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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.

To establish how vulnerability changes under changing urbanization, we indexed vulnerability to the system state U, where "U" is the state of urbanization of the basin – measured by the fraction of the land area that is urbanized.

$$Vulnerability_{state\,U} = \%\ population\ consuming\ less\ than\ 40\ LPCD\ per\ day\ during\ a\ drought$$

Forty liters per capita per day (LPCD) was chosen as the minimum quantity of water needed for drinking, cooking, bathing, sanitation, and dish and clothes washing based on WHO standards and Government of India standards.

### 2.3. Coupled human–environment systems (CHES) approach

We examine how vulnerability changes over time as the urban extent expands. To identify the functional relationships between the stressors and the variables of concern (drought and household water consumption respectively), we adopt a coupled human–environment systems (CHES) modeling approach to urban water supply. Our approach of using a systems model is consistent with previously suggested methodologies to assess vulnerability (Turner et al., 2003) and considers (*i*) the coupled nature of the human–environment system of concern involving dynamic feedbacks, impacts, and adaptation, (*ii*) broader human and biophysical processes operating on the coupled system (e.g., political constraints on pricing or inter-state transfers), and (*iii*) exogenous stresses on the system (e.g., drought). Our conceptual model of urban water supply in developing world cities depicts an urban area that is supplied by surface-water and groundwater sources (Fig. 1).

This conceptual model distinguishes our study from previous vulnerability assessments, by integrating both pessimistic and optimistic perspectives, explicitly accounting for basin water balances, adaptive behavior by the water utility and individual households, and the spatial expansion of urban areas. Specifically we:

1) evaluated sensitivity to drought (changes in groundwater recharge and reservoir inflows in response to decreased precipitation) and adaptive capacity (increased storage, desalination plants, and improved distribution infrastructure) as both spatially and dynamically varying with environmental conditions. While previous spatial vulnerability assessments have used "indicator-based" maps (Cutter et al., 2000) or statistical regression analyses (Luers et al., 2003), they do not reflect the dynamic nature of vulnerability (Eakin and Luers, 2006). We used a simulation model, making it possible to trace causal pathways and to evaluate how policy options affect vulnerability to droughts.
2) distinguished between different temporal scales: The study considered both slow and fast processes associated with urbanization and distinguished between short-term coping strategies such as rationing, temporary cuts in water use and source-switching, versus long-term adaptation such as investments in infrastructure or retirement of water rights.
3) included adaptive actions by multiple agents, a necessary step to establishing linkages between water vulnerability at the household scale and macro-scale water availability under environmental change. Previous assessments of urban water vulnerability in developed world cities typically only considered adaptive actions by urban water utilities (Collins and Bolin, 2007). We accounted for infrastructure investments by both households and the water utility.
4) distinguished between micro (household) versus macro (cumulative regional) vulnerability (Leichenko and O'Brien, 2002). We further recognized vulnerability to be demographically differentiated. Because households differ in their ability to cope with unreliable supply and make adaptive investments, different sections of society are vulnerable to different degrees.

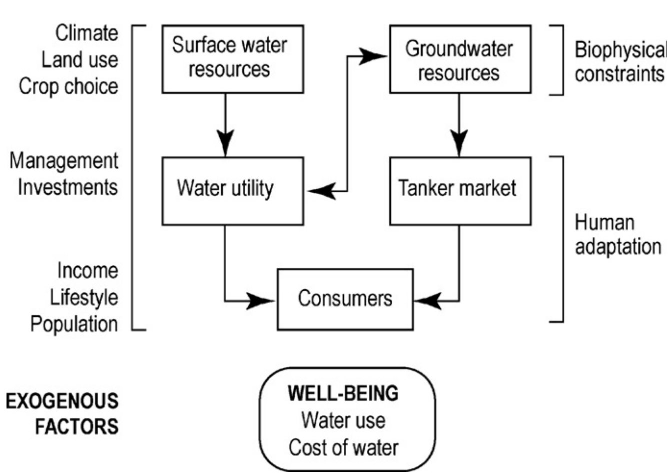


**Fig. 1.** Conceptual model of linked land–water system.

### 2.4. Linking urbanization and water supply/demand across scales

We simulate and incorporate feedbacks between multiple spatial grains (i.e., basin, city, household) and temporal scales (i.e., decadal, daily). We considered macro-scale, long-term processes (infrastructure investments in reservoirs and pipe mains, changes in land cover) and macro-scale, short-term processes (reservoir releases, water distribution rules) as well as micro-scale, long-term processes (changes in household income, investments in wells and underground sump storage) and micro-scale, short-term processes (household coping behavior including adjusting demand and source-switching).

#### 2.4.1. Long-term or "slow" processes

Urbanization is a complex process associated with changes in land cover and land use as well as socio-economic (demographic, economic, infrastructure) processes. Each "slow" or long-term process is associated with biophysical or social changes impacting the water resources system (Table 1). In a simulation model, these could be parameters that change gradually over time or one-time discrete changes such a new desalination plant or pipeline.

As urban areas expand, the resulting land use and land cover changes affect hydrologic processes through changes in recharge, runoff and evapotranspiration, which affect the quantity of surface water in reservoirs and aquifers, and ultimately available for urban uses. For instance, as paved surface area increases, groundwater recharge declines locally and surface water runoff increases.

Socio-economic processes associated with urbanization also influence water supply and demand. A city may build new reservoirs or import water from other basins to increase supply, thereby altering the hydrologic balance. As new residential communities develop, new urban water demand replaces demand for water by irrigated or rain-fed agriculture. Depending on the location and magnitude of the demand for water, the urban water utility makes decisions to build pipes and set tariffs to manage demand. Households make independent decisions on how to manage their available supply. If piped supply infrastructure is insufficient or degraded, households may adapt by investing in private wells and sump storage. As incomes rise, households are better able to make adaptive investments. These investments are

**Table 1**
Links between urbanization process and water system changes.

| Process type | Macro-scale process change associated with urbanization | Corresponding long-term change in water system at the household or pixel[a] scale |
|---|---|---|
| Land use | Change in land use from "agriculture" or "barren" to urban | Reduction in evapotranspiration ⇒ change in groundwater recharge |
| | Change in land use from unpaved to paved | Reduction in groundwater recharge (% of rainwater infiltrating) and runoff |
| Economic | Increase in number and location of commercial establishments | Increase in commercial demand for water in each census area |
| | Decrease in irrigated area | Reduction in irrigation demand in each pixel ⇒ reduction in groundwater extraction for agriculture |
| Demography | Change in population density and spatial location | Change in quantity and location of urban water demand |
| | Increase in wealth of the population | Increase in household-level investments |
| | | Increase in total water consumption – as penetration of indoor plumbing increases |
| | | Increase in ability and willingness to pay for water ⇒ shift in demand curve |
| Infrastructure | Location of new water and sewerage pipes, reservoirs and treatment plants | Change in availability of piped water |

[a] The pixel size in the integrated model was 220 m × 220 m.

"sticky" – once made they permanently alter the choice set available to households.

*2.4.2. Short-term or fast processes*

Droughts are associated with several short-term processes, both biophysical and socio-economic. Shortfalls in precipitation result in reduced inflows into the city's reservoirs and decreased groundwater recharge. The water utility decides how to allocate the scarce resources available usually by increasing imports or curtailing hours of supply. Households in turn may cope with the curtailed supply by switching sources, depending on their prior investments and ability to pay. Therefore, the quantity of water consumed by households is influenced both by biophysical and socio-economic factors (Table 2). By our definition, an individual household is vulnerable to drought when its consumption falls below a pre-defined threshold. The cumulative vulnerability of the system as a whole is determined by the fraction of households that become vulnerable.

## 3. Materials and methods

### 3.1. Model development

The conceptual model described in the previous section was implemented as a systems model for Chennai, formerly Madras, India's fourth largest city. About 7 million people reside in the urban agglomeration, which includes peri-urban areas, towns and villages. The public water utility supplies only the municipal area, which, with a population of 4.5 million constitutes about 14% of the land area of the entire Chennai metropolitan region. The water utility supplies water to households within the municipal corporation area via a piped network, obtaining water from rain-fed reservoirs and well-fields outside the city (Metrowater, 2008). Almost 70% of Chennai's households have private wells as a supplementary source. Beyond the city limits, peri-urban towns and villages are served by a patchwork of groundwater-based municipal and village supply schemes. Peri-urban agriculture, primarily paddy, sugarcane, and groundnut cultivation, is largely groundwater-based. The city is expected to continue to grow rapidly (CMDA, 2007), driven by private sector investment in housing and commercial property in peri-urban areas (Dupont and Sridharan, 2006). Peri-urban areas are expected to be eventually supplied with water and sewerage services via the city municipal supply agency.

The coupled human–environment systems model of Chennai covers the 2550 $km^2$ area incorporating the entire Chennai Metropolitan Area and simulates each component of the water system- basin-scale groundwater and surface water flows, utility decision making, supply of water via private tankers sourced from peri-urban areas, and household level decision making. The model was formulated based on extensive primary and secondary data including household surveys, government statistics, census data, lithologic data, water level data, reservoir data, and satellite images in MS Excel, Visual Basic, and MODFLOW-2000, a groundwater flow model (Chiang and Kinzelbach, 2001; Harbaugh et al., 2000). The model was calibrated and validated from January 2002 to April 2006, which included one of the wettest and one of the driest periods in recorded history for which we had both socio-economic and hydrologic data—making it possible to assess adaptation to drought. A complete description of the model calibration and validation based on primary and secondary data appears in Srinivasan et al. (2010a). Only details of how the slow and fast processes were simulated are presented in this article.

**Table 2**
Links between drought and water system.

| Process Type | Macro-scale process change associated with drought | Micro-scale changes at the household or pixel scale |
|---|---|---|
| Rainfall | Decrease in rainfall (e.g., below average) | Decrease in quantity of piped supply available |
| | ⇨ Decrease in inflows into reservoir system | Drop in groundwater levels due to less recharge |
| | ⇨ Decrease in groundwater recharge | |
| | ⇨ Decrease in water available from inter-state projects | |
| Water utility decisions | Decrease in reservoir storage, very little water released from reservoir system | Decrease in quantity of piped supply available<br>Drop in groundwater levels due to less recharge from leaking pipelines |
| Household decisions[a] | Decrease in piped supply hours and quantity | Switch to alternative sources of supply such as wells or private tankers |

[a] Long-term trends in household level adaptation by investments in private wells were assumed to be driven by slower demographic trends such as household income rather than specific drought events. Although well deepening does spike slightly during droughts, in Chennai well drilling is a standard part of home improvement and new constructions. Well-drilling was not treated as a response to a stressor in the model – but rather a slowly changing variable.

*3.1.1. Long-term or "slow" processes*

We used the SLEUTH "cellular automaton" urban growth model (Clarke et al., 1997) to project land use change to 2025. SLEUTH extrapolates land use change rates from a set of historical images to predict future patterns of urban land change. We generated land use maps with four land use classes, water, agriculture/forest, urban, and ocean, using 30 m resolution Landsat-5 TM satellite images for 1988, 1991, 2000 and 2007. Reserve forests and known salt marsh areas were excluded as areas not prone to land use change. The classified images show a consistent pattern of urban growth: of agricultural land converted to urban areas; of peri-urban areas becoming core urban areas. Urban growth was fastest along major highways. The calibration of SLEUTH is subjective, labor intensive, and highly sensitive to parameter inputs (Wu et al., 2009; Dietzel and Clarke, 2006; Silva and Clarke, 2002; Herold et al., 2003), and the calibration step is often also the validation process. Because the 1991 image was too close temporally to the 1988 image to be useful for calibration, effectively only 3 Landsat scenes were available for calibration. There are a number of tests and metrics that can be used to evaluate the calibration methodologies for the analyst to choose from. The Lee–Sallee index is commonly used and compares the forecasted growth with actual growth using measures such as the number of urban pixels, the number of urban clusters, the size of urban clusters, and the spatial match (Jantz et al., 2004; Dietzel and Clarke, 2006; Wu et al., 2009). We used the Lee–Sallee index and obtained values between 85% and 95% for the different input parameters. The calibration was found to be sensitive only to the spread coefficient and road extents; since Chennai is very flat, topography did not influence growth.

To obtain spatially disaggregated water demand, we geo-referenced census population data onto the SLEUTH land use projections to locate urban households in each grid cell for future periods. We used a Google Earth image to establish the initial household density for each pixel for the year 2007 and calibrated it so that the aggregate population in each census unit matched census data. For future periods, the population density was assumed to increase at a uniform rate such that the aggregate population remains consistent with project population figures (CMDA, 2007) for each census tract. Once the spatially disaggregated population density was obtained, it was overlaid on the land use map (Fig. 3).

Infrastructure projections were based on planned infrastructure expansions. In the baseline scenario, we assumed that the utility will expand piped supply to the densely populated peri-urban area around Chennai in three phases between 2010 and 2025. The utility will secure relatively modest amounts of "new" water resources from two new desalination plants commissioned in 2009 and 2015. We assumed that as households become wealthier, they adapt to the situation by making investments in underground sumps and wells.

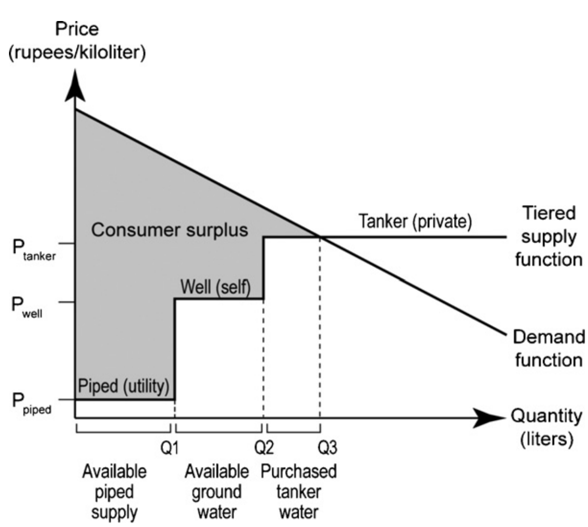


**Fig. 2.** Tiered supply curve.

*3.1.2. Short-term or "fast" processes*

In formulating the model, we used published reservoir data, pumping station data, and utility annual reports to codify the utility's water management principles. For instance, despite having a complex bureaucratic process for reservoir operations, the data suggest that the utility follows a simple, approximately linear rule to determine reservoir releases to city supply. These were confirmed in field interviews. Shortfalls in reservoir water availability are made up by increasing well-field extractions and in the case of extreme drought emergency imports from other basins and purchases from peri-urban farmers (see Srinivasan et al., 2010a,b for a detailed discussion). Because residential supply was not metered at the time of the study, the utility used rationing to control demand. That is, the utility adjusted the number of hours of piped supply based on water resource availability.

Households go through a similar process of optimizing their daily water consumption based on the available quantity and quality of water. The options available to households in the short-term are contingent on their prior investments: households can only self-supply if they have a private well. For short-term decisions, based on interviews, we assumed households obtain water from the lowest-cost sources until they run into a supply constraint. The households' cost-minimizing behavior in effect results in them facing a tiered supply curve (Fig. 2). The total quantity consumed is determined by the intersection of demand and supply curves. The tiered supply curve shown represents a particular category of high-income households who have piped connections, underground storage, and private wells (Fig. 2).

The model allows us to recreate a narrative of the 2003–2005 drought in Chennai. As both rains and inter-basin imports did not materialize, the reservoir system dried up and piped supply was curtailed. As households turned on their own wells and recharge from leaky pipelines dropped, the water table fell almost 8–10 m (27% of ~420,000 wells). Many residential wells went dry and households were forced to purchase expensive water from private tankers. Household consumption dropped sharply. Thus, households in Chennai were highly vulnerable to a stressor such as a multi-year drought.

*3.2. Vulnerability assessment*

To understand how water vulnerability changes under urbanization, we need to simulate the same stressor (drought) occurring at two different times in a city's growth. To do this, we used a simulated rainfall scenario where rainfall patterns from 1988 to 2007 are repeated from 2008 to 2025. Under this scenario, the multi-year drought that occurred from 2003 to 2005 is simulated to recur from 2021 to 2023. Because the model simulates vulnerability to the same multi-year drought at two different points in time, it is possible to assess change in urban water vulnerability to the state of urbanization. Vulnerability to water shortages was then evaluated by comparing the impacts of the historical and simulated future drought.

## 4. Model results

*4.1. Baseline scenario*

We begin by qualitatively discussing the nature of urbanization in Chennai, both in terms of land use and demography.

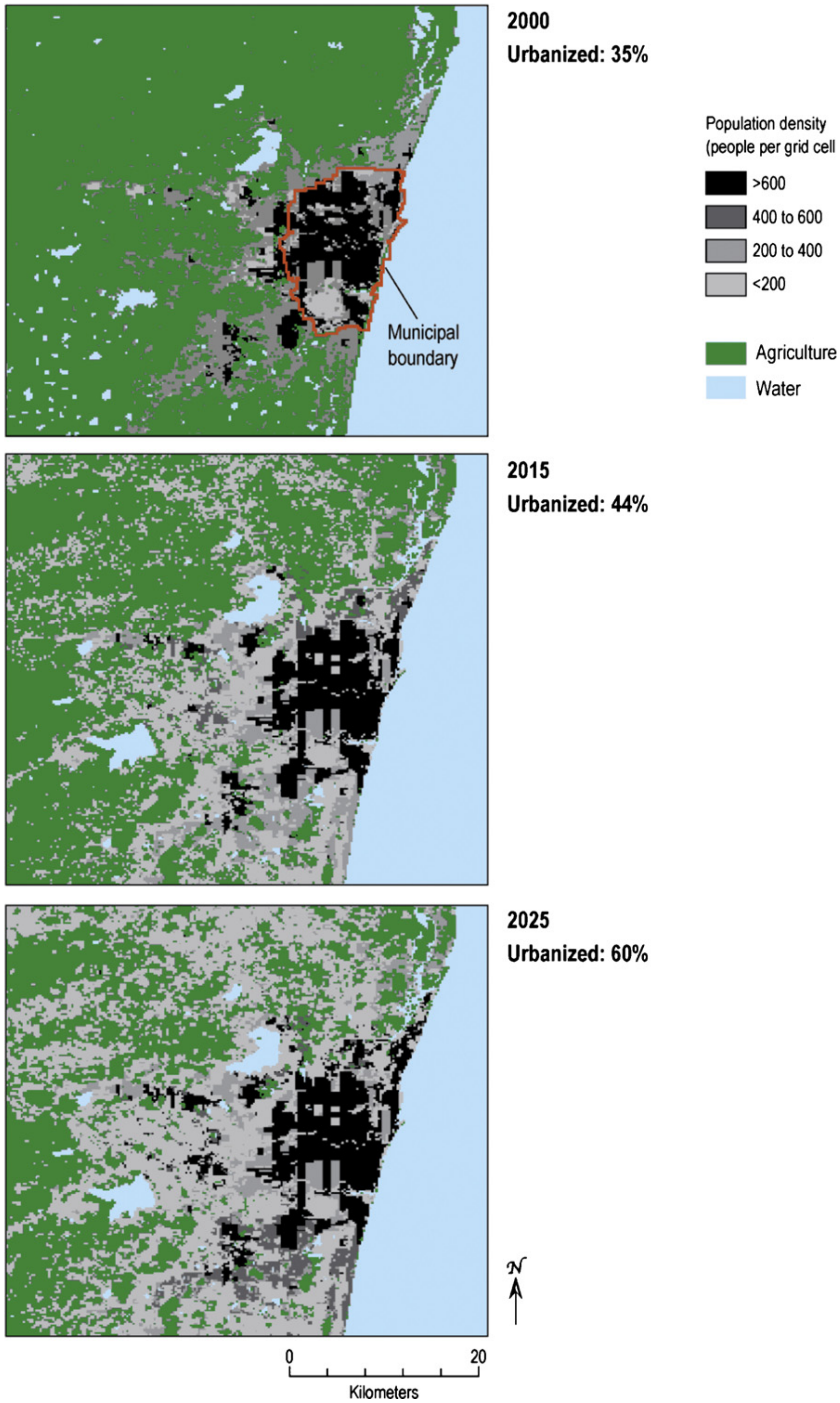


**Fig. 3.** Land use forecasts.

Land use was projected using a cellular automaton model (SLEUTH) which is based on the Clark urban growth model.

Our land use projections indicate that if past trends continue, there will be large-scale land conversion from agricultural to urban land uses (Fig. 3). The proportion of urban and agricultural land, as a fraction of basin land cover, is expected to change from 35% urban and 61% agricultural land in 2000, to 60% urban and 36% agricultural land in 2025, with the remaining 4% area being surface water. The projections indicate that urbanized land area is growing much faster than population growth; so that much of the peri-urban land converted out of agriculture is expected to be low-density housing or land awaiting development. Thus although peri-urban land urbanizes, the density of population in peri-urban areas is relatively low.

In presenting the simulation results (Table 3), we chose July 2003 and July 2023 as the two reference years because they both represent the peak of the drought. The water vulnerability index for 2003 represents the vulnerability to drought in a "low urbanization state," when the urbanized area constitutes only a third of the whole basin. The water vulnerability index for 2023 represents the vulnerability to water shortages in a "high urbanization state," when the urban land area covers over two-thirds of the whole basin.

**Table 3**
Water vulnerability index in Chennai.

| | Chennai City | Peri-Urban Area |
|---|---|---|
| Historical vulnerability (2003) (low urbanization state) | 65% | 75% |
| Future simulated vulnerability (2023) (high urbanization state) | 99% | 67% |

The results suggest that the link between urbanization and vulnerability to water shortages is spatially differentiated—households within the urban center become more vulnerable, whereas households in the peri-urban area become less vulnerable in the future drought (2023) compared to a historical one (2003). We explain these results with the following logical arguments that illustrate the relationship between vulnerability and urban growth.

First, for a given water resource availability, household water consumption and hence vulnerability depends on access to piped supply and self-supply via wells. Piped supply is jointly determined by the utility's decisions (e.g., where to lay mains) and the household's decisions (e.g., whether to get a connection). In contrast, self-supply via private wells depends exclusively on whether the household has a well, which in turn depends on household income. Second, even as households make adaptive decisions that make them individually better off, the cumulative effect of millions of uncoordinated decisions may make the system as a whole more vulnerable. This cumulative vulnerability depends both on population density and aquifer characteristics. In the following sub-sections we further elaborate each of these arguments by presenting model results to support them.

*4.1.1. Household-level vulnerability*

The model results reflect that water consumption is dependent on household level adaptive investments. A comparison of household water consumption across households in 2006—one of the wettest periods on record—suggests that consumption is a function of household adaptive investments (Table 4). Households with access to both piped supply and private wells consume more than households with only private wells, who in turn consume more than households who must collect water manually from public standpipes or communal wells.

During the 2003–2005 drought, peri-urban dwellers were vulnerable to shortages because few households had indoor plumbing, deep borewells, or municipal piped connections. Peri-urban households, dependent on shallow public wells, were particularly affected by drops in the water table. However, if current urban growth trends continue, in a future drought, the situation in peri-urban areas will be very different. Infrastructure investments in peri-urban areas are expected to increase – either by households investing in wells or selling to developers of modern housing complexes with deep borewells. Piped supply services will also be gradually extended to peri-urban areas. These improvements in infrastructure alone will result in a significant <u>decrease</u> in water vulnerability in peri-urban areas.

**Table 4**
Household-level vulnerability as a function of investments.

| LPCD of consumption[a] | Chennai |
|---|---|
| Consumption (2006) – wet year | |
| Households with piped supply and wells | 133 |
| Households with no piped supply only private wells | 78 |
| Households with no piped supply or wells | 35 |

[a] Liters per capita per day – although the values presented here are from model simulations, the model was calibrated against household survey data for this period. So these values also reflect actual data.

*4.1.2. Cumulative vulnerability*

Our analysis suggests that the cumulative effects of these decisions will be spatially differentiated and largely driven by continued reliance on private wells, which causes water availability to be driven by the cumulative effect of decentralized pumping by millions of households. Despite modest increases in water supply from desalination plants, water demand will continue to be met mainly by self-supply from private wells (Fig. 4). The quantity of planned increases in water resources augmentation is not enough to meet the higher demand in the future and most households will need to supplement water from private wells.

However, the model results show that there are spatial differences in the behavior of groundwater trends between the core city and peri-urban areas (Fig. 5). The model predicts that the average depth of the water table within the city of Chennai will increase over time, but there will be a corresponding decrease in peri-urban Chennai. Thus, the urban core of Chennai city is more vulnerable than the peri-urban areas. This suggests potential trade-offs between urbanization strategies for climate change mitigation versus adaptation. Although compact, dense, and multi-use urbanization could reduce energy use and greenhouse gas emissions (National Research Council, 2009; Ewing and Rong, 2008), in the case of Chennai, it also increases the vulnerability of the city to water stress. In contrast, peri-urban areas in Chennai are less vulnerable to water stress but low-density development could result in higher energy use (Norman et al., 2006).

Several factors determine how groundwater levels fluctuate. Groundwater availability is a function of aquifer recharge, extraction, and storage – each of these factors varies spatially. First, when land is first sold from farmers to developers, groundwater extraction decreases significantly as pumping for irrigated agriculture ceases. Second, as the area begins to develop, total groundwater extraction is determined by the cumulative pumping of all households and therefore depends both on the density of households with wells, as well as the extraction per household. As more households invest in private wells and indoor plumbing, extraction increases. As piped water services are extended to peri-urban areas groundwater extraction decreases. The net effect on groundwater extraction would depend on the density of housing and how quickly piped supply is extended to peri-urban areas. Third, groundwater recharge in turn has two components. While paving over of urban areas may cause some decrease in recharge, as new pipelines are installed, a significant fraction (~10–30%) of the piped water often leaks and recharges the aquifer. Fourth and finally, aquifer storage is an important contributor to vulnerability. The storage capacity and transmissive properties of the aquifer determine how much the water table drops for a given level of recharge and extraction. For instance, Chennai's aquifer is highly heterogeneous; the water table drops faster in the hard rock areas of South Chennai compared to areas overlying the deep alluvial aquifers in north eastern Chennai.

Thus, the observed trends can be explained by the combination of these four factors. Net groundwater extraction in the peri-urban area *decreases* initially (Fig. 6). As the city grows, agricultural water extraction steadily drops and groundwater extraction for domestic uses steadily increases. The quantity of water used for irrigated agriculture is far more than the water abstracted for domestic use by peri-urban households. Therefore, even though individual households begin to extract more per household (as more households install borewells and indoor plumbing), groundwater extraction decreases in the early stages of urbanization. The opposite is true in the densely populated core urban area. The

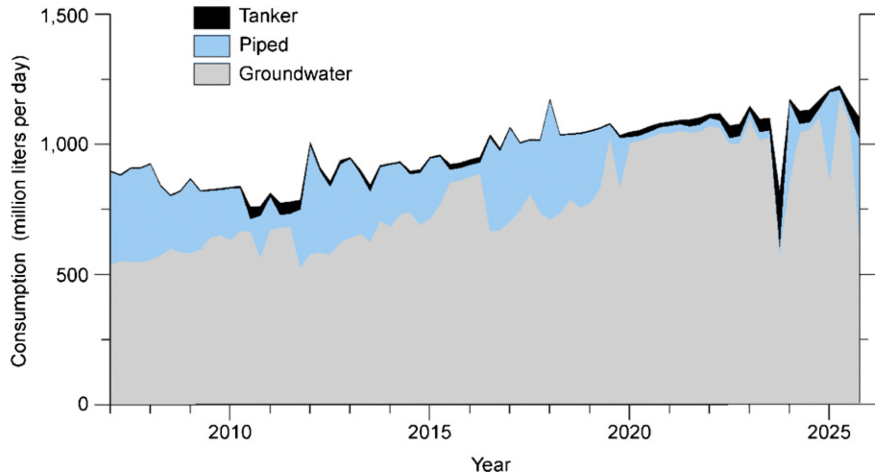


**Fig. 4.** "Business-as-usual" water use forecast by source – for one specific rainfall scenario where a past drought is assumed to recur in the future.

urban core already has high levels of indoor plumbing, private borewells, and piped supply connectivity and there are more households per square kilometer owning private wells. Consequently, groundwater extraction increases sharply during droughts when piped supply is cut back. As Chennai's population grows, the water utility must now satisfy a larger population with the existing reservoir infrastructure. Therefore, over time the piped system delivers less and less to each household and reservoir storage is depleted even faster during droughts. Here, in the urban core, vulnerability to water shortages worsens over time. In summary, low density peri-urban areas are vulnerable because they are infrastructure constrained while the high-density urban core areas are vulnerable because they are resource constrained.

Basin wide groundwater extraction decreases over time. However, while extraction fluctuates wildly within the densely populated city (dark gray) in the peri-urban area, extraction remains more or less stable (light gray).

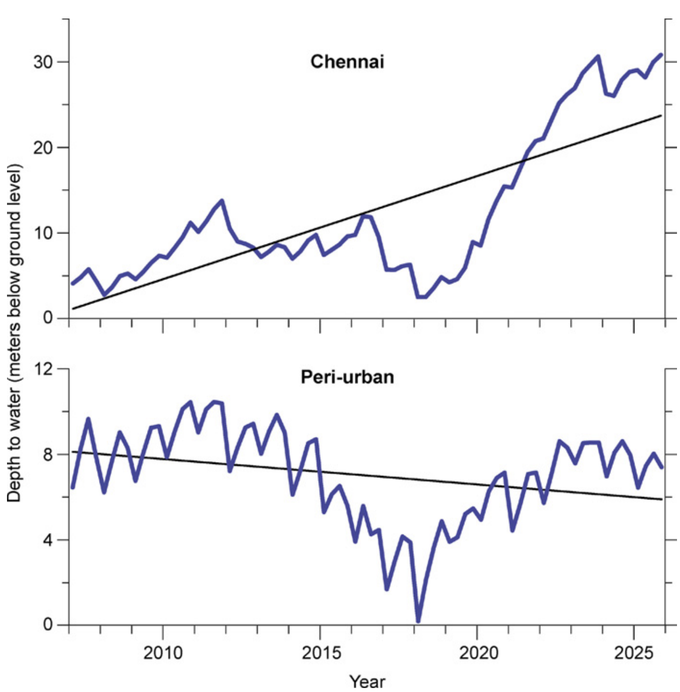


**Fig. 5.** Depth to water table of shallow aquifer in Chennai and peri-urban Chennai over time for one specific rainfall scenario where a past drought is assumed to recur in the future (2021–23).

The results described in this paper are based on a baseline or "business-as-usual" projections of investments in the water sector. However, adaptations at the utility or consumer scales can alter these trajectories. A more detailed discussion of water policy options has been published elsewhere (Srinivasan et al., 2010b). The impact of various adaptation options on vulnerability is presented in an online supplement s1.

Supplementary material related to this article found, in the online version, at doi:10.1016/j.gloenvcha.2012.10.002.

## 5. Discussion

### 5.1. The nature of the land-water transformation

This study offers a new perspective into the nature of the urbanization–water link. The conventional wisdom (Rogers et al., 2000) is that developing cities obtain water via *centralized systems*: a public or private water utility locates a new water source, then treats and distributes the water to urban households via a piped network. Instead, our study suggests that the primary land-water transformation in Chennai is a *decentralized* one, accomplished by private individuals.

Three mechanisms by which water is reallocated to cities are commonly cited in the literature: administrative reallocation, market reallocation, and user reallocation (Dinar et al., 1997). None of these mechanisms account for the patterns observed in Chennai. Even though several new supply augmentation projects are being planned, they often get mired in the resettlement and environmental issues which take decades to resolve (Nikku, 2004). Similarly, although market reallocation has been suggested as an effective mechanism to transfer water from low-value agricultural uses to high-value urban uses, formal water markets have not emerged in a significant way in India as there are no private property rights to water (Singh, 1992). Temporary purchases of groundwater from farmers both by the water utility and tanker operators do occur but these only constitute a small fraction of total urban supply during normal or wet periods. Likewise, user reallocation where communities jointly agree to transfer a communal water source for a new purpose has been minimal; a few peri-urban irrigation tanks were transferred to the urban water system as their watersheds urbanized, but these provide very little storage. Most of the defunct peri-urban irrigation tanks (ponds) are being revived as percolation ponds and not as surface reservoirs. The three reallocation mechanisms commonly cited in the literature implicitly refer to large surface water sources that can be reallocated to supply a piped supply scheme in an urban

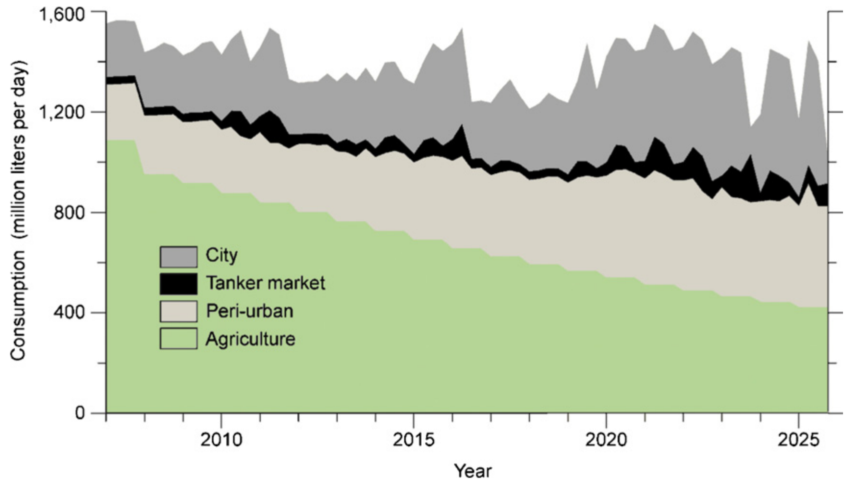


**Fig. 6.** Basin-wide groundwater extraction.

area. However, in the region around Chennai, there is no surface water body and almost all of the irrigated agriculture is dependent on private wells. As the city grows and new peri-urban areas develop, the pace of growth is so high that it is virtually impossible for infrastructure and governance to keep up. The newly developed peri-urban housing complexes simply drill wells. Thus, the major transformation in Chennai's water resource system has been the replacement of groundwater-irrigated agriculture by groundwater-supplied peri-urban areas. In effect, a distributed set of irrigation wells is replaced over time by a distributed set of urban wells. This decentralized nature of the land-water transformation, has tremendous implications for water vulnerability, but has been largely under-examined.

### *5.2. Links between urbanization and vulnerability*

By integrating both water resources and spatial geographic perspectives, this study shows that the relationship between urbanization and water vulnerability is much more nuanced than either pessimistic or optimistic views suggest.

First, when infrastructure is underdeveloped and resources are not being imported into the city at the required rate, households must depend entirely on the local resource base. Therefore, a higher population density results in greater fluctuations in the water table and thus greater vulnerability. This presents a sustainability paradox. While previous research suggests that compact urban development may reduce energy use and carbon emissions, our study suggests that there are limits to this if urban dwellers are directly dependent on local resources. However, the vulnerability also depends on the nature of the groundwater system. If all households in a densely populated area install wells, the buffering capacity of the aquifer is eroded. Chennai's shallow aquifer no longer can sustain the entire urban population over multiple years. Where a deeper aquifer would be able to support a higher population density, a less productive aquifer cannot.

Second, the relationship among the piped system, the aquifer and water vulnerability is influenced by the length and frequency of drought. Because groundwater is a supplementary source, vulnerability is also dependent on availability of surface water. The study suggests that Chennai's reservoir system only has about 13–15 months of storage, which is insufficient to tide over a multi-year drought. The benefits of having an efficient piped supply system are only realized as long as there is water in the reservoir system to distribute. As long as surface water storage remains constrained, maintaining the aquifer's buffering capacity by other means such as artificial recharge will be necessary to reduce vulnerability. This finding has implications for how cities manage their water to adapt to climate change. In particular, it suggests that climate resilience depends on the relative proportion of investments in centralized storage and distribution (reservoirs and pipes) versus decentralized storage and distribution (aquifers and private wells), the scale at which adaptation occurs, and physical characteristics of the rainfall and the aquifer.

**Table 5**
Links between urbanization process and water system changes.

| Sub-system | Macro-scale process change associated with urbanization | Impact on vulnerability |
|---|---|---|
| Economic | Increase in number of commercial establishments | + |
| | Decrease in irrigated area | − |
| Demography | Increase in population density | + |
| | Change in wealth of the population | + |
| | Increase in access to utility connections, indoor plumbing | − |
| Infrastructure | New water and sewerage pipes, reservoirs and treatment plants | − |
| | Decrease in pipeline leakage | +/− |
| Land use | Change in land use from "agriculture" to urban to low density housing | − |
| | Increase in density of housing in peri-urban areas | + |
| Hydrogeology | Low transmissivity and storage of aquifer | + |

+: more vulnerable; −: less vulnerable; +/−: more or less vulnerable depending on other conditions.

In summary, by combining the strengths of modeling and spatial analysis, we developed new insights on how different processes associated with urbanization impact water vulnerability (Table 5). Whether urban areas will become more or less vulnerable will depend on the relative magnitude and rate of each of these factors.

### *5.3. Implications for governance*

A major implication of the decentralized nature of this land–water transformation in the Chennai region is that no single water planning agency likely can "optimally allocate" water resources during a drought. Instead, water consumption and hence vulnerability to drought is shaped by hydrologic sensitivity to drought conditions, adaptive actions taken by the water utility and individual households, and the scale and form of urban development – but in a way that likely cannot be controlled by a single agency. Traditional urban planning processes and governance institutions do not have the capacity to address this. Managing vulnerability to water shortages in cities like Chennai, will require new governance structures and planning processes that are capable of accounting for and managing decentralized actions by millions of individuals.

## 6. Conclusions

There will be between 3 and 5 billion new urban dwellers by 2100. One of the biggest challenges of the 21st century will be to find infrastructural, institutional and financial solutions that promote sustainable and resilient water systems to serve these populations. Three key results for Chennai have important implications for sustainable urbanization and water vulnerability. First, the land-water transformation is a decentralized process. Individual households adapt to water stress by investing in wells, piped supply and other strategies, but they are constrained both by the utility infrastructure and characteristics of the aquifer. Therefore, although investments at the household scale make individuals less vulnerable, cumulatively they make the region as a whole more vulnerable. Second, where and how urbanization unfolds has enormous impacts on the aquifer and suggests tradeoffs between different urbanization strategies and environmental impacts. Our model results show that compact and dense urbanization increase vulnerability to water stress while peri-urban development places less stress on the aquifer. However, these two types of urbanization also have differentiated impacts on energy use and carbon emissions, neither of which are considered in this study. Third, no single municipal water authority can likely "optimally allocate" water resources during a drought. The relationship between urbanization and vulnerability to water shortages depends on multiple factors: the formal water infrastructure, the rate and spatial pattern of urbanization, adaptation by households, and the local geology. Therefore, there is a need for new governance structures and planning processes that can reduce the vulnerability of rapidly urbanizing regions to water shortages. The study suggests that future research is needed on: 1) the combined impacts of multiple stressors – demographic, climatic and land use change at different spatial and temporal scales, 2) the scale of adaptation actions and their cumulative effects, 3) the role of institutions in mediating between water resources availability at the basin scale and vulnerability at the household scale and 4) the dynamic and scale-dependent nature of vulnerability.

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