MEASURING URBAN VULNERABILITY USING A MODEL OF ECOLOGICAL RESILIENCE: AN ASSESSMENT METHODOLOGY

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INTRODUCTION

It is argued here that urban vulnerability can be assessed and operationalized using the model of ecological resilience; however, modifications are needed to capture the complexities of cities. A framework is presented that allows categorization of urban subsystems thereby reducing complexity. The ecological resilience model is modified to allow individual subsystems within a city to move independently within a resilience landscape; however, linkages between subsystems are defined to capture interdependencies of subsystems and feedbacks within cities. It is argued a subsystem can cross vulnerability thresholds without causing the entire urban system to shift regimes. A methodology is presented to allow city policy makers to quantify urban vulnerability and implement adaptations to reduce vulnerability.

COMPONENTS DEFINING URBAN VULNERABILITY

A flexible approach is needed to analyze and manage the services we require from our socio-ecological systems; this is especially true for urban systems (cities). We must view our cities with intent to sustain those functional properties (services) most important to our urban populations. This flexible approach is crucial due to the dynamic complexities within our socio-ecological systems (Chapin, Folke, & Kofinas, 2009); any management or analysis strategy based on a ridged paradigm cannot sufficiently capture the necessary complexities. Ridged management increases the vulnerability of a city because perturbations will be more difficult to absorb. Resilient systems are better suited to adapt when faced with change (Berkes & Folke, 1998). Therefore, what is needed is to focus on the promotion of resilience within cities.

It is crucial for an urban system to shape stressors and perturbations in ways that sustain those crucial system services, feedbacks, structures, and identities (Chapin, Folke, & Kofinas, 2009). If a city's governance structure is ridged and incapable of responding to change in a timely manner, the city will be more sensitive to stressors. A transformation could occur within the city if a stressor is 'felt' strongly enough. This transformation into a new system would mean a city has crossed some threshold of well-being (e.g. a 'tipping point'). However, cities are complex systems, made up of many subsystems. These subsystems often react in nonlinear, abrupt, and unpredictable ways to stressors. Furthermore, they are particularly sensitive near their respective threshold, and if a threshold is crossed, the results may be disastrous for the city. Many thresholds for urban subsystems can be defined using a critical distinct value; for example, the threshold for air quality may be defined as the 'non-attainment' level for regional particulate matter. However, not all urban subsystems lend themselves to easily defined thresholds. This is a problem because current human activities may be working to undermine the resilient and/or adaptive capacities of urban subsystems without acknowledgement by the city governance. As resilience or adaptive capacity is threatened, the urban subsystem, and therefore the city will become more vulnerable to stressors.

Urban resilience

Resilience is the ability of a socio-ecological system to absorb unexpected perturbations and to sustain its fundamental services, structure, identity, and feedbacks through either recovery or reorganization in a new environment (Holling, 1973) (Walker B. , Holling, Carpenter, & Kinzig, 2004). It is crucial for cities to incorporate resilience into the many urban subsystems interacting to produce services for the urban population. If a management scheme or infrastructure system does not have capacity to function in the face of any number of climactic or social stressors, the system may not continue to provide those services crucial to urban residents. The failures of one urban subsystem may feedback and increase the risk of failure in other urban subsystems. A more narrowed definition of resilience, specific to urban environments, allows for a more meaningful discourse and easier application in an urban vulnerability assessment. Therefore the following definition, modified from Ernstson, 2008, will prove more meaningful when considering urban resilience: urban resilience is the capacity of a city to sustain a certain set of urban subsystem services, in face of uncertainty and change, for the inhabitants of the city. This definition lends itself to application because it requires the assessment team to analyze not only the how urban subsystems are managed, but also which urban subsystems are prioritized. This opens the urban system and the concept of subsystem services for political analysis by an assessment team, without losing the scrutiny of interactions within city subsystems under uncertainty and change.

Urban adaptation

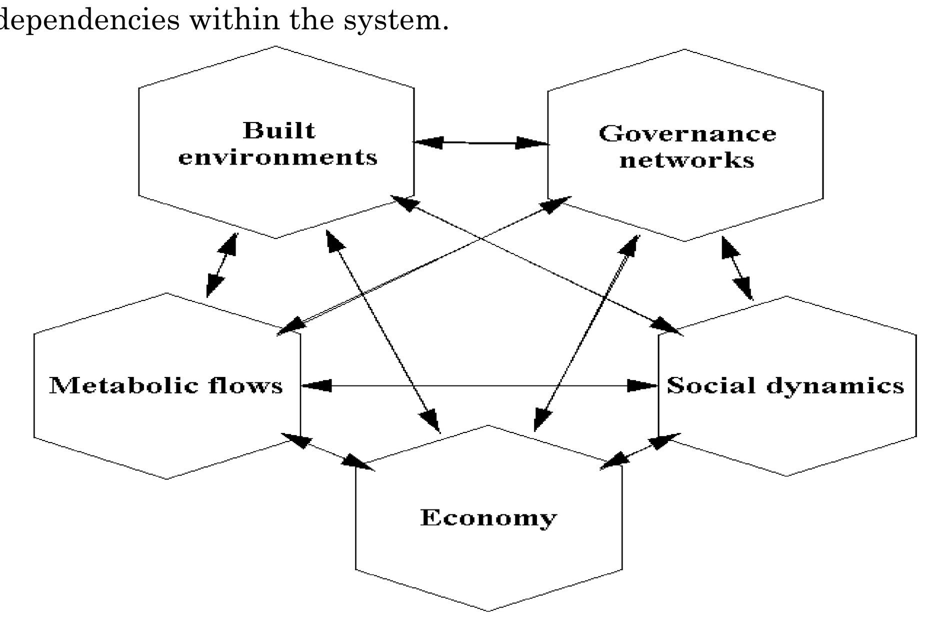
Adaptability is the capacity of actors, both individuals and groups, to respond to, create, and shape variability and change in the state of the system. Applying this definition to cities, the adaptive capacity of any urban system depends on three primary components: (1) ecological, economic, and cultural diversity that provides the ability to adjust to change; (2) the capacity of residents and city organizations to learn how their city functions and how and why it is changing; and (3) capacity to govern effectively by selecting, communicating and implementing appropriate solutions (modified from Chapin, Folke, & Kofinas, 2009).

Urban transformation

Transformation is the capacity to reconceptualize and create a fundamentally new system with different characteristics. Transformations are sometimes needed and are actively managed; however the study of vulnerability focuses on unintended transformations. Unintended transformations occur when governance efforts have prevented adjustment within a city to changing conditions, resulting in a fundamentally different system (often degraded), characterized by different urban state variables and feedbacks (Chapin, Folke, & Kofinas, 2009). The transformation point (vulnerability threshold) is sometimes difficult to define. Transformations rarely result in the total collapse of a city (Diamond, 2005), but transformation will typically cause hardship for the city and the city's residents (Alberti, Marzluff, Shulenberger, Bradley, Ryan, & Zumbrunnen, 2003).

URBAN VULNERABILITY FRAMEWORK

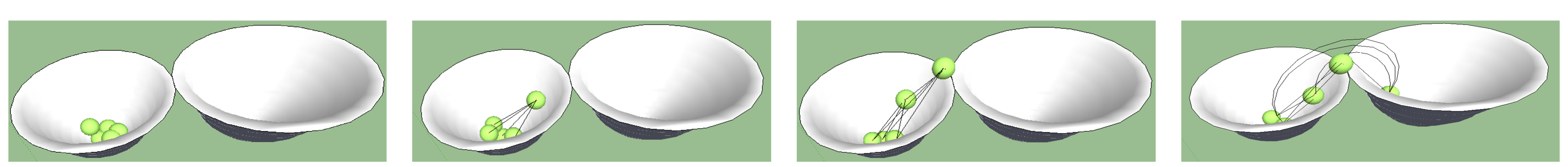
The ecological resilience model allows city managers and planners to visualize and mitigate vulnerability to stressors through adaptation and resilience strategies; however, the complexities associated with city systems impose a barrier to the quantification of vulnerability. This complexity needs to be managed in a structured way which allows a general understanding of the city system. A 'lens', or framework, is presented here that will allow city officials to constructively assess urban vulnerability. Five key components should be analyzed to determine vulnerabilities within any city. The figure below shows these five components and the interrelationships between them. It should be noted, this framework assumes each component will affect, and will be affected by every other component. This complexity is necessary to capture interdependencies within the system.



Urban vulnerability framework
Source – Modified from (Barnett, Elmqvist, Redman, Kearns, & Bai, Under Review)

USING ECOLOGICAL RESILIENCE TO ENVISION URBAN VULNERABILITY

The ecological resilience model coupled with the urban vulnerability framework provides the necessary structure to begin thinking about urban vulnerability in a constructive manner. It can be assumed each of the five components of the urban vulnerability framework operates as a unique system; furthermore, systems within each of the five components can operate as unique systems. For example, the water distribution system is one component of a cities built infrastructure. The water system will respond to stressors, adapt to perturbations, and move within its own resilience landscape. However, the water system is directly connected to many other city systems including urban growth, roadways, and human health. If a cities water distribution system is stressed (water distribution system stressors include drought, poor maintenance, terrorist attack, etc.) this could limit the ability to provide water to the city's fringe areas, thereby limiting urban growth in those areas. This phenomenon can be represented as seen in the figures below. The built infrastructure can begin to move toward the vulnerability threshold. As the built infrastructure nears the vulnerability threshold, it begins to affect other urban subsystems. The built infrastructure begins to 'pull' other subsystems toward the vulnerability threshold. This process can continue until the entire city has crossed the vulnerability threshold and has thereby transformed into a new system. The figures below show this transformation process.



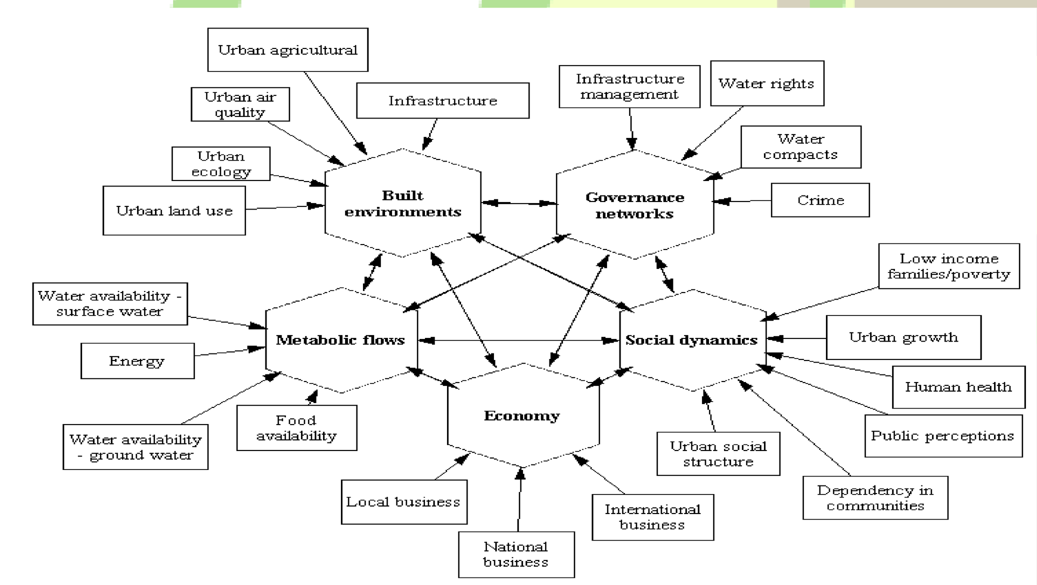
PRACTICAL STEP-BY-STEP ASSESSMENT STRATEGY

1) Construct and define objectives

It is crucial for a city's vulnerability assessment team to clearly define their objectives and anticipated outcomes from a vulnerability assessment. Outputs should be decided upon and deliverable time lines should be established before any assessment begins.

2) Define subsystems using urban resilience framework

The development of urban subsystems must start with a carefully defined concept identifying the purpose of the vulnerability assessment (see step 1). Urban subsystems must be chosen so as to allow planners and administrators in the municipal government to evaluate those systems within the city that are most vulnerable (Huang, Wong, & Chen, 1998). Using the urban vulnerability framework, the assessment team should select urban subsystems. Each sector of the city (urban metabolism, built environment, social networks, urban economy, and city government) will contain unique subsystems. The assessment team has multiple techniques available to them to select those urban subsystems most necessary for a vulnerability assessment. The selection process could simply be a laundry list of city systems (e.g. water distribution, urban agriculture, wastewater treatment, etc); however, in many instances a more robust method, such as the Analytic Hierarchy Process (AHP) (Saaty, 1986) will be needed. The following figure represents urban subsystems most important within Phoenix, AZ as defined by the authors.



3) Establish a vulnerability baseline for each urban subsystem

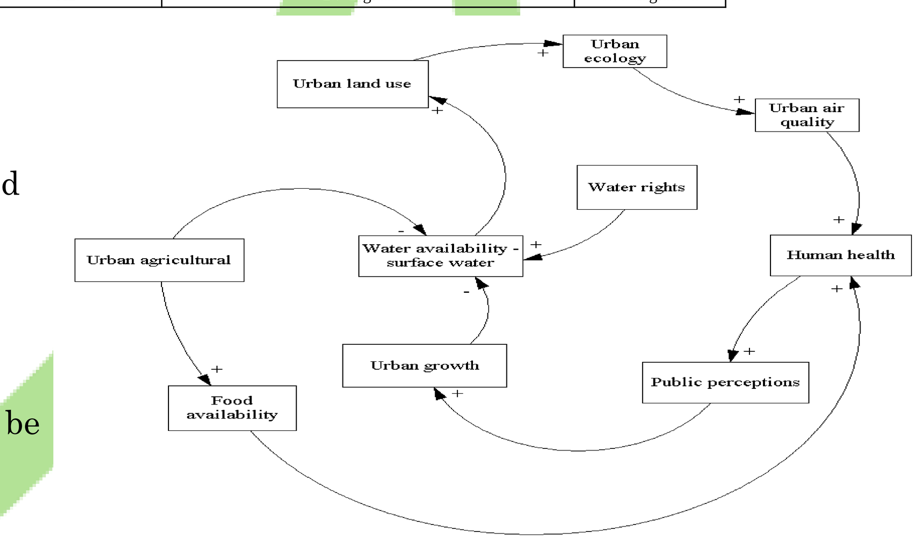
The current welfare of each critical subsystem must be determined to allow the assessment team to create a 'vulnerability baseline.' This baseline will serve as the starting point for a critical comparison with vulnerability thresholds (established in the next step) which will result in the determination of vulnerability for each subsystem.

4) Establish a vulnerability threshold for each subsystem

A vulnerability threshold developed for each urban subsystem will provide a crucial comparison with the subsystem's welfare baseline. The threshold should be set at a level where the assessment team deems the subsystem will no longer function as intended. This determination may vary from one individual team member to another; however, consensus should be reached in the development of vulnerability thresholds. Generally, the difference between the vulnerability baseline and the vulnerability threshold will provide an indication of vulnerability. Furthermore, this difference will be normalized with those of other subsystems to provide a definitive comparison of subsystem vulnerability throughout the city.

5) Establish interdependencies between subsystems

Linkages between urban subsystems should be defined. For example, if the city being assessed uses hydroelectric power produced from the same source as its water supply, these two subsystems (energy supply and water supply) are very closely linked; if prolonged drought caused by climate change reduces flow rates in the river, both systems will suffer. These linkages are crucial because they provide valuable insight into system feedback loops, both positive and negative. Positive feedback loops indicate potential adaptation points in the city system. Negative feedback loops represent points of necessary change. Adaptation policy can be created using these feedbacks as justification. The figure to the right shows an example of the interconnectedness of 'urban ecology' within the Phoenix area.



6) Develop stressors

Urban stressors can be economic, social, or environmental. Recently, much effort has been spent attempting to define stressors resulting from global climate change. Many global climate change models have been created in an attempt to predict future climate patterns based on the meshing of historical climate data with greenhouse gas emission predictions. Most of these models predict climate at a global scale. Scaling global climate change models produces inherent difficulties in the attempt to apply their results to predict future local urban conditions. However, much work has been done in the past years to attempt to more accurately scale global models to predict the effect of climate change on specific regions. Therefore, while it may not be possible to accurately predict the effects of climate change on a specific city, regional predictions do exist. The table below presents temperature change data developed by the IPCC for the Phoenix area.

IPCC scenario family	Proposed temperature change in central Arizona in 2060	Error margin
AIB	2.75 degrees C	0.75 degrees C
B1	2.25 degrees C	0.75 degrees C
A2	2.7 degrees C	0.75 degrees C

7) Determine and rank subsystem sensitivity to stressors

A quantitative measurement of subsystem vulnerability can be useful to the assessment team. Measurements will allow individual urban subsystems to be ranked. This ranking will allow the assessment team to focus their efforts on those subsystems most vulnerable to climate change. Luers et al. (2003) have developed a vulnerability measurement that attempts to assess the relationship between a range of stressors and variables. The equation was developed for application at any scale and for potential use in a wide variety of systems (Adger, 2006). The following equation (modified from Luers et al. 2003), in its most general form, can be used to assign a specific vulnerability to each subsystem. It should be noted, all variables needed for the vulnerability equation have been determined previously in this methodology. The vulnerability of each subsystem can be generally measured as follows:

$$vulnerability = risk - adaptation$$

where

$$risk = \frac{sensitivity\ to\ stress}{state\ relative\ to\ threshold} * probability\ of\ exposure\ to\ stress$$

or

$$risk = \int \left(\frac{|\partial W / \partial X|}{W / Wo} \right) Px dX$$

where

W = wellbeing
Wo = threshold value of wellbeing
X = stressor
Px = probability of the occurrence of stressor X

and

$$adaptation = risk(existing\ conditions) - risk(modified\ conditions)$$

8) Establish linkage thresholds between components for increased vulnerability, resilience, and/or adaptation

Urban subsystems approach vulnerability thresholds when stressed, as stated previously; however, other subsystems my increase or decrease the rate and overall distance a particular subsystem travels within the urban resilience landscape. These relationships must be analyzed and included in the urban vulnerability assessment.

9) Develop adaptation strategy from vulnerability assessment results

The results of the urban vulnerability assessment must be communicated to policy makers in a way that would enact change. This is the final crucial step of the vulnerability assessment. Each individual assessment will require different methods of communication and implementation.

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