Sustainable urban water supply in south India: Desalination, efficiency improvement, or rainwater harvesting?

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[1] Indian megacities face severe water supply problems owing to factors ranging from growing population to high municipal pipe leakage rates; no Indian city provides 24/7 water supply. Current approaches to addressing the problem have been "utility centric," overlooking the significance of decentralized activities by consumers, groundwater extraction via private wells, and aquifer recharge by rainwater harvesting. We propose a framework that makes it possible to evaluate a wider range of centralized and decentralized policies than previously considered. The framework was used to simulate water supply and demand in a simulation model of Chennai, India. Three very different policies, supply augmentation, efficiency improvement, and rainwater harvesting, were evaluated using the model. The model results showed that none of the three policies perfectly satisfied our criteria of efficiency, reliability, equity, financial viability, and revenue generation. Instead, a combination of rainwater harvesting and efficiency improvement best meets these criteria.

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1. Introduction

[2] Urban areas in India have been experiencing unprecedented growth in population and income [*United Nations*, 2001]. As cities grow and incomes rise, a new challenge has arisen: that of supplying water reliably to rapidly growing, increasingly wealthy populations and businesses, while ensuring that the poor are not left unserved. Faced with uncertain rainfall, limited reservoir storage, aging piped infrastructure, and rapidly growing demand, no Indian city today has 24/7 water supply; instead piped supply is typically intermittent, available for only a few hours each day [*McIntosh*, 2003; *Water and Sanitation Program-South Asia*, 2003]. Developing cities in India represent both a challenge and an opportunity. Because much of the infrastructure is still being built, there is the opportunity to follow a different development path.

[3] Traditionally, scholars have tended to view the problem of urban water supply as consisting of two distinct components: a resource problem and a delivery problem. Options including desalination, water markets, interbasin transfers [*Briscoe and Malik*, 2006] and wastewater recycling and reuse [*Gupta and Deshpande*, 2004] have been suggested to address the resource problem. But development scholars have long argued that the problem in developing cities is not one of scarce resources, pointing out that urban water demand typically constitutes only a small fraction of utilizable water resources [*Meinzen-Dick and Appasamy*, 2002]. Instead, the problem stems from mismanagement in delivery. Water utilities do not properly meter water or pass on the full costs of supply, so consumers use water wastefully. As utilities are unable to recover costs, they cannot make appropriate investments in expansion or maintenance [*McIntosh*, 2003; *Water and Sanitation Program-South Asia*, 2003]. Distribution becomes inefficient and supply is unreliable. This in turn erodes consumer confidence and willingness-to-pay creating a "low-level equilibrium" where the fraction of households connected to the piped supply system remains low, the utility remains financially weak, and much of the water is lost or used wastefully [*Singh et al.*, 1993]. *Rogers et al.* [2000] summarize the solutions to the world's urban water problems as follows: reallocate water from agriculture to address the resource problem and charge more to fund infrastructure improvements and conservation to address the delivery problem.

[4] In recent years, the concept of integrated urban water management has gained prominence. This paradigm views water supply, distribution, storm water and sewage as one integrated system [*Mitchell*, 2006]. Although in principle integrated urban water management allows for decentralized management and demand-side approaches, in practice both the traditional and more recent integrated urban water management approaches take a largely "utility-centric" view of urban water supply, wherein the urban water utility is viewed as the principal entity that abstracts, manages, and distributes water. Consumers' actions are limited to improved management of water, gray water reuse, or collection of rainwater.

[5] However, the prevailing utility-centric view of urban water supply is inadequate to describe the water supply situation in many large Indian cities. The utility-centric view omits three important types of decentralized activity prevalent in Indian cities. (1) A large fraction of urban consumers regularly depend on private sources despite having piped

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connections. No Indian city has 24/7 supply, as piped supply is often inadequate and available for only a few hours each day. A recent study of seven Indian megacities [*Shaban and Sharma*, 2007] indicated that between 25% and 80% households in six cities relied on private wells for some portion of their water needs. Reliance on multiple sources of water by a majority of consumers renders the utility-centric view of urban supply inadequate; the resource and delivery components are no longer cleanly separable. Consumers receive water from the utility via the piped system, but also directly independently abstract water via private wells or via private suppliers. (2) Some consumers remain unconnected to the piped supply system, choosing to rely exclusively on wells. Others invest in a variety of coping mechanisms such as sump storage and private wells [*Pattanayak et al.*, 2005] to cope with poor reliability of piped supply. As a result, the price, reliability, and quantity of water experienced by the consumer are a function of the coping investments made by the consumer as opposed to factors controlled by the water utility. (3) In recent years in India, the idea that water management is the exclusive responsibility of government or the water utility is giving way to a "paradigm built on participative and local management of the resource" (as described in the Stockholm International Water Institute's 2005 statement of the Stockholm Water Prize Award). Specifically, cities are promoting decentralized management policies to improve aquifer recharge such as rooftop rainwater harvesting by individual households, commercial establishments and institutions. However, even as urban rainwater harvesting regulations are being promulgated in many Indian cities, resources devoted to implementation have been limited to information dissemination rather than enforcement. Within the academic and development community, no comprehensive attempt has ever been made to quantify the costs and benefits of rainwater harvesting policies.

[6] The three types of decentralized activities described above have been inadequately addressed in part because the theoretical frameworks and scientific analyses required to evaluate their effectiveness lag behind. Unfortunately, without a suitable framework key questions have remained unanswered. Can improved aquifer recharge eliminate the need for a desalination plant? How does the water generated by recharging the aquifer get to consumers? What is the relationship of leaking supply pipes to aquifer recharge? Can fixing pipeline leaks alone make consumers better off? Indeed, these questions remain unanswerable within the traditional "utility-centric" framing of the urban water supply problem. This research study offers the following contributions. (1) The paper presents an integrative framework uniquely suited to evaluating both centralized and decentralized policy solutions. (2) By applying this framework, we were able to come up with new policy insights. The key insight from the policy analysis is that a combination of rainwater harvesting and efficiency improvement is best able to meet critical social goals.

[7] This paper is organized as follows: First we present a framework that makes it possible to evaluate both centralized and decentralized policies for urban water supply. We describe our approach to developing a systems dynamics hydrologic-economic model of water supply in Chennai (formerly Madras) in South India. We present results from the Chennai hydrologic-economic model. The model is used to develop a range of policy scenarios through 2025 evaluated using multiple criteria. We conclude by presenting a policy that is optimal for Chennai.

2. Integrative Framework

[8] The primary challenge to be addressed in comparing centralized and decentralized policy solutions was the absence of a theoretical framework. In this paper, we propose a new integrative framework to represent consumer behavior. The framework makes it possible to compare a range of centralized and decentralized policies on an apples-to-apples basis. Although the framework is applied to a specific case study site in this paper, the framework is general enough to be applicable elsewhere in the developing world.

[9] The framework considers four dimensions of water supply relevant to consumers: modes of supply accessed by consumers, investments made by consumers in acquisition, storage, and treatment of water, quality (potability) of water, and time periods in which consumers make decisions. A consumer is defined as a "household" for domestic consumers and an "establishment" for commercial consumers. Each of these dimensions is explained below.

2.1. Modes of Supply

[10] Consumers have access to multiple modes of supply; for example, piped connections, standpipes, private wells, and water vendors. However, the quantity of water available from each mode may be restricted, the potability and price of each may be different. Rational consumers make decisions on how much of a particular source to use so as to minimize their costs (including time costs), subject to constraints on quantity and quality. We employ a discrete-choice model that allows consumers to use water from multiple sources assuming supply constrained conditions. We assume consumers are rational and have perfect information regarding the price and potability of water and the time taken to acquire water from different sources. The solution *to* the consumers' choice problem yields a "tiered supply function" as shown in Figure 1. Essentially, 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.

[11] Economists define the incremental benefit gained from consuming a single unit of water as the difference between what consumers would be willing to pay for a good and what they actually do pay for water. The consumer surplus is the total benefit gained from all units consumed. It is a monetary measure of consumer well-being that applies regardless of what mode of water supply the consumer uses. In Figure 1, it is the area below the demand curve and above the tiered supply function.

2.2. Investments

[12] Consumers make long-term investments in acquiring and managing water, both from the utility and otherwise. These long-term investments determine the quantity, quality and price of water from the different modes of supply in the consumers' cost minimization problem. For example, consumers only have "piped supply" as an option if they have previously connected to the utility system, paying a connection fee. To account for differential investments, consumers are classified on the basis of investments in connectivity, bore

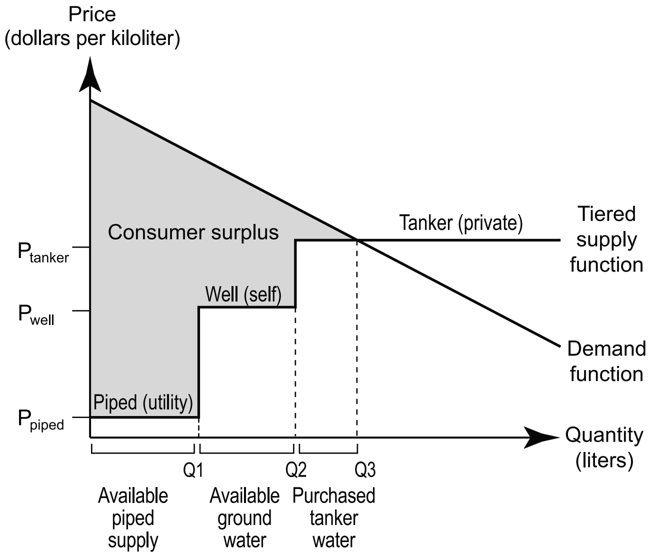

Figure 1. Representation of the consumer choice problem and an example solution. The total quantity of water consumed is determined by the intersection of the tiered-supply curve with the consumers demand curve.

wells, in-house storage (Table 1). Households can be classified into four categories, "unconnected," "connected," "well owners," and "sump owners," on the basis of increasing levels of investments.

[13] Classifying consumers on the basis of their level of investments has three advantages. (1) Classifying consumers determines which modes are available to a household. For instance "Unconnected" consumers are not connected to the utility. These consumers are dependent on public standpipes (hand pumps that tap the partially filled utility pipelines) community wells, water vendors, or utility tankers ("mobile supply"). "Connected" consumers have utility connections but these are typically yard taps or hand pumps. They often lack indoor plumbing. But whether they have indoor plumbing or not, because piped supply is intermittent, consumers must collect water in 15 L "pots" each morning and use the water manually using mugs. "Well Owners" have access to yard/street utility connections, but also have motorized borewells connected to taps inside the house. "Sump owners" typically have underground sumps, in which intermittent piped supply is received, the water is lifted by a motorized pump to an overhead tank and flows by gravity to taps in the house. Having a storage sump allows consumers to convert an intermittent utility supply into an effective "24/7" piped supply. In our framework, (wealthy) sump owners are assumed to also have wells. (2) Long-run investments determine the short-run costs of supply to the consumer. For instance, once a consumer has invested in storage sumps, pumps, overhead tanks, and indoor plumbing, the "marginal cost of piped supply" is simply the cost of pumping water from the sump to taps within the household. The capital costs are sunk costs; they do not factor in the consumers day-to-day decisions. In contrast, consumers lacking sumps must factor in the cost of time spent in hauling the water around the house, each time he/she needs to use water. Even at a conservatively low opportunity cost of time, collecting and using water stored in pots is much more "expensive" than pumping water to indoor taps. (3) For residential consumers, the consumer categories serve a third purpose; they also correspond to different income groups. Unconnected consumers are the poorest, while consumers with in-house storage and wells are the wealthiest. Therefore, differential impacts by consumer group can be used as a proxy for equity impacts of various events or policies.

2.3. Quality

[14] Consumers distinguish between different qualities of water. We developed a simplified model of consumer perceptions of water quality on the basis of our survey data as follows: (1) There are two major categories of water quality distinguished by consumers, both in terms of supply and demand: potable and nonpotable. (2) Of the various sources of water, only water supplied by the utility is potable quality; that is, usable with little or no treatment. Groundwater is considered nonpotable. Other sources can be converted to potable quality, but the cost of treatment is higher. (3) There are certain end uses that require potable-quality water. We define potable demand as water used in the kitchen for drinking, cooking, and washing. Nonpotable demand is defined as water used for bathing, sanitation, washing, and gardening. (4) Potable demand is assumed to be inelastic, fixed at 20 L per capita per day. This was based on the average quantity of water used for drinking and cooking purposes reported in our household survey. Nonpotable demand is estimated as a function of price, household income and family size [*Srinivasan*, 2008]. (5) Consumers use only potable-quality water to meet their potable demand, but use either quality of water to satisfy nonpotable needs. (6) Consumers derive a higher marginal benefit from drinking and cooking water, and these will be the last uses to be eliminated during shortages. Thus, if availability of water is limited, consumers will allocate scarce potable water to meet their drinking and cooking needs first.

2.4. Time Periods

[15] Both the quantity, quality, and price of water available from each mode of supply may vary over time. So the consumers' cost minimization problem must be solved for each time period. Allowing consumers to optimize their water use each period accounts for changes in consumption water availability caused by drought or seasonal variability.

[16] This framework addresses important conceptual problems with the utility-centric framework. (1) The framework allows consumers to use multiple modes of supply and qualities of water. The framework implicitly distinguishes between short-run decisions by solving the consumers' cost-minimization problem assuming a fixed set of source choices in a given time period as well as long-run decisions by accounting for consumers' coping mechanisms and thus the choice set available to them. This also allows considerations of quality, price, reliability, and convenience to be expressed

Table 1. Coping Investments by Consumer Category

	Connectivity	Borewells	In-House Storage (Sumps and Overhead Tanks)
Unconnected	–	–	–
Connected	✓	–	–
Well Owners	✓	✓	–
Sump Owners	✓	✓	✓
Commercial	✓	✓	✓

in equivalent terms. (2) The framework accounts for the trade-off between time and monetary costs. Long-run investments in storage and borewells, improve the reliability of water supply, so consumers spend less time hauling water. This lowers the price of water from that source in the consumers' day-to-day optimization problem. (3) The framework allows estimation of a single demand function that is independent of the sources or availability in water. Estimation of a single demand function allows consumers to change modes of supply depending on varying supply conditions between wet and dry years. Prior demand estimation studies [*Nauges and Strand*, 2007; *Strand and Walker*, 2005] have specified separate demand functions for household "tap" and "nontap" consumption in developing countries, making it difficult to simulate demand where the categories are fluid and consumers switch between those with taps and those that collect water from public sources depending on availability. (4) The framework establishes consumer surplus as a common measure of consumer well-being regardless of the type of consumer, coping investments, or modes of supply used. This makes it possible to compare the benefits from a range of diverse policy options on an apples-to-apples basis. For instance, simulating consumer switching between private wells and piped supply, allows the benefits of improved groundwater management and improved piped supply to be compared.

[17] This framework offers several contributions to the water resources management literature. First, methodologically, the framework is applied to developing a simulation model of Chennai's water supply to compare a range of centralized and decentralized policies. However, this is not the only application. In another paper [*Srinivasan et al.*, 2010], we briefly describe how the framework was applied to estimate the residential demand function for water, where the tiered supply curve is treated as a special case of an increasing block rate tariff. Applying this framework to demand estimation addresses many of the problems encountered with estimation of residential demand in the developing world; in particular, dependence on multiple sources of water and simultaneous use of manual and piped sources. Second, although the model and policy insights apply to one case study area, the underlying system characteristics of multiple source dependence, inadequate surface water storage, poor demand management, low tariffs, high leakage rates, and crises during multiyear droughts are similar to those described elsewhere in the developing world [*Baisa et al.*, 2008; *von Bertrab*, 2003]; this suggests the results may provide insights have wider applicability beyond Chennai and India.

3. Background and Approach

3.1. Background on Chennai, India

[18] The framework presented above was implemented in an integrated simulation model of water supply in Chennai, India, a growing metropolitan region with 7 million people. We selected Chennai as our case study area for three reasons.

[19] First, Chennai's water availability at 40–100 L per capita per day (LPCD) is the lowest of all megacities in India. Although 95% of the households within Chennai city have some sort of access to public supply, piped water supply is highly intermittent and available for only a few hours each day. Consumers rely on private wells and water tankers to cope with the unreliability of public water supplies. Increasing population, urban expansion, increasing demand on the already strained reservoir system, lack of new reservoir sites combined with climate variability make Chennai vulnerable to water shortages. Although Chennai's water problem is particularly severe, these patterns are common to all rapidly growing megacities in India and elsewhere in the developing world.

[20] Second, the choice of Chennai as a case study was partly opportunistic. Chennai suffered from a severe drought in 2003 and 2004, 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 socioeconomic survey data and physical data for both hydrological states, made a systems analysis study feasible. Analysis of this historical period led us to several observations about the impact of water resource availability on Chennai's water supply. In 2004–2005, Chennai's reservoirs went completely dry; water available from all sources combined was insufficient to deliver water via a piped system, resulting in the shutdown of piped supply. 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, collected in 15 L pots. As piped supply was shut off, consumers switched to private and community wells. As the drought progressed, groundwater levels in Chennai fell 8 to 10 m; consumers wells became increasingly dependent on private tanker operators who trucked in water sourced from periurban farms. The cessation of piped supply for almost a year prompted speculation that the city might have to be evacuated [*Rao*, 2004]. Eventually, a heavy monsoon in 2005 and a new water project averted the crisis. After 2005, the reservoir system and aquifer replenished and normal piped supply was resumed.

[21] Third, Chennai also recently became the first Indian city to mandate rooftop rainwater harvesting for aquifer recharge. Simultaneously, the city utility is in the process of commissioning several desalination plants. This made questions about how to compare diverse solution options immediately relevant for Chennai.

3.2. Research Approach

[22] To determine which policy approach would best address Chennai's water supply needs, the integrative framework was implemented in a systems model of Chennai's water supply. Systems models are commonly used in water policy analysis because they expose structural relationships among the important policy variables and allow prediction of the consequences of a particular policy [*Simonovic and Fahmy*, 1999]. Systems models typically involve simulating different components of an interconnected system, then linking the components using appropriate feedbacks.

[23] In this work, different components of the Chennai water-supply system were simulated using a dynamic, spatially explicit, model of the Chennai basin. The model simulated surface water flows into the reservoir system, and groundwater flows in the Chennai aquifer; the model allocated the quantity of water available to the utility from the reservoir system and other sources across different categories of consumers. The consumer's cost-minimization problem

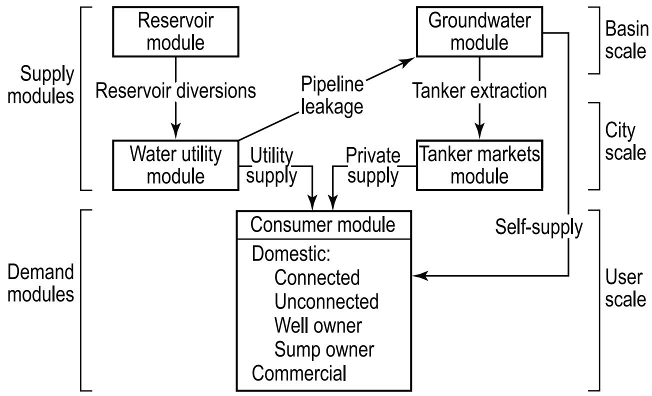

Figure 2. The integrated model estimates supply and demand for each census unit, consumer category, and time period using five interlinked components: the reservoir, the groundwater, and utility, tanker, and consumer modules. Each module was developed and calibrated independently using appropriate spatial and temporal units.

was solved to determine the modes of supply, quantity consumed and the consumer surplus, given the quantity, potability, coping investments and price of water from the various sources. Both the model components and the whole model were calibrated using observed data for a historical period.

[24] After calibration, a "baseline" forecast to 2025 simulated the business-as-usual scenario; that is, the calibrated model was then used to determine how much water will be consumed in the Baseline scenario in 2025 given expected growth in population, income, and water infrastructure and the state of consumers' well-being? Once a baseline was established, the model was used to evaluate multiple policy alternatives. The model was run by changing model parameters to reflect different policy changes. This determined the incremental value of consumer well-being under different policies.

[25] The policies were evaluated by quantifying the values of four criteria. (1) Economic efficiency: Net benefits from a given policy can be estimated as the sum of gains in consumer surplus and producer surplus; the latter defined as utility revenues less policy costs. If benefits exceed costs, the policy is economically efficient. (2) Piped supply shutdown: This criterion evaluated if the utility was able to avoid complete shut-downs in piped supply, the sole source of potable drinking water to consumers. (3) Revenue maximization: Similarly, if the policy yields significant revenues to the utility, the utility may be more likely to promote and implement the policy, so determining profits to the utility is useful. (4) Financial viability: By comparing average tariffs with average costs, we can determine if the utility can remain financially viable without government subsidies.

4. Simulation Model

4.1. Model Development

[26] The integrated model was constructed to simulate all the components of the Chennai water system. A modular approach was adopted in which five interlinked modules were linked (Figure 2). The different components of the Chennai water system were simulated using a multiscale, dynamic, spatially explicit model of the Chennai basin. Detailed simulation results were produced for 3 month time periods and 10 census zones, and were then cohesively analyzed on a system-wide basis. The model of historical behavior (January 2002 to April 2006) was used to calibrate the model parameters, and the model was used to develop insights into the dynamics of the urban water system. The model was formulated and calibrated on the basis of extensive primary and secondary data including large-scale household surveys, lithologic data, water level data, reservoir data, satellite images, government statistics, census data, etc. The details of the model, including equations and calibration are available in the work of *Srinivasan et al.* [2010]. In this article, we focus only on the policy outcomes.

4.2. Baseline Scenario to 2025

[27] The Baseline scenario of Chennai's water supply for the intermediate-term (up to 2025) projects the water supply situation in Chennai assuming status quo. To project water demand and supply in the baseline scenario, we used reasonable projections of population, land use, infrastructure (new desalination plant) and additional consumer investments (in sumps, borewells and connections). Although the model was run under multiple rainfall scenarios, for the sake of brevity results are presented for one scenario in which the historical rainfall record from 1989 to 2006 is repeated from 2008 to 2025; because other rainfall scenarios, discussed in the sensitivity analysis section, do not change the rankings of the policies or insights developed. In developing the baseline scenario, population projections were based on the latest Chennai Master Plan [*Chennai Metropolitan Development Authority*, 2007]. The only infrastructure project included was the proposed 100 million liters/day (MLD) desalination plant to be commissioned in 2009. The Clark urban growth model was used to forecast land use change up to 2025 [*Clarke and Gaydos*, 1998].

4.3. Three Policy Scenarios

[28] The integrated model was used to analyze the effects of three policy interventions to alleviate a future drought. To simulate the policies, appropriate parameter changes were made to the integrated model for each policy. Each of the three policies is described in detail below.

4.3.1. Supply Augmentation via Desalination

[29] Supply augmentation approaches involve increasing the total quantity of water available by building new water supply projects, desalination plants or purchasing water rights from agriculture. These approaches are usually favored by water utilities. Unfortunately, Chennai has no local, undeveloped sources. Historically, large interbasin water transfer projects have proved challenging, taking decades to complete; even after being commissioned deliveries have remained unreliable and subject to political bargaining each season [*Briscoe and Malik*, 2006; *Maitra*, 2007; *Nikku*, 2004]. Although these interbasin transfers will be needed in the long term, only policies currently under consideration aimed at water management through 2025 are addressed. To address the resource scarcity problem, Chennai's water utility recently commissioned one desalination plant to the north of the city, and is considering a second plant to supply the rapidly growing suburbs to the south of the city [*The Hindu*, 2008]. To simulate this, in the model, under this policy, a second 100 MLD desalination plant is added beginning in

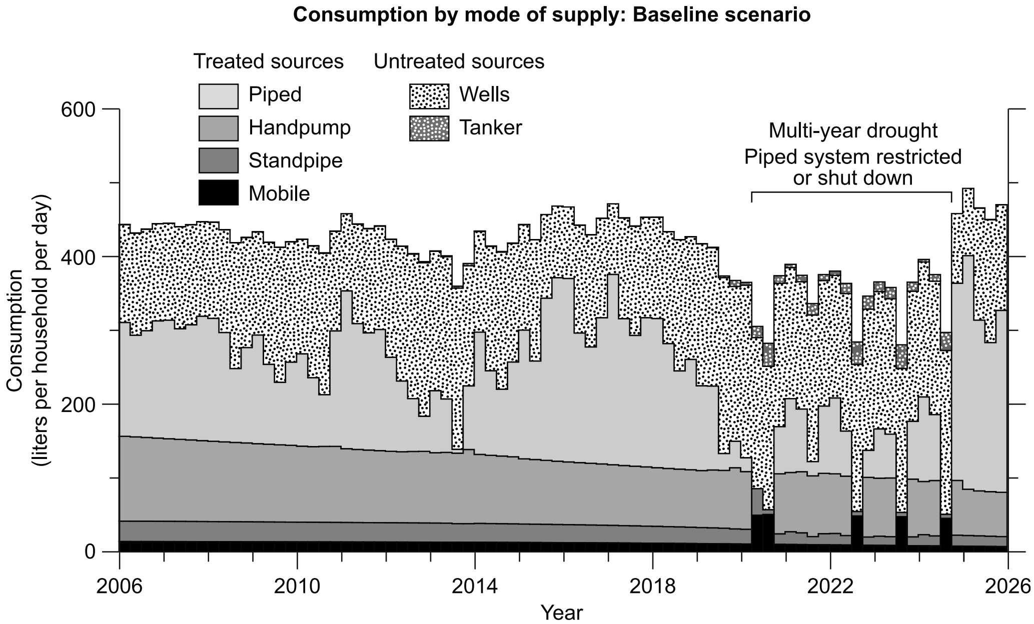

Figure 3. Baseline consumption of water by model of supply (average across households).

2015 to boost utility supply. The cost of desalination was conservatively assumed to be \$1.02/kL (Rs 45/kL) [*The Hindu*, 2005].

4.3.2. Efficiency Improvement

[30] Efficiency improvement policies have long been advocated by development agencies. They consist of (1) raising tariffs and implementing metering to allow the water utility to recover costs and develop water infrastructure to keep pace with growing demand, and (2) improving delivery efficiency by reducing pipeline leaks. Most developing world cities suffer from pipeline losses as high as 50% compared to as low as 5% in the world's best run utilities [*Tortajada*, 2006]. Chennai pipe losses were estimated between 15 and 35% (K. Sivakumar, personal communication, 2006) depending on the zone. The historical groundwater model calibration estimated an average pipeline leakage rate of 25%. In the policy scenario, efficiency improvement was simulated by doubling piped supply costs to the consumer to \$0.11/kL (Rs 5/kL) for the consumer category "sump owners." Pipeline leakage was linearly reduced in half by 2025. Costs of improving the water distribution were assumed to be \$115/connection (Rs 5000/connection) (V. Chary, personal communication, 2008). These costs include metering and pipeline leakage reduction based on expert opinion.

4.3.3. Rainwater Harvesting

[31] Rainwater harvesting is being advocated by various environmental groups in India. In Chennai, "rainwater harvesting" refers to enhanced aquifer recharge; rather than collection of rainwater in cisterns for end use, a more common usage of the term. The "rainwater harvesting" policy involves improving recharge of the urban aquifer by installing rooftop and yard rainwater harvesting structures to direct rainwater into the aquifer. Rainwater harvesting may also be implemented at the community scale by rejuvenating traditional temple tanks and ponds as infiltration structures. These activities involve desilting these structures restoring the storm water inlets into them [*Agarwal and Narain*, 1997]. Without harvesting, only an estimated 9% of rainwater in Chennai makes it to the aquifer; the rest runs off into the ocean [*Srinivasan*, 2008]. In the policy scenario, the rainwater harvesting policy was implemented by increasing recharge to 27% of rainfall. This estimate is based on "expert estimates" by advocacy groups since definitive scientific assessments of the effectiveness of rainwater harvesting were unavailable. Instead, extensive sensitivity analyses were conducted as discussed later in the paper. Costs of rainwater harvesting were assumed to average \$60/borewell owning household. Note that these are average costs per household in Chennai. Large single family homes or communities may invest a lot more per household, with slum dwellers investing nothing at all.

5. Results

5.1. Baseline Simulation (2008–2025)

[32] A baseline scenario was developed using the historical rainfall sequence 1989–2006 repeated during 2008–2025. As population and income grow through 2025, pressure will mount to provide even more water. Analysis of historical data indicates that the Chennai's reservoir system at 15 months of storage is inadequate to guarantee a minimum supply over a multiyear drought even at current levels of demand; in future years the demand-supply gap will worsen. Model results indicate that Chennai will suffer another severe water crisis during a future multiyear drought. In a simulated future drought, the reservoir system dries up and remains dry for a prolonged period of almost 4 years. The piped supply system shuts down for over a year during the 4 year dry spell, because not enough water is available. As consumers become increasingly dependent on self-supply and recharge drops, portions of the aquifer dry up, and many consumers are forced to purchase water from private tanker suppliers. Figure 3 shows the water consumed by mode of supply averaged across households in Chennai. The dependence on expensive

Table 2. Qualitative Comparison of Policies

System Component	Supply Augmentation	Efficiency Improvement	Rainwater Harvesting
Reservoir	same as baseline	same as baseline	same as baseline
Utility	new desalination plant in 2015, keeps piped supply operational in future multiyear drought	reduction in pipeline leakage keeps piped supply operational in future multiyear drought	same as baseline: piped supply system shuts down for 9 months at the peak of the drought.
Groundwater	aquifer is drawn down, but to a slightly lesser degree compared to the baseline because more utility supply is available	aquifer is drawn down, but to a slightly lesser degree compared to the baseline because more utility supply is available	rainwater harvesting helps minimize aquifer draw down
Tanker market	tanker market is about half the size compared to the baseline, because of increased availability of utility supply and groundwater	tanker market is about half the size compared to the baseline, because of increased availability of utility supply	tanker market is only about a fourth of the baseline case
Consumer	consumers benefit from improved utility supply from second desalination plant	consumers benefit from improved utility supply owing to lower pipeline leakage	consumers benefit from improved groundwater availability

tanker water causes tremendous losses in consumer well-being measured by consumer surplus during the multiyear drought. Furthermore, the model predicts that the first desalination plant expected to come online in 2009, will not generate enough additional water to sustain Chennai's growing population during a future drought. Instead, the simulations predict that consumers will actually be worse off during a future multiyear drought.

5.2. Three Policy Simulations

[33] The three policies supply augmentation, efficiency improvement and rainwater harvesting, were compared in two ways: qualitatively, in terms of their impacts on the physical system and consumer well-being, and quantitatively, using five criteria, economic efficiency, equity, financial viability, revenue and reliability. The model results suggest that none of the three approaches: supply augmentation, efficiency improvement and rainwater harvesting, is best by all criteria.

5.3. Qualitative Evaluation of the Policies

[34] In this section, the physical and welfare effects of the three policies are described. The three policies differ significantly in terms of their impacts on the physical system and consumers.

[35] 1. The supply augmentation policy increases availability in the piped supply system because of the water produced by the second desalination plant. This policy allows the piped supply system to remain operational, albeit at curtailed levels, even in the driest periods. Consumers receive a minimum quantity of potable water; dependence on wells and tankers is reduced relative to the Baseline Scenario. Consumer categories with private connections benefit most from the availability of piped supply in dry periods.

[36] 2. The efficiency improvement policy also results in more reliable utility supply. Because pipeline leakage is decreased, more water is delivered to consumers in every period. However, because tariffs for sump owners are raised significantly, consumers use less water. Although sump owners suffer net losses in consumer surplus, these losses are more than offset by revenue gains to the water utility and consumer surplus gains by poorer consumers who enjoy improved supply without paying more.

[37] 3. The rainwater harvesting policy does not improve piped water supply. It cannot prevent a shut-down of the utility system, as the policy generates no new water that can be used in the piped system. However, improved recharge allows groundwater to become available to consumers via private wells, greatly reducing dependence on private tankers in the driest periods. Table 2 presents a summary of the effects of each policy relative to the Baseline Scenario.

5.4. Quantitative Evaluation of Policies

[38] The policies were also compared on the basis of four quantitative criteria. These criteria reflect a range of stakeholder concerns. The quantitative comparison of the policies is explained below. The metrics and formulae used are provided in Appendix A.

5.4.1. Economic Efficiency (Welfare Maximization)

[39] The economic efficiency criterion tests if a particular policy results in a better allocation of societal resources by comparing benefits and costs to society accruing from a policy. If benefits exceed costs, the policy is economically efficient. Analysis of the costs and benefits of the policies indicates that supply augmentation is not cost effective; costs exceed benefits by $177 million over the 18 year future period. The cost of operating a desalination plant far exceeds the increase in consumer surplus enjoyed by consumers. In contrast, the efficiency improvement and rainwater harvesting policies are each independently cost effective. Efficiency improvement yields benefits $21 million because the improved reliability of piped supply, particularly during drought periods, allows consumers to depend less on private sources of supply. The benefits from rainwater harvesting arise entirely from the increased availability of groundwater; consumers net benefits are $33 million higher during prolonged droughts.

[40] Additionally, the distribution of consumer surplus by consumer category shows that the rainwater harvesting policy yields the most benefits to poor, unconnected consumers, because it delays the drying up of shallow community wells during multiyear droughts. Efficiency Improvement greatly improves the condition of consumers with access to piped supply, but unconnected consumers reliant on public standpipes benefit only marginally. During multiyear droughts the decrease in recharge from leaky pipelines, slightly worsens

Table 3. Quantitative Comparison of Policies[a]

Criterion	Metric	Supply Augmentation	Efficiency Improvement	Rainwater Harvesting
Economic efficiency (welfare maximum)	net benefits between 2009 and 2025: consumer surplus + utility revenues – policy costs	(\$177 million)	\$21 million	\$33 million
Piped supply shut down	months of piped supply shut-down	0	0	9 months
Revenues (utility profit maximum)	total utility revenues between 2009 and 2025	\$2 million	\$60 million	*
Financial viability	full cost recovery: average tariff > average cost	no	no	no

[a]Values in parentheses are negative values.

the groundwater situation; so consumers drawing water from shallow community wells are worse off.

5.4.2. Piped Supply Shutdown

[41] The supply augmentation and efficiency improvement policies are able to prevent a complete shutdown of the piped supply system because the water produced by the desalination plant and reductions in pipeline leakage improve pipe supply. Not surprisingly, under rainwater harvesting there are no improvements in piped supply relative to the baseline. The captured water is directed into the aquifer. Under rainwater harvesting, the piped supply system shuts down for 9 months during a future multiyear drought as in the baseline case.

5.4.3. Revenue Maximization

[42] Utility revenues were included as a criterion, because a regulated utility's goal is revenue maximization, not social welfare maximization. The water utility's incentives to implement a policy are likely to be influenced by this goal. The efficiency improvement policy yields the highest revenues to the utility; \$60 million over 18 years. Efficiency improvement is the only policy that involves metering and raising tariffs and not surprisingly the only one to yield significant revenues.

5.4.4. Financial Viability

[43] The purpose of the Financial Viability criterion is to determine if the water utility can recover average supply costs in the absence of a perpetual subsidy from the government or tax payers. None of the three policies described recovered the full cost of supply. Even under the efficiency improvement policy, the only policy which involves metering and charging consumers for water, the tariff was arbitrarily set to twice the current rate to \$0.11/kL (Rs 5/kL); without considering the utility's costs of procuring and supplying water. However, to recover costs, the average tariff must be set at a rate at least equal to the average historical cost of piped supply. While the average cost of supply to Chennai is not known with certainty, it has been estimated to be about \$0.29/kL (Rs 13/kL) [*McKensie and Ray*, 2009]. Thus, the efficiency improvement policy still involves a massive subsidy to consumers. Supply augmentation and rainwater harvesting entail an even higher subsidy.

[44] Table 3 presents a summary of the performance of each policy relative to the baseline scenario by the four quantitative criteria. The results indicate that none of the policies perfectly satisfies all criteria. Desalination is not cost effective. Efficiency improvement is cost effective. Although it does not make "new" water available, it results in more efficient use of existing resources. However, the efficiency improvement policy fails to address the problem of lack of water resources during multiyear droughts; if the reservoirs dry up lower pipeline losses yield limited benefits. In fact, because the efficiency improvement policy reduces leakage and thus recharge into the aquifer, groundwater availability during multiyear droughts is reduced and a greater fraction of private wells go dry. In contrast, rainwater harvesting is cost effective and allows the urban aquifer to capture and store rainwater which can be used during droughts. The problem is that rainwater harvesting does not prevent a shutdown of the piped supply system, the sole source of potable drinking water available to consumers. The rainwater harvesting policy also does not generate any revenues for the utility, making it challenging for the utility to devote resources to implementing rainwater harvesting regulations. Importantly, none of the three policies allows the utility to recover the full cost of supply.

6. A New Combination Policy

[45] Although none of the three policies perfectly satisfies all criteria, from Table 3 it is apparent that rainwater harvesting and efficiency improvement are somewhat complementary in their effects and both policies are cost effective. However, neither policy lets the utility to remain financially viable. In this section we propose a policy approach that combines rainwater harvesting and efficiency improvement combined with a steep tariff increase. This policy allows overcomes some of the shortcomings of each efficiency improvement and rainwater harvesting and ensures full cost recovery at the same time.

6.1. Combination Policy: High Tariffs, Fix Leaky Pipelines, and Rainwater Harvesting

[46] In the combination policy we assume universal metering for sump owners along with a steep tariff increase to \$0.34/kL (Rs 15/kL). This tariff increase, though steep is not unreasonable; many Indian cities have announced plans to raise tariffs to these levels. Water is assumed to be sold at a flat rate per month to consumers with hand pumps; that is, utility connections lacking indoor plumbing. Public standpipes continue to be free. The revenue generated would be used to decrease pipeline leakage and improve distribution efficiency. Additionally, it is assumed that the utility, households, and communities would aggressively pursue rainwater harvesting to recharge the aquifer.

[47] This tariff hike assumption was made because the efficiency improvement policy presented earlier still involves a massive subsidy to consumers. The tariff is set to a little more that the estimated average historical cost of supply of \$0.30/kL (Rs 13/kl) [*McKensie and Ray*, 2009]. Adopting such a policy would resolve two problems: First, the utility can recover costs and make appropriate investments in

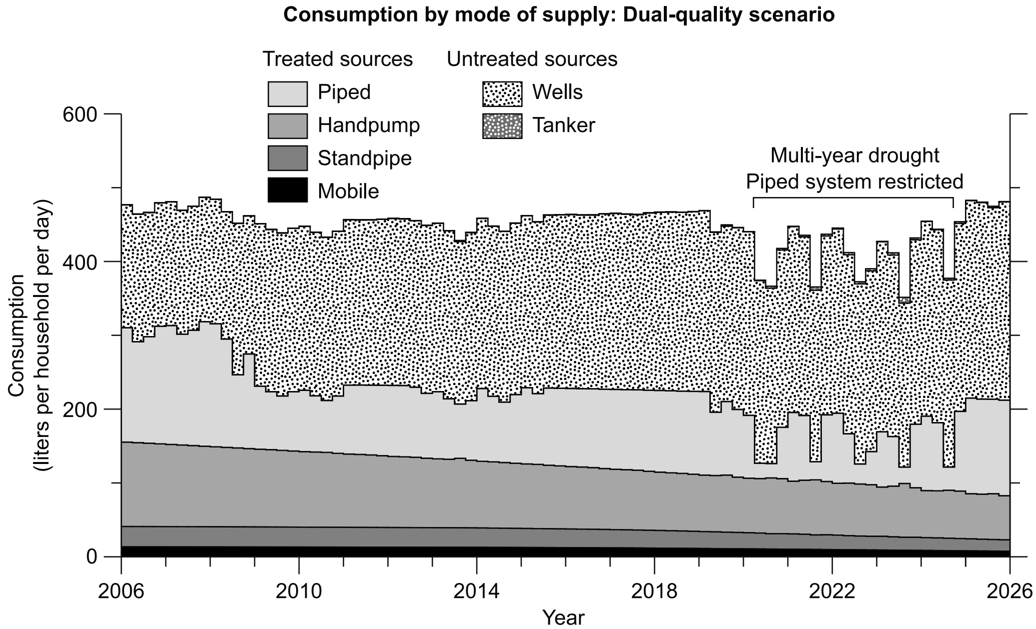

Figure 4. Combination (dual quality) consumption of water by mode of supply (average across households).

expansion and maintenance. Second, increasing the tariff allows the utility to raise funds for new infrastructure projects, including compensation for displaced populations and mitigating environmental damages. Consumers will have an incentive to use water efficiently, bridging the demand supply gap.

6.2. Model Results: Dual-Quality Usage

[48] The combination policy, though seemingly a minor change, represents a significant departure from the three policies presented earlier for the following reasons: (1) Because of the steep increase in tariffs, piped supply is no longer the cheapest source to sump owners. As a result, these consumers switch from utility piped supply to private wells for their nonpotable (washing, sanitation, and bathing) needs, not just during droughts but in all periods. (2) As consumers turn to private wells to meet their nonpotable needs, the demand for piped supply is reduced and the consumption of groundwater based self-supply is increased. (3) The demand for potable piped supply drops significantly in all periods because of the shift to groundwater for nonpotable end uses. At the same time reduction in pipeline leakage allows existing water resources to be delivered more efficiently to consumers. This allows the utility to bridge the demand-supply gap. (4) Consumers cut back on piped supply in favor of partial use from private wells. The decrease in piped water use (by almost half) implies the utility has surplus water that can be sold at the higher rate to commercial establishments growing suburbs and periurban towns in all periods. (5) Simultaneously, an aggressive artificial recharge program prevents groundwater levels in the aquifer from declining. In summary, the combination policy results in “dual-quality” water usage where consumers depend on piped supply only for potable needs and rely on private wells for nonpotable needs. For convenience we will refer to this policy as the “dual-quality” policy.

[49] The model results indicate that under this policy, consumption is less variable as compared to the baseline shown earlier (Figure 4). Consumers use less piped supply and more private well water. Figures 5 and 6 compare the dual-quality and baseline scenarios. Figure 5 shows that percentage of wells drying up under the dual-quality scenario. The results indicate that the aggressive rainwater harvesting keeps the aquifer recharged; a smaller fraction of private wells run dry at the peak of a multiyear drought. From Figure 6 we see that this policy reduces the tanker market to a third of the Baseline case during the multiyear drought. Figure 7 shows the difference in consumer surplus between the dual-quality and Baseline scenarios. It may be noted that while sump owners suffer a loss of consumer surplus in wet periods because of higher tariffs, they benefit greatly during droughts. The dual-quality solution was found to yield net benefits of about $80 million over the forecast period. The benefits accrue from avoided tanker purchases, improved piped supply and groundwater availability as well as significant revenue gains to the water utility from sale of water in all periods.

6.3. Sensitivity Analysis

[50] Extensive sensitivity analyses were conducted on all policy parameters. First, the results presented in sections 5 and 6 represented one future rainfall scenario. Clearly, a longer historical sequence is needed to capture the range of natural rainfall variability. Therefore, sensitivity of the results to alternate rainfall scenarios was evaluated. Second, there is considerable uncertainty in the costs of implementing the various policies. We assigned policy costs on the basis of expert assessments, so it was necessary to assess the robustness of the results to a range of policy costs. Finally, the effectiveness of artificial recharge policies like rooftop rainwater harvesting has never been scientifically established.

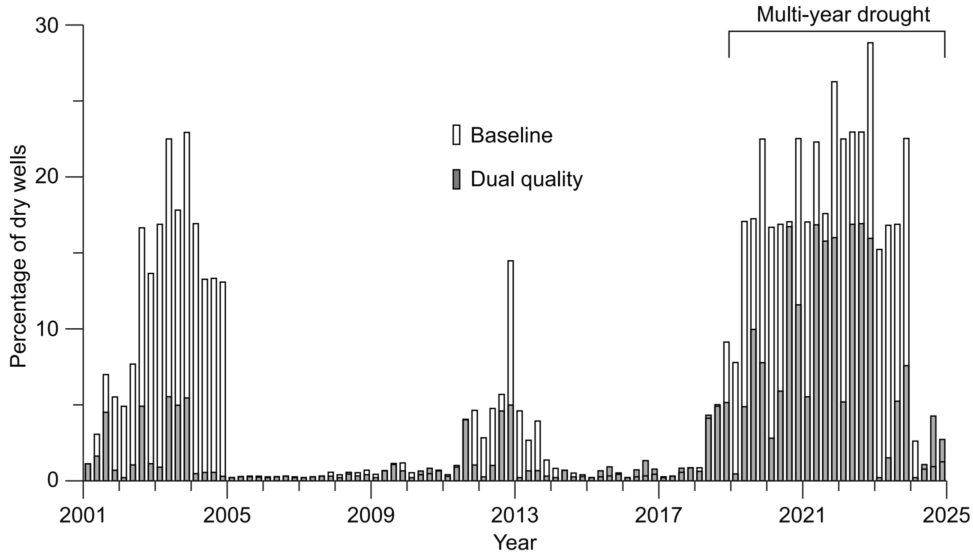

Figure 5. Percentage of wells dry: combination (dual-quality) scenario versus the baseline.

Accordingly, sensitivity of the results to assumptions regarding implementation efficacy was necessary.

[51] To test alternative rainfall scenarios, the critical period method, interchanging 5 year snippets of the rainfall record from 1965 to 2007, to generate alternative rainfall scenarios was used. The sensitivity analyses on six different rainfall scenarios (Table 4) showed that because the benefits of the policies are realized mainly during drought periods, the results were somewhat dependent on the length and severity of the critical drought in a given rainfall scenario, measured by the "maximum drought duration" [*Maidment*, 1993]. The model results show that the efficiency improvement policy yields benefits in normal periods when the reservoir system is not dry, but rainwater harvesting yields benefits during droughts, when piped supply is inadequate and consumers become dependent on private wells. Therefore in scenarios where the severity of the critical drought was higher, rainwater harvesting was optimal; for less severe droughts, efficiency improvement was optimal.

[52] When we evaluated the policies under different cost scenarios, desalination was not found to be cost effective under any realistic cost assumption. On average, efficiency improvement and rainwater harvesting are each cost effective up to double the costs assumed. Therefore, for the specific rainfall scenario presented, some additional enforcement costs (up to $60/borewell owner) may be included.

[53] Finally, the model results were tested under different effectiveness rates. Specifically, in the results presented earlier, the quantum of recharge that can be achieved by rooftop rainwater harvesting was based on "expert assessments" by

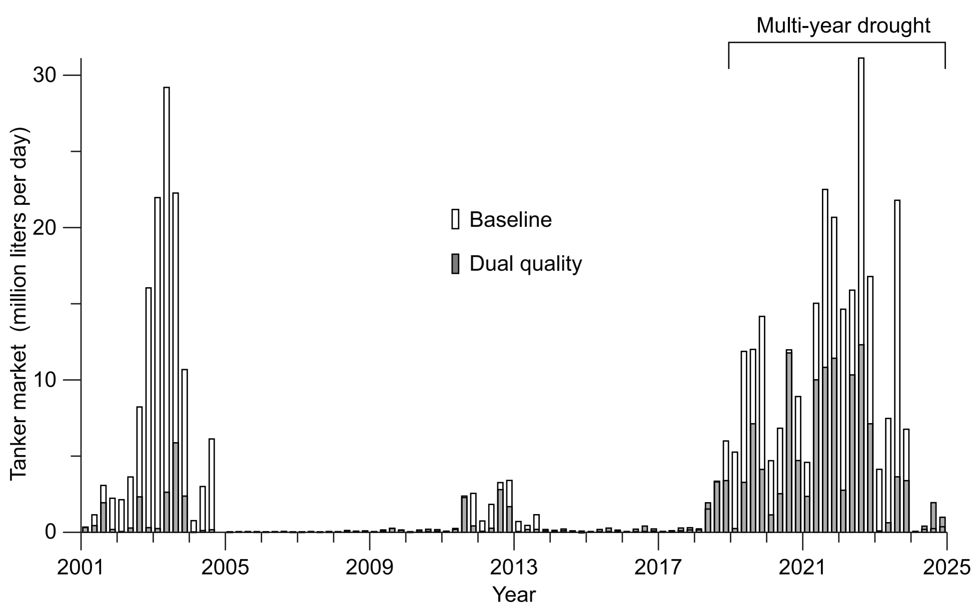

Figure 6. Size of Chennai tanker market: combination (dual-quality) scenario versus the baseline.

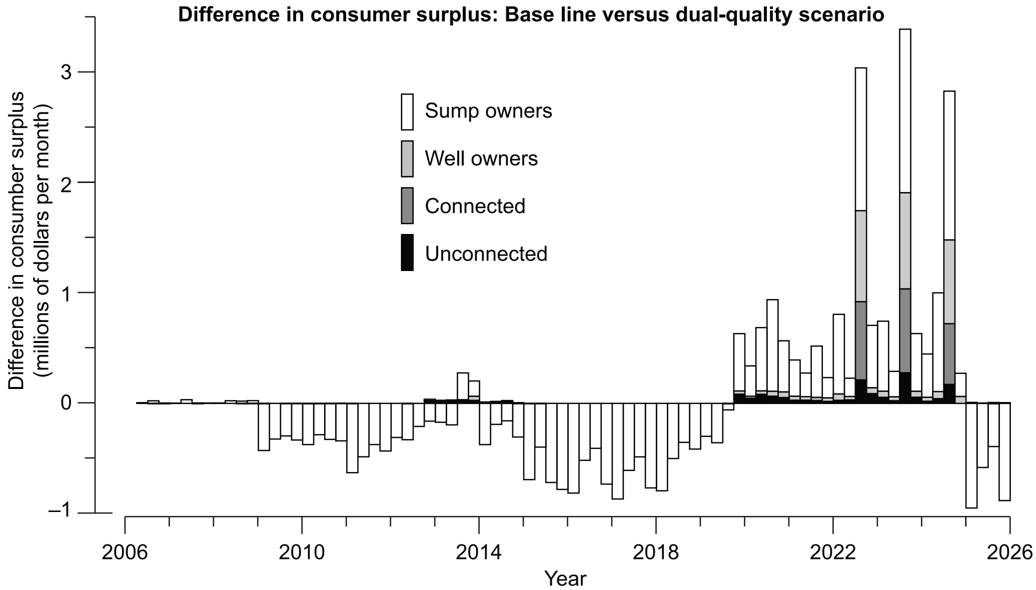

Figure 7. Consumer surplus: combination (dual-quality) scenario versus the baseline (aggregated across households).

NGOs. However, sensitivity analyses indicate that the viability of the rainwater harvesting option depends critically on the level of recharge assumed. Sensitivity analyses to effectiveness of rainwater harvesting showed that to be cost effective, rainwater harvesting policies need to at least double groundwater recharge rates from 9% to 18% of rainfall for the specified rainfall scenario. It may be noted that 18% was the calibrated recharge rate estimated for agricultural and fallow areas versus 9% in built-up urban areas. Further scientific studies are recommended to assess the improvement in recharge generated by various rainwater harvesting schemes.

[54] Finally, the policies are sensitive to the shape of the residential consumer demand function; specifically, the extent to which consumers incur losses in consumer surplus when forced to cut water use. If residential consumers incur steep losses in consumer surplus from cutting water use, the additional water made available by rainwater harvesting provides great benefits. However, if residential consumers can cut back on water use easily, with little loss in consumer surplus, efficiency improvement is more beneficial. In this case, the utility can sell the water to commercial consumers or adjacent urban areas at a higher rate while imposing relatively little pain on residential consumers, but the additional water made available by rainwater harvesting is not cost effective. This is significant because it highlights the extent to which cultural preferences shape policy outcomes. The dual-quality policy is relatively insensitive to the rainfall scenario, because it generates benefits in both wet and dry years.

7. Discussion

[55] An examination of the costs and physical factors reveals that the feasibility of combination (dual-quality) policy is not coincidental. It can be explained by a combination of physical and economic factors characteristic of the Chennai water system. (1) The cost of new supply in Chennai is very high relative to current willingness to pay. (2) There is a high level of investment in private (coping) infrastructure versus a low level of investment in public piped infrastructure (pipeline maintenance and metering). (3) Surface water storage is inadequate; but a comparable volume of subsurface storage is available. Efficient use of the urban aquifer addresses a critical system constraint, lack of reservoir storage. This benefits consumers during multiyear droughts, the period when consumers suffer the highest losses in consumer surplus.

Table 4. Net Benefits of Policies Under Different Rainfall Scenarios

Rainfall Scenario	Critical Drought[a] (mm)	Rainwater Harvesting[b] (million $)	Efficiency Improvement (U.S. dollars)	Supply Augmentation (U.S. dollars)
Original scenario[c]	1492	33	21	−177
1	926 (least severe)	5	27	−215
2	1034	21	38	−192
3	1537	31	−9	−199
4	1797	24	19	−197
5	2032 (most severe)	83	12	−147

[a]Maximum deficit duration defined as the maximum sum of rainfall deficit over consecutive years of drought [*Maidment*, 1993].
[b]Values given in 2005 dollars.
[c]Policy for which results are presented.

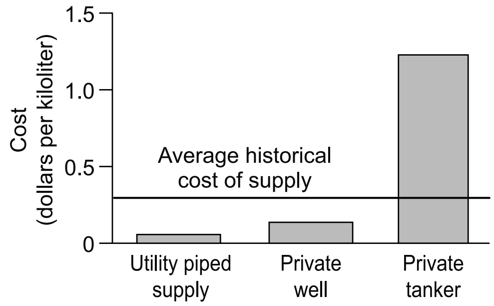

Figure 8a. Average cost of options available to the consumer.

7.1. High Projected Cost of New Water Supply Sources

[56] In Chennai, desalination ends up being the marginal source of water to the utility, by process of elimination. There are no local untapped surface water sources. Even when interstate projects have been constructed, deliveries across state boundaries have remained unreliable and Chennai lacks reservoir storage capacity to store the water when it is delivered (see *Srinivasan et al.* [2010] for details). Geologically, Chennai has a shallow alluvial aquifer, making large-scale groundwater production within the city infeasible. Although, the utility has well fields to the north, these are already overexploited and suffer from coastal seawater intrusion. Purchase of groundwater rights from farmers' in surrounding agricultural areas is being considered; but legal and social issues such as lack of private property rights to groundwater and how to compensate landless laborers dependent on periurban agriculture remain to be resolved. The utility argues that wastewater recycling efforts have stalled owing to the lack of demand for wastewater from industrial consumers and low levels of acceptability for blending treated wastewater into the city's reservoirs. Finally, while decreasing pipeline leaks improves distribution efficiency, during droughts when the reservoirs dry up, a highly efficient delivery system yields limited benefits.

[57] Analysts have suggested that in the long term Chennai must eventually import water, either by purchase from other states or by national river-linking schemes [*Briscoe and Malik*, 2006]. However, on the basis of historical precedent, it is doubtful that this can be achieved within the next decade when Chennai's rapid growth is projected to occur. In the past, proposed storage projects have been delayed over compensation and resettlement issues for years, even decades. Thus, from the utility's perspective, desalination is the default option to augment piped supply in the immediate future. Unfortunately, desalination is very expensive; the current cost of desalination at \$1.02/kL far exceeds any willingness-to-pay estimate in a developing country setting.

7.2. Private Wells Cap Willingness-to-Pay for Piped Supply

[58] The challenge is in getting consumers to bear the high cost of new water supply schemes, whether to purchase water, adequately compensate affected parties, mitigate environmental damages, build new infrastructure projects or desalination plants. However, two recent household surveys of a stratified sample of 1500 households in Chennai [*Srinivasan*, 2008; *Vaidyanathan and Saravanan*, 2004] reveal that over two-thirds of households have private wells. This widespread presence of private wells makes increasing piped supply tariffs difficult. A comparison of the cost of supply from different models of supply reveals that contrary to common wisdom, if the utility tries to recover the current costs of supply, piped supply will no longer be the cheapest source of supply. Figures 8a and 8b compare the cost of water both from various sources, both from the consumers' perspective as well as from the utility's perspective.

[59] A cost comparison of the options available to consumers (Figure 8a) suggests that extraction from private wells costs twice as much as piped supply at current subsidized rates. Not surprisingly, consumers prefer piped supply to private wells both from a cost and quality standpoint. However, if the utility's raises tariffs in an attempt to fully recover the costs of procuring and delivering water, piped supply will become more expensive than extraction from private wells; rational consumers who already own wells (and thus consider only pumping costs) would switch to private wells, at least for nonpotable uses; although if consumers do not already have wells they would not be induced to build them.

[60] The widespread presence of private wells highlights a "path-dependency" problem in urban water supply in India. Once a large fraction of consumers have already invested in private wells, they have access to a cheap backstop source; their willingness-to-pay for expensive piped system improvements is likely to be lower. This makes it difficult to fund expansions or improvements. Our model results indicate that once this occurs, it is more efficient for the utility to raise tariffs, and actively encourage consumers supplement with water extracted from private wells (Figure 8b).

7.3. Artificial Recharge Augments Water Storage in the Urban Aquifer

[61] The average cost comparisons presented in section 7.2 obscure a key issue of temporal dynamics: the biggest losses in consumer well-being occur during prolonged droughts, when consumers lose access to both piped utility supply and private wells. The combination dual-quality policy, overcomes this problem because efficiency improvement and rainwater harvesting policies yield water at different times. Efficiency improvement improves piped supply in normal and wet periods, but rainwater harvesting keeps the aquifer recharged assuring a back-up source during droughts, when the reservoirs are dry and there is insufficient water available in the piped system. Furthermore, the combination

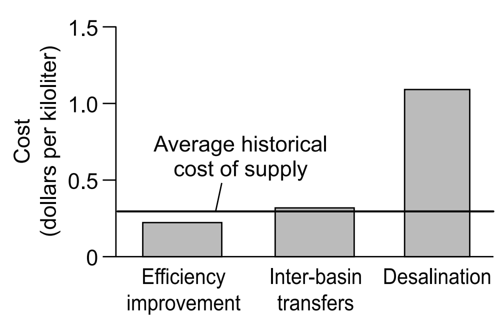

Figure 8b. Average cost of options available to the utility.

policy is better than efficiency improvement alone, because it addresses the problem of insufficient reservoir storage [*Srinivasan et al.*, 2010]. The urban aquifer makes available much-needed additional storage, by capturing runoff in wet periods and making water available via private wells in dry periods. The availability of a backup source during droughts enables consumers to avoid purchasing expensive private tanker water, minimizing losses in consumer well-being at the time when consumers are worst hit.

7.4. Discussion: Transition Path to 24/7 Supply

[62] As low tariffs and lack of metering have persisted, it is a challenge to maintain the existing infrastructure or expand, trapping Chennai in the classic "low-level equilibrium" [*Singh et al.*, 1993]. As more consumers have made private investments in coping mechanisms the willingness to pay for public investments in infrastructure has decreased. There is an urgent need to find a way to transition out of this trap. The debate on the transition to 24/7, continuous supply has largely revolved around "big push" solutions of steep tariff hikes and infrastructure improvements. However, steep tariff increases, even to the wealthiest consumers, have proved politically challenging. What is needed are small, intermediate steps that are achievable in short-term, but promote the evolution toward a "high-level equilibrium," of high-quality, sustainable piped supply with full-cost recovery, in the long term.

[63] We speculate that the dual-quality solution could be such an intermediate step. We argue that the assurance of a reliable supplementary source of lower-quality water via wells could make the much-needed tariff hike more palatable than simply raising rates with no investments in artificial recharge. Consumers can reduce their piped water use (and thus water bills) with little impact on their total water use or lifestyle. Clearly, not all consumers will choose this, some may switch entirely to private wells, others may choose a combination of piped supply and self-supply from private wells, and some may prefer high-quality piped supply for all end uses. However, by establishing groundwater as a low-cost, low-quality alternative source, it would be easier to contrast piped supply as a high-cost, high-quality option. Over time, as incomes increase, consumers may choose to turn off private wells and bear the full cost of supply for all end uses or continue using private wells for landscaping, and toilet use. Thus, the dual-quality approach could allow for a transition into efficient, sustainable, 24/7, high-quality piped supply in the future with full cost recovery; a scenario that remains a pipe dream today.

8. Conclusion

[64] As cities grow and incomes rise in the developing world, new challenges arise: supplying water reliably, fixing the aging infrastructure, and expanding to new areas. It is critical to meet these challenges while ensuring that a basic supply of water is affordable to all. Prior studies have focused on centralized piped supply to address the challenge of urban water supply. This study is unique in considering jointly centralized and decentralized supply.

[65] We proposed a framework that makes it possible to evaluate a wider range of centralized and decentralized policies than previously considered. The framework considers four dimensions of water supply relevant to consumers: modes of supply accessed by consumers, investments made by consumers in acquisition, storage, and treatment of water, quality of water, and time periods in which consumers' make decisions. The framework addresses the three main conceptual problems with the utility-centric framework described earlier. We developed a framework that makes it possible to evaluate a wider range of centralized and decentralized policies than previously considered. The framework addresses the three main conceptual problems with the utility-centric framework described earlier by:

[66] 1. Considering four dimensions of water supply relevant to consumers: modes of supply accessed by consumers, investments made by consumers in acquisition, storage, and treatment of water, quality of water, and time periods in which consumers' make decisions.

[67] 2. Distinguishing between short-run decisions (by solving the consumers' cost-minimization problem assuming a fixed set of options in a given time period) as well as long-run decisions (by accounting for consumers' coping mechanisms and thus the choice set available to them).

[68] 3. Establishing consumer surplus as a common measure of consumer well-being making, regardless of the type of consumer or modes of supply.

[69] The framework was implemented in a model of water supply and demand in Chennai, India. Three very different policies: supply augmentation, efficiency improvement, and rainwater harvesting were evaluated using the model. However, none of the three policies alone perfectly satisfied our criteria of equity, efficiency, revenue generation and financial viability in addressing Chennai's water problems. The policy simulations suggest that expanding centralized supply is not always the least cost option; instead combination of efficiency improvement and rainwater harvesting may be optimal.

[70] In the combination policy, we propose that the utility raise charges significantly to wealthier consumers who own sumps, so as to recover the average costs of supply. The utility will then invest the revenues to fix leaky pipes and enhance aquifer recharge. This combination policy has an unexpected result: because tariffs are raised significantly and the vast majority of Chennai's consumers have access to private wells, consumers begin to depend on private wells, particularly for nonpotable needs. This decreases piped supply demand considerably. The utility is able to meet demand, raise additional revenue and even expand to periurban suburbs. Aggressive recharge management in the local aquifer prevents the aquifer from drying up.

[71] An examination of the factors that contribute to the viability of the "dual-quality" policy, suggests that it be explained by a combination of physical and economic factors prevalent in Chennai. (1) Most consumers already have access to private wells. (2) New sources of water will be significantly more expensive. (3) Lack of reservoir storage is one of the main reasons for unreliable urban supply, particularly during droughts. Rainwater harvesting option provides much-needed additional storage in the form of the urban aquifer. It helps consumers tide over multiyear droughts.

[72] Our results suggest that having a reliable source of nonpotable supply will boost consumers' willingness to pay for high-quality, reliable piped supply and make demand more manageable. In the short term, cities should explicitly plan on relying on a combination of high-cost high-quality continuous piped supply and low-cost, low-quality decentralized self-supply. They should raise piped supply tariffs

and fix the piped infrastructure, but at the same time manage recharge aggressively in urban aquifers, so consumers have access to a supplementary source of water through private and community wells. Over time, as incomes and consumers' willingness to pay for high water quality increases, consumers may turn off private wells and accept the full cost of supply for all purposes; Indian cities may evolve naturally into 24/7, high-quality piped supply in the future. However, a transitional solution that employs a combination of rooftop rainwater harvesting and tariff increases can provide the necessary transition in a manner that is cost effective.

Appendix A

A1. Economic Efficiency: Welfare maximization

[73] The economic efficiency criterion tests if a particular policy results in a better allocation of societal resources by comparing benefits and costs to society accruing from a policy. If benefits exceed costs, the policy is economically efficient. Since benefits include both producer and consumer surplus, an economically efficient policy maximizes total social welfare, not just utility profits. The definitions of benefits and costs used here is fairly narrow: external costs or benefits were not included.

A1.1. Estimation of Benefits

[74] Two types of policy benefits were considered: consumer surplus and utility revenues. Because the utility is publicly owned, any revenues to the utility can be assumed to flow back to consumers in the Chennai metropolitan area. Total policy benefits are therefore the sum of the benefits to each consumers and the utility. Benefits to consumers are measured in terms of consumer surplus and benefits to the utility in terms of utility revenues.

A1.2. Consumer Surplus Gains

[75] Benefits to consumers are estimated as the total difference (versus the Baseline) in consumer surplus over the 18 year period from 2008 to 2025.

$$CS^{Policy} = \sum_{t=r1}^{NP} \sum_{j=1}^{12} \sum_{i=1}^{6} L_{i,j,t}^{Policy} * HH_{i,j,t}$$

Where CS^{Policy} is the aggregate consumer surplus for all Chennai consumers under the policy; $L_{i,j,t}^{Policy}$ is the consumer surplus for a representative consumer in a particular consumer category i, located in zone j, in time period t; $HH_{i,j,t}$ is the number of households for a representative consumer in a particular consumer category i, located in zone j, in time period t; and NP is the number of periods in the model.

[76] Consumer surplus under the baseline scenario $CS^{Baseline}$ is similarly estimated. The difference in consumer surplus, ΔCS from a particular policy is defined as

$$\Delta CS = CS^{Policy} - CS^{Baseline}$$

The model does not discount costs and benefits. This decision was made for two reasons. First, for all policies, most of the benefits accrue during droughts. So the timing of the costs and benefits are arbitrary and depend on the particular rainfall scenario. Second, the costs of the policies are often ongoing O&M costs, not upfront capital costs. Even the desalination plant in Chennai is run by a private company from which the utility buys water at a fixed volumetric rate each period. Likewise leak-detection programs have ongoing program costs.

A2. Piped Supply Shutdown

[77] This criterion tests the extent to which policies can prevent the shutdown of the piped supply system. There are three main reasons one may wish to have some piped utility supply available in all periods, regardless of whether water from alternate source is available. First, utility supply is the only source of cheap potable water. So there may be health effects of having no access to piped supply, as consumers are fully dependent on untreated, potentially contaminated groundwater. Second, the shutdown of the piped supply system and complete dependence on mobile supply imposes additional costs on the utility. Finally, it is embarrassing for both the utility and the government to face a situation of a prolonged period with no piped supply. The reliability metric used is the fraction of periods that sufficient utility supply is available over the 18 year period defined as follows

$$Shutdown(Months) = 3^{*} \sum_{t=1}^{NP} u_t$$

where
u_t = 1 if piped supply is completely shut down
u_t = 0 if piped supply is available
NP = Number of periods in the model
The factor of 3 is because the model runs in 3-month time steps

A3. Utility Revenue Maximization

[78] The revenue criterion tests if a particular policy results in improved revenues to the water utility. This was estimated as difference in piped water revenue to consumers over 18 years between the policy case and the base case.

$$\Delta \mathrm{Re}\, venue = \mathrm{Re}\, venue^{Policy} - \mathrm{Re}\, venue^{Baseline}$$

In estimating revenues accruing from various policies, only volumetric charges were assumed. No connection charges or fixed charges were included as these were assumed to remain constant between the baseline and policy cases. Moreover, only sump consumers were assumed to be metered and assessed with volumetric charges. So the revenue accrued is

$$\mathrm{Re}\, venue^{Policy} = \sum_{t=1}^{NP} \sum_{j=1}^{10} \sum_{i=1}^{6} (PipedTariff_t^{Policy}/1000) \; {}^*Piped\_Qty_{i,j,t}^{Policy} * HH * 90$$

Where
Piped_Tariff is the volumetric tariff in Rs/kL in a given year.
Piped_Qty is the quantity of piped supply consumed in liters/household/day
HH is the number of households with sumps and indoor plumbing
NP = Number of periods in the model
90 = Number of days in each period

[80] Costs of implementing the policy were estimated as follows. The capital costs for each policy were assumed to

last 25 years. Costs were prorated over the 18 year forecast horizon (January 2008 to December 2025) of the model. In the case of rainwater harvesting the costs were assumed to be one-time costs of installing rooftop and yard water collection systems in each household and commercial establishment in Chennai. In the case of efficiency improvement and supply augmentation, the costs were assumed to be ongoing O&M costs and were linked to the quantity of water generated by the various policies such as leakage savings and desalination plant costs.

A4. Financial Viability

[81] The purpose of the financial viability criterion is to determine if the water utility can fully recover costs in the absence of a continuing subsidy from the government. The metric used the comparison between the piped supply tariff to the wealthiest consumers ("sump owners") and the average historical cost of supply.

$$FV = \text{“Yes” if } P_{\text{Piped}} >= AHC$$

$$= \text{“No” if } P_{\text{Piped}} < AHC$$

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