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A hydrologic-economic modeling approach for analysis of urban water supply dynamics in Chennai, India

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[1] In this paper, we discuss a challenging water resources problem in a developing world city, Chennai, India. The goal is to reconstruct past system behavior and diagnose the causes of a major water crisis. In order to do this, we develop a hydrologic-engineering-economic model to address the complexity of urban water supply arising from consumers' dependence on multiple interconnected sources of water. We integrate different components of the urban water system: water flowing into the reservoir system; diversion and distribution by the public water utility; groundwater flow in the aquifer beneath the city; supply, demand, and prices in the informal tanker-truck-based water market; and consumer behavior. Both the economic and physical impacts of consumers' dependence on multiple sources of water are quantified. The model is calibrated over the period 2002–2006 using a range of hydrologic and socio-economic data. The model's results highlight the inadequacy of the reservoir system and the buffering role played by the urban aquifer and consumers' coping investments during multiyear droughts.

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1. Introduction

[2] Urban areas in India have been experiencing unprecedented growth in population and income [*United Nations*, 2001]. Faced with highly variable and yet uncertain rainfall, limited reservoir storage, aging piped network infrastructure, and rapidly growing demand, no Indian city today has 24/7 water supply; instead piped supply is intermittent, available for only a few hours each day, a situation strikingly different than that in other Asian countries where 24/7 supply has been achieved in at least some major cities [*McIntosh*, 2003]. To deal with unreliable water supply, many Indian urban consumers depend on private sources. A recent study of seven Indian mega-cities [*Shaban and Sharma*, 2007] indicated that between 25% and 80% of households in six cities supplemented piped supply with private wells. Additionally, many Indian cities have seen the emergence of informal markets, where private tanker operators purchase water from peri-urban farmers and transport the water into urban areas in tanker trucks [*Londhe et al.*, 2005; *McKenzie and Ray*, 2009].

[3] The main challenge facing Indian cities is that of supplying water to a burgeoning population reliably at an affordable price. However, in addressing the problem, analyses of urban water supply in Indian cities have been incomplete in two ways. First, the scholarly literature has tended to take a "utility-centric" view of urban water supply, wherein the urban water utility is the sole entity supplying treated water to consumers via pipes. This conceptualization is reflected in previous studies of urban water supply, which tend to focus on various aspects of the utility supply system. Engineering models of urban water distribution and wastewater treatment have been well-established for many decades. Examples of economic analyses have focused on evaluating and comparing options to improve supply or better manage demand for piped supply in cities [*Saleth and Dinar*, 1997] or water transfers from agricultural to urban water districts [*Rosegrant and Binswanger*, 1994]. Consumer models have focused on demand responses to various conservation, pricing or delivery scenarios [*Rosenberg et al.*, 2007]. Second, even empirical analyses that have examined non-utility supply have been focused narrowly on one aspect such as, informal water markets [*Solo*, 1999], or consumer coping behavior [*Pattanayak et al.*, 2005]. These studies have tended to treat coping behavior as being independent or at least separable from the problem of utility supply. Third, there is a long history of hydrologic-economic modeling of water resources [*Cai et al.*, 2003; *Harou and Lund*, 2008; *Pulido-Velázquez et al.*, 2006; *Ringler et al.*, 2004; *Rosegrant et al.*, 2000; *Schoups et al.*, 2006; *Ward et al.*, 2006] in various basins reviewed in two recent publications [*Harou et al.*, 2009; *Simonovic*, 2008]. However, very few studies have focused on urban areas particularly under intermittent conditions [*Rosenberg et al.*, 2008].

[4] We suggest that the "utility-centric" framing of the problem has contributed to the lack of integrated analyses in urban water supply. As long as the utility is viewed as the sole entity that abstracts, treats, and distributes water in urban areas, models combining ground and surface water flows, consumer behavior and piped distribution are viewed as unnecessary. However, the current utility centric framing in excluding non-utility supply and consumers' coping mechanisms, leads to erroneous conclusions. For instance,

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ignoring supply from private and self-supply could result in overestimating demand for piped supply or underestimating the quantity of wastewater flows. Overlooking coping investments may result in overestimating consumers' willingness-to-pay for piped system improvements. Ignoring private abstractions from wells may result in overestimating the quantity of ground and surface water available for other purposes. Assimilating utility and non-utility supply in a single system overcomes these issues. There are additional benefits. The integrative approach makes it possible to represent the impacts of water resource variability (dry and wet years) on consumers. It correctly represents how consumer behavior changes in response to past investments by both consumers and the water utility. Finally, it provides a basis to evaluate a range of policies from improving recharge to raising tariffs to desalination to improved efficiency, using standardized metrics of equity and sustainability. However, no existing studies have combined utility-supply, self-supply, private supply, and consumers' coping mechanisms into a single modeling framework.

[5] In this paper we present a unified hydrologic-engineering-economic systems modeling approach to deal with the complexity of urban water supply in India and attempt to replicate past system behavior. The model is analyzes urban water supply in a comprehensive manner, taking into account the critical interdependencies between different components of water supply. This paper is organized as follows: In the next section, we provide a brief introduction to the hydrologic-economic modeling literature and the contributions of this work. We describe the systems approach and our case study site, Chennai, India. We present details on model calibration and development, including a discussion of the primary methodological challenges in integrative modeling. We present the model results and discuss the dynamics of the water supply system in Chennai. Finally, we discuss how the analysis provides insights that could not have been gained without an integrated systems model of urban water supply.

2. Literature Review and Contributions

[6] There is a long history of hydrologic-economic modeling in representing regional scale hydrologic, engineering, environmental and economic aspects of water resources systems within a coherent framework [*Harou et al.*, 2009; *Simonovic*, 2008; *Simonovic and Fahmy*, 1999]. The recent review by *Harou et al.* [2009] provides a comprehensive review of the current hydrologic-economic modeling literature. The authors discuss how economics has helped water resources managers to move away from a static conception of demand based on population projections, rights and development priorities to that of economic value. They discuss how this monetization allowed a range of different policy options to become comparable. The authors also provide a useful guide to the types of choices hydrologic-economic modelers need to make: (1) simulation versus optimization, (2) modular versus holistic, and (3) stochastic versus deterministic.

[7] In this paper we present a unified hydrologic-engineering-economic simulation modeling approach to deal with the complexity of urban water supply in India. The model is modular, spatial and dynamic. It is designed to analyze urban water supply in a comprehensive manner, taking into account the critical interdependencies between different components of water supply. Of the various options, the choice of simulation modeling versus more common optimization modeling warrants further discussion. *Bredehoeft et al.* [1995] suggest that the benefits of optimization solutions are limited particularly when inefficient water institutions are taken as fixed constraints. We concur and offer two additional justifications for the simulation modeling approach used here. (1) Optimization models are necessarily forward looking, in recommending better management options. However, the intent of this model described here is to offer a careful diagnosis of a past water crisis. Optimization models implicitly assume that the underlying relationships between variables are known; the goal is to manage a well-understood system better. But this necessitates confidence in the feedbacks between the model sub-systems. This was not the case in our case study site, which was poorly characterized. Using a simulation model allowed us to explore multiple working hypotheses and test a range of possible dynamic feedbacks between model sub-systems and identify the most important ones. The modular simulation model presented here is particularly useful when integrating non-economic social sciences into water resources management, where the use of reduced form equations in optimization often masks unsupported assumptions about the coupled human-natural-engineered system. It also makes it possible to change institutional constraints in future periods. (2) Optimization models implicitly assume the existence of equilibrium. In the case of Chennai, the water system is inherently dynamic and path-dependent. In each time period, incentives to various stakeholders depend on their past actions and beliefs about the future. Our simulation model allowed consumers to optimize over their various options in each time period, a "simulation model using an optimization computational engine" [*Harou et al.*, 2009, p. 632].

[8] This paper offers several contributions to both the water resources management literature as well as the hydrologic-economic modeling literature. Although we describe a complex model addressing one case study area, the underlying system characteristics of multiple source dependence, inadequate storage, poor demand management, high leakage rates, and crises during multiyear droughts are similar to those described elsewhere in the developing world [*Baisa et al.*, 2010; *von Bertrab*, 2003]; this suggests the results may provide insights beyond this case. Methodologically, the model provides a basis to compare policy interventions using standard criteria. In particular, the modeling approach presented here makes it possible to explore the costs and benefits of various policies on consumer well-being (efficiency), by consumer type (equity), across time (weak sustainability). Water resource availability over time (strong sustainability) can also be represented. Finally, the model demonstrates how modules with different temporal and spatial scales can be successfully integrated and calibrated, something which remains relatively challenging [*Harou et al.*, 2009].

3. Background

3.1. Systems Approach

[9] Systems approaches involve modeling and linking different components of an interconnected system. The model components and/or the whole model are calibrated

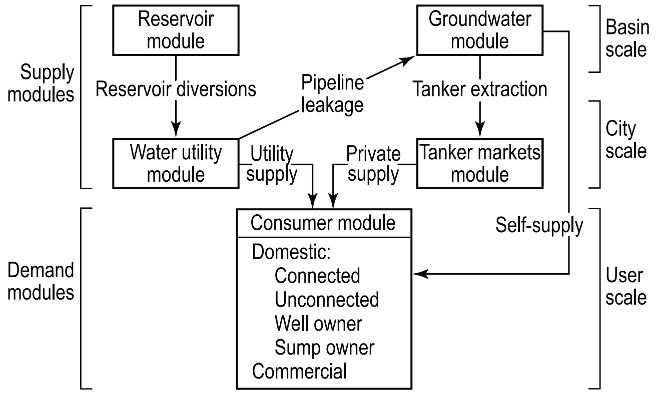

Figure 1. Integrated simulation model linkages: The integrated model estimates supply and demand for each census unit, consumer category, and time period using five interlinked components: the Reservoir, the Groundwater, Utility, Tanker and Consumer Modules.

using observed data. As indicated above, a systems approach is crucial for understanding the availability and use of water in urban areas in India. In this work, different components of the Chennai water-supply system were simulated using a dynamic, spatially explicit model of the Chennai basin. The integrated model simulates and links surface water flows into the reservoir system, and groundwater flows in the Chennai aquifer. Then the model allocates to consumers the quantity of water available to the utility from the reservoir system and other sources. Finally, a consumer cost-minimization problem is solved to estimate actual consumption and consumer surplus (a measure of consumer well-being), subject to constraints of quantity, potability, and price of water available from the various sources.

3.2. Case Study Area: Chennai, India

[10] Chennai, a growing city of 4.5 million is located in the semi-arid state of Tamil Nadu in South India. Chennai's water situation is particularly severe. Its water availability is the lowest of all Indian mega-cities. Chennai experienced one of its driest years in 2003, followed by the heaviest rains in its recorded history in 2005. The fortuitous occurrence of both extremes within our study timeframe, and the availability of both socio-economic survey data and hydrologic data for both years, made a systems analysis of water supply ideal.

[11] A public water utility, Metrowater, supplies the municipal area via a piped network, using water from rain-fed reservoirs and well-fields outside the city. In a normal year, most of Chennai's water comes from four dedicated reservoirs (~350 million liters per day, MLD) just north of the city. The Chennai reservoir system receives water from runoff from the local watershed in the rainy season, and the inter-state Telugu Ganga project. The intrastate Veeranam project supplies water (~180 MLD) from the Cauvery basin about 250 km south of Chennai by pipeline. A small fraction (~60–80 MLD) is sources from well-fields located in the Araniar-Koratalaiyar basin 20 km north of Chennai and other minor local sources (Metrowater, Development of the water supply system to Chennai city, Chennai Metropolitan Water Supply and Sewage Board, 2008, http://www.chennaimetrowater.com/operationmain_main.htm).

[12] Over 95 percent of the households within Chennai city have some sort of access to utility supply: private piped connections, yard hand-pumps or taps, public standpipes or utility-run "mobile supply" tankers that are run to low-income neighborhoods. Piped water supply is highly intermittent and available for only a few hours each day. Chennai's water availability per capita, at 40–100 L per capita per day (LPCD), is the lowest of any large metropolitan area in India [*Asian Development Bank*, 2007]. Consumers rely on private wells to cope with the unreliability of public water supplies. Over two thirds of households in Chennai have private wells, an estimated 420,000 wells within Chennai [*Vaidyanathan and Saravanan*, 2004], an average well spacing of just 20 m in the densely populated urban area. Outside 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.

[13] During the climatic drought of 2003–2004, Chennai's reservoirs went completely dry; the piped supply system was shut down for a year. The entire city became dependent on "mobile supply": utility-run tankers that went from neighborhood to neighborhood delivering a "lifeline" supply of water, about 20 L per capita per day, that individuals collected in 15-L pots. In response to the cessation of supply, informal tanker markets emerged in which water was purchased from peri-urban farmers and sold to residents in Chennai. Eventually, a heavy monsoon in 2005 ended the crisis and piped supply was restored.

4. Structure of Model

[14] The systems model of water supply of Chennai covers a 2550 sq. km area incorporating the entire Chennai Metropolitan Area. The historical model was run over the period Jan 2002 to Apr 2006 spanning both the wettest and one of the driest periods in recorded history. 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. A complete list of the primary and secondary data used is provided in Table S1 in the auxiliary material.[1] The model was developed in MS Excel, Visual Basic and MODFLOW-2000. The integrated model represented five system components or "Modules" (Figure 1): the Reservoir Module, the Groundwater Module, the Utility Module, the Tanker Module and the Consumer Module. The modules were then linked to incorporate feedbacks.

[15] Each module simulated one component of the Chennai water system. A complete list the equations in each module can be found in Appendix A. The Reservoir and Groundwater Modules simulate basin-scale groundwater and surface water flows. The Utility Modules allocates the available water to consumers. The Tanker Module simulates supply of water via private tankers in the informal water market in Chennai. The Consumer Module, solves the consumers' cost-minimization problem, given the quantity, quality, and price of water available from the various sources and prior investments in coping mechanisms by consumers. The

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2009WR008693.

modules were developed and calibrated independently. This allowed each module to have a different spatial and temporal unit when necessary. This made it possible to combine models of individual consumers (with a decision making time-frame of a day), with a reservoir and utility operations (with monthly data) and groundwater flows (with seasonal fluctuations in the water table).

[16] The model used two different types of spatial domains within the model area with appropriate transformations. While the Groundwater Module simulated hydraulic head using a spatial grid, the Utility, Consumer, and Tanker Modules used census zones; i.e., the consumer-choice problem was solved for a "representative agent," in each of 10 census zones within Chennai. The integrated model generated results for sequential 3-month time periods. The 3-month time period enabled us to capture seasonal fluctuations in groundwater levels while maintaining reasonable simulation times. The consumer cost-minimization problem was solved assuming the consumer has a decision-making time-frame of one day. However, the daily consumption was assumed to be constant over each 3-month period so that effectively the Consumer Module also used a time period of 3 months. Only the Reservoir Module was simulated at a one-month time period; highly variable month-to-month inflows from rainfall and inter-state transfers made averaging over a 3-month time period inadequate. The inputs, transformations, and output variables for each module are listed in Table 1, which shows the inputs, outputs and main transformations achieved by each module. In Table 1, calibrated parameters are shown in a bold font; variables for which surveyed or observed data are available are shown in italics.

[17] For some modules, results are presented for only two periods Jan–Mar 2004 (a dry period) and Jan–Mar 2006 (a wet period), even though the model generated outputs for all 3-month time periods between Jan 2002 and Apr 2006. This was done for the following reason; the data used for calibration included two household surveys covering about 1500 households each: one conducted at the peak of the multiyear drought period in January and February 2004, by the Centre for Science and Environment, New Delhi [*Vaidyanathan and Saravanan*, 2004], and resurveyed by us in January–March 2006, a period following one of the heaviest monsoons on record. This panel data set provided a rare opportunity to observe a large number of households across two different hydrologic states. However, because household surveys are labor intensive and expensive, household survey data were not available for every 3-month period, so calibrations of consumer behavior were based only on two time periods. To maintain consistency and contrast the wet and dry periods, through the paper the periods Jan–Mar 2004 (a dry period) and Jan–Mar 2006 (a wet period) are used as reference periods.

5. Model Development and Calibration

[18] In this section we present the model development and calibration of the five modules.

5.1. Reservoir Module

[19] The purpose of the Reservoir Module was to estimate the quantity of water available to the urban water utility. The Reservoir Module estimated storage in the three-reservoir system at the end of each month based on inflows, evaporation, releases, and leakage. The Reservoir Module simulates Chennai's three reservoirs as a single system. The reservoirs, Poondi, Cholavaram and Red-Hills, receive surface water runoff from rainfall from the local watershed as well as deliveries from an inter-state project, the Telugu Ganga project. Since the reservoir system is exclusively managed for urban supply, no considerations for irrigation, in-stream flows or flood control were necessary. Data on monthly inflows and outflows into the city's reservoir system, and average monthly rainfall at the three reservoirs were obtained from the utility's Internet-based database (Metrowater, Lake level data, 2007, Chennai Metropolitan Water Supply and Sewerage Board, Chennai, India, available at http://www.chennaimetrowater.com).

[20] The Reservoir Module estimated storage in the three-reservoir system at the end of each month. In the historical period, data on reservoir storage, inflows, rainfall and diversions were available. However, for future periods, each element of the reservoir water balance needed to be determined either as a function of rainfall, or remain constant in future years, so the reservoir storage could be projected for a given rainfall scenario. The inflows and outflows into the reservoir system were estimated as follows. (1) Inflows contributed by the local watershed were estimated, deliveries of inter-state water at the state boundary were subtracted from total reservoir inflows for the historical period. Then monthly inflows from local runoff were estimated as a function of monthly rainfall, using a regression on the last 5 years monthly data. The rainfall-inflow function thus estimated was found to be log linear. (2) Monthly evaporation was set at the mean monthly lake-evaporation obtained from a 40-year period of record [*United Nations Development Programme*, 1987]. This captured seasonal variability in evaporation rates. (3) The inter-state Telugu Ganga project comprised the single largest component of the reservoir water balance. We found that in the historical period deliveries across the state boundaries correlated with total annual rainfall in the Chennai region. (4) Hydrologic data and basic engineering calculations suggest very little leakage from the reservoir system into the aquifer as a thick clayey aquifer layer underlies the reservoir in this area. (5) Downstream spills into the sea occurred in periods when the reservoir was filled to capacity. (6) Monthly diversions to city supply were estimated to be the lesser of two quantities: a fixed component of 170 million liters per day (MLD) plus a variable component or total available storage. The variable component was determined to be 25% of reservoir storage in months when the inter-state Telugu Ganga water was received and 10% in other months. Simulated and observed reservoir storage values were matched with a R^2 of 96% (Figure 2).

5.2. Groundwater Module

[21] The purpose of the Groundwater Module was to determine the role of private wells in providing water supply in Chennai over space and time. The model was essential in understanding consumer behavior when faced with fluctuating groundwater levels and in some cases wells that dried up seasonally.

[22] A 3-D transient model was developed to simulate the Chennai aquifer system. The model area was discretized into a uniform grid of 231 rows and 231 columns.

Table 1. Function of Individual Modules in Integrated Water Supply Model[a]

Module	Inputs	Transformation	Outputs
Reservoir Module	*Rainfall* **Inter-state water transfer parameters**	Inter-state water transfer algorithm	*Inter-state water transfer quantity*
	Rainfall **Inter-state water transfer parameters**	Inter-state water transfer algorithm	*Inter-state water transfer quantity*
	Rainfall	Rainfall-inflow equation	*Inflows into reservoir system*
	Rainfall *Reservoir Storage* *Reservoir Evaporation* *Reservoir Leakage* *Reservoir capacity* ***Rainfall-runoff parameters*** ***Reservoir operation parameters***	Reservoir water balance	*Water diverted from reservoir system for utility supply*
Groundwater Module	*Land use* **Hydraulic Conductivity** **Storage Coefficient** **Recharge rate Extraction** **Initial Conditions (Heads)** **Boundary Conditions**	3-D Transient groundwater model (MODFLOW)	*Groundwater head over space and time*
	Well depths *Groundwater heads*	Well depth distribution	*Percentage of dry wells*
	Hydraulic Conductivity **Storage Coefficient** **Well efficiency** ***Groundwater heads***	Theim equation	Maximum quantity of water that can be drawn from a well
	Groundwater head Electricity price Pump efficiency	Pumping cost calculation	Price of groundwater = cost of extraction
Water Utility Module	*Water diverted from city reservoirs for city supply* *Water abstracted from other sources* ***Pipeline Losses***	Hierarchical distribution algorithm	Water supply by utility to different consumer categories
Tanker Market Module	Demand for tanker water Location of source areas	Competitive market pricing of tanker water	*Size of tanker market Price of tanker water* Extraction by tanker operators
Consumer Module	Water demanded by consumer, by source: utility, groundwater, surface water and tankers **Price of utility supply** **Price of groundwater** **Price of tanker water** **Opportunity cost of time** **Collection time from private hand-pumps** **Collection time from standpipes** **Consumer demand function** **Population, Income**	Consumer cost-minimization algorithm	*Water consumed by consumer category, by mode of supply, and quality*
	Water consumed by consumer category, by mode of supply, and quality	Consumer surplus estimation equation	Consumer surplus

[a] Calibrated parameters are shown in bold; variables for which surveyed or observed data are available are shown in italics.

The aquifer system was conceptualized as consisting of three non-uniform layers, an upper sandy unconfined layer, a clay aquitard and a lower confined sandy layer. The impermeable bedrock comprised shale to the west and hard rock (charnokite) to the east and south of the city. The permeable weathered portion of the charnokite was included as part of the lower confined layer. The aquifer was found to be thickest to the northwest of the model where the shale occurs at a depth of over 100 m. To the southwest of the Chennai, the weathered bed-rock outcrops. The complex structure referenced geological maps prepared by other scholars and development agencies [*Balukraya*, 2006; *United Nations Development Programme*, 1987]. However, the MODFLOW layers were developed independently from cross sections constructed from 137 reliable well-drillers logs; the basin was divided into seven hydrogeologic zones [*Srinivasan*, 2008]. Pump test results for storativity and hydraulic conductivity, obtained from published reports [*Central Ground Water Board*, 2004; *Ravi*, 1997; *Scott Wilson Piesold*, 2004; *Water Resources Organization*, 2005] were used as the basis for zonal model parameters of aquifer properties. To minimize the number of parameters in the groundwater model, recharge and extraction rates were estimated based on land-use. A Google Earth image was manually classified to derive a current land use map (Figure 3) which was used in the MODFLOW groundwater model. The land-use map was verified using extensive ground-truthing and a supervised classification of a 2007 Landsat TM image. In addition, each grid cell was also assigned to a census zone so that the groundwater model could be linked to the consumer model, which simulated representative households in each census area.

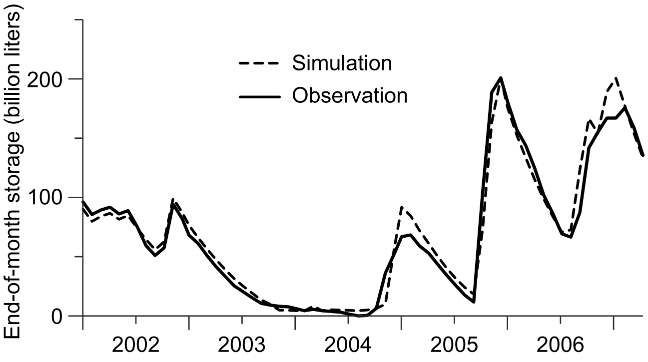


Figure 2. Reservoir storage calibration comparison: Simulated versus observed.

[23] Hydraulic conductivities and storage coefficients were estimated by calibration of hydraulic heads every calendar quarter from 2002 to 2005 (Figure 4). For some wells, only depth-to-water data were available in published form. A differential GPS was used to measure well elevations for these wells, to translate depth-to-water measurements into hydraulic heads. Simulated and observed groundwater head maps were matched within 1 m (on average) at the end of each 3-month period, using data from over one hundred and fifty shallow observation wells from three different agencies [*Central Ground Water Board*, 2007; *Metrowater*, 2006; *Water Resources Organization*, 2007]. Additionally about sixty private wells, both shallow and deep, were monitored with help from local collaborators in 2006 and early 2007. The calibrated flow model suggested that about 18% of rainfall recharges the aquifer in rural areas, and 9% of rainfall recharges in the city.

5.3. Utility Module

[24] The Utility Module estimates the quantity of water supplied by the utility to different consumers. The Chennai public water utility, Metrowater, supplies piped water to the incorporated areas as well as in bulk to adjacent towns and industrial zones outside the city. The Utility Module first simulates the total quantity available to the utility for supply. If total quantity of water available to the utility falls below half the aggregate demand, the model triggers a shut-down of the piped supply system. In case of a total shut-down, the utility switches to "mobile supply," utility operated tanker trucks that deliver a "lifeline" amount of 90 L of water per household (or 20 L per capita per day assuming average household size of 4.5) the pumping stations to households. In normal periods slums in Chennai are supplied via mobile supply.

[25] The Utility Module uses a hierarchical distribution algorithm to allocate the available water among different modes of utility supply (mobile supply tankers, piped supply, hand-pumps, and standpipes). The hierarchical distribution algorithm allocates water to the different connection types making simplified assumptions about flow in the piped distribution system. The algorithm makes the following assumptions. (1) It was assumed that mobile supply and bulk industrial supply are accorded the highest priority. Bulk industrial consumers have dedicated pipelines; the mobile-supply tankers supplying slums are refilled directly at the distribution pumping stations. Therefore, water supply to these consumers is determined only by the utility's management priorities and is independent of the pressure in the distribution system. (2) Once water is allocated to bulk consumers and mobile supply, the remaining water is distributed via the piped distribution system. Consumers access piped water in three ways: via private hand-pumps, public standpipes or via sumps and the quantities accessed by consumers are governed by the physical limitations of the piped distribution system. (3) For consumers with underground sumps, water from the piped mains is delivered to the sumps; the water has to be pumped by an electric motor to an overhead tank and flows by gravity to taps in the house/building. The storage sump allows consumers to convert an intermittent utility supply into "24/7" piped supply. (4) Consumers accessing water through hand-pumps or standpipes must manually pump water out of the piped mains. We assumed that consumers with in-house hand-pumps face no physical or institutional restrictions on how the amount of water they can collect. In theory, they can fill pots continuously for the entire time water is available each day. However, most consumers only need to

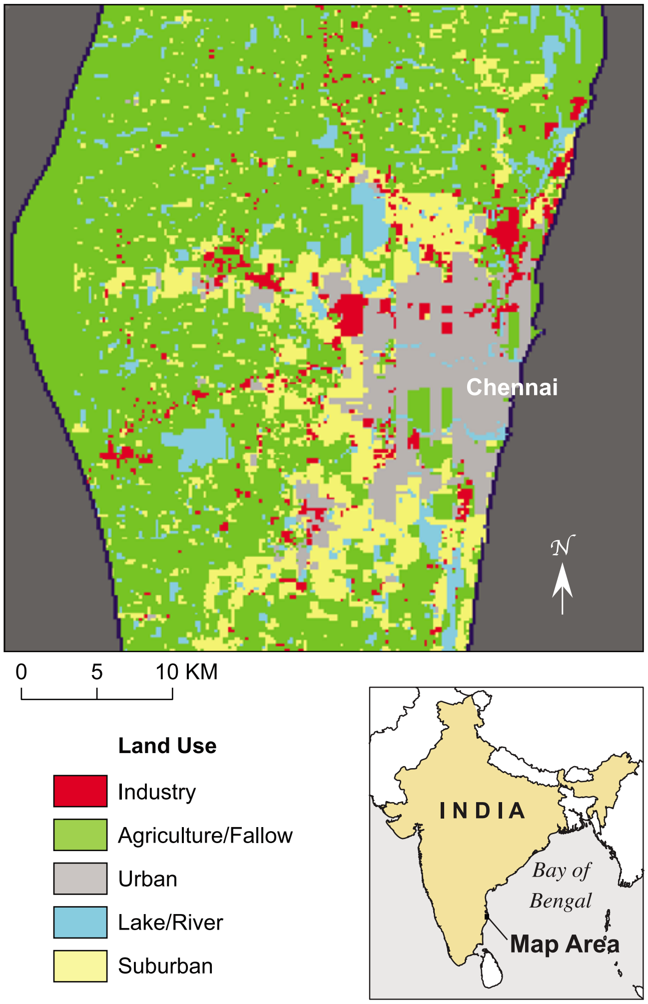


Figure 3. Land-use classification of the Google Earth: Pixel classification was done manually; each grid cell was visually assigned as urban, suburban, industrial, agricultural, fallow, and water. The classification was validated against a supervised classification of a 2007 Landsat TM image. The dark gray areas indicate areas outside the model boundaries.

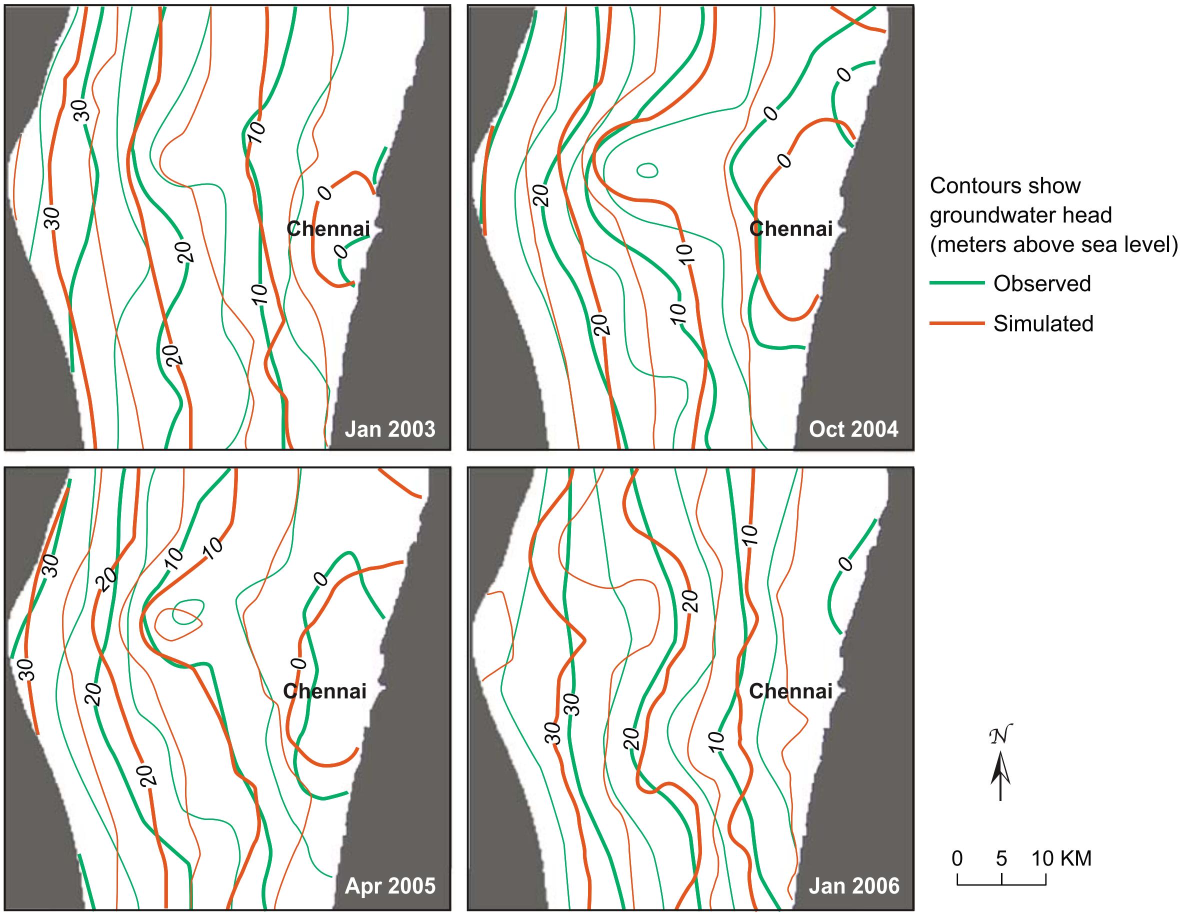


Figure 4. Calibrated head maps (unconfined aquifer) in Chennai basin.

pump for about 15–20 min to collect the ~300 L of water they need each day. Thus consumers with private hand-pumps or yard taps are not supply constrained. Only the time costs of actually hauling the water around the house limit water use, so these consumers with private hand-pumps or taps are demand-constrained. (5) In contrast, consumers accessing water from public standpipes may be either supply or demand constrained, because each public standpipe is shared by about twenty households. If water is available in the piped mains for several hours everyone waiting in line will be able to satisfy their daily needs. However, if piped water is available only for an hour or two, we assume the households share the time equitably, so each household gets proportionately less. (6) To simulate these assumptions, consumers accessing water manually were assumed to satisfy their demand first; then the rest of the water available was allocated to underground sumps until the consumers' daily demand is satisfied. (7) Any residual water was assumed to satisfy the demand of large commercial establishments. Even when supply was plentiful, piped supply never exceeded 10–12 h each day, indicating that demand is never completely satisfied. In wetter periods, the additional hours result in increased uptake by large commercial consumers, frivolous water use by residential consumers, and leaks into the aquifer. In fact, without metering and rational pricing, rationing hours of supply is the only demand management tool available to the utility. But this method ignores the opportunity cost of delivering the additional water, which with additional storage would be saved for drier periods.

[26] The output of the Utility Module is the maximum quantity of water supply theoretically available to households via public standpipes, hand-pumps and sumps. But the quantity theoretically available to consumers is not an observable entity, only the quantity actually consumed can be estimated and that was determined by the Consumer Module. As a result, the calibration of this module was done via the calibration of the Consumer Module.

5.4. Consumer Module

[27] The Consumer Module simulated consumers' decision-making processes. Consumers make two types of decisions. They make long-term decisions regarding investments in acquiring and managing water. They also make short-term decisions on how to manage water on a day-to-day basis. The long-term investments determine the quantity, quality, and cost of water available to consumers from different sources on a day-to-day basis. For instance, consumers only have piped supply as an option if they previously connected to the utility system, paying a connection fee, and installed indoor plumbing.

[28] To account for differential investments, household were classified into four categories, "Unconnected," "Connected," "Well Owners," and "Sump Owners," based on increasing levels of investments. The number of households in each

category in 2001 was estimated from the Housing Census which lists number of households by primary source of drinking water, as well as household survey data by census zone [*Government of India*, 2001]. The number of households in each category was changed from one period to the next, to reflect changing long-term investment decisions by consumers. Three assumptions were made regarding long-term investments. (1) Once the coping investment is made, it would remain active for the rest of the model. I.e., once installed consumers do not remove wells or sumps. (2) Consumers constantly climb up a "water ladder" by increasing their level of coping investments, starting with utility yard taps or hand-pumps, then borewells, and finally sumps. This assumption was based on household survey data, which support the water ladder hypothesis; only a small fraction of consumers had sumps without borewells, or borewells without utility connections. (3) Consumers invest in the next tier of coping investments as soon as they can afford it; the shift in the fraction of households in each consumer category is driven only by changes in real income. Both an ex-ante analysis (will consumers invest in a sump or borewell at a given opportunity cost of time and expectation of average supply conditions?) and ex-post analysis (did past investments in sumps or borewells pay-off given the simulated consumption patterns from 2002 to 2006?) support the idea that rational consumers will make coping investments under intermittent supply conditions, if their opportunity cost of time is high enough.

[29] Once households were classified based on their long-term investments, the short-term choice problem of a representative household in each category, time period, and census zone, could be solved. The short-term decision making is assumed to be a day-to-day optimization. However, because supply availability is only modeled at 3-month intervals, in effect demand is assumed to be identical for each day within a 3-month period. In each period, the consumer chooses modes of water supply given the price, quantity and quality available from the different modes (1a)–(1e).

Minimize

$$C(P,Q) = \sum\nolimits_{k=1}^{M} p_k q_k(i,j,t) \tag{1a}$$

$$q_k(i,j,t) \le \overline{q_k}(i,j,t) \tag{1b}$$

$$p_1 \le p_2 \le \ldots.. \le p_M \tag{1c}$$

$$D(p_k,\ldots,N,I) \tag{1d}$$

$$Q_M = \sum\nolimits_{k=1}^{M} q_k(i,j,t) \le D(p_i,\ldots,N,I) \tag{1e}$$

where

q_k = the quantity actually consumed from kth source

$\overline{q_k}$ = the maximum quantity available from source k (determined by feedbacks from other Modules)

p_k = costs of water from kth source, including time costs

D = the quantity demanded is a function of prices, income, number of members

Q = the total quantity consumed from all sources

M = Number of sources

N = Number of household members

I = Income group

k = Source of water: Piped Supply, Private well, Private Tanker, Public Standpipe

i = Census zone

j = Consumer Category: Unconnected, Connected, Well Owners, Sump Owners

t = Time Period

[30] The Consumer Module also estimated consumer surplus, a measure of consumer well-being. The incremental benefit gained from consuming a single unit of water is the difference between what consumers are willing to pay for a good and what they actually do pay for water. Economists define the consumer surplus to be the total benefit, i.e., the integral of the benefit, from all units consumed. The consumer surplus is defined by equation (2):

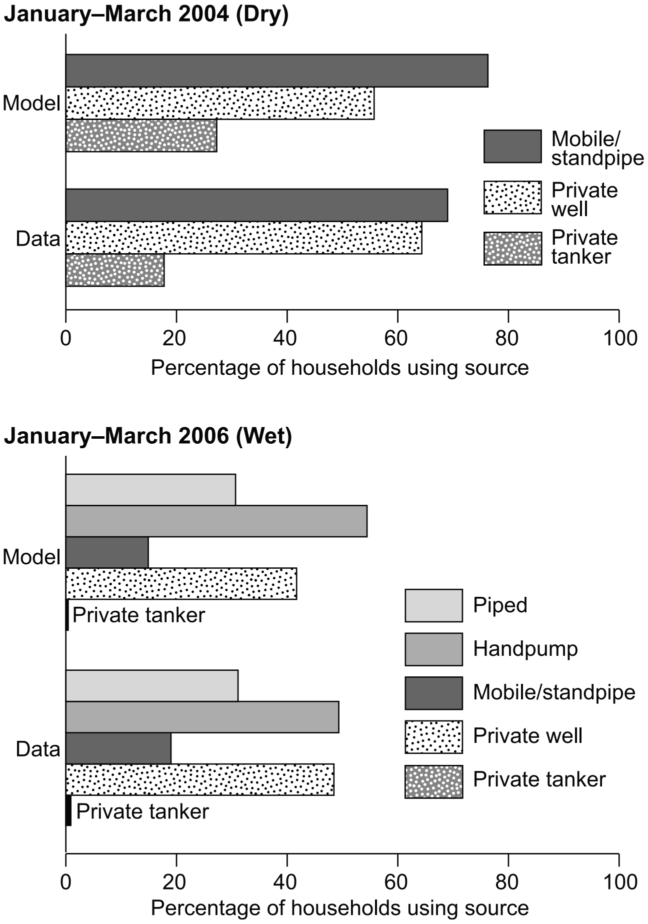
$$CS(Q) = \int_0^{Q_M} W(Q)dQ - \int_0^{Q_M} C(Q)dQ \tag{2}$$

where W(Q) is the willingness-to-pay function, C(Q) is the cost function to consumers, the price paid for water from each source, and Q_M is the total quantity of water consumed from M sources.

[31] The consumers cost minimization problem was solved for a representative household in each consumer category (four domestic and two commercial) and census zone (ten zones within Chennai) for each 3-month time step. This amounted to 1020 optimizations over the period Jan 2002 to Apr 2006. The solution to the consumers' choice problem yields a solution where, rational consumers rank the sources of water available to them from least to most expensive. They use as much of the least cost source available before switching to the next lowest cost source until their demand is satisfied.

[32] The model adopts a relatively simple approach in its treatment of water quality. It assumes households first allocate the lowest-cost potable (treated) supply for drinking and cooking (fixed at 20 L per capita per day or 90 L per household per day). The optimization problem refers only to the non-potable component of demand. The total use (potable and non-potable) is determined by the consumers' demand function, estimated as described below.

[33] An important contribution in this research is the estimation of residential and commercial demand functions in Chennai. The estimation of residential demand has been a subject of intensive research for many decades [*Arbués et al.*, 2003; *Dalhuisen et al.*, 2003; *Gunatilake et al.*, 2001; *Hewitt and Hanemann*, 1995; *Strand and Walker*, 2005]. However, we found that none of the established methods could be usefully applied in Chennai. For purposes of estimating demand, studies in the developing world have been limited in four ways, because they do not address the following problems: (1) the quantity estimation problem, inability to estimate quantity correctly in the absence of metering, (2) the multiple source problem, the use of multiple sources of water causes total demand to be incorrectly estimated, (3) the manual collection problem, simultaneous use of both manual collection and piped sources, and (4) the "Income effect problem," the fact that water sourced from


January–March 2004 (Dry)

January–March 2006 (Wet)

Figure 5a. Fraction of households by mode of supply (simulated versus survey values). Data based on two household surveys of approximately 1500 households each conducted in 2004 and 2006 respectively.

different sources does not cost the same, so any demand estimation method must account for the fact that the marginal price and the average price of water may be very different.

[34] Prior studies in the developing world address some but not all of these issues: (1) by separating consumers by access type into "tap" and "non-tap" households [*Nauges and Strand*, 2007], (2) considering only the primary source of supply, or (3) working with metered households [*Gunatilake et al.*, 2001]. In Chennai, all of these techniques posed problems; the categories "tap" and "non-tap" were fluid as consumers shifted between manual collection ("non-tap") and piped supply ("tap") depending on availability. Moreover, water supply was unmetered. To be useful in our simulation model, we needed a demand function to be independent of the sources of supply and allow for multiple sources of water. A detailed description of the methodology, in particular how quantities were estimated in the absence of metering, pricing, and with multiple source dependence, can be found in Text S1.

[35] The demand function for residential consumers (for all consumer categories) was determined from the two surveys of approximately 1500 households each. Residential water demand was expressed as a function of price, income, the difference variable and household size. The constant price elasticity of demand, α, was estimated to be −0.46 well within the range of estimates by others [*Arbués et al.*, 2003; *Dalhuisen et al.*, 2003; *Gunatilake et al.*, 2001]. The demand function for commercial consumers was determined using a survey of 117 commercial establishments conducted by us in January–March 2006. Commercial water demand was estimated as a function of price, number of employees, the difference variable and water-intensiveness of the establishment, where hotels and hospitals were defined to be water-intensive. The constant price elasticity of demand, α_c, for commercial consumers was estimated to be −0.21.

5.5. Calibration of Consumer Module

[36] The key parameter that was calibrated in the Consumer Module was the opportunity cost of time. The cost of water from public standpipes and yard taps, depends on how much consumers value their time and how much time they spend collecting water. A consumers' opportunity cost of time is critical in determining whether the consumer would prefer to buy (expensive) water from a vendor instead of walking to the nearest hand-pump and back. Furthermore, since wealthier consumers value their time more than poorer consumers, the opportunity cost of time would vary by consumer category. The problem is that the opportunity cost of time is not independently observable; it is usually inferred from consumer behavior [*Whittington et al.*, 1990].

[37] In our systems model the opportunity cost of time was treated as a model parameter. The opportunity cost of time was input into the demand estimation as well as into the consumers' cost-minimization problem. The opportunity cost of time was then varied so that simulated and surveyed quantities matched. Figure 5a compares the fraction of households accessing water by mode of supply, for the periods Jan–Mar 2004 (drought) and Jan–Mar 2006 (wet), respectively. Figure 5b compares the quantity of water consumed in liters per household per day for the periods Jan–Mar 2004 (drought) and Jan–Mar 2006 (wet), respectively. The model was able to match both the fraction of households accessing different sources and the average quantity consumed by source each day within 10%, in both wet and dry years. The opportunity cost of time thus estimated was \$0.05/hr for the poorest Unconnected consumers. For the wealthiest consumers, Sump Owners, the opportunity cost of time was estimated at \$0.22/hour. The estimate for wealthiest consumers was a reasonable estimate of the cost of unskilled labor in Chennai, very close to the minimum wage.

[38] One final point on the Consumer Module calibration concerns the validity of using the same household survey data set for both demand estimation (model input) as well as calibration (model outputs). This is justified as follows: the demand estimation involved regression of the household survey data set to estimate a constant (the maximum quantity of water consumed each day) and slope (change in quantity consumed with price, income). Because the demand function constrains the quantity households will use each day, it is not surprising that average simulated and surveyed daily consumptions match. However, the simulation model predicts much more than average consumption; using a single demand function the model successfully replicates the quantity consumed by source, in both wet and dry years, as well as the fraction of households dependent on each source. This could only be achieved if the model correctly simulates changes in

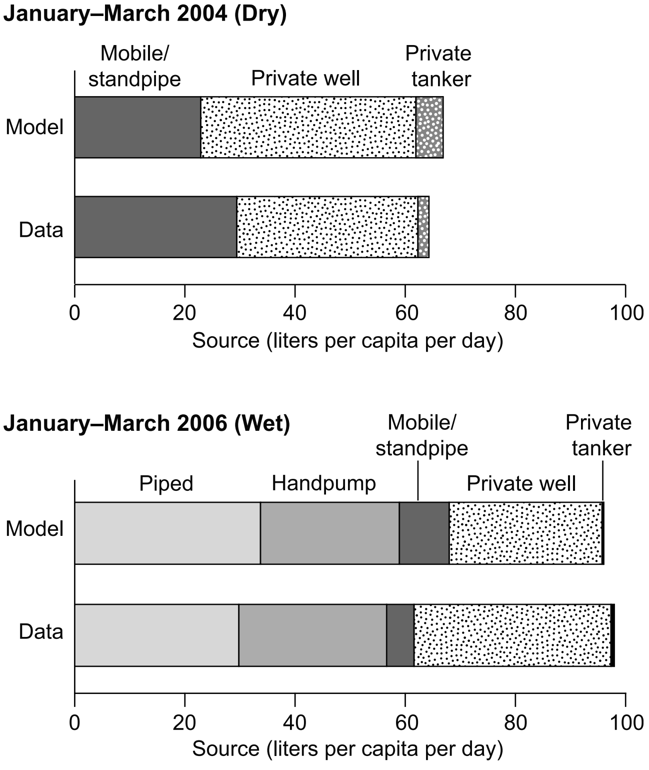


Figure 5b. Average water use by mode of supply (simulated versus survey values). Data based on two household surveys of approximately 1500 households each conducted in 2004 and 2006 respectively.

water availability from various sources as well as consumer responses to those changes in both wet and dry periods.

5.6. Tanker Module

[39] The Tanker Module simulated the size of the private tanker market and quantity and location of peri-urban groundwater extraction by private tankers. This module served two purposes: (1) to determine the size of the tanker market under different hydrologic conditions and (2) to provide the Groundwater Module with the quantity of peri-urban groundwater extractions used to fill tankers. The size of the tanker market was obtained from the Consumer Module. The aggregate consumption of tanker water (the total size of the tanker market) in each period could be estimate by adding household demand across consumer categories (equation (3)):

$$TQ_{Tan\ker}(t) = \sum\nolimits_{i,j} q_{\tan\ker}(t) \qquad (3)$$

Next the tanker "source areas" were identified. In the model, grid cells were considered tanker source areas if they met the following criteria: the depth to water in the grid cell was shallower than 10 m, the land-use classification was agriculture or fallow, the grid cell was located within 500 m of a major road. The total quantity of tanker water demanded was assumed to be uniformly distributed among the most proximate source areas. The extractions used to fill the tankers were then input into the groundwater model.

[40] The simulated size of the tanker market was compared to observations. Tanker movement into Chennai was observed and recorded as follows: two persons ("tanker counters") were stationed on the boundary of Chennai at each of 11 major highways entering the city. The tanker counters were stationed for 12-h periods at a time during the months of Oct–Dec 2005. Each highway was observed for one or two days. The total size of the tanker market was obtained by multiplying the number of tankers entering Chennai daily by 12000 L, the capacity of each tanker. The total size of the tanker market simulated for the period Oct–Dec 2005 was 17 million liters per day (MLD) was close the 18 MLD estimated by tanker counters' observations. The simulated tanker market size of 60 MLD during Jan–Mar 2004 also correlates well with the 55 MLD reported by *Londhe et al.* [2005] in 2004. The parameter adjusted to match the observed and simulated tanker market size in October 2005 was average well efficiency. This parameter in the Groundwater Module, used in the Theim equation, determined the extent to which establishments and households were limited by groundwater and thus forced to purchase tanker water.

6. Systems Model

[41] Systems modeling approaches offer several advantages over statistical approaches or reductionist models. (1) They ensure consistency with established physical and economic principles, (2) they account for dynamic feedbacks between sub-components, and (3) they can utilize descriptive studies to yield information that is not usually viewed as quantifiable, in particular institutional constraints, informal rules, or non-compliance with regulations or compacts. We describe each of these ideas below.

6.1. Consistency With Established Disciplinary Principles

[42] The use of a systems model ensures consistency with established hydrologic and economic theory. The characterization of each module is based on well-established principles and methodologies from the relevant disciplines. Thus, the groundwater flow equation in the Groundwater Module, cost-minimization by consumers in the Consumer Module, mass balance in the Reservoir Module, and profit-maximization for tanker operators in the Tanker Module, each reflects well-established principles. The systems model ensures these would not be violated in conducting scenario analyses in future periods.

6.2. Dynamic Feedbacks

[43] One of the main features of the systems model was the establishment of dynamic feedbacks between different system components. This was challenging because while some feedbacks between system components are well-understood, e.g., groundwater extractions by consumers lower hydraulic heads; others are less so, e.g., how exactly hydraulic heads affect consumers. The choice of which feedbacks to incorporate was determined by evaluating multiple hypotheses and testing if a feedback generated sufficient variation to make it relevant. Many semi-structured

interviews were conducted with experts, facility managers, and Chennai residents, to gain insights into decision-making processes. A description of the main feedbacks between the modules follows.

6.2.1. Groundwater and Consumer Modules

[44] The Groundwater Flow Equation establishes that groundwater levels fluctuate as a function of extractions by consumers. However, the reverse feedback is not well-established. There is no single mechanism by which groundwater levels impact consumer well-being. For instance, do consumers stop using wells because their wells dry up? Or do falling groundwater levels increase pumping costs relative to other sources such that use is self-limited? Or does groundwater quality become saline and unusable at depth? Or do wells simply yield an insufficient quantity of water as the water table drops? Or is there no relationship, i.e., the quantity extracted by consumers in a given period is unrelated to groundwater levels? We had to examine each possibility and by the process of elimination only retain the significant feedbacks. Based on hydrographs for the historical period from 2002 to 2006, it was known that the water table dropped 5–15 m during the 2003–2004 drought. (1) A simple calculation showed that the impact of a 15 m drop on the cost of groundwater extraction would be too small to be perceptible to consumers. Therefore, cost of extraction was held constant assuming an average depth to water in all periods. (2) Although there were a few anecdotal reports that water quality in the confined aquifer was poor, this did not appear to be a significant factor based on interviews except in some coastal neighborhoods where seawater intrusion severely restricted private well use. However, seawater intrusion was confined to a few streets close to the beach; the model resolution was insufficient to simulate consumer behavior in those streets separately. Instead, water-quality from private wells was simply classified as "non-potable" in all periods. (3) By applying the Theim equation, the in-well drawdown in a representative private well in each zone in Chennai was estimated. In-well draw down was found to be a possible limiting factor in the quantity that could be extracted by large water-intensive commercial establishments as explained below. (4) An examination of the distribution of well-depths within Chennai indicated that a falling groundwater table would render many wells dry. Moreover, household surveys conducted during the drought also indicated that many consumers reported their wells had gone dry [*Srinivasan*, 2008].

[45] Based on this, the main feedback between the Groundwater and Consumer Modules was assumed to be non-availability of water from private wells. Figure 6 shows the distribution of reported depths of private wells derived from a household survey of a sample of 1488 households conducted in January 2006 [*Vaidyanathan and Saravanan*, 2004]. This distribution of wells was assumed uniform throughout Chennai over the historical period. Based on this distribution, the fraction of wells that went dry could be estimated. For instance, if the water table fell to 20 m below ground level, 35% of Chennai wells would go dry. The fraction of dry wells was based on groundwater levels at the start of each period.

[46] The Groundwater Module was also used to predict the maximum quantity of water extractable per day at a representative private well. Because the MODFLOW based model produced maps of average heads in each grid cell, the Theim equation [*Trescott et al.*, 1976], was applied to correct for subgrid-scale effects due to the impact of individual wells. The Theim equation allowed us to determine the maximum quantity that could be withdrawn at a representative well in each grid cell of the MODFLOW model defined as that quantity that would induce a drawdown of no more than 80% of the standing water column in the well. We assumed a 5% well efficiency based on expert assessments. The model predicted that maximum quantities extractable per day ranged between 20 and 90 kiloliters per day.

6.2.2. Groundwater and Utility Modules

[47] The water utility estimates that between 15 and 35 percent of the water was lost to pipeline leakage between 2002 and 2006 (K. Sivakumar, Chennai Water Supply and Sewerage Board, personal communication, 2006). Since water supply is largely unmetered, theft or water use by illicit connections is not measurable, so these loss estimates refer to actual leakage. A simple calculation showed that if the reported levels of pipeline (water and sewer) leakage rates were accurate, they would contribute a large fraction of recharge within the city. Therefore, in the groundwater model, both rainfall and pipeline recharge was included. Since the water utility does not extract groundwater locally; piped supply does not depend on groundwater levels in the Chennai aquifer; i.e., the only link is from the Utility to the Groundwater Module not vice versa.

6.2.3. Groundwater and Tanker Modules

[48] The industrial region to the northwest of Chennai reported a significant drop in groundwater levels during the drought. The steep drop in groundwater levels during the drought period, could only be explained by explicitly accounting for tanker extractions; both for supply to households within Chennai as well as the industrial areas outside the city. This represented a two-way feedback between the Tanker and Groundwater Modules wherein tanker extractions depend on groundwater availability at a shallow depth; but sustained extractions by private tanker operators in turn cause a drop in the water table.

6.3. Quantitative Representations of Descriptive Processes

[49] Our study relied on descriptive analyses to specify plausible quantitative relationships between model variables. In particular, based on interviews with local officials and work by other scholars [*Nikku*, 2004] it was clear that the quantity and timing of water diversions from the reservoirs are determined by political considerations rather than hydrologic or legal principles. Descriptive studies were critical in understanding the factors that govern water diversions; but these could not be used directly in a simulation model. Instead, the descriptive analyses were used to derive plausible relationships between diversions and rainfall/storage.

6.3.1. Inter-state Deliveries

[50] We assumed that during a severe drought the needs of small towns and irrigation districts in the northern state of Andhra Pradesh, where the inter-state Telugu Ganga Project originates, would take precedence. Additionally, in drought years farmers across the state border immediately north of Chennai would pump water from the open canal and no punitive action would be taken to stop these illegal diversions. These assumptions were based on conclusions by other studies that have described how water policy in India falls under state, not federal jurisdiction and state politics

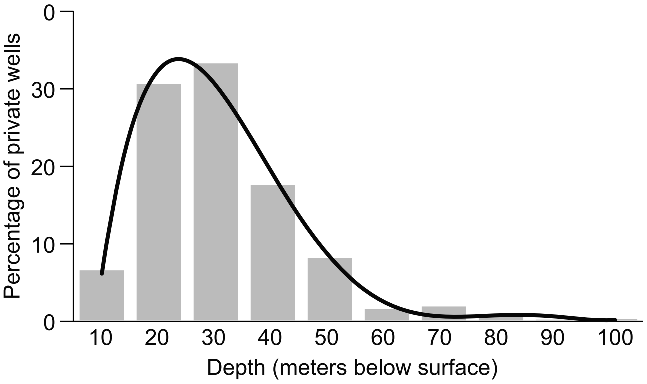


Figure 6. Frequency distribution of depth below ground surface of 941 domestic wells in Chennai obtained from the 2006 household survey of approximately 1500 households.

in Southern India are controlled by state-specific political parties with no incentive to appease constituents across boundaries [*Maitra*, 2007; *Nikku*, 2004]. Our assumption that water deliveries to Chennai via the inter-state Telugu Ganga project would decrease in drought years is consistent with the pattern of historical deliveries. However, this assumption contradicted hydrologically based estimations by the water utility when planning the project. The plans assumed that because the Telugu Ganga headwaters' southwest monsoonal rainfall regime is uncorrelated with Chennai's northeast monsoonal rainfall regime, the inter-state project would be a reliable source in drought years. The utility did not anticipate the non-compliance with the inter-state compact that subsequently occurred. In contrast to our assumptions on inter-state deliveries, delivery from the intrastate Veeranam project was assumed to be reliable. Not only is the water delivered via a pressurized pipeline reducing chances of en-route theft, but both the source and destination are within the control of a single state government.

6.3.2. Spatial Distribution of Tanker Extractions of Groundwater

[51] To determine tanker source areas, interview data were compiled to come up with a set of criteria about how tanker operators source water. Selling water to tanker operators is far more profitable than farming [*Ruet et al.*, 2007], so it was assumed that tanker operators will always be able to purchase water from farmers as long as the groundwater is available in the shallow agricultural wells. Based on interviews with tanker drivers, it was determined that in Chennai, tanker water is sourced from wells located within 0.5km of a major road and only from peri-urban agricultural wells, not residential neighborhoods. Newspaper reports provided additional anecdotal evidence that tanker extractions were not allowed in residential neighborhoods near Chennai. Once the possible source areas were narrowed down to a few village clusters, it became possible to establish a spatial pattern for tanker extractions to be input into the groundwater model.

7. Model Results and Discussion

[52] The systems approach ensured that the model was able to link reservoir-storage and depletion to variability in piped supply, groundwater levels, informal tanker water markets, and finally consumer well-being. This made it possible to diagnose the causal factors of the recent water crisis.

7.1. Summary of Systems Dynamics

[53] The model highlights the "buffering role" that the Chennai aquifer plays during droughts. The model results indicate that when Chennai's reservoirs went completely dry in 2003–2004, the water available to the utility from all sources was simply not enough to deliver water via a piped system, resulting in the total shutdown of piped supply. As piped supply was shut off in 2003–2004, consumers switched to private and community wells. The elimination of (leaky) pipe supply caused a reduction in aquifer recharge. As extractions increased and recharge decreased, simulated groundwater levels in Chennai fell 8 to 10 m; 23% of the residential wells went dry in 2004, at the peak of the drought. As consumers' wells dried up, they had to purchase water from private tankers. Figure 7 shows the simulated total quantity of water consumed in Chennai by source.

[54] From Figure 7, it is apparent that the historical period could be divided into three distinct phases. Between Jan 2002 and Apr 2003, water supply in Chennai was restricted. Chennai did not have enough supply from existing sources. During this period, private wells served as a supplementary source of water supply. Though piped supply was restricted throughout this period, consumers were able to supplement their needs via private wells. Between Oct 2003 and Dec 2004, piped supply was cut back and groundwater levels also dropped.

[55] Despite the drop in groundwater levels, both the total consumption from private wells and the fraction of households using private wells was higher in dry years compared to wet years. This can be explained as follows: two-thirds of households in Chennai have access to private or community wells. However, many households do not need water from private wells when piped supply is plentiful. In fact, in the wet period, only 43% of households reported using private wells. In contrast, during the dry periods when piped supply was cut back, all households became well-dependent. Although some wells went dry, overall well-dependence was higher during the drought.

[56] As some consumers lost access to both utility supply and self-supply via their own wells, they were forced to obtain water from private tankers. But because tanker water is much more expensive than either piped supply or private well supply, overall consumption decreased sharply. At the peak of the drought consumption dropped by a third compared to the wettest periods. Following the heavy rains in Oct–Dec 2005, groundwater levels recovered completely. Simultaneously, the reservoir system was replenished. The intrastate Veeranam project commissioned during the drought and increase of deliveries from the Telugu Ganga project ensured that utility supply was restored at a much higher level than it had been before the drought. As consumers regained access to the piped supply, private well dependence decreased substantially and the tanker market returned to pre-drought levels. In the following sections, each sub-component of the Chennai water supply system is discussed.

7.2. Reservoir Dynamics

[57] The Reservoir Module showed that Chennai's reservoir system, 15 months of storage at current demand, is

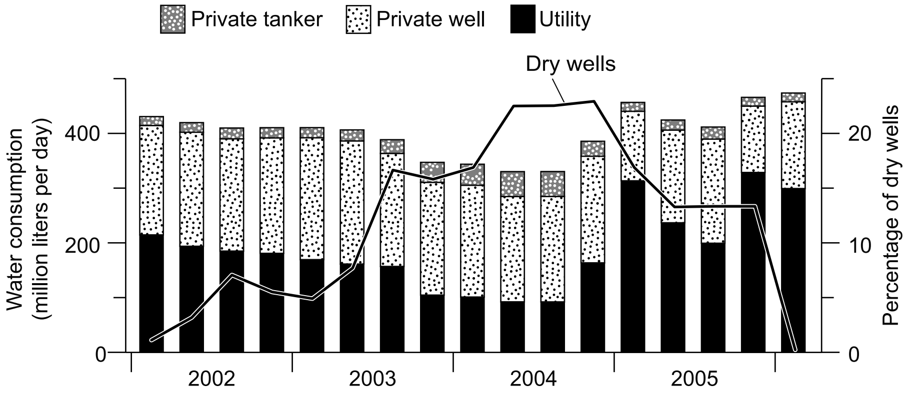


Figure 7. Source-wise consumption for a typical residential consumer with a piped connection.

inadequate to guarantee a minimum level supply in all periods. Furthermore, the estimated log linear form of the rainfall-reservoir inflow function implies that a 10% drop in median monthly rainfall causes a 40% decrease in reservoir inflows, while a 10% increase in median monthly rainfall almost doubles reservoir inflows. The reservoir system depends on large rainfall events to get replenished; but just two consecutive median rainfall years without inter-state imports results in the reservoir system completely drying up, as occurred in 2003 and 2004. The reservoir system lacks the capacity to smooth inter-annual or seasonal variability in supply. While these constraints are well-understood by local engineers, the utility has been unable to address the problem politically, mainly because of the challenge of resettling displaced populations. The inter-state Telugu Ganga Project originally commissioned to rectify this problem fails to do so. In fact, it exacerbates the problem. Historically deliveries have correlated with rainfall in Chennai; inter-state deliveries were highest in the years Chennai also received plenty of rain. In 2003–2004, when Chennai received less than median rainfall, little or no water was delivered across state boundaries at all. Even within one year, deliveries have occurred in the months (Sep–Dec) when Chennai also receives rains. The lack of reservoir storage is clearly illustrated by the following statistic: the monthly delivery from the Telugu Ganga project constitutes as much as one third of the entire storage capacity of the Chennai reservoir system. The utility has to draw down the reservoir in anticipation of delivery from the Telugu Ganga Project, but has little control over the magnitude and timing of deliveries. In months prior to delivery of Telugu Ganga water, the utility expands the hours of supply in Chennai. The additional hours induce increased uptake by large commercial consumers, frivolous water use by residential consumers, and leaks into the aquifer. Subsequently, if the rainfall or the anticipated inter-state delivery fails, the utility resorts to rationing till the following monsoon. But this creates a "feast or famine" situation.

7.3. Utility Dynamics

[58] The reservoir storage constraint has the following effect: the total quantity of water available to the utility in Chennai is highly variable, both seasonally and inter-annually. In the historical period, the total simulated quantity of water available to the utility (for supply within Chennai) varied from over 650 million liters per day (MLD) in Oct–Dec 2005, to less than 200 MLD in Jul–Apr 2004. Because of the inadequacies in reservoir storage, the daily water delivered to consumers by the utility varied as much as 50% within a single year (Figure 8).

7.4. Groundwater Module Dynamics

[59] The model results show that when utility supply falls, so do groundwater levels. This occurs for two reasons. (1) When utility supply is curtailed, households extract more groundwater as they are unable to meet their needs from piped supply. Groundwater extraction contributed between 25% (wet period) and 70% (dry period) of total water supply within Chennai. (2) When utility supply is curtailed, recharge from leaking pipelines decreases. Distribution water pipeline leaks (and sewage pipes), at 25% of supply were estimated by calibrating the groundwater model; pipeline leaks constitute the only source recharge in spring and summer months. Importantly, while the increase in extractions was small, only about 10% during the drought recharge dropped by 50%. Importantly, the model suggests that the distribution pipeline leaks contributed more than half of the total recharge of the Chennai aquifer (Figure 9), so the drop in recharge was critical.

[60] Finally, the model estimated the total storage in the Chennai aquifer, estimated to be 100 Gigaliters, about half the capacity of the reservoir system. However, the model results suggest that this storage is critical. The calibrated rainfall-runoff and groundwater infiltration functions suggest that the aquifer is much more effective at capturing and storing rainfall than the reservoir system; aquifer recharge was estimated to be a linear function of rainfall, so recharge occurs even with a relatively minor rainfall event. In contrast, the log linear form of the rainfall-runoff function that governs reservoir inflows, implies that the reservoir system gets little or no inflow during minor rainfall events.

7.5. Consumer Behavior Dynamics

[61] The simulated consumption patterns indicate that consumers depend on different sources of water under different supply conditions; consumers depend on private sources in dry years and utility supply in wet years. As a result, consumers benefited from different types of coping investments in different periods. Moreover, the biggest loss

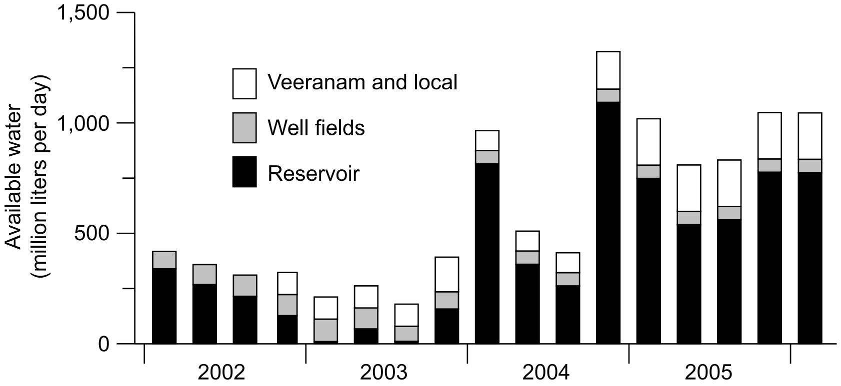


Figure 8. Simulated total water availability to the utility for supply within Chennai from different sources.

in consumer well-being was suffered by consumers who lost access to both piped supply and private wells and became tanker dependent. Table 2 shows the simulated quantities of water consumed by different consumer categories in the wet and dry year and the simulated consumer well-being by consumer category. It is important to note that absolute consumer surplus values are difficult to interpret; only differences in consumer surplus are meaningful. Therefore, the consumer surplus values presented in Table 2 are relative to unconnected consumers during the drought. Because no aggregation across periods is being done, no discounting was necessary. To adjust for inflation all figures in 2005 dollars.

[62] Table 2 shows that during the dry year (2004), consumers benefited mainly from having private wells. Well Owners with functional borewells consumed significantly more water than Well Owners who saw their wells dry up (68 versus 22 L per capita per day) and enjoyed a higher level of consumer surplus (CS = \$5.70/HH/month versus \$2.30/HH/month). As utility supply was virtually nonexistent, any investments in improving utility supply yielded no benefit. Thus, Connected consumers and Unconnected consumers both ended up with the same level of consumption (37 L per capita per day). Both were reduced to depending on community wells or utility-run mobile supply. Consumers did not benefit from having storage sumps as there was little or no piped water being delivered into sumps during the drought. Sump Owners enjoyed the same level of consumption as Well owners who lack sumps.

[63] In contrast, in the wet period the results in Table 2 indicate that Connected consumers with private connections were better off (CS = \$4.8/household/month) compared with Unconnected consumers (CS = \$2.5/household/month) lacking private connections, as the latter had to walk to the nearest public standpipe and wait in line. Connected consumers consumed significantly more water than Unconnected consumers (71 L per capita per day versus 41 L per capita per day). Similarly, Sump Owners were much better off (CS = \$8.9/household/month) than all other categories. Sump Owners consumed almost 50% more water than Connected consumers lacking sumps. This result can be explained as follows: even in the wettest period piped supply in Chennai remained intermittent, available for only a few hours each day I.e., consumers lacking sumps still had to collect water in pots during the few hours water is available and haul it around the house as needed, a labor-intensive task. Text S2 provides additional details on the relative economics of manual labor and pumping under different opportunity costs of time. However, even at fairly low opportunity costs of time, hauling water to the point of use is expensive.

[64] The model results in Table 2, demonstrate that the steepest loss in well-being during the drought, was experienced by wealthier consumers who saw their wells dry up

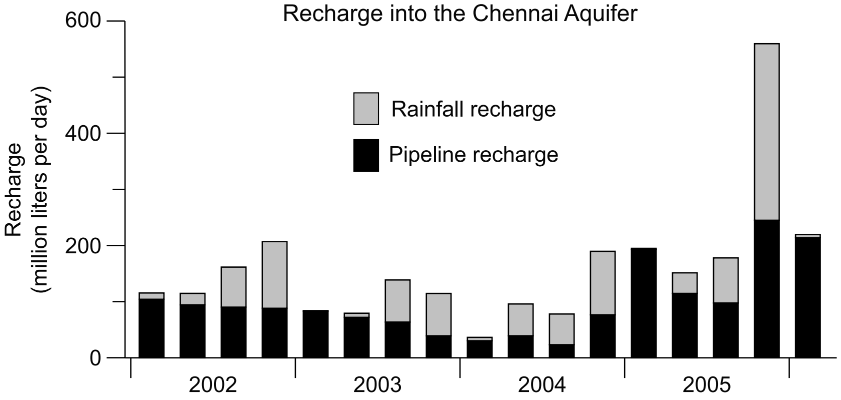


Figure 9. Simulated aquifer recharge within Chennai. Leaking pipelines contribute more than half the total recharge in Chennai.

Table 2. Quantities Consumed and Consumer Surplus by Consumer Category[a]

Category	C	W	S	Dry Consumption Jan–Mar 2004 (L/capita/day)	Wet Consumption Jan–Mar 2006 (L/capita/day)	Dry Consumer Surplus Jan–Mar 2004 ($/household/month)	Wet Consumer Surplus Jan–Mar 2006[b] ($/household/month)
Unconnected	-	-	-	37	41	0	2.50
Connected	✓	-	-	37	71	0	4.80
Well Owners (Dry Well)	✓		-	22	NA	0.5	NA
Well Owners (Wet Well)	✓	✓	-	68	68	5.30	7.10
Sump Owners (Dry/No well)	✓		✓	22	114	2.70	8.90
Sump Owners (Wet Well)	✓	✓	✓	68	114	5.30	8.90

[a] C = Connectivity, W = Well, S = Sump.

[b] Average household size of 4.5 people.

and piped supply cut back (Sump Owners with dry wells). Poor unconnected consumers had much lower consumer surplus in both wet and dry periods. The model's representation of the plight of poor consumers is somewhat limited for two reasons. First, although these consumers are always vulnerable, during the drought they suffered to the extent their daily delivery of mobile supply was curtailed. Interviews with slum dwellers revealed a very wide variability in the delivery of the lifeline supply even across demographically similar slums, located within a km of each other. Instead, the quantity delivered depended on the local politics and ability of the slum-dwellers to collectively demand better services [*Srinivasan*, 2008]. It is difficult to value the time spent in lobbying/agitating for mobile supply or the effectiveness of their lobbying or the motivations of the local depot manager or tanker driver in a simulation model, so the model is imperfect. Second, consumer surplus itself is an imperfect measure of well-being. Because it measures well-being as the integral of difference between willingness-to-pay and cost, it is thus bounded by income. I.e., consumers can at best spend every dollar they own to buy water. As a result, in aggregating across all consumers, supply reductions to richer consumers result in higher losses in consumer well-being. In this respect, both the model and the economic theory informing it understate the suffering of poor consumers.

8. Policy Implications

[65] In this paper, we have presented a model of a severely challenged water resources problem in the developing world. The goal of the model was to reconstruct past system behavior accurately and diagnose the underlying causes of a major water crisis. Development of an accurate historical model offers a basis to make projections into the future and evaluate a range of policies. Although the actual policy evaluations are addressed in a separate paper [*Srinivasan et al.*, 2010], the historical model results highlight where the major trade-offs will likely occur. First, the model results demonstrate an unexpected trade-off between efficient delivery and storage. In the historical period, pipeline leaks allowed the aquifer to provide supplementary storage. Allowing highly treated water to leak through a piped distribution system into an aquifer is clearly bad policy. However, the model results indicate that because the aquifer proves to be a critical supplementary source of water during multiyear droughts, if the pipelines are fixed, the loss of the buffering role of the urban aquifer must be compensated in some other way (drought pricing, short-term contracts, artificial recharge). Second, the model results show that lack of reservoir storage is a serious problem; the greatest drops in consumer well-being occur during multiyear droughts. So the goal must be to secure supply during severe droughts rather than increase total or average supply. Finally, consumers' day-to-day decisions depend on prior coping investments. While we did not attempt to formally model political action or consumers' willingness to tolerate steep tariff increases, it is probable that the once consumers have invested in expensive private coping mechanisms they will be less motivated to support tariff increases to improve efficiency, perpetuating the "low-level equilibrium trap" [*McIntosh*, 2003; *Singh et al.*, 1993]. So water resources policy in the developing world must incorporate coping investments explicitly, either dis-incentivizing them or finding some way to account for them in policy analyses.

9. Summary and Conclusions

[66] As Indian cities grow, the problem of their water supplies is likely to become more severe. Faced with uncertain rainfall, limited reservoir storage, aging piped infrastructure, and rapidly growing demand, no Indian city today has 24/7 water supply. Indian water managers have failed to fully understand the nature of their problem, in part because of a "utility-centric" view of urban water supply that fails to account for private investments by consumers.

[67] In this paper, we discuss a challenging water resources problem in a developing world city, Chennai, India. The goal is to reconstruct past system behavior and diagnose the causes of a major water crisis. We have presented a unified hydrologic-economic model to simulate the dynamic interactions responsible for urban water supply in Chennai, where consumers depend on multiple sources of water and invest in coping mechanisms. The systems approach allowed us to break-away from the traditional "utility-centric" sole focus on the provision of water through piped supply and explicitly consider consumers reliance on multiple sources of water.

[68] By adopting a modular approach, individual components of the simulated Chennai water system were developed and calibrated separately, and then linked. The model simulated surface water flows into the reservoir system, groundwater flows in the Chennai aquifer and distribution of water by the water utility. The model solved the consumers' cost-minimization problem, given the quantity, quality, and price of water available from the various sources to estimate consumer well-being. The model was calibrated using the

historical period from 2002 to 2006, a period that included both one of the worst droughts as well as one of the wettest monsoons in recorded history.

[69] Prior analysis of the reservoir data revealed that (1) the utility's piped supply system is vulnerable because Chennai's reservoir system, the main source of water to the utility, has inadequate storage given the current unmanaged demand. (2) The utility diverts large amounts of water in wet periods into city supply via a leaky piped water distribution system, but resorts to rationing when the rains or inter-state deliveries fail. From the model results we conclude that (3) the leaky distribution pipelines recharge the urban aquifer. This has the effect that the leaky pipes transfer water from the reservoir system to the urban aquifer in wet periods. (4) The water is then extracted by consumers via private wells in dry periods. The aquifer inadvertently thus acts as the supplementary storage the city has been unable to build. (5) During prolonged multiyear droughts, groundwater levels drop as recharge decreases and extraction increases. The loss of recharge from leaking pipelines (as cut-backs in piped supply are instated) is the biggest contributor to falling groundwater levels. (6) As consumers lose access to piped supply and private wells, they turn to private tankers. (7) Consumers who are become reliant on expensive water from private tankers suffer steep losses in well-being.

[70] By integrating hydrologic, economic, and engineering components into a system model, both the monetary and physical impacts of consumers' dependence on multiple sources of water were quantified. The study highlights the buffering role played by the urban aquifer particularly in droughts making the case for improved management of urban aquifers in Indian cities. Although collecting the data required to develop an integrated dynamic model for developing-world regions is challenging, such models are essential analytic tools that should be a key component to understanding the nature of urban water problems in cities like Chennai.

Appendix A: Equations of Integrated Model

A1. Reservoir Water Balance

[71] The reservoir water balance at the end of each month m, is given by

$$\begin{aligned}\text{Res\_Stock(m)} = {} & \text{Res\_Stock(m-1)} + \text{Inflows(m)}\\ & + \text{TG(m)} - \text{Evap(m)} - \text{Div(m)}\\ & - \text{Rel(m)} - \text{RLoss(m)}\end{aligned}$$

where

Res_Stock(m) is the total combined storage in the three reservoirs in any given period in million cubic feet. Initial Reservoir_Stock in January 2002 is known.

TG(m) is the water received during the month from the Telugu Ganga water scheme in million cubic feet/month, an inter-state water transfer project.

Evap (m) is the reservoir evaporation less direct rainfall

RLoss(m) is the leakage from the reservoir system to groundwater

Spill(m) is the quantity spilled downstream when reservoir storage levels are dangerously high

Div(m) is the quantity diverted for utility supply to Chennai The equations for the components of the water balance (estimated empirically or observed) were

$$\text{Inflows(m)} = 1.19\ e^{0.0171\,\text{Rainfall(m)}}$$

$$\begin{aligned}\text{Evap(m)} = {} & (\text{Avg\_Lake\_Evap} - \text{Rainfall(m)})\\ & * \text{Reservoir\_Surface\_Area(m)}\end{aligned}$$

$$\text{Reservoir\_Surface\_Area(m)} = 0.00465 * \text{Reservoir\_Stock(m)} + 5.99$$

$$\begin{aligned}\text{RLoss(m)} = {} & \text{Reservoir\_Surface\_Area(m)} * \text{Lake\_Level}\\ & * \text{Clay\_Leakance/Clay\_Thickness} \sim 0\end{aligned}$$

$$\begin{aligned}\text{Spill(m)} = {} & \text{MAXIMUM } (0, \text{Reservoir\_Stock(m-1)} + \text{Inflows}\\ & + \text{TG(m)} - \text{Evap(m)} - \text{Div(m)} - \text{Reservoir\_Cap})\end{aligned}$$

$$\begin{aligned}\text{Div(m)} = {} & 25\% * (\text{Reservoir\_Stock(m)} + 170) \text{ if } \text{TG(m)}\\ & > 100 \text{ Mcft and}\\ & = 10\% * (\text{Reservoir\_Stock(m)} + 170) \text{ otherwise}\end{aligned}$$

A2. Groundwater Module: Estimation of Groundwater Heads

[72] The groundwater heads were estimated in each period using the 3-D transient groundwater flow equation solved by MODFLOW 2000.

Head(x,y,z,t) was estimated by the 3-D transient groundwater equation

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z\frac{\partial h}{\partial z}\right) = S_s\frac{\partial h}{\partial t} + R + E$$

where
E = Extraction
R = Recharge
K = Hydraulic Conductvity
S = Specific Storage
h = Hydraulic Head
and
depth = Depth to water = Land Surface Elevation - Hydraulic Head
x,y = Horizontal co - ordinates of aquifer grid cell
z = Vertical co - ordinate of aquifer grid cell
h = Head (x, y, z, t) = f (Recharge(x, y, z, t), Extraction (x, y, z, t), Conductivity(x, y, z, t), Storage(x, y, z, t))
R = Recharge(x,y,t) = Rainfall(t) * Recharge_Rate(Land Use (x,y,t)) + Pipeline_Recharge (x,y,t)
E = Extraction(x,y,t) = f(Land Use (x,y,t)) outside city

A3. Groundwater Module: Estimation of Fraction of Dry Wells

[73] The depth to the water table was used to estimate the fraction of wells that went dry. The fraction of wells that dried up in Chennai was estimated by combining the statistical distribution of well-depths (determined from household surveys) with groundwater levels in Chennai. Consumers'

wells which were shallower than the water table were assumed dry.

$$FDry(j,t) = FDist(depth(j,t))$$

where
FDry = Fraction of households with dry wells
FDist = Distribution of depths of domestic wells

[74] Based on1500 household surveys, the distribution of 941 wells well-depths could be fitted by the polynomial function:

$$\mathrm{Frac\_dry}(j,t) = -5.10E-09x^5 + 1.32E-06x^4 - 1.22E-04x^3 + 4.50E-03x^2 - 3.59E-02x + 6.99E-02$$

x = Depth (j,t), the average depth to the water table in zone j
For dry wells, the quantity extractable per day is 0. Otherwise the quantity extractable was assumed to be GW_MAX, the maximum quantity of groundwater extractable at an individual private well.

$$\begin{aligned} Q_{Well} &= 0 && \text{if household well is dry} \\ &= GW\_MAX && \text{if household well is wet} \end{aligned}$$

A4. Groundwater Module: Maximum Quantity Extractable From Individual Wells

[75] The groundwater module also predicted the maximum quantity of extractable groundwater in each part of the basin. The maximum quantity of groundwater extractable per day was estimated using the analytic Theim equation [*Trescott et al.*, 1976]. The Theim equation calculates the impact of on individual wells.

$$GW\_Q_{MAX} = Theim\,(Aquifer\_Transmissivity, Well\_Radius, Well\_Efficiency, Average\_GW\_Head)$$

where
GW_QMAX is the quantity of water extracted each day
Aquifer_Transmissivity is a hydrogeologic property that specifies how much water flows through a cross - section of the aquifer for a unit increase in the hydraulic gradient.
Well_Radius is the internal radius of the well, assumed to be 10 cm for a representative well.
Well_Efficiency is the average efficiency of a representative well based on expert assessments
Average_GW_Head is the simulated groundwater elevation above mean sea level.

A5. Tanker Module: Price of Tanker Water

[76] The competitive market price for tanker water was depended on the costs of procurement and distance to the nearest source villages.

$$\mathrm{Price}(j,t) = (2 * \mathrm{Distance}(j,t) * \mathrm{PFuel} \div \mathrm{Fuel\_Eff} + \mathrm{PLabor} + \mathrm{PWater} + \mathrm{PProfit})/12$$

where,
PLabor = Wage rate to driver and helper ~ Rs 100/12 kL Tanker load
PFuel ~ Cost of fuel = Rs 30/liter
PWater ~ Price paid to farmer = Rs 50/12 kL Tanker load
PProfit ~ Profit to tanker operator = Rs 100/12 kL Tanker load
Fuel_Eff ~ Fuel efficiency = 2.5 km/liter
(based on interviews with tanker operators)"j"is the spatial unit within city limits.
All costs given above were based on interview data collected in 2005–2006. Distance is multiplied by a factor of two because the tanker makes a round-trip from the city, to the source-collection point and back to the consumer.

A6. Utility Module: Total Quantity of Water Available for City Supply

[77]

$$\mathrm{Utility\_Supply}(t) = (\mathrm{Div}(t) + \mathrm{Veeranam}(t) + \mathrm{Well\text{-}Fields}(t) + \mathrm{Other}(t)) * \mathrm{City\_Frac} + \mathrm{Emergency}(t)$$

where
Well_Fields(t) = Water extracted from well fields
Veeranam(t) = Water delivered by intrastate Veeranam Project
Other(t) = Minor local sources
City_Frac = 65% (assumed 65% of available supply is used for Chennai, rest for industry and peri-urban towns)
Emergency(t) = Emergency purchases for farmers implemented during drought ~ 100 million liters/day

A7. Utility Module: Hierarchical Distribution Algorithm

[78] Quantities of utility supply per household are given by

$$Q_{\mathrm{MOBILE\_SUPPLY}} = \overline{q_1} = 90 \text{ LPHD}$$

$$Q_{\mathrm{HANDPUMP\_SUPPLY}} = \overline{q_2} = \mathrm{Hours\_Supply}(t) * (60 \text{ min/hr}) * 1(\text{pot/min}) * 15(\text{liters/pot})$$

$$Q_{\mathrm{STANDPIPE\_SUPPLY}} = \overline{q_3} = Q_{\mathrm{HANDPUMP}}(t)/\mathrm{Sharing\_HH}$$

$$Q_{\mathrm{SUMP\_SUPPLY}} = \overline{q_4} = \mathrm{Total\_Piped\_Supply}(t) - \mathrm{Total\_Manual\_Use}(t)/\mathrm{Sump\_HH}$$

where
Sharing_HH is the number of households typically sharing a public standpipe assumed to be 20.
Total_Mobile_Supply(t) = $Q_{\mathrm{MOBILE\_SUPPLY}}$ * Unconnected_HH(t)
Total_ Bulk_Supply (t) = MIN (40 MLD, 10% of Utility_Supply(t))
Total_Piped_Supply(t) = Utility_Supply (t) − Total_Mobile_Supply(t) − Bulk_Supply (t)
Hours_ Supply (t) = Total_Piped_Supply(t) * α. We parametrized α to be 0.01, when Total_Piped_Supply(t) is in million liters per day and Hours_ Supply (t) is in hours.
Manual_use(t) = $\frac{1}{10^6} \sum_{j=1}^{12} Q_{\mathrm{STANDPIPE\_USE}}(j,t)$ * Unconnected_HH(j, t) +

$Q_{HANDPUMP\_USE}$ (j, t) * Connected_HH(j, t) + $Q_{HANDPUMP\_USE}$ (j, t) * Borewell_HH(j, t)
where
Manual_Use (t) = Total water collected manually from piped system, includes standpipes and private yard hand-pumps. Note that the quantities of supply (Q_{MOBILE_SUPPLY}, $Q_{HANDPUMP\_SUPPLY}$) is determined by availability, but the quantity actually used ($Q_{HANDPUMP\_USE}$, $Q_{STANDPIPE\_USE}$) is an outcome of the consumers' optimization problem. Number of households in each category = % of households * Total_Households

[79] In 2001, per census, Total_Households = 217,574 and the fraction in each category are % Unconnected_HH = 15%, %Connected_HH = 21%, %Borewell_HH = 35% and %Sump_HH = 29%.

A8. Consumer Module: Consumer Demand Functions

[80] The residential demand function estimated from the household survey was

$$Q_{HOUSEHOLD\_WEEK} = 4.6 * P^{-0.46} * N^{0.44} * D^{0.27} * I^{0.19}$$

The commercial demand function estimated from the survey was

$$Q_{COMMERCIAL\_WEEK} = 6.17 * P^{-0.21} * FE^{0.85} * D^{0.06} * WI^{1.9}$$

Note that these functions generate weekly demand for water so to obtain daily demand must be divided by 7.

A9. Consumer Module: Consumer Optimization Problem

[81] Minimize

$$C(P,Q) = \sum_{k=1}^{M} p_k q_k(i,j,t)$$

$$q_k \leq \overline{q_k}$$

$$p_1 \leq p_2 \leq \ldots.. \leq p_M$$

$$D(p_k, \ldots, N, I)$$

$$Q_M = \sum_{k=1}^{M} q_k \leq D(p_i, \ldots, N, I)$$

where
q_k is the quantity actually consumed from *k*th source
$\overline{q_k}$ is the maximum quantity available from source k, determined by the other Modules
p_k are costs of water from *k*th source, including time costs
D is the quantity demanded is a function of prices, income, number of members
Q is the total quantity consumed from all sources
M = Number of sources
k = Source of water: Piped Supply, Private well, Private Tanker, Public Standpipe
i = Census zone
j = Consumer Category: Unconnected, Connected, Well Owners, Sump Owners
t = Time Period

A10. Consumer Module: Consumer Surplus Estimation

[82] The model also estimated consumer surplus, the total benefit gained from all units consumed. The consumer surplus is defined by the equation

$$CS(Q) = \int_0^{Q_M} W(Q)dQ - \int_0^{Q_M} C(Q)dQ$$

where W(Q) is the willingness-to-pay function as and C(Q) is the cost function and, Q_M is the total quantity of water consumed from M sources.

A11. Tanker Module: Groundwater Extractions by Tankers

[83] Total size of the tanker market is simply the sum of tanker water demand across consumers in all categories and zones.

$$TQ_{Tan\ker}(t) = \sum_{i,j} q_{\tan\ker}(t)$$

Tanker extractions in peri-urban areas were input into the groundwater model as follows.
Tanker_Extractions(x,y,t) = Tanker_Source_Area (x,y) * TQ_{Tanker}(t)/10^3
No_of_Source_ Cells
where tanker source areas are
Tanker_Source_Area (x,y) = 1 if Depth(j,t) < 10 m, LandUse (x,y) = "Agriculture" or "Fallow," and Tanker_Source_Area (x + n,y + n) is a road where n = −1,0,1 (i.e., within 1 grid cell of a road)

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