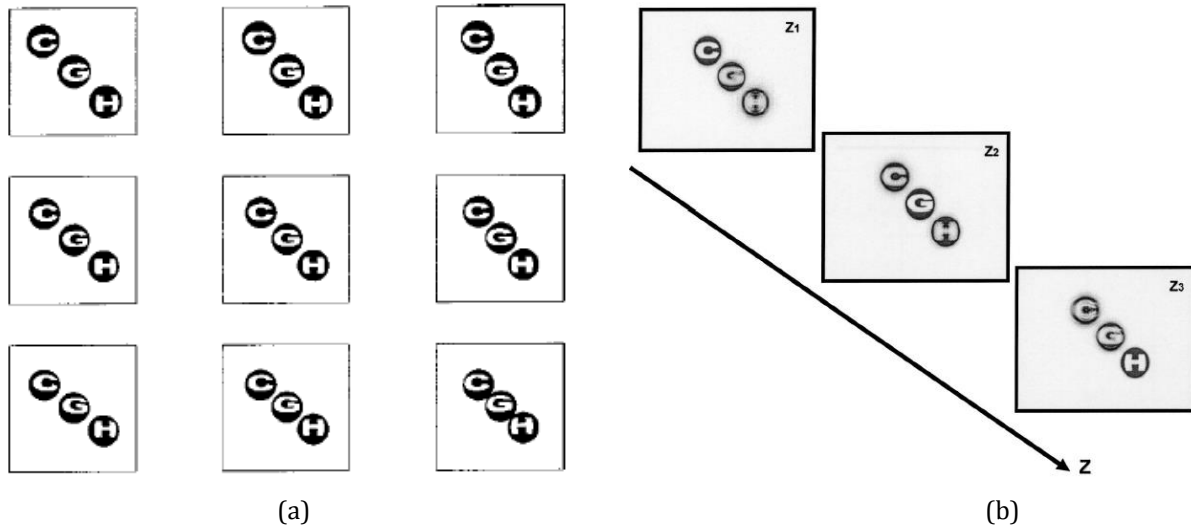


Figure 4: (a) Nine projections of the 3D objects projected from various viewpoints. (b) 3D image reconstruction in different depth values (where C, G and H are located) based on wave optics (incoherent holography) [28].

In both explained 3D imaging techniques the set of multi camera images are merged through the principles of optics. Thus, the image content of each camera does not affect the fusion process. In other words, object detection and image processing does not interfere in the image fusion procedure. They are just used in final step when the 3D vehicle or other object location is to be extracted from the reconstructed 3D still images or it should be tracked in 3D video images. In this way, adding the concept of optical 3D imaging to the image processing technique, multi-camera vision could be more helpful in finding the exact location of vehicles in streets and parking lots and tracking moving cars, making the smart traffic control system more perfect. This superior performance could be concluded by comparing the 3D images obtained from optical principals shown in Figs. 3 and 4 and the 3D images from image processing based fusion demonstrated in Fig. 2. It could be seen that, optical 3D image reconstruction yield more 3D spatial information with much less computational complexity compared to image processing based fusion. Furthermore, in emergency conditions, obtaining the 3D image of the disastrous regions will be faster and more accurate by making use of the mentioned 3D optical multi-camera image fusion techniques in addition to image processing.

## 5. CONCLUSION

By employing distributed camera networks, traffic video surveillance systems substantially extend their capabilities and improve their robustness through data fusion and cooperative sensing. With multi-camera traffic surveillance systems, activities in wide areas are analyzed, the accuracy and robustness of vehicle tracking are improved by fusing data from multiple camera views, and one camera handovers objects to another camera to realize tracking over long distances without break. Multi-camera vision is also advantages in preparing for and rescuing from the emergency conditions by providing the location of ruined regions and rescue centers.

As the sizes and complexities of camera networks increase, there are higher requirements on the robustness, reliability, scalability, transferability, self-adaptability and less human intervention of intelligent multi camera traffic video surveillance systems. Recent studies show that different modules actually should support each other. For example, activity modeling can improve inter-camera tracking and multi-camera tracking provides information for camera calibration and inference of the topology of camera views. Notwithstanding with this fact, this interference in turn gives rise to error propagation resulted from different image processing and pattern recognition techniques.

Multi-camera stereo image fusion could also be performed through the concepts of geometrical and wave optics. These fusion techniques do not dependent on image processing and object recognition and tracking. Therefore, in these fusion techniques, no feedback is essentially required from the final object detection and image processing step. This in turn lessens the amount of resulted error propagation and thus improves the accuracy of multi-camera traffic surveillance systems while lessening the computational complexity by a great amount.

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# The Efficacy of Remote Sensing Technologies for Building Damage Assessment – An Analysis of the December 26, 2003 Bam, Iran Earthquake

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### ***Abstract***

This paper, originally published as a preface to a collection of papers on the Bam, Iran earthquake [1], is reproduced for this workshop to demonstrate the efficacy of remote sensing technologies for post-earthquake building damage assessment. The referenced papers collectively are a significant milestone in post-earthquake loss estimation. For the first time, independent evaluations of regional damage are documented which will ultimately allow an assessment of the efficacy of these technologies as tools for post-earthquake damage detection and quantification. Not only were different sensors used, but radically different approaches were implemented in quantifying damage. The conclusions and recommendations of the different papers are generally consistent and strongly suggest that regional damage assessment using remotely sensed data is highly feasible. The papers, however, acknowledge that more research is needed before these technologies can be used to make critical emergency response decisions. Finally, the role of the Earthquake Engineering Research Institute through its *Learning from Earthquakes* Program is acknowledged, largely for helping to promote the use of remote sensing technologies in earthquake studies and for recognizing the value of international collaboration among researchers. EERI has granted the authors permission to reproduce the preface in whole; this permission is gratefully acknowledged.

***Keywords: Remote Sensing, Damage Assessment, Bam, EERI***

## **1. INTRODUCTION**

The twelve papers mentioned in Table 1 come from engineers and scientists in five different countries and chronicles research on detecting region-wide building damage after the December 26, 2003 Bam, Iran earthquake. This collection of papers is significant for many reasons. Importantly, the methods of damage detection that are documented in these papers are based solely on the use of remote sensing technologies. Additionally, the Bam earthquake is one of the first events where a broad range of sensors were available to record the effects of the event, and for which an archive of satellite data existed prior to the occurrence of the event. Many of the datasets used by the authors were provided by DigitalGlobe, Inc. through a multi-user license purchased by

the Earthquake Engineering Research Institute through its *Learning from Earthquakes* Program. This support is gratefully acknowledged.

It should also be noted that a decision was made by the editor of this special issue (Earthquake SPECTRA, Special Issue 1, Volume 21) [2] to publish each paper as a separate contribution. It was felt that because the area of remote sensing within the context of post-earthquake damage detection is evolving so rapidly (in large part due to the rapid advancement in commercial remote sensing technologies), and because the intended audience for these papers are generally familiar with the effects of earthquakes but perhaps not in the use of remote sensing technologies for damage assessment, that a comprehensive presentation of results – albeit preliminary - would be most valuable.

## 2. IMAGERY TYPES AND METHODOLOGIES

Each of these studies suggest that satellite remote sensing can supplement more traditional post-earthquake reconnaissance practices by providing independent and more global assessments of damage in large events. Huyck et al. [3] suggest the following benefits from using remote sensing technologies in combination with field-based surveys:

- *Overview of damage:* The imagery used for damage assessment spans a large geographic area, including numerous urban settlements with a single frame.
- *Near-global coverage:* Earth-orbiting satellites support damage assessment throughout the World, including both developed and lesser developed nations, where the effects of natural disasters may be particularly acute.
- *Supplements existing maps:* Satellite imagery provides an easily interpreted visual representation of damage, in the context of surrounding urban areas. This capability is particularly useful for lesser developed regions, where map coverage and geographic databases are often limited.
- *Low risk:* For international emergency response and aid organizations, decisions concerning the scale of relief efforts can be safely made in the immediate aftermath of an earthquake event, at a time when ground based assessment is extremely dangerous.
- *Resilient communication:* When the usual communication channels are down, satellite connections remain active.
- *Independent of time and weather:* Synthetic aperture radar (SAR) satellites offer 24/7, all weather monitoring. SAR imagery can be acquired under the cover of darkness and in cloudy conditions.
- *Fast response:* Satellites will ultimately provide real-time post-disaster information.
- *Loss estimation:* The damage assessment provides input data for initial loss estimates.

Fig. 1 provides a contextual framework for the papers that follow. The papers have been categorized based on several different criteria: 1) whether single or multiple images are used to assess building damage; 2) the type of sensor, i.e., radar versus optical imagery; and 3) the resolution of the data, i.e., high versus moderate resolution. In all cases, images were developed from spaceborne platforms (satellites).



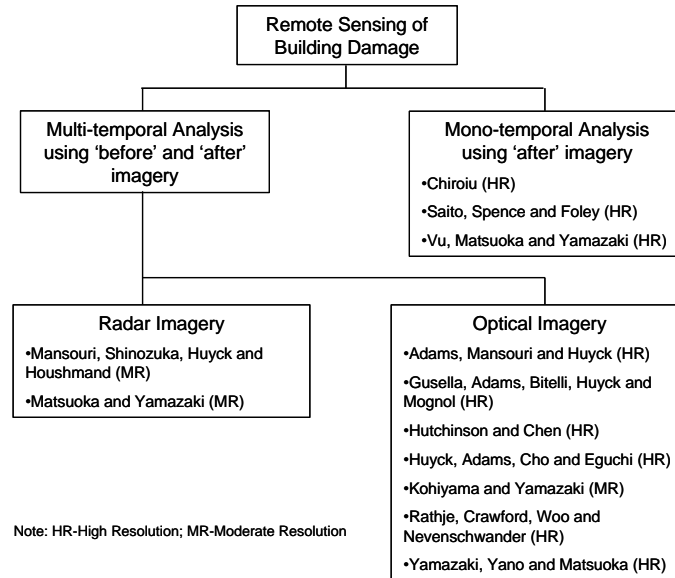


Figure 1: Contextual Framework for Remote Sensing Papers.

For the Bam, Iran earthquake, the methodological approaches employed are either *mono-* or *multi-temporal*. While the former distinguishes between the appearance of damage and non-damaged structures within a given scene, the latter infers damage in terms of change between a temporal sequence comprising ‘before’ and ‘after’ images. Multi-temporal damage detection is an extremely active research area, where considerable progress is attributed to collaborative efforts in Japan and the U.S.

The papers on the Bam, Iran earthquake constitute a progress report on the development of qualitative and quantitative approaches to building damage detection using satellite imagery. Even though these studies were done over a decade ago (i.e., in 2003), the general conclusions and recommendations made are still useful. These studies employ both optical and radar coverage and use moderate- and high-resolution images. Optical sensors such as QuickBird (operated by DigitalGlobe) and IKONOS (operated by Space Imaging) are widely used in earth observation. Images are easy to interpret as they depict the ground surface as it appears to the human eye. Although more difficult to interpret as it records surface geometry, radar imagery has the advantage of 24/7, all weather viewing capability. As shown in Fig. 1, both types of imagery have been implemented in the assessment of building damage after the Bam earthquake, with the vast majority of papers documenting the use of high-resolution optical data.

### 3. MAJOR FINDINGS

Table 1 in Appendix 1 on page 258 provides a summary of major findings from each of the remote sensing papers. In general, the following overarching findings encompass the essence of these papers:

- Multi-temporal analysis using high-resolution optical imagery serves as a good indicator of severe building damage (i.e., building collapse), and is a valuable complement to field-based surveys.
- Mono-temporal analysis using high-resolution optical imagery also produces good indicators of severe building damage. However, in some cases, damage is underreported or underestimated.
- Currently, measurable damage states using high-resolution optical technologies are limited to collapsed and severe but non-collapsed states.

- Synthetic aperture radar (SAR) sensors are effective at measuring large-scale, regional damage. However, because of their coarse resolution, they cannot be used to assess damage to individual buildings.
- Damage assessments using two independent but similar sensors (QuickBird and IKONOS) show consistent results.

These findings are considered preliminary and may change with further research. Furthermore, it is anticipated that as remote sensing technologies continue to develop and improve, the ability to differentiate damaged from non-damaged structures, and to characterize different levels of damage, will also improve. Given the progress achieved over the last several years, it seems reasonable to assume that by the year 2010, accurate and near real-time assessments of damage region-wide will be possible using a combination of moderate- and high-resolution optical and radar satellites.

#### **ACKNOWLEDGMENTS**

The authors wish to thank EERI for kindly allowing the authors to publish the preface from the 2005 Special Issue on the Bam, Iran.

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APPENDIX 1, TABLE 1: SUMMARY OF MAJOR FINDINGS FROM REMOTE SENSING PAPERS ON BAM EARTHQUAKE. NOTE: ALL OF THE PAPERS IN TABLE 1 WERE PUBLISHED IN EARTHQUAKE SPECTRA [2]

Author(s)	Paper Title	Approach	Major Findings
Adams, Mansouri and Huyck	Streamlining Post-earthquake Data Collection and Damage Assessment in Bam using VIEWS (Visualizing Impacts of Earthquakes With Satellites)	Post-event data collection system that uses real-time GPS feeds to geo-locate and geo-reference video and photos to before- and after-event satellite imagery.	High-resolution satellite imagery and GPS feeds helped EERI survey team members to navigate through the city, collect perishable damage data, and pinpoint locations of collapsed structures.
Chiroiu	Damage Assessment of Bam, Iran using IKONOS Imagery	Visual interpretation of post-event image to identify areas of significant building damage; estimate casualty levels based on damage mapping.	Compared with published statistics, methodology underestimates number of injuries by about 50% and number of fatalities by about 25%. One of the first attempts at quantifying casualty levels based on remotely sensed data.
Gusella, Adams, Bitelli, Huyck and Mognol	Object-oriented Image Understanding and Post-Earthquake Damage Assessment for Bam, Iran	Compare changes in pre- and post-event imagery using object-based classification schemes.	Re-classification scheme based on initial training sets led to an accuracy index of about 70% in identifying number of collapsed structures. About 6,500 buildings were estimated to have collapsed during the Bam earthquake out of a total of 19,000 structures.
Hutchinson and Chen	Optimized Estimated Ground Truth for Object-based Urban Damage Estimation using Satellite Images	Multi-level damage assessment approach based on scale of region-of-interest; detailed assessment based on object-based segmentation.	A three-level damage scale (collapse, very heavy damage, negligible) appears to be adequate in representing the distribution of individual house damage in this event.
Huyck, Adams, Cho and Eguchi	Towards Rapid City-Wide Damage Mapping using Neighborhood Edge Dissimilarities in Very High Resolution Optical Satellite Imagery	Assess edge dissimilarities between pre- and post-event images to quantify extent of building damage.	Methodology useful in detecting areas of individual building collapse; more refinement needed to examine lower damage levels.
Kohiyama and Yamazaki	Damage Detection for Bam, Iran using Terra-ASTER Satellite Imagery	Uses moderate-resolution imagery (15m) to create pre- and post-event probability distributions of digital numbers (DN) to characterize changes associated with damaged structures.	Good success in identifying areas of heavy structural damage; however, more work is needed in separating these effects from other conditions leading to change, e.g., dusty roads, debris removal.
Mansouri, Shinozuka, Huyck and Houshmand	Earthquake-Induced Change Detection in Bam by Complex Analysis using Envisat ASAR Data	Examines various change detection indices using repeat pass interferometric synthetic aperture (SAR) radar data.	Cross-power differencing correlates well with regional damage statistics.
Matsuoka and Yamazaki	Building Damage Mapping of Bam, Iran, Earthquake using Envisat/ASAR Intensity Imagery	Assesses differences in backscattering coefficients between pre- and post-event synthetic aperture radar (SAR) images to quantify the degree of change in images.	Automated damage detection technique that was applied in the 1995 Kobe earthquake appears to work well in the Bam, Iran earthquake when adjustments are made to reflect local backscattering characteristics.
Rathje, Crawford, Woo and Neuschwander	Damage Patterns from Satellite Images from the 2003 Bam, Iran Earthquake	Employs a semi-automated thematic classification algorithm to identify damage patterns based on a comparison of pre- and post-event high-resolution imagery.	Results compare well with field survey data. Suggests that parameter optimization may be possible, but will depend in large part on the area of the world that is imaged.
Saito, Spence and Foley	Visual Damage Assessment of Bam, Iran using High-Resolution Satellite Images following the Bam Earthquake on 26 <sup>th</sup> December 2003	Visual interpretation of damage using post-event images only, and pre- and post-event images.	Damage levels are generally underestimated when only post-event images are used. Good correlation of results when pre- and post-event images are used.
Vu, Matsuoka and Yamazaki	Detection and Animation of Damage in Bam City using Very High-resolution Satellite Data	Applies edge intensity and variance algorithms to post-event images.	Distribution of damage consistent when two independent, high-resolution optical sensors (QuickBird and IKONOS) are used.
Yamazaki, Yano and Matsuoka	Visual Damage Interpretation of Buildings in Bam City using QuickBird Images	Visual damage interpretation based on European Macroseismic Scale	Comparison with field results shows good agreement; however, underestimation of damage occurs for some higher damage states.

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# Water Reuse – A Bridge to Sustainable Water Management

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### **Abstract**

Water Reuse has long been a way for communities to decrease the stress on their drinking water supplies. Considering the current drought in California and much of the Southwest and the reality of climate change and population growth trends, communities in the Southwest are looking for new and sustainable methods for managing their already scarce water resources. Water reuse can be viewed as a bridge to the sustainable management of water resources as it creates the potential to close the loop between wastewater treatment and drinking water supply. By speeding up the natural water cycle, it can offer communities a local and more stable supply of drinking water through the concept of direct potable reuse. When evaluating water supply options, it is important that communities consider the full economic, environmental, and social benefits of all options. When these costs and benefits are analyzed, communities will have the tools to use a holistic approach to balance the availability of potable water and the costs of new supplies to select the appropriate water reuse activity.

**Keywords:** *Water, Water Treatment, Water Reuse, Direct Potable Reuse, Sustainability, Triple-Bottom-Line*

## **1. INTRODUCTION**

With advancing technologies, high profile drought events, and improving public perception, communities are increasingly turning to reusing wastewater and stormwater as a means to supplement dwindling drinking water supplies and meet the needs of a growing population. As communities move to a more sustainable approach of managing their limited water resources, water reuse will become a key tool by serving as the bridge from wastewater treatment to drinking water supply. Water reuse can give communities the opportunity to better manage their resources on a local level by reducing their reliance on outside sources of water. Additionally, communities can save money by reusing wastewater for applications that do not require potable water, thereby preventing the overtreatment of water.

Water reuse has received increased attention of late due to the well-publicized and ongoing drought in California. As of June 3rd, 2014 nearly 25% of California is classified as being under Exceptional Drought while over 76% is under Extreme Drought [1]. This threatens significant economic damage to the state especially from its traditionally vibrant agricultural sector throughout the Central Valley. In some ways this is a replay of recent droughts in the Midwest and

Texas in 2011 where at its peak, 88% of the state was under Extreme Drought [2]. The Texas AgriLife Extension Service estimated that the 2011 drought in Texas resulted in \$7.62 billion in agricultural losses [3].

It is important to view these drought events not as anomalies unlikely to occur again but as warning signs of what might become a “new normal” for precipitation patterns as the effects of climate change become more acute. The Intergovernmental Panel on Climate Change (IPCC) has stated that global warming of approximately 2°C is very likely to result in more frequent low snow years, earlier snowmelt, and more intense droughts [4]. Aside from growing pressure from climate change, population growth in California and the Southwest threaten to put further strain on freshwater resources. From 2000 to 2010 the five fastest growing states (AZ, ID, NV, TX, and UT) are all in the western region of the country in regions with limited freshwater resources. In addition California added 3.4 million more residents in this time period, second to only Texas [5]. It is evident that drought is not going anywhere, and communities are going to have to find ways to manage their water resources in a more sustainable fashion, of which water reuse is an integral part.

## **2. WATER REUSE AND ECONOMIC SUSTAINABILITY**

One of the basic challenges facing utilities nationwide is funding necessary operations and maintenance activities and infrastructure improvements. In many cases, user rates do not cover the full cost of construction, operations, and eventual replacement of vital infrastructure with water utilities struggling to raise sufficient revenues. Water reuse creates new opportunities by creating new revenue streams by selling reclaimed water, decreasing costs by avoiding the overtreatment of wastewater, and lessening the need to expanding potable water systems by reducing demand.

In many applications of potable water, users do not need water treated to current drinking water standards. Water intensive activities such as irrigation and industrial cooling consume large quantities of water, but neither application necessarily requires water treated to full drinking water standards. Obviously there is a cost to treating water and if water is treated beyond what is necessary, there is then significant room for savings. This topic was investigated in the recently released report from the WaterReuse Research Foundation entitled “Fit for Purpose Water: The Cost of Overtreating Reclaimed Water” (WRRF-10-01). This report aims to quantify the costs of overtreating wastewater, including environmental and social costs. These are costs that can be recovered by utilizing a robust water reuse program by matching the end-use need for water quality to the proper level of treatment.

When planning for the future, it is always better for water utilities to have reliable methods to project future costs. In general, barring any unforeseen regulatory changes the cost of treating wastewater/drinking water can be expected to follow historical trends. In terms of water reuse, this predictability of cost is especially valuable as it can allow a utility to accurately predict the cost of maintaining a reliable stream of water able to be used for a variety of purposes. This is especially important in drought prone areas such as California that rely on imported water, which can vary year to year in price, for their supply. It is much easier to plan for the future with a predictable cost rather than an unpredictable one.

With any type of water reuse, there is always some level of upfront investment needed to get a reuse program off the ground. The type and amount of investment needed varies depending on the level of treatment required and the end users of recycled water. For nonpotable reuse for landscape irrigation and many industrial uses, the primary upfront cost is the “purple pipe” distribution system needed to ensure that recycled water does not contaminate potable water. This can be a substantial investment especially if established communities need to be disrupted in order install pipes or pump stations. However, capital improvement programs that schedule the installation of purple pipe whenever existing drinking water or wastewater pipes are being serviced can reduce

the need for disturbing neighborhoods and communities. For advanced water reuse applications such as indirect or direct potable reuse, new distribution systems are limited and in some cases non-existent, thereby reducing costs. Instead, much of the upfront costs will be in the form of advanced treatment systems such as reverse osmosis and/or advanced oxidation processes. This topic will be explored further in an upcoming White Paper on the *Economics of Direct Potable Reuse* from WaterReuse. In times of water stress, there may be a tendency to hope that conditions will change to make such investments unnecessary, but based on current climate patterns and population growth, it is likely only a matter of time before water reuse investments are necessary. There are certainly communities in the south and west that wish they had such investments already in place. Even in regions with sufficient supplies of potable water, future population growth will necessitate expansion in capacity for drinking water treatment and distribution. In this case, water reuse can offset potable water demand and therefore reduce the need for future expansions and their attendant costs.

### **3. ENVIRONMENTAL BENEFITS OF WATER REUSE**

In addition to the potential economic benefits from pursuing water reuse, there are environmental benefits as well. One such benefit of water reuse is that it has the potential to reduce the need for surface or groundwater as a source of potable water, thereby protecting existing resources. One example of this in action is the Groundwater Replenishment System (GWRS) in Orange County, California. The GWRS is an indirect potable reuse system that injects half of its purified water into recharge basins to replenish its groundwater supply. The other half is pumped into injection wells to prevent seawater intrusion from contaminating Orange County's groundwater basin. Many aquifers, both coastal and inland, are under threat from salt intrusion that can contaminate freshwater sources. These aquifers carry enormous importance both as a source for drinking water and irrigation for agriculture. Reuse applications such as those implemented by the GWRS provide a proven framework for putting these valuable resources on a sustainable path forward so they can be utilized by future generations.

In California, a major source of controversy regarding the management of their water resources is the protection of endangered species, primarily the delta smelt in the San Joaquin Delta. This fish is often viewed as a bellwether for the overall health of the watershed in the northern part of the state that can affect the water allocations in the southern part of the state. Current drought conditions have greatly reduced the amount of water available to pump to the southern portion of the state through the State Water Project and the Central Valley Project, in part to protect the aquatic habitat in the San Joaquin Delta. If implemented in southern California, water reuse has the potential to reduce the need for imported water from the north, thereby supporting the natural flow of water in the San Joaquin Delta. This would allow for greater protection of the delta smelt, the potential restoration of native salmon populations, and decreased tension between agricultural interests in the Central Valley and environmental groups.

Additionally, by reducing the transfer of water from the northern to the southern part of the state, the environmental cost of transporting this water is greatly reduced. In part, this cost comes in the form of the energy required for conveyance along with the subsequent air emissions from energy production. California has estimated that the State Water Project uses between 3.9 and 9.9 million MWh of electricity per year to pump water through its system. This results in emissions of between 1.2 million and 4.1 million Megatons of CO<sub>2</sub> per year [6]. Overall, 20% of electricity used in the state comes from the transportation, treatment, and disposal of drinking water and wastewater [7]. Utilizing water reuse can decrease reliance on energy intensive water transfers and decrease the attendant greenhouse gas and other associated air pollutant emissions. While these costs may not directly affect the bottom line of a community or utility, they should be factored into the decisions made in regards to water supply.

#### 4. SOCIAL BENEFITS OF WATER REUSE

Aside from the potential economic and environmental benefits of water reuse, there are significant social benefits that can be difficult to quantify. For one, there is prestige attained in “green” design and activities. Studies have shown that buildings with LEED or Energy Star Certification have sale prices 15-30% higher than comparable properties without certification [8,9]. This is partially due to the economic benefits of green buildings from energy savings but it also reflects a preference among potential residents and commercial tenants to live and work in a more sustainable environment. This preference can come from a general feeling of contributing to environmental sustainability but it can also come from the aesthetics of a green roof or the novelty of unique architectural designs. Therefore, it can be expected that a community pursuing a progressive water reuse program can gain new interest and investment due to environmentally sustainable activities.

Additionally, some water reuse applications like landscape irrigation can result in valuable green space and recreation facilities that are attractive to new residents while improving the general quality of life of existing residents. This can take the form of increased physical activity due to attractive green spaces, habitat for wildlife, and public spaces for community events. In communities at risk of drought, this can go even further by giving residences peace of mind that they have an increased level of control over their water supply and are less reliant on outside sources. Unlike economic benefits, the social and environmental benefits are harder to quantify. However, they should be considered when evaluating the possibility of pursuing a water reuse scheme. WateReuse will explore this topic further in the upcoming project titled “Methodology for a Comprehensive Analysis (Triple-Bottom-Line) of Alternative Water Supply to Direct Potable Reuse” to give communities greater clarity when evaluating water reuse options (Fig. 1).

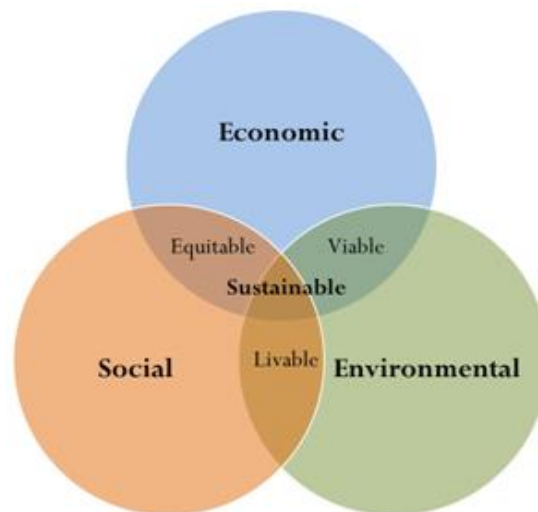


Figure 1: Triple Bottom Line Approach.

#### 5. SELECTING WATER REUSE OPTIONS

Utilities and other decision makers should take the preceding economic, environmental, and social factors into consideration when evaluating potential water reuse strategies. By looking at a community’s water needs and combining those needs with these economic, environment, and social factors, beneficial water reuse options can be identified resulting in projects that can reap benefits all along the triple bottom line spectrum. A simplified way to look at this is to view recent trends in water availability and the cost of alternative water supplies to water reuse (Fig. 2).

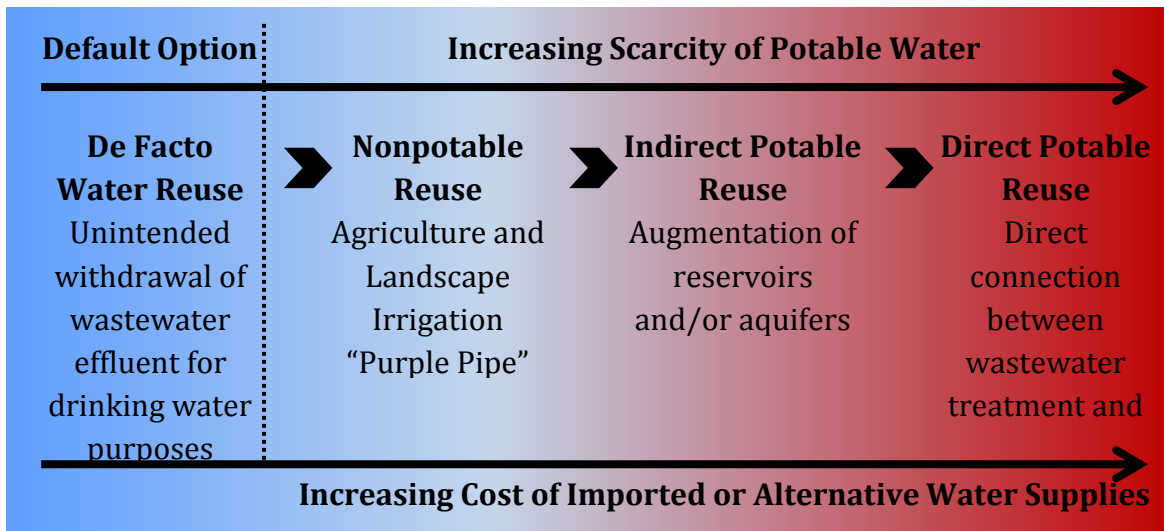


Figure 2: Water Reuse Option Selection Hierarchy.

This is a simplified approach, but it illustrates the reality that as potable water supplies diminish and the cost of alternative supplies increases, communities will need to look towards water reuse to meet their potable water needs. A full accounting of costs and benefits (economic, environmental and social) of different water supply options can give communities the necessary tools to match their water supply needs to the available supply options. For example, communities with stable water supplies but a growing population may find the best option to be nonpotable reuse to reduce potable water demand and delay the expansion of drinking water treatment plants. Communities with few resources and rising costs may find it advantageous to pursue a more aggressive approach. Regardless of the final outcome, it is important that communities and utilities conduct a complete evaluation of all available options to ensure the long-term fiscal health of utility operations and protect the environment and existing water resources for future generations all while serving the specific needs to existing residents and businesses.

## 6. DIRECT POTABLE REUSE

Of the Water Reuse options outlined above, direct potable reuse (DPR) offers the most direct connection between wastewater treatment and drinking water supply. This differs from de facto water reuse and indirect potable reuse in that there is no environmental buffer between the treatment process and introduction into the drinking water supply. This is a proven concept that has been implemented in places like Windhoek, Namibia and the International Space Station. However, to ensure that DPR is protective of public health, the WaterReuse Research Foundation's Direct Potable Reuse Initiative is funding over \$6 million in research to investigate every step of the DPR process. This includes investigating the reliability and robustness of a variety of treatment train options, real-time monitoring of various chemicals and pathogens that may pose a threat to public health, and identifying critical control points in the treatment process. Utility concerns will also be addressed by determining the full cost and benefits of DPR compared to other sources of potable water as well as ensuring that operators of such facilities have the proper knowledge and training. Public perception will also be addressed through research to determine community concerns and develop communications strategies.

In general, it is the goal of the Direct Potable Reuse Initiative to give communities the resources to develop DPR facilities that are reliable, self-monitoring and healing, and protective of public health (Fig. 3). So far this work has been focused in California where the aforementioned drought



has significantly strained drinking water sources. However, DPR facilities are already in operation in Texas (Big Spring and soon Wichita Falls) and other small facilities are being planned in the Southwest. This makes the WaterReuse Research Foundation’s research all the more important because a failure at one facility has the potential to set back the adoption of DPR.

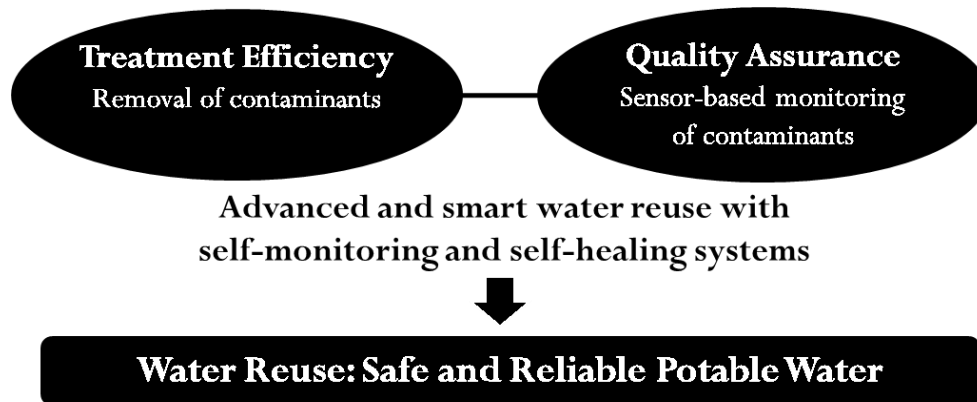


Figure 3: Self-Monitoring System.

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## U.S.-Iran Symposium on Resilient Cities

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# Integrated Water Management for Resilient Cities

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### **Abstract**

Sustainable urban development is now a major concern in many emerging and developing countries. Provisions of education, employment, health, social and cultural services are seen as basic demands of urban dwellers, and it definitely has a great effect in formation of resilient cities. Naturally central as well as local governments are forced to provide proper infrastructures to face the ever increasing needs of the urban population. One of the most important necessities of modern cities is availability of potable water and acceptable sanitation. In arid and semi-arid regions of the world, water is considered as an expensive commodity. Resources are limited and supply of fresh potable water is not freely available. Therefore the need for better resources management and efficient water use is significant. In this context the water consumption and water provision could be dealt with in a cycle of what is called “Integrated Urban water Management.” It may also be part of a modern concept in development of cities with potentials to resist difficulties in time of water shortages and drought seasons.

District 22 of greater Tehran municipality is a classic case. Fast development and very limited resources in this area has forced authorities to consider various alternatives to meet their ever increasing needs for water. Within available means, efficient treatment and reuse of wastewater and collection of runoff are considered as the main sources of make-up water for the artificial lake under construction in the area. Change in consumption patterns and provisions of water with different qualities for households are met with resistance by the population but it may inevitably be accepted in near future.

**Keywords:** *Water Reuse, IUWM, Tehran's Water, Water Management*

## **1. INTRODUCTION**

Water is a scarce commodity in many new urban developments, particularly in arid and semiarid regions. The frequently used term of “Integrated Urban Water Management” (IUWM) has been considered as an overall solution to ease water needs of high populated metropolises for some time. The traditional practice of centralized urban water supply, sanitation, and drainage systems dates back to the mid-19th century, as a response to typhoid and cholera epidemics that swept European and American cities between the 1830s and 1870s (London outbreak of cholera is a typical example) [1]. The need for better hygiene eventually led to development of centralized urban water services and modern sewage collection and treatment systems [2]. Although benefits

of centralized water services are clear and considered as basic necessity of modern era developments, over consumption of natural resources has led to adverse impact on the environment and has limited planned urban programs. There are many examples of over reliance on natural resources that have resulted in disastrous consequences. Drying up of natural lakes in recent years, such as "Urumieh" and "Bakhteghan" are catastrophes that have occurred in Iran and are known as good examples of environmental negligence. Apart from constraints on the natural environment, other issues that may be as important include: adverse effect on aquatic habitat and natural ecosystems due to reduced naturally available flows; salinity of aquifer and rising contaminations in underground or surface waters (recent case study of Tehran's aquifer [3]), negative consequences for native flora and fauna and stream-flow quality of river basins and coastal waters, and finally economic burdens due to high cost of maintenance and repair or replacement of distribution networks [4]. These are only some of the more important consequences of over reliance on centralized water systems that are common in many urban areas. In addition, in areas of fast urban growth, population increase creates a need for additional water supply that has even resulted in social conflicts (e.g. recent community clashes over "Zayandehrud" river water in central Iran). Climate change and lower rainfalls and long draught periods have contributed to this issue greatly.

In this paper the IUWM principle studied for many large cities in different parts of the world has been overviewed and compared to a suburban area of Tehran. The concept of alternative water resources considered as a lever to lower water demands is looked at in more detail. As "water recycling" and re-use has grown to the extent that it forms a formidable part of water resources in many large urban environments, the arguments for and against its implications are mentioned.

## **2. IUWM CONCEPTS**

Considering the definition of resilient cities and the case for water consumption, water shortages may be a potential treat. There could be a conflict over meeting increased urban water demands and the traditional means of water supply. Internationally, the appropriateness of the traditional centralized urban water supply, sanitation, and drainage systems, each separately designed and operated, is now subject to consideration. If one looks at cities of both developed and developing countries, it becomes apparent that rather urgent decisions must be made with regard to the way in which urban water services are provided [5]. The emergence and acceptance of the idea of IUWM has occurred globally during the last three decades [6], although historically it has always been present and practiced in arid regions all over the world [7]. Some researchers have rightly attributed the idea to natural necessity that has emerged due to water shortages as a result of over population and rapid developments. The idea of a water balance in urban water resource issues, and the need for a more holistic and integrated understanding about the way water supply, sanitation, and drainage systems operate is now an important part of any development scheme adopted in many parts of the world [8,9].

The emergence of IUWM in Iran has not happened as a planned program and still is not considered as an overall practice by different water authorities in the country. Being a vast country, different climates exists from north to south with large variations in rainfall and water abundance. As a geographical factor and due to shortages in supply and the need to meet the demand of regional population, different strategies has taken place that may be classified as part of an IUWM program. Wastewater reuse has been practiced from many centuries ago mainly for irrigation and agriculture, without any prior planning and consideration of its health implications. In modern era the main part of this strategy in cities is on provision of water for irrigation of urban green area and domestic gardens. However the case for "water management" in industry, is more advanced and progressive [10]. Reuse of treated wastewater in industry has been warmly received, particularly in water hungry oil industry situated on the north edge of Persian Gulf. Many companies are now

using, or plan to use IUWM principles in industry, including desalinated sea water and treated wastewaters [11].

Of course the current situation is far from ideal and the demand has over passed the present practices. Today many water authorities throughout Iran believe that conventional water supply, sewerage, and drainage practices that rely on central collection network and centralized treatment facilities with various discharge systems cannot solve development demands. A strategy based on IUWM principle places an emphasis on demand-side management as well as supply-side management, utilization of nontraditional water resources, and the concept of purposeful decentralization.

Availability of water has integrated with land use policy, town and green area planning, building construction, local economics including viability of small industries, regulation and legislation, education and social acceptance, and community involvement [12]. This case becomes more meaningful when arid and semi-arid areas with low rainfall are considered. As an example the increase in urban uptake of traditional water resources (including surface water or ground water) could reduce water for irrigation and adversely affect agriculture, reduce green area and enhance desertification. The outcome could be limitation in development, economical drawbacks and even vast migration of population which has been observed in central cities of Iran, in recent years.

In order to orientate urban areas towards sustainability, as a necessity for resilient cities, it is important to recognize and view the different aspects of urban water systems in association to each other, which requires the adoption of an integrated approach to urban water system planning, provision and management. IUWM discusses the relations of different aspects of a water system. It takes a comprehensive approach to various parts of a water supply including drainage; sanitation as well as water use and water reuse systems. It further provides an integrated physical system that is controlled by an organizational framework and covers all aspects of supply and demand including technical, social and economic considerations.

The principles of an integrated urban water management for resilient cities must:

- Recognize alternative water sources (including recovered treated wastewater);
- Match water quality with water use;
- Integrate water storage, distribution, treatment, recycling, and disposal;
- Protect, conserve and exploit water resources at their source;
- Account for non-urban users;
- Consider grey water as a source for on-site use;
- Recognize and seek to align formal and informal institutions and practices;
- Pursue efficiency, equity and sustainability;
- Encourage participation by all who may be concerned, especially inhabitants; and
- Recognize relationships among water, land use, and energy consumption.

The key to IUWM is that individual processes should be planned and managed in such a way that the collective impact is minimized, and the collective system efficiency is maximized, as much as practically possible. The primary aim of IUWM is to enable multi-functionality of urban water services to optimize the outcomes achieved by the system. The dimensions of this multi-functionality include affordability, provisions for recreation, community satisfaction, ecosystem protection, energy usage while reducing greenhouse gas emissions, groundwater management, maintenance of biodiversity, pollution prevention and control public health protection and sanitation, sharing of water resources with other users, including the environment, storm water flow management, including flood protection, storm water quality management, waste minimization including solid waste recycling and management and water supply [12]. (Note that ecosystem protection includes the maintenance of the natural surface and groundwater balance within urban areas and the protection of supply catchments and receiving waters.)

There is a broad range of tools that are employed within IUWM, including, but not limited to water conservation and efficiency; water sensitive planning and design, including urban layout and landscaping; utilization of nonconventional water sources including roof runoff, storm water, grey water and wastewater; the application of fit-for-purpose principles; storm water and wastewater source control and pollution prevention; storm water flow and quality management; the use of mixtures of soft (ecological) and hard (infrastructure) technologies; and nonstructural tools such as education, regulations, and restriction regimes [13]. Of course, economic incentives, tax reductions, water rates for different consumers are equally important in IUWM planning procedures.

The case study reviewed in this article employs some of these tools, where applicable according to site characteristics, providing practical demonstrations of how the application of IUWM produces urban water systems that depart from traditional practice in Iran. For example, the application of roof run-off is not a practical mean for high rise buildings but may be advocated for some areas with one or two story buildings and where physically possible. Furthermore, hygienic factor risks involved with non-centralized water systems leaves much room for consideration [14].

The first principle of IUWM, as mentioned above, indicates that not all ideas are applicable under present situation without changing attitudes before proper actions can take place. Changing people’s way of thinking and consequently their expectations could result in a system that will have downstream or upstream impacts and will affect all who are concerned. The translation of the concept of IUWM into the practice of urban water system planners and designers has varied internationally. In relation to urban drainage, some researchers [2] termed this as the creation of “national drainage schools of thought”, observing that there are quite different approaches being developed, especially in Australia, Germany, France, Japan, the United Kingdom, Denmark, and the United States. They expressed that the international exchange of ideas on IUWM is less influential than in other fields, because the order of problem encountered are different in each country. Therefore there seems to be a lack of unilateral concepts on application of urban water management and site considerations and specifications play an important part on how IUWM can be applied [15,16].

A summary of IUWM principles, that all or parts of it may be applicable to add resiliency to all modern metropolises under development, is provided in Table 1.

TABLE 1: COMMON CONCEPTS AND IUWM PARADIGM AND EXPECTED BENEFITS.

Common Thinking	IUWM paradigm	Benefits
Human waste is a nuisance. It should be disposed of after treatment.	Human waste is a resource. It should be captured and processed effectively, used to nourish land and crops.	Reducing pollution to surface waters and ground water.
Stormwater is a nuisance. Convey stormwater away from urban area as rapidly as possible.	Stormwater is a resource. Harvest stormwater as a water supply, and infiltrate or retain it to support aquifers, waterways, and vegetation.	Recreational needs for water can be met by stormwater, reducing demands for fresh water.
Demand is a matter of quantity. Amount of water required or produced by different end-users is the only parameter relevant to infrastructure choices. Treat all water available (surface or ground) to potable quality, and collect all waste water for treatment.	Demand is multifaceted. Infrastructure choice should match the varying characteristics of water required or produced for different end-users in terms of quantity, quality, level of reliability, etc.	Less treatment required, resulting in saving in energy and chemicals, ultimately providing economic benefits.
One use (throughput). Water follows one-way path from supply, to a single use, to treatment and disposal to the environment.	Reuse and reclamation, Water can be used multiple times, by cascading from higher to lower quality needs, and reclamation treatment for return to the supply side of infrastructure.	Reduces dependency for higher quality of water and resulting in more water becoming available for alternatives uses.
Grey infrastructure. Infrastructure is made of concrete, metal, or plastic.	Green infrastructure. Infrastructure	Enhances and promotes green areas such as woodlands and forests. May reduce overall costs and saves energy consumption.
		Reduces costs of water and wastewater distribution and

Bigger/centralized is better for collection system and treatment plants.	includes not only pipes and treatment plants made of concrete, metal, and plastic, but also soils and vegetation.	networks. Provides more water for local application.
Limit complexity and employ standard solutions. Small number of technologies by urban water professionals defines water infrastructure.	Small/decentralized is possible, often desirable for collection system and treatment plants.	Most appropriate technologies means better and practical low cost solutions
Integration by accident. Water supply, wastewater and stormwater may be managed by the same agency as matter of historical happenstance. Physically, however, three systems are separated.	Allow diverse solutions. Decision makers are multidisciplinary. Allow new management strategies and technologies.	Water for diverse consumption and applications will become available on-site. Environmental enhancement by availability of more water is achieved.
Collaboration = public relations. Approach other agencies and public when approval or pre-chosen solution is required.	Physical and institutional integration by design. Linkages must be made between water supply, wastewater, and storm water, which requires highly coordinated management.	Allows more public involvement in decision making and problem solving, creating social satisfaction and communal understanding of the situation.
	Collaboration = engagement. Enlist other agencies and public in search for effective solutions.	

Within the framework of IUWM, the benefits of large central wastewater treatment plants compare to small decentralized wastewater treatment plants is an interesting subject open to discussion. On-site recycling practices that may apply in areas without central wastewater and storm water run-off drainage systems for provision of irrigating green areas are considered too. As pointed out earlier the economic, technical and health hazards of wastewater recycling must be seen and evaluated against social awareness, environmental benefits and public acceptance.

### 3. CASE STUDY FOR DISTRICT 22, CITY OF TEHRAN

Tehran's geographical location is between the latitudes of 35\_ and 36\_ north and the longitudes of 50\_ and 53\_ east. According to the latest national census, Tehran is the most populated province of Iran. Being the capital of Tehran province, the City of Tehran, with an approximate population of more than 11 million people, is one of the most populated cities in the world. It is said that one out of every seven Iranians lives in this city. Through uncontrolled migration in recent decades, population explosion has occurred and a mega city with insufficient infrastructure has appeared. The sudden growth, without proper and adequate planning for a modern city, has created many problems including inadequate sanitation, pollution of aquifers, and shortage of drinking water during the peak summer demand.

Geographically, Tehran demonstrates a specific situation. Having an elevation of around 2,000 m, northern regions of the city are adjacent to "Alborz" mountainsides and the southern boundaries are close to a great salt desert. The elevation shows a stable decreasing pattern southwards, from 1,800 m above sea level to around 1,100 m in southern skirts. Such a topographical pattern dictates a similar groundwater flow and also contaminant transport direction. The climate is considered as semi-arid with total rainfall of nearly 250 mm per year.

Historically, the main sources of drinking water in Tehran are "Karadj" river in the northwest and "Jajrood" river in the northeast, enhanced by other low flow rivers in the down skirts of Alborz mountains (such as "Taleghan" and "Lar" rivers) [17]. Although it was expected that the two rivers should reliably supply water for the city's inhabitants, due to water shortages more than 54 percent of potable water is now provided from more than 450 wells scattered all over the city, mainly in the south parts, Considering all known resources, Tehran is no stranger to water shortages and consequent water rationing in the past.

Tehran's municipality consists of 22 districts (Fig. 1). District 22 is a fast developing satellite town with many problems including water shortages. It therefore could be a good example for implementation of IUWM system. Some 320,000 residents (with a growth rate of nearly 12 percent per year), of this urban area may be facing acute water shortages very soon. While potable water is provided from Tehran's centralized distribution system as well as deep wells, water for recreational areas, irrigation, green areas and further developments is very limited. An artificial lake is under development in this region with a total area of some 300 hectares. It is believed that this lake will eventually hold some 6-7 million cubic meters of water when fully constructed and operated. A large constructed park (Chitgar forest) is another location in this district that requires good quantities of water for 6-8 months of the year.

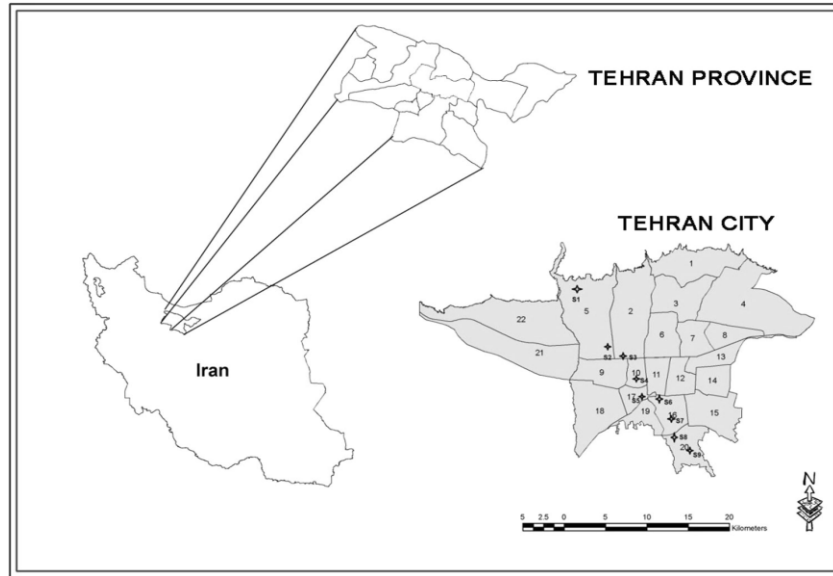


Figure 1: Geographical position of district 22 within "Greater Tehran area."

District 22 is considered as a middle class area, but being part of greater Tehran metropolis all modern amenities of new cities have been foreseen for it. However the region is considered as a fast developing suburban area and new infrastructure is being provided to meet the population demand. One of the main challenges of the district is supply of fresh water. Water is needed for various aspects of development including potable use by the rapidly growing population, for green areas, parks, private gardens and the artificial lake. With so many sectors competing for limited resources, an integrated approach to urban water management is required. The IUWM approach offers a versatile set of options to deal with the challenges facing the region.

### 3.1. Water Supply and Available Resources

Currently water demand of the District 22 region is estimated as some 50,000 m<sup>3</sup> per day excluding water needs for irrigating green area and compensating for lake evaporation-transformation (leakage and ex-filtration) and natural loss due to distribution system. Current ongoing development and rising dwellings, as well as water distribution losses due to broken and faulty facilities are pushing up figures rapidly.

At the present time most of the potable water is supplied from greater Tehran's centralized distribution system and mixed with some ground water withdrawn from the regional aquifer. Other resources include several seasonal and small streams that flow through the area with very high

turbidity and often muddy characteristics and are considered as low and poor quality. The largest stream, “Kan River”, a seasonal storm run-off stream, is currently under attention for treatment and use for non-potable applications (Fig. 2).



*Figure 2: River Kan (seasonal stream) catchment to be used as second grade water.*

The quality of Tehran’s water in the distribution network is shown in Table 2. It should be noted that the quality listed is mainly Karaj River water, mixed with a small percentage of ground water in District 22 region, as different parts of Tehran have different shares of river water. The quality of ground water withdrawn from different deep wells is also quite variable in terms of salinity, nitrate and other concerned components. The average quality of Tehran’s ground water (drawn from wells and injected into distribution public networks) is also provided in Table 2. It is clear that the centralized distributed (tap) water has a better quality than ground water. A main concern for inhabitants of this area is gradual replacement of good quality water (surface water from river catchments) by lower quality (ground) water. As this table shows, one of the main objections of the local inhabitants in using ground water is increasing nitrate concentration. Whereas southern parts of greater Tehran receive water with nitrate as well as water salinity levels that are already too high, other regions, including District 22, receive water that is not too bad yet, but of declining quality. Recent studies [3], and current investigations not published yet, also confirm that some hazardous organics, such as drug residues may have found their way to ground waters. It is therefore no surprise that the local population is becoming worried about their potable water quality. To protect water quality, consumption diversification must take place. In fact high quality water may not necessarily be needed for consumption in all sectors. For many purposes, such as development and maintenance of green area (public parks and private gardens), and artificial lake as well as water needs of municipality for public cleansing, lower quality may still be acceptable. Table 3 briefly describes average water demand for different purposes in the greater Tehran area.



TABLE 2: CHEMICAL COMPOSITION OF TAP AND GROUNDWATER IN DISTRICT 22.

Quality Parameter		Mean value of tap water	Mean value of ground water
EC	( $\mu\text{S}/\text{cm}$ )	390	480
Total dissolved solids	(mg/L)	320	440
Total Hardness	(mg $\text{CaCO}_3/\text{L}$ )	110	150
$\text{K}^+$	(mg/L)	2	3
$\text{Na}^+$	(mg/L)	35	33
$\text{Ca}^{+2}$	(mg/L)	36	45
$\text{Mg}^{+2}$	(mg/L)	5	3.9
$\text{Fe}^{+2}$	(mg/L)	0.05	0.2
$\text{HCO}_3^-$	(mg/L)	120	134
Sulfates <sup>2-</sup>	(mg/L)	48	54
Chlorides <sup>-</sup>	(mg/L)	45	56
Nitrates <sup>-</sup>	(mg/L)	8	20
Sodium Adsorption Ratio		0.7	0.9

TABLE 3: MAIN WATER CONSUMPTION OF DISTRICT 22.

Water Use per capita	Liters per day per capita	Mean percent of total consumption
Drinking, cooking	8	0.03
Bathing	45	18.9
Washing	75	31.5
Cooling facilities (summer time)	30	12.1
Gardening	30	12.1
Public use (municipality)	60	25.3
Total	238	100

### 3.2. Application of IUWM Thinking

Principles of IUWM have been discussed in detail above. Solutions that may help solve water shortages and provide more efficient use of available resources are brought to attention and considered as viable alternatives. Alternative water management scenarios and IUWM approaches discussed for this area must include the use of low quality ground water and re-use of treated wastewater for certain non-potable applications. Separate water distribution networks must be used for supplying different grades of water for a wide spectrum of non-potable consumptions.

As an example, the wastewater effluent quality from one of the wastewater treatment plants in the region ("Ekbatan" plant) is shown in Table 4. Although the wastewater treatment plant, according to set environmental constraints and Iranian "Environmental Protection Organization" standards, is operating satisfactory, better quality is required if the treated effluent is to be re-used for other needs.

Reduction of nutrients (nitrogen and phosphorous) and bacterial contamination in particular are important issues affecting any decision making on re-use policies. Nutrients are main causes of algal growth and consequent development of green color and biological sludge if they exceed limits. Furthermore, bad odors may rise due to secondary biological activity and development of anaerobic conditions. As part of the solution, the following action plans must be considered and were recently suggested to the District's authorities and are currently under review.

TABLE 4: COMPOSITION OF WASTEWATER TREATMENT PLANT EFFLUENT (EKBATAN WATER WORKS) AND THE QUALITY OF WASTEWATER REQUIRED FOR RE-USE STATED BY REGIONAL AUTHORITIES.

Characteristics		Mean Values	Required Values
pH		7.4	7-8
BOD5	(mg/l)	18	<7
COD	(mg/l)	65	<20
Total Nitrogen	(mg/l)	24	<5
Total Phosphorous	(mg/l)	14	<1
Suspended solids	(mg/l)	20	<2
EC	( $\mu$ S/cm)	620	-
Total dissolved solids	(mg/l)	430	--
Total Hardness	(mg CaCO <sub>3</sub> /l)	190	--
<i>E. Coli</i>	(MPN/100 ml)	150	<10
Sodium Adsorption Ratio		1.2	<3

### 3.3. *The Concept and Idea of Three Separate Distribution Network System*

As stated above, diversity in water use can reduce over consumption of high quality water. On this trend, a "Three distribution network" has been suggested that includes:

1. A network of high quality water, free of any possible contamination, to be supplied to households for drinking, cooking and human consumption (high potability quality). To meet this demand "Karaj" river water already existing in the region's treatment works must be supplied to households through a very limited network system. A small size tap connection placed in every kitchen could fulfill the objective. Pricing of this water should be such that it acts as a powerful deterrent for unnecessary applications. As the quantity of this category of water is only in the order of 0.03 percent of total consumption, the regional authority is reviewing the idea of distributing potable water in plastic containers to each household.
2. Medium quality water, mainly drawn from groundwater sources or treated local streams with minimum treatment can be supplied for bathing, washing and non-potable consumption. Of course biological quality must be high to prevent any hazard due to accidental or un-intentional human consumption. Full disinfection must be applied to ensure microbial contamination does not exist.
3. Low quality water, mainly from wastewater treatment plant, subject to tertiary treatment to meet set and approved quality standards (Table 4) can be supplied for gardening, green areas, artificial lake and other uses. In terms of microbial contamination, the quality of this water must be as safe as possible to be harmless in case it is consumed accidentally.

The above policy is an important part of an integrated urban water management system that sooner or later will come into practice for District 22 or other regions short of fresh water resources. Other IUWM features that must be considered in similar situations may also include:

- Collection of storm water and better use of rainwater, collected from roof tops and run-off, in low level buildings for clothes washing. Although in many areas, where high level apartment buildings exist, this may not be a viable solution.
- On-site treatment of less-polluted and low-level contaminated wastewater (grey water) for landscape irrigation and gardening.
- Water-efficient usage including water-efficient taps and shower heads, low consumption toilets (6 liter flush tanks!), low water use landscaping and more efficient cooling devices (in terms of water usage) are other features of IUWM approaches not to be missed.

Capital, operating, and maintenance costs are not considered here because this is an area faced with difficulty. First of all assessment of price of water in different qualities and quantities is difficult. Second, the beneficiary costs and gains of development are not always accountable. Third, when a conventional water-servicing approach is not feasible, the notion of cost advantages or penalties relative to conventional practice cannot be justified.

#### 4. CONCLUSION

Naturally if the above practices come into operation, a large quantity of water would become available for further development and would ease a lot of pressure on already strained water resources of the region. The shadow of water rationing already existing over the capital city, at least for hot summer days, may be averted if integrated water management strategies are applied. If the experience proves to be successful, more regions in the country could follow and benefit from the experience gained in District 22. Of course the lesson not to be missed and the point learned is that applying the IUWM strategy will turn the region into a resilient city in terms of water needs, avoiding water rationing in drought seasons and providing more water for enhancing environmentally sound developments.

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# Role of Natural Attenuation Processes in Water Reuse Systems

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### **Abstract**

Human population and economic growth are driving an increasing global demand for water. In addition, availability of freshwater resources is declining in many areas as consequence of climate change. Water reuse is an increasingly important strategy for water supply management, particularly in arid and semiarid regions of the world. Among water reclamation strategies, natural systems can comprise a reliable component of a “treatment train” for sustainable water reuse. Here, we examine the role of natural processes for attenuation of effluent organic matter (EfOM) and trace organic contaminants (TOrcs) in managed (soil aquifer treatment, SAT) and unmanaged (river transport) natural systems receiving wastewater effluent. EfOM is of concern because it can serve as organic precursor for formation of halogenated disinfection byproducts (DBPs) during chlorine-based disinfection. TOrcs are of emerging concern due to unknown/uncertain toxicity they may impose on human and/or ecological health. EfOM removal rates during SAT are sustainable over time. Data collected at the Sweetwater Recharge Facilities (Tucson, USA) over a 10-year period show EfOM removal rates exceeded 90% with no temporal change in treatment performance. Based on field and laboratory evidence, biodegradation is the most important removal mechanism for EfOM during SAT. Some TOrcs are substantially attenuated on time scale of hours to days during river transport. Many, but not all, TOrcs are further attenuated by biodegradation and sorption during percolation to ground water. The attenuation processes acting to improve water quality during SAT and during river transport/percolation are robust and sustainable; these natural treatment processes can comprise a reliable component of multi-barrier sustainable water reuse systems to support resilient cities.

**Keywords:** *Water Reuse, Wastewater, Effluent, Trace Organic Contaminant, Soil Aquifer Treatment*

## **1. INTRODUCTION**

Global demand for water is increasing over time due to the combined effects of economic growth and development along with increasing human population [1]. Furthermore, in many regions additional stress on surface water and groundwater resources is occurring due to climate change impacts that include reductions in spring surface water runoff and decreases in aquifer recharge rates.

In the semi-arid southwestern United States, and particularly in the State of Arizona, water supply, more than any other environmental factor, is connected to economic well-being and quality of life. Water reuse is already an integral part of state water resource planning, and its role will increase in importance. The City of Tucson, located in southern Arizona, has produced a water master plan (“Water Plan 2000-2050”) that calls to “maximize the future use of the City’s effluent through additional treatment and recharge in order to augment the aquifer” [2]. This concept was further developed in 2014 with the release of the City’s Recycled Water Master Plan [3].

There are a number of constituents/contaminants of potential concern in reclaimed water, including dissolved organics, heavy metals, pathogenic microorganisms, nutrients (nitrogen, phosphorous), and emerging contaminants such as pharmaceuticals, personal care products, and nanoparticles. Here, we focus on effluent organic matter (EfOM) and trace organic contaminants (TOrcs).

The purpose of this paper is to summarize research conducted by the authors on the fate of organics during SAT and during river transport to illustrate that these natural treatment methods can comprise part of a system (“treatment train”) for sustainable water reclamation to support water supply resilience for cities in the future. Specifically, we examine the fate of EfOM during SAT and the fate of TOrcs during river transport and percolation to ground water.

### 1.1. Effluent organic matter and disinfection byproducts

The presence of EfOM in wastewater is by itself not of inherent concern from a human health perspective. Research has shown [e.g. 4-6] that there is great similarity between EfOM and natural organic matter, NOM. However, concern regarding presence of bulk organic matter arises during chlorine-based disinfection, which can lead to the formation of a wide range of compounds known as disinfection byproducts (DBPs) (Fig. 1), a finding first recognized by Rook [7]. Constituents of concern that are regulated by USEPA include total trihalomethanes (THMs), haloacetic acids (HAAs), and bromate. DBPs are of concern due to their potential toxicity/carcinogenicity.

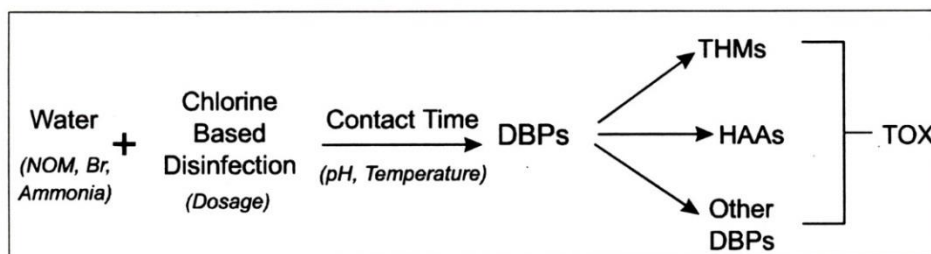


Figure 1: Formation of disinfection byproducts during chlorine-based disinfection. Dissolved organic matter serves as precursor that combines with chlorine to form THMs, HAAs, and other DBPs.

### 1.2. Trace organic contaminants

Impediments to unrestricted use of reclaimed water include the presence of chemical residuals that survive wastewater treatment. These include a bewildering array of xenophobic and natural organic contaminants that are added to water as a consequence of domestic and industrial use. The vast majority of these chemicals have not been identified, and many survive conventional wastewater treatment in trace quantities [8]. Their long-term impacts on human and environmental health due to chronic exposure are subjects of active research. Many pharmaceutically active compounds (PhACs), including a number of endocrine disrupting compounds (EDCs), are present in domestic wastewater and some of these survive conventional secondary treatment in trace quantities. The best studied and perhaps the most damaging class of

these contaminants are xenobiotic and natural estrogens. Estrogenic compounds in treated wastewaters at part-per-trillion levels can disrupt normal sexual development in exposed fish [9,10]. The presence of these compounds in wastewater effluent raises new issues regarding the acceptability of water reuse and the level of wastewater treatment that should precede discharge to surface waters.

More than any other groups of TORCs in municipal wastewater, EDCs have attracted the attention of environmental professionals and the public. EDCs interfere with endocrine system function by blocking normal signaling and response or stimulating inappropriate endocrine activity. The breadth of potential physiological change arising from exposure to EDCs is enormous, and the number of chemicals that can potentially affect endocrine function is large [11]. For example, chemicals present in municipal wastewater that promote estrogenic response in exposed organisms are either natural steroidal estrogens such as estrone ( $E_1$ ),  $17\beta$ -estradiol ( $E_2$ ) and estriol ( $E_3$ ); or anthropogenic estrogen mimics such as ethinylestradiol ( $EE_2$ ) and alkylphenols (APs) [12,13].

Early evidence of EDCs existing in treated sewage was in the form of elevated incidence of intersex characteristics in male fish taken from waters influenced by effluent discharges. Below wastewater treatment plant outfalls in rivers of the United Kingdom, intersex characteristics were apparent in 100% of the males examined from some fish populations [9]. Intersex characteristics take the forms of compromised gonadal growth, spermatogenesis, sperm motility, and fertilization success [9,14].  $E_2$  and  $EE_2$  can elicit physiological changes in continuously exposed organisms at nanogram per liter levels, while the pharmaceutical compounds generally require much larger exposures (on the order of micrograms per liter) for physiological disruption to occur. Some of the EDCs are removed during the treatment process, while the others can survive from the WWTPs and be released to the receiving waters [15,16].

TORC loadings to the effluent-dependent lower Santa Cruz River (SCR) in Tucson are largely unknown. In a 2002 nationwide survey, the USGS measured some of the highest in-stream concentrations of EDCs in the lower SCR [8]; local groundwater concentrations likewise remain largely unknown. Targeted testing by the City of Tucson during 2009 and 2010 under their Microconstituent Sentinel Program detected the compounds perfluorooctane sulfonate (PFOS), carbamazepine, and sulfamethoxazole in three groundwater production wells located along the lower SCR (15-20 mi downstream from effluent outfalls), suggesting that extracted water may include a component of effluent origin.

The fate of TORCs during in-stream river transport has been studied only sparingly. Gross et al. [17] studied transport of nonylphenol ethoxylate metabolites and pharmaceuticals in an effluent dominated river and wetland in southern California. They observed partial removal of ibuprofen, gemfibrozil and chlorinated tris-propylphosphates and transformation of alkylphenol polyethoxylates to APs. Fono et al. [18] studied the attenuations of a small suite of trace contaminants in the Trinity River, an effluent dominated waterway in Texas. Compounds measured were ethylenediamine tetraacetate, gemfibrozil, ibuprofen, metoprolol, naproxen, and total adsorbable organic iodide. With the exception of the iodated compounds, concentrations decreased between 60% and 90% during a travel time of two weeks over a distance of 500km. In a recent study in Phoenix, AZ, Chiu and Westerhoff [19] measured a suite of eight trace organic compounds in local surface waters. Samples contained sucralose, sulfamethoxazole, acetaminophen, cotinine, dilantin, caffeine, DEET and oxybenzone. They did not determine in-stream compound attenuation, but compared seasonal concentrations, concluding that average levels were higher during the summer, particularly for oxybenzone, a sunscreen component. In general, components linked to greater use in the human population (sucralose, oxybenzone) produced higher average levels during the summer months, likely due to greater recreational water use. Beside these two compounds, the trace organics were present at lower concentration in the summer.



## 2. FIELD SITES AND SAMPLE COLLECTION

*Sweetwater Recharge Facilities (SRF).* The SRF is owned and operated by the City of Tucson and consists of eight infiltration basins (Fig 2) that received chlorinated secondary effluent from the Roger Road Wastewater Treatment Plant from 1991 to 2013. A new facility that provides nutrient removal, the Agua Nueva WRF, was built and began operation in spring 2014. Approximately  $1.23 \times 10^8$  m<sup>3</sup> of secondary effluent per year is infiltrated and recovered annually at the SRF.

Water samples were obtained from three locations at the SRF. Sampling points included ponded water from infiltration basin RB-1; water from suction lysimeters located within RB-1 at depths of 0.76, 3.0, 5.2, and 12.2 m, and ground water from a monitoring well (WR-199A) located in RB-1 that samples the unconfined aquifer from near the water table. Well WR-199A is screened from 26.8 to 63.4 m below land surface (BLS) but is equipped with a packer for sampling ground water near the water table (~37 m BLS). Previous boron isotope measurements indicated that these waters are effluent dominated (> 90% effluent by volume) [20].



Figure 2: Sweetwater Recharge Facilities (graphic courtesy of Tucson Water).

*Santa Cruz River.* The Santa Cruz River (SCR) in the Tucson area is an effluent-dependent stream. Tucson's two major wastewater treatment plants, the Roger Road Wastewater Reclamation Facility (RRWRF) and the Ina Road Wastewater Reclamation Facility (IRWRF), together discharge ~50,000 AFY (acre-feet per year) ( $6.17 \times 10^8$  m<sup>3</sup>/year) of municipal wastewater effluent to the Santa Cruz River in the vicinity of Tucson. The IRWRF, located about 8 km downstream from the RRWRF outfall, discharges an average of 40,000 AFY ( $4.93 \times 10^8$  m<sup>3</sup>/year). Except for large rainfall events, this flow is the only water in the effluent dependent river channel. The degree to which reclaimed waters contribute to local well waters and affect groundwater quality characteristics in wells along the Santa Cruz River was described by Quanrud et al. [20]. Galyean [21] estimated that 90% of the effluent discharged to the Santa Cruz River infiltrates within the 40 km reach of the river downstream from the RRWRF. TOrCs loadings to the effluent-dependent lower Santa Cruz River in Tucson are largely unknown. In a 2002 nationwide survey, the USGS measured some of the highest



in-stream concentrations of EDCs in the lower SCR, and TOxCs concentrations in local groundwater likewise remain largely unknown (Kolpin et al., 2002).

Surface water and groundwater samples were collected from twelve locations along a 37-km reach of the lower Santa Cruz River (Fig. 3). Groundwater samples were collected from monitoring wells proximate to the surface water sampling points. Surface water sampling along the lower SCR was performed three times along the study reach. Groundwater samples were obtained from a series of monitor wells owned by the PCRWRD along the 37-km study reach, permitting assessment of TOxC attenuation rates during effluent infiltration/percolation.

### 3. ANALYTICAL METHODS

All samples were collected in 1-L amber glass bottles that had been acid washed and muffled (550°C). Samples were filtered through pre-rinsed 0.45 µm cellulose acetate membranes (Millipore). Dissolved Organic Carbon was analyzed using a combustion technique with a Shimadzu TOC-5000 Total Organic Carbon Analyzer. Samples were acidified then analyzed 4-6 times to produce a coefficient of variation <0.02. The lower level of detection and practical quantitation limit for DOC measurement with this analyzer were 0.2 and 0.5 mg/L, respectively.

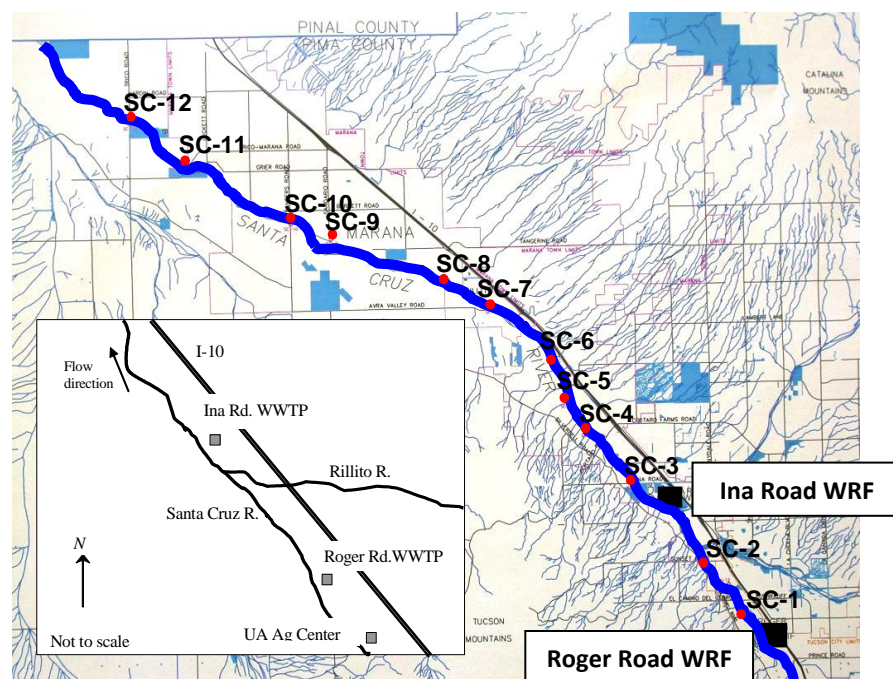


Figure 3: Site map of the lower Santa Cruz River study area (inset map: Tucson, Arizona). The Sweetwater Recharge Facilities are located adjacent to the Roger Road WRF at the bottom right in the figure. Red circles show locations of the twelve monitor wells along the Santa Cruz River that were sampled during this study. Surface water samples were collected along the Santa Cruz at corresponding well locations. The length of the study reach is about 37 km.

A representative suite of 12 emerging TOxCs, spanning a range of physical/chemical characteristics (Table 1) was investigated. Choice of TOxCs was based not only on likelihood of occurrence, but also upon analytical convenience and expected fate. Key chemical classes include pharmaceuticals, steroid hormones, surfactants, personal care products, flame retardants, pesticides, and other industrial chemicals.

Trace organic contaminant analyses were performed at the Arizona Laboratory for Emerging Contaminants (ALEC). Extracts were obtained by solid phase extraction (SPE) and analyzed by Ultra Performance Liquid Chromatography-Tandem Mass Spectrometry (UPLC-MSMS) using the method of isotope dilution. Accepted analytical laboratory QA/QC procedures included use of method/field blank samples, blank and matrix spiked samples, and replicate field and laboratory samples. All samples were analyzed in triplicate. Isotopically labeled surrogate compounds were added to samples prior to extraction to monitor method performance.

TABLE 1: TRACE ORGANIC COMPOUNDS MEASURED IN THIS STUDY.

<b>Compound</b>	<b>Use</b>	<b>Log K<sub>ow</sub></b>	<b>Mol. Wt. (g/mol)</b>
Iopromide	X-ray contrast agent	-2.3	790.1
PFOS	Surfactant	-1.08	538.2
Sucralose	Sweetener	-1.0	396.0
PFOA	Surfactant	-0.90	414.0
Primidone	Anti-convulsant	0.11	218.3
Sulfamethoxazole	Antibiotic	0.48	253.1
Trimethoprim	Antibiotic	0.91	290.1
TCEP	Flame retardant	1.63	285.5
Fluoxetine	Anti-depressant	1.8	345.8
DEET	Mosquito repellent	2.18	191.3
Carbamazepine	Anti-epileptic	2.45	263.3
Tonalide	Fragrance	5.9	258.4

## 4. RESULTS

### 4.1. Fate of Bulk Organics during SAT

During SAT at the Sweetwater recharge site, removals of DOC were robust, averaging >90 percent during percolation through the local 37-m vadose zone, with the majority of removal occurring within the first 1.5 m of soil. Comparison of data collected in the early 1990s (Fig. 4a) and during early 2000s (Fig. 4b) showed equivalent DOC removal performance. That is, there was no apparent reduction in DOC removal efficiency over time, indicating sustainability of the natural attenuation processes. Laboratory studies using 1-m soil columns under controlled conditions to simulate SAT showed that the majority (>80%) of the DOC removal is due to aerobic biodegradation by soil microorganisms, indicating a sustainable removal mechanism over time [22,23]. DOC concentrations continue to decrease during percolation through the remainder of the unsaturated zone (37-m depth profile) (Figs. 4a and 4b).

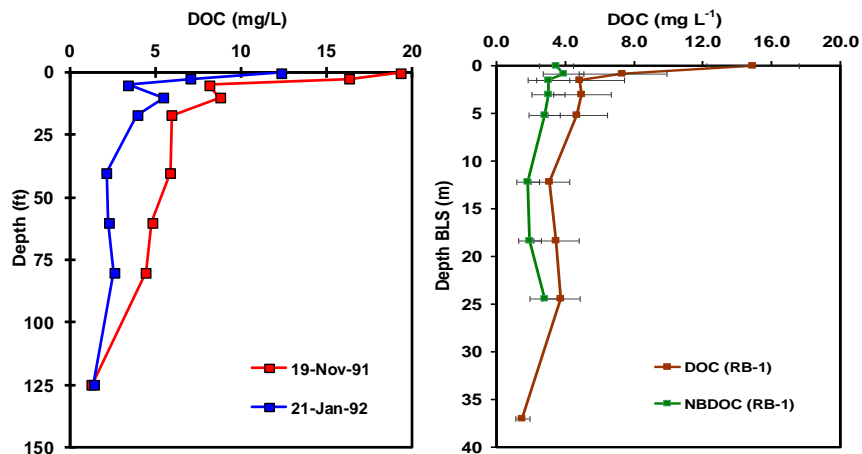


Figure 4: DOC concentration as function of depth for samples collected from suction lysimeters (pore water samplers) in a recharge basin at the SRF: (a) samples obtained in 1991-1992 and (b) samples collected during 1996-2001. Error bars in (b) represent one standard deviation from the mean.

Following percolation of secondary effluent through the 37 m of unconsolidated sediment at the SRF, organic residuals were about 1-2 mg/L, independent of the influent DOC concentration. Reductions of DOC were most dramatic in the uppermost 3 m of sediments, and DOC values were seldom >5mg/L below that depth. In a prior field-scale study at the Sweetwater recharge site, Wilson et al. [24] reported a 90 % reduction of DOC during percolation through the 37-m vadose zone over the first 3-4 years of full-scale operations (i.e. 1990-1993). Equivalent removals occurred during 1996-2001 (Fig. 4b), indicating that the natural attenuation processes had not diminished over the ten years of facility operation. The initial performances of newer recharge basins suggest that basin maturation occurs over the first 6-12 months of operation [25].

Studies of riverbank filtration (RBF) provide additional evidence supporting the sustainability of EfOM removal during SAT. During RBF, surface water passes through aquifer sediments before being collected by extraction wells and subsequently used as source water for drinking water treatment. Riverbank filtration has been used extensively in Europe to augment drinking water treatment processes for over 100 years. In Switzerland, RBF is used for 80% of all drinking water and in France it is used for 50% of water supply. The same natural attenuation mechanisms (e.g. biological degradation, sorption, ion exchange, and precipitation) that improve water quality during RBF also occur during SAT. Studies on RBF along the Rhine River in Germany have demonstrated consistent performance over time for attenuation of dissolved organic matter and have shown most organic matter removal occurs during early stages of RBF [26]. Given the similarity of processes during RBF and SAT, it is reasonable to postulate that bulk organic removal during SAT will remain consistent over very long timeframes, e.g. hundreds of years.

#### 4.2. Fate of Trace Organics in Santa Cruz River

*Surface Water.* All twelve investigated TOrcs were detected in all SCR samples. TOrcs found at the highest concentrations in the river were sucralose (2,726 to 4,661 ng/L), sulfamethoxazole (759 to 1,446 ng/L), trimethoprim (208 to 597 ng/L), and DEET (308 to 786 ng/L). Compounds that were conserved over the 37-km river reach were carbamazepine, sulfamethoxazole, TCEP, sucralose, PFOS, and PFOA. Effluents discharged from the two PCRWRD treatment facilities exhibited differences in TOrcs concentrations; DEET, trimethoprim, and iopromide were substantially higher from the (upstream) RRWTP whereas primidone and fluoxetine were greater at the IRWRF. Differences in source water quality and/or treatment efficiency at the two plants

may account for this variability. Several TOrcs (tonalide, fluoxetine, iopromide, DEET, and trimethoprim) were attenuated during surface transport along the 37-km reach of the SCR (examples shown in Figs. 5a and 5b). Possible removal mechanisms during river transport include photo-oxidation, biodegradation, and/or sorption to suspended particles that may have then settled onto the riverbed. Direct and indirect photolysis may contribute to in-stream compound disappearance [27,28]. Direct photolysis occurs when a compound undergoes transformation as an immediate result of light absorption. Indirect photolysis is initiated through light absorption by other chemicals, leading to production of reactive intermediates such as hydroxyl radicals that react chemically with the target compound [28]. Both pathways can contribute to the degradation of trace organics in natural waters [29].

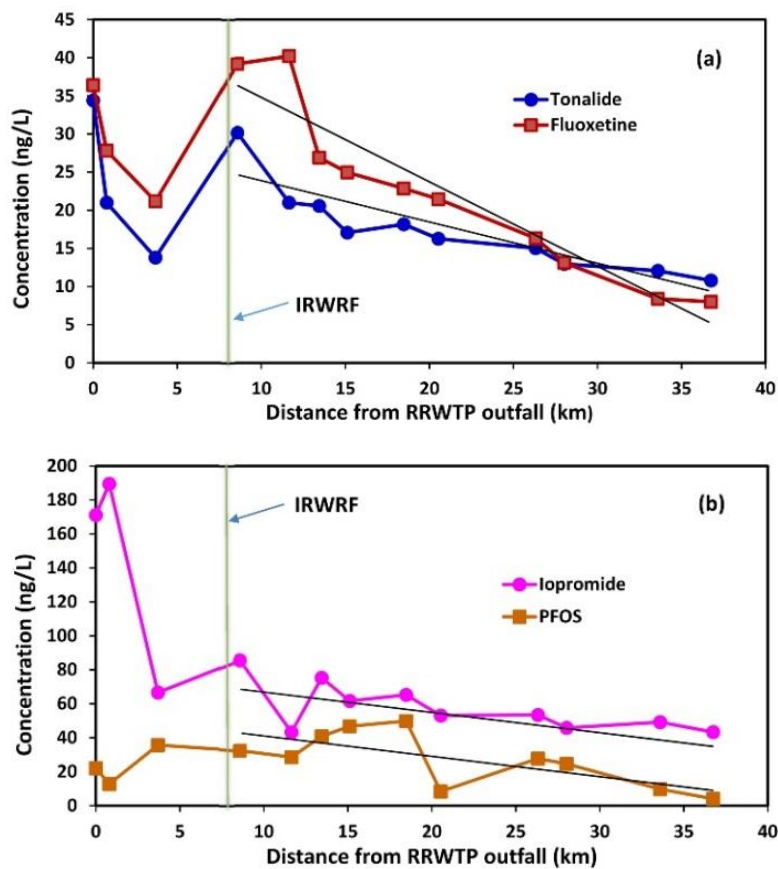


Figure 5: Concentrations of selected trace organic contaminants along a 37-km reach of the lower Santa Cruz River near Tucson, Arizona, USA: a) tonalide and fluoxetine, b) iopromide and PFOS.

**Ground Water.** Eight of the twelve TOrcs were detected in the eleven monitor wells sampled along the Lower SCR study reach; those compounds not detected in the wells include DEET, TCEP, fluoxetine, and trimethoprim. There were substantial differences in TOrcs concentrations in the different wells along the SCR with the highest concentrations generally in wells SC-3 and SC-5. Previous work along the same reach showed that these two wells contained the highest fractions of water of wastewater origin [20]. TOrcs concentrations in the monitor wells were generally at least one order of magnitude lower than in the SCR and iopromide decreased by two orders of magnitude, which may have resulted from a combination of biodegradation, sorption and/or dilution. Exceptions included PFOS (8 to 80 ng/L), PFOA (8 to 18 ng/L), sucralose (71 to 3,470 ng/L), and carbamazepine (7 to 374 ng/L); these were present at similar or sometimes even

greater concentrations in the wells. The wide range of groundwater concentrations for these TOrCs is likely due to substantial differences in the amount of dilution occurring at the various wells. Dilution factors could not be determined in this study and are an important topic for future studies to help assess TOrCs attenuation mechanism(s) during percolation. In addition, there are other possible sources of TOrCs to ground water along the Lower SCR, including agricultural activities and septic systems; TOrCs inputs to the aquifer from these sources are unknown and, if occurring, would be expected to continue after completion of upgrades in wastewater treatment at the Roger Road and Ina Road wastewater reclamation facilities.

## 5. CONCLUSIONS

*Soil Aquifer Treatment.* The dissolved organic matter in wastewater effluent is composed of a combination of EfOM and NOM. These organics are largely attenuated during percolation through unconsolidated sediment (i.e. soil aquifer treatment), a process that was found to be sustainable over time. Based on the longer record of data that exists for organic matter removal rates during riverbank filtration, a similar process, it is expected that removal rates of organic matter during SAT are sustainable in the long-term.

*River Transport and percolation.* Many, but not all, trace organic compounds are attenuated during river transport by a combination of natural mechanisms including biodegradation, photolysis, and sorption. Percolation to ground water provides additional opportunity for trace organics removal by natural mechanisms. These processes are considered sustainable over time.

In summary, natural systems can provide sustainable water quality improvements for bulk organic content and for many, but not all, trace organics of wastewater origin. Finally, this work shows that natural attenuation processes can comprise a reliable component within sustainable water reuse systems to support resilient cities in water short regions of the world.

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# Addressing Acute Failures during Infrastructure Planning

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### *Abstract*

Infrastructure systems are stressed by a range of disturbances that can cause system failure. Compared to chronic disturbances that occur over a long period of time and permit adaptation to the emerging conditions, acute events are more abrupt and avoiding detrimental impacts requires active planning and/or rapid response to minimize the failure impact.

Criticality analysis is presented as a tool to understand the implications of the loss of key components on services provided to customers. Functionality and volume severity (in the case of water supply) are recommended as tools for such an evaluation. The approach is demonstrated on a water supply network. A wide range of component failures and timing are examined and the benefit of water storage is clear and consistent with expectations. Although a useful tool for operators to prepare for failure events, criticality analysis can also play a key role in water supply system design. The second part of this paper describes the development and application of a robust optimization scheme for system design over time. The results showed a large improvement in system resilience at a relatively small cost. A limitation of the optimization code is the number and range of acute events that can be examined. Alternative algorithms are needed to be capable of expanding the range of conditions considered.

**Keywords:** *Acute Stresses, Failure Recovery, Resilience, Water Infrastructure*



## 1. INTRODUCTION

Well engineered and operated infrastructure systems function despite disturbances that test the abilities of built systems to provide service, mitigate the magnitude of failures and recover from failure. Per the NSF EFRI RESIN project teams [1] and Bruneau et al. [2], we define resilience as the ability to “gracefully degrade and recover from some set of disturbances” and robustness as “the ability to maintain function in the face of some set of disruptions.” Following Scholz et al. [3], some operational disturbances can reasonably be anticipated and accommodated (specified resilience). These might include, for example, periodic failures of infrastructure elements. Extreme catastrophic events, on the other hand, are essentially impossible to anticipate and may severely strain the ability of infrastructure to remain functional (general resilience). Such disturbances are superimposed on infrastructure planning and operational schema (Fig. 1) to illustrate the full temporal breadth of relevant design and operational decisions. At the left end of the spectrum are planning and design processes that allow our built environment to address chronic stress. Such stresses generally increase monotonically over infrastructure service life with, for example, population, climate change and economic growth. At the right (Fig. 1), are shorter term facilities management activities that must respond to acute disturbances. Here, we emphasize designing for acute events that represent specified and, potentially, general resilience and an approach to optimize a system while considering this form of resilience. A regional water supply infrastructure is the application system.

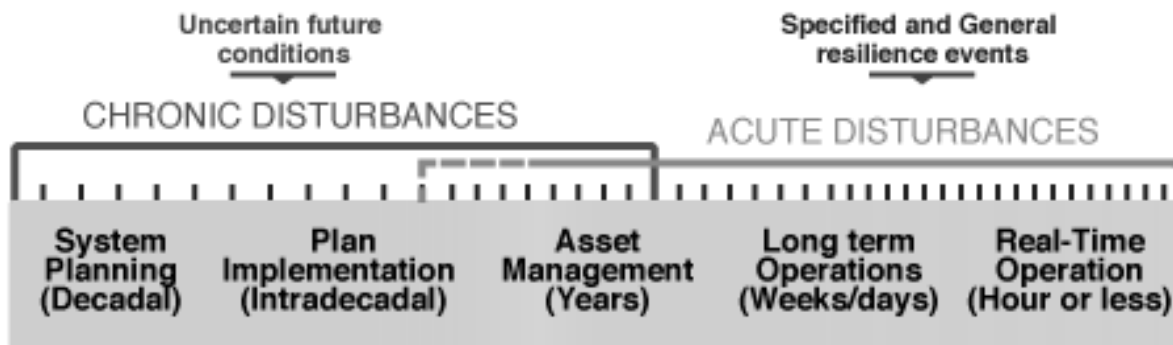


Figure 1: Continuum of planning/design decisions.

## 2. ACUTE DISTURBANCES

Acute disturbances are events occurring relatively abruptly compared to slowly changing conditions or system decay over time (chronic disturbances). Component failures, cutoff of external resources (e.g., power), or a significant external event (hurricane or earthquake) may cause local or regional impacts. Generally, lifeline infrastructure systems are repaired after a failure to the pre-disturbance condition due to the critical nature of the supplied resource. This is not always the case if a failure event has a broad impact (e.g., post-Katerina New Orleans).

A specified failure event usually focuses on “failure of what on what” and may have some reasonable expectation of occurrence (e.g., pipe failure on water deliveries/pressures in a water distribution system). According to Scholz et al. [3], general resilience is a conceptual property on how well a system recovers and has not been well-defined. It could be adaptation to very unlikely events or inherent property related to a system’s redundancy and recoverability. Highly unlikely events appear to straddle specified and general resilience since the failure probabilities are quite

small and poorly estimated. Our focus here is on such events and defining their impact through a criticality analysis.

### 3. FAILURE MAGNITUDE

Failure magnitude is dependent upon the failed component its location, failure timing, and system redundancy. The relationship between the component and the failure impact can be measured by the loss of system functionality and defines the components criticality to system performance (Huizar et al. [4]). Functionality is a metric that defines the proportion of the services that can be provided relative to the system demand or:

$$\text{Functionality} = f = \frac{S_t}{D_t} \quad (1)$$

To capture the severity and duration of a failure, a second metric of volumetric severity is defined as:

$$\text{Volumetric Severity} = \max\left(\frac{\sum_{T_0}^{T_f} -X_t}{D_{t_f}}, 0\right) \quad (2)$$

where  $X_t$  equals  $S_t - D_t$  and  $T_0$  and  $T_f$  are the times corresponding to the beginning and end of the failure event, respectively. As shown in Figure 2, a normally functioning system ( $T < T_0$ ) has a functionality of one since it will provide all of the system demands. The function drops when a failure occurs and, for this example, remains at a constant value until it is repaired and the component is again functioning at time  $T_f$ . The volumetric severity is the area below the line with functionality equal to one. A system capacity indicator could measure the ability to provide supply and could be greater than one.

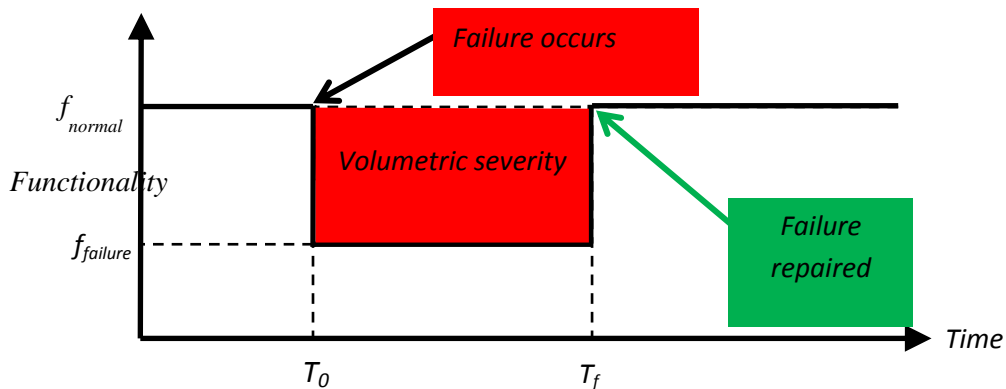


Figure 2: Functionality and volumetric severity definitions

### 4. RESILIENCE APPLICATION

To demonstrate system resilience, consider the water supply system shown in Figure 3 that represents potential development in Tucson AZ. Water is supplied from the CAP (on left) through a set of recharge facilities (CAVSARP, SAVSARP, and SCWF) to demand zones C to I. Wastewater is collected and treated at the reclaimed water facilities. If demand and capacity exists, flow will be returned to the demand zones for non-potable uses. Within each zone, pump stations lift potable or non-potable water to the zone to its left that is normally 100' feet higher in elevation. The pump stations draw water from the downstream pipe or a storage tank.

To assess functionality, the flow distribution through the system is determined in a linear programming optimization problem to minimize overall cost. Costs are associated with water and wastewater treatment, system maintenance and pumping. The supply, users, and treatment facilities are defined as arcs and links between them are arcs. Over-period storage is permitted in the recharge facilities. A daily time step is considered for a forty-one year design period beginning in 2010 with increasing demands over time. A failure in the main pump station delivering flow to zone C is assumed to occur on June 1, 2030 (circled in Fig. 3) that lasts for four days.

Figure 4 shows the functionality and volumetric severity for different storage tank capacities. As the total storage capacity of the eight tanks increases in relation to the daily demand of 66.3 million gallons (MG), the volumetric severity decreases. The functionality is always greater than zero because the northern pressure zones are not impacted by the pump station failure. The cost of the tank storage increases with capacity. The volumetric severity is plotted versus tank cost in Fig. 5. As noted, values are in MG of unmet demand and since the failure lasts for multiple days can exceed one. This curve provides decision makers a tradeoff between failure consequence and cost to inform the selection of tank investment. Hwang et al. [5] extend this analysis by introducing the risk of the failure event to the risk priority number [6].

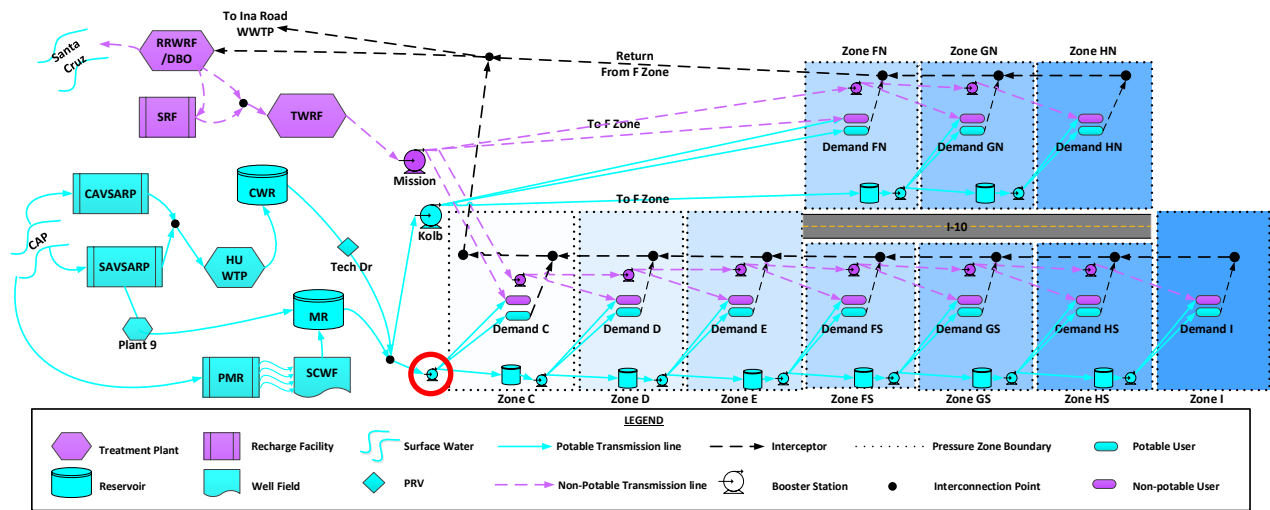


Figure 3: Schematic of application water supply system.

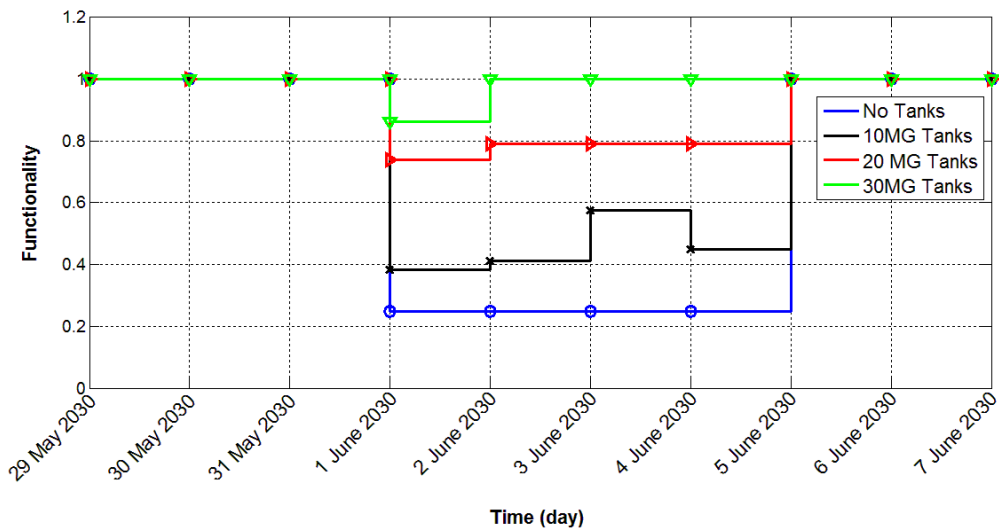


Figure 4: Functionality over time for application system with 4 day pump station failure noted in Fig. 3.

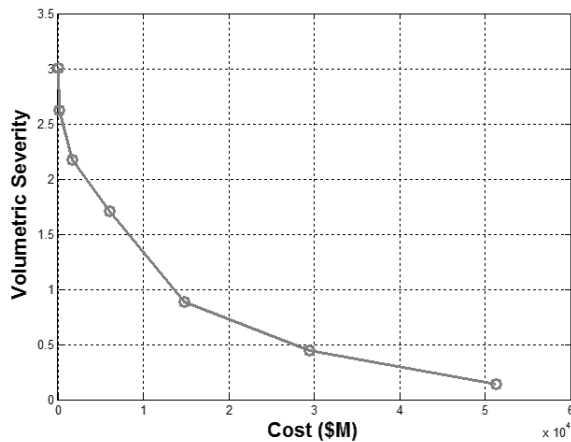


Figure 5: Tank cost versus volumetric severity for example conditions. Points correspond to 0, 5, 10, 15, 20, 25 and 30 MG per tank.

The volumetric severity decreases with tank storage. A rule of thumb in sizing tank volumes is to provide 3 days of storage in the tanks. This is consistent with results here. Eight 30 MG tanks (240 MG) corresponds to about 3.6 days of storage and results in a relatively small loss of functionality.

Selection of June 2030 as the failure period is driven by that fact that June has the highest daily demand for Tucson. The functionality and volumetric severity vary with the demand thus time of year. In addition, since volumetric severity examine the total undelivered demand versus the instaneous drop in functionality, the failure duration also affects its value.

To examine this tradeoff, volumetric severity was computed as a function of time of year and failure duration (Fig. 6). The failure time is now 2010 and 8 – 5 MG tanks are installed (one at the lower end of each pressure zone). The monthly peak daily demand is about 5 MGD in June. Thus, all demands are satisfied if the failure duration is less than about 6.5 days. For a longer failure, the volumetric severity increases. The daily demand is maximum in June and is about 60% of June’s demand in Dec. – Feb. Thus, if a pump station failure occurred in those months, all water could still be delivered from storage. A 14-day June failure, however,

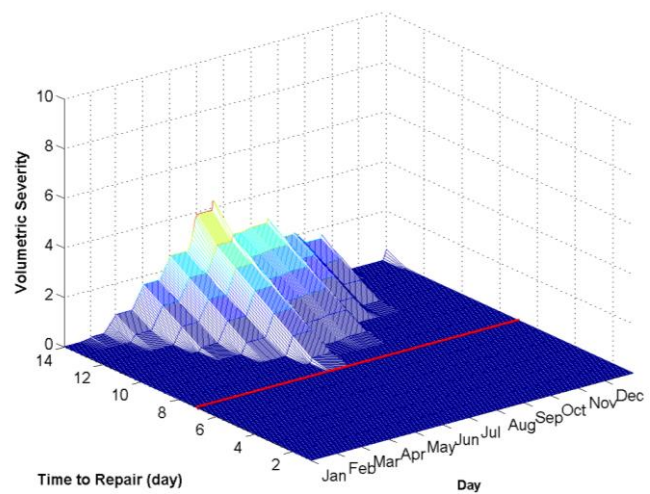


Figure 6: Volumetric severity as a function of failure duration and timing for 2010 with 5 MG tanks in the example system.

would result in an about 4 day equivalent demand not being met. Similarly, plots like Fig. 6 can be developed for different failure periods and tank capacities.

## 5. SYSTEM COST OPTIMIZATION CONSIDERING RESILIENCE

In the previous section, a volumetric severity indicator was demonstrated to be useful in assessing the resilience of a water supply system to acute failures. The indicator responds as

expected in response to system storage and can adapt to alternative demand conditions. Hwang et al. [5] have shown results for a range of failures with equally satisfactory results.

As an assessment tool, this so-called criticality analysis is useful but it is limited as a design tool without conducting a large number of simulations directed by engineering judgment. Lan et al. [7] have embedded the severity indicator in a global optimization methodology to design the system in Figure 3. The weakness that will be seen is that a single failure period is considered (June 2030) and a month time step and failure conditions. Thus, tanks are not considered rather the pipes and pumps to provide flow are sized to meet demands. However, a number of failure conditions are assessed within the optimization because the worst case condition is not known a priori.

A brief description of the optimization problem formulation is presented here with a summary of the model results. A complete exposition of the problem and the application are presented in Lan et al. [7]. The goal of the problem is to balance two objectives cost and system robustness. The latter is defined as the maximum volumetric severity across the set of acute disruptions. The problem objectives is a weighted sum of the those two goals. To develop the tradeoff surface, the weight is varied and the individual goals and system designs can be examined.

System costs are the design and operations costs and the decision variables are the component sizes and the flows on each system arc. An identical network flow model formulation is posed as discussed above but for multiple demand sequences. The no-failure condition and its flow distribution is taken as the operating condition over time and used to compute that portion of the cost objective. As noted, each failure is assumed to occur in June 2030. The water distribution in the system and groundwater storage at the beginning of the failure are assumed to equal to those in the no-failure condition. The monthly flow distribution for the period from June 2030 to Dec. 2050 are then computed for each failure condition.

Design decision are permitted at 2010, 2015, 2025, and 2040 and can construct of expand satellite wastewater and indirect potable reuse plants. Seven critical components (selected based on simulation analysis) are considered as failing (CAVSARP, SAVSARP, TWRF, HUWTP, MR, Kolb and the booster station at the Zone C interconnection point (shown by the circle in Fig. 3).

Constraints on the no-failure condition are mass balances at each connection point and a mass balance for each aquifer node represented by the rectangles in Fig. 3. Bounds are included for the flow rate on each pump, pipe, and treatment facility arc. A set of constraints are defined to address the integer constraints on selecting alternative designs and allowing for expansion of existing versus constructing new plants after the initial period. Finally, a robustness parameter,  $\Theta$ , is constrained to be greater than or equal to the largest volumetric severity.  $\Theta$  is scaled by a weighting parameter that will be varied in multiple problem solutions and added to the cost portion of the objective. A larger weight on  $\Theta$  will increase the importance of system resilience and, as a result, increase design component capacities.

The resulting optimization problem is a mixed integer linear program. Given even the limited set of failure conditions this problem quickly becomes very large and requires tailored decomposition algorithms to be computationally tractable. Here, a modified Benders decomposition is applied to disaggregate into more rapidly solved subproblems by failure condition [6].

Solving the above problem for varying levels of  $\Theta$  gives the results shown in Fig. 7. When  $\Theta$  equals one, the volumetric severity is equal to 100% or no water is delivered for one or more of the defined critical failure conditions but it does satisfactorily provide water under the no-failure case. As  $\Theta$  is decreased the resilience increases and volumetric severity is reduced. With virtually the same cost as no-failures, the volumetric severity can be reduced about 40% ( $= 1 - \Theta$ ). To provide all water under all failure cases which implies a fully redundant system with adequate capacity for at least one peak month, the system cost increases by about \$13 million of a total cost of about \$326 million (about 4%). This result demonstrates the value of considering multiple failure conditions and that the additional cost to provide a robust system is not excessive.

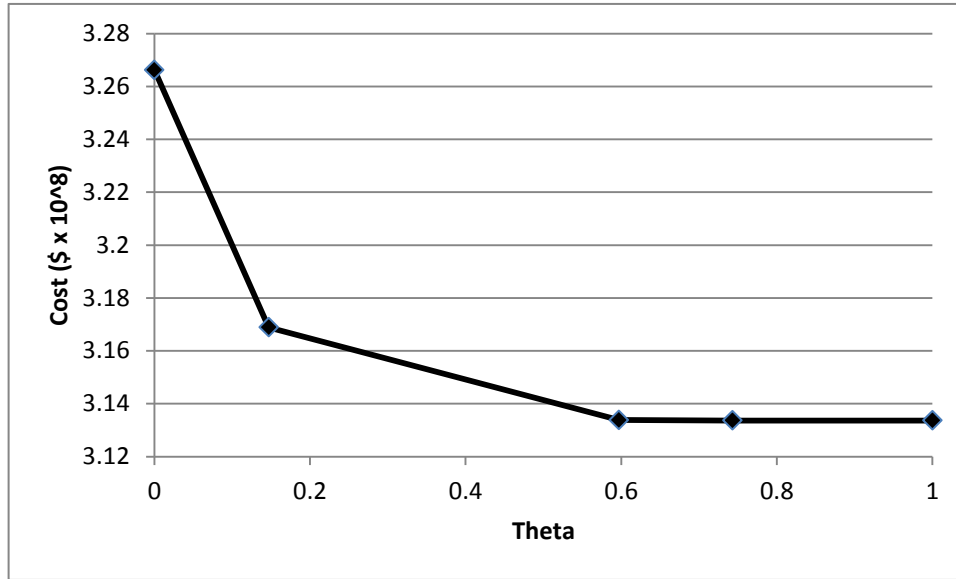


Figure 7: Optimal trade-off between robustness and cost for Fig. 3 system.

The Benders decomposition algorithm progressively updates upper and lower bounds on the optimization problem in search for the global optimum solution. As such, the computation time can be long. In this problem, solutions with  $\Theta$  greater than 0.6 to within less than one percent tolerance were obtained in about 10 minutes of computation time on a 2.4 GHz Intel Core 2 Quad processor with 3.7GB of memory. The more complex solutions with  $\Theta$  equal to 0.15 and 0 required 2.5 and 10 hrs, respectively. If more complex problems are to be solved or additional failure conditions considered, tailored solution algorithms will be needed.

## 6. CONCLUSIONS

Criticality analysis and its extension, risk priority number, provide system operators and designers an understanding of the vulnerability of a system to potential acute threats. These approaches are useful for assessing specified and, potentially, general resilience. In a water supply system, storage provides robustness to the acute events. Finally, the work by Lan et al. [7] demonstrates that determining optimal designs under these uncertainties is possible. Simultaneous consideration of various failure modes can significantly improve resilience and, in the real example considered, at a relatively small cost. However, more comprehensive assessments in both analysis and optimization frameworks come at price but will give decision makers valuable information.

## ACKNOWLEDGEMENT

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## U.S.-Iran Symposium on Resilient Cities

June 16-18, 2014

Irvine, California



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# Resilient Transportation-Introductory Remarks

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### ***Abstract***

Resilience, in urban context, has been best described as the capacity and ability of a city to withstand stress, survive, and bounce back from a crises or a disaster, and rapidly move on. Resilience reflects uncertainty about the future of the nature of the potential disaster and the future of technology and the transportation system; and therefore requires a dynamic, smart, redundant, and diverse plan for a wide range of possible conditions. A high mobile transportation system would play a crucial role in responding to a region's pre-disaster, evacuation, and post-disaster recovery.

This presentation discusses the concept of sustainable and resilient cities, and introduces the user's needs and functional requirements for a resilient transportation. It discusses sustainable development and transportation, and the role of intelligent transportation system (ITS) in developing a dynamic plan that meets long-term economic, social, and environmental sustainability goals under a wide range of unpredictable future conditions.

The plan must acknowledge uncertainty and develop a contingency-based strategy to satisfy a set of pre-defined functional requirements. It must be a diverse plan to include all modes of mobility, with an emphasis on transit. It must be a redundant network of connected roads and transit routes. It should be designed to withstand extreme conditions, and it should have a redundant communication system that provides the collaborative ability of exchanging data and information during unexpected disasters.



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# Shared Ride Systems for Mass Transport

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### ***Abstract***

Mass Transit systems have traditionally been considered as essentially larger-vehicle systems with fixed routes and schedules. The advent of cheap peer-to-peer communication raises the possibility of larger scale passenger transport using demand-responsive services in smaller vehicles. This can include in some cases even the use of spare capacity in private automobiles. The systems can be flexible for many different types of private and public operations, as well as taxi type services. Though regulatory reforms are often needed for such systems to be licensed to operate, certain forms of on-the-fly services have existed in various forms around the world as well. An example of such a system for mass transport concept is High Coverage Point-to-Point Transit (HCPPT) that is an alternative design for mass passenger transport with real-time shared rides. It ensures that no passenger has more than one transfer and involves transfer hubs, trunk routes between hubs with semi-flexible vehicle re-routing and local rerouting around hubs. In a general peer-to-peer ride share system, any type of vehicles can be used and the associated optimization problems involve matching rides among drivers and riders. The associated real-time optimization problems are not simple, though solvable with proper problem decompositions. The focus of this presentation is on an overview of the possibilities in this arena, and on the benefits of such systems in reducing vehicle and thus help in improving the sustainability and resiliency of future cities.

***Keywords: Sustainability, Mass Transport, Shared Rides, Cities***

