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The impact of urbanization on water vulnerability: A coupled human–environment system approach for Chennai, India

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ABSTRACT

While there is consensus that urbanization is one of the major trends of the 21st century in developing countries, there is debate as to whether urbanization will increase or decrease vulnerability to droughts. Here we examine the relationship between urbanization and water vulnerability for a fast-growing city, Chennai, India, using a coupled human–environment systems (CHES) modeling approach. Although the link between urbanization and water vulnerability is highly site-specific, our results show some generalizable factors exist. First, the urban transformation of the water system is decentralized as irrigation wells are converted to domestic wells by private individuals, and not by the municipal authority. Second, urban vulnerability to water shortages depends on a combination of several factors: the formal water infrastructure, the rate and spatial pattern of land use change, adaptation by households and the characteristics of the ground and surface water system. Third, vulnerability is dynamic, spatially variable and scale dependent. Even as household investments in private wells make individual households less vulnerable, over time and cumulatively, they make the entire region more vulnerable. Taken together, the results suggest that in order to reduce vulnerability to water shortages, there is a need for new forms of urban governance and planning institutions that are capable of managing both centralized actions by utilities and decentralized actions by millions of households.

1. Introduction

The developing world is undergoing a major demographic transition from a rural, agrarian society to an urban, industrial one. By 2050, 70% of the global population will inhabit urban areas, up from about half today (United Nations, 2001). Almost all of this increase in urban population will occur in the developing world and more than half the growth will occur in just two countries, India and China (Cohen, 2004). The urbanization transition in developing countries today is fundamentally different from historical patterns in terms of the scale and rate of change (Seto et al., 2010). One of the challenges associated with the magnitude and speed of urban change will be to supply water to urban areas. With growing urban population size and density, additional water supply must be arranged from sources located outside the boundaries of the cities (Lundqvist et al., 2003) and more wastewater is collected, treated and released safely into the environment at a pace and scale unprecedented in history. Climate change is likely to further impact water supply by changing the frequency and severity of droughts. An estimated 3.1 billion urban dwellers will experience seasonal water shortages by 2050; almost a billion of these will experience perpetual shortages within their urban areas (McDonald et al., 2011).

There is emerging consensus that the relationship between urbanization and environmental change is bi-directional (Seto and Satterthwaite, 2010; Seto et al., 2010). However, the relationship between urbanization and water vulnerability is highly debated. An optimistic view, usually supported by engineers and hydrologists (Lundqvist et al., 2003; Meinzen-Dick and Appasamy, 2002), argues that urban water supply is rarely constrained by lack of sufficient water resources in the developing world, and that freshwater availability to cities can be increased by reallocating water from agricultural to urban uses (Rogers et al., 2000). Because urban uses currently account for, on average, 10–20% of the total water withdrawals in developing world basins (Gleick et al., 2002), modest improvements in agricultural water-use efficiency and storage could yield sufficient quantities of water to serve urban areas. It is also economically efficient to transfer water from low-value agricultural uses to high-value urban uses and many governments

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explicitly give high priority to drinking water provision (Meinzen-Dick and Appasamy, 2002). Urbanization may actually play a positive role in lessening inter-sectoral competition and reversing groundwater declines because of the conversion of agricultural land to less water-intensive urban-related uses (Kendy et al., 2007) and urban growth also is not generally constrained by competition with agriculture (Molle and Berkoff, 2006).

A more pessimistic view, usually taken by geographers and urban planners, argues that many urban centers will be unable to expand supply to meet the demand because of poor governance or inadequate co-ordination among relevant agencies (Vo, 2007a,b). As cities grow without adequate supply infrastructure, they may become reliant on unsustainable extraction of groundwater or face frequent water shortages stifling further growth (Güneralp and Seto, 2008; Vo, 2007a,b). Beyond a certain level of urban growth, a lack of water resources could slow down development and constrain further urbanization, a carrying-capacity based threshold which some call a "water resources constraint" (Bao and Fang, 2007).

These two perspectives have developed in parallel but distinct academic communities, and the contrast stems in part from disciplinary differences in framing the issue. By relying primarily on water-balances, water resources researchers overlook the coupling between water and urban systems and the problem of path-dependence: different human adaptations lead to different patterns of urban growth. By viewing urban water supply independently of the larger hydrologic system, urban planners and geographers often overlook the relatively small footprint of urban water supply on basin water balances (recent work on Phoenix's water supply linking governance and decision-making to land cover and water resources is a notable exception e.g. Gober and Kirkwood, 2010). Moreover, focusing only on average supply and demand neglects the variable nature of hydrologic systems. In reality, most water "crises" occur during droughts – when resource availability drops sharply albeit for a short period. Understanding the bi-directional links between urbanization and water resources requires examining the underlying nature of the relationship. Does urbanization result in *long-term unsustainability* of the resource base (e.g. via groundwater depletion)? Does urbanization mainly impact *short-term vulnerability* to water shortages during droughts?

This study contributes to the understanding of dynamic water vulnerability by addressing the following research question: Does urbanization increase or decrease a region's vulnerability to water shortages? We focus on vulnerability caused by water shortages during multi-year droughts under changing environmental conditions; no long-term trends in water resources availability were discernible in our study site. Long-term unsustainability in water resources occurs when a stored stock of water (aquifers, lakes, or wetlands) is gradually depleted over time. In places where the aquifer has limited storage and there is no surface freshwater body, the problem is not one of depletion of a non-renewable resource. Rather the problem is one of managing a renewable, but temporally variable, resource under an increasing baseline demand. Quantitative assessments of dynamic vulnerability remain rare and none have considered the impacts of large-scale urbanization in the developing world in a dynamic manner.

The article is organized as follows: Section 2 describes the conceptual framework used to evaluate the relationship between urbanization and water vulnerability. Section 3 describes the model including the assumptions and feedbacks between urbanization, supply and demand for water, and vulnerability. Section 4 presents results of the simulation model for the study site, Chennai, India and present vulnerability assessments in two different urbanization states. Section 5 discusses the results, followed by conclusions and directions for future research in Section 6.

2. Theory

2.1. Theoretical approach

Vulnerability, defined as the degree to which a system experiences harm due to exposure to stressors (Turner et al., 2003), is a dynamic quality: both the sensitivity and adaptive capacity to stressors change over time with changing social and biophysical states (Adger and Kelly, 1999). To assess how environmental change influences vulnerability, assessments need to be conducted under changing environmental conditions, but few studies have used empirical data to quantify changes in vulnerability under changing environmental conditions (Luers et al., 2003; Luers, 2005).

Dynamic vulnerability has been defined as "the extent to which environmental and economic changes influence the capacity of regions, sectors, ecosystems, and social groups to respond to various types of natural and socio-economic shocks" (Leichencko and O'Brien, 2002). Assessing dynamic vulnerability as an integral part of a coupled human–environment system (CHES) remains a challenge (Turner, 2010) for two reasons. First, while land use, demographic and economic changes associated with urbanization are often decadal-scale "slow" processes, water shortages during individual drought events are short-term relatively "fast" processes (Luers, 2005). Although urbanization in the developing world can be rapid compared to the ability of institutions to adapt, it is slow compared to a drought event when water availability could halve within a year or two. Second, while environmental indicators such as soil-moisture, groundwater levels and surface water flows are macro- or basin-scale variables, human impacts are experienced at the micro-scale of a household. Biophysical processes of environmental change are mediated via a range of social institutions and these jointly determine impacts on human well-being. For example, based on reservoir levels, water utilities make decisions on how much water to release and how much to allocate to different neighborhoods. In response, individual households make private arrangements to deal with shortages.

The current definition of vulnerability does not distinguish between slow and fast stressors. To clarify these, we define *drought* to be the "stressor" and *urbanization* to be the "system state" which changes relatively slowly over time. We evaluate the links between urbanization and water vulnerability by comparing the impact of an identical (simulated) severe drought at two different periods in time of the city's growth.

2.2. Measuring urban water vulnerability

Most studies use proxy indicators of vulnerability, which are not empirical and are difficult to validate (Luers et al., 2003). However, most empirical indicator-based vulnerability assessments cannot be related back to theoretical definitions (Fussel, 2007), are static, and do not consider dynamic feedbacks between human and natural systems.

We define a vulnerability metric based on a widely accepted theoretical definition – *the susceptibility to harm caused by exceeding a damage threshold under exposure to a stressor* (Turner et al., 2003). In this study, the unit of analysis is the household, the variable of concern is household water consumption and the threshold is a basic minimum level of water consumption. Thus, vulnerability is defined by the fraction of population that drops below a minimum consumption level of 40 l per capita per day at the peak of a multi-year drought.