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Factors determining informal tanker water markets in Chennai, India

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Many developing world cities have seen the emergence of informal markets where private tanker truck operators transport water extracted from peri-urban wells to urban consumers. This study adopted a systems-modelling approach to analyzing the informal tanker market in India. The results indicate that the demand for tanker supply was caused by lack of groundwater availability in private wells as well as unreliable piped supply. The study shows that two groundwater factors are relevant: depth to water and aquifer productivity. Together, these could explain the difference in spatial, temporal and consumer-specific variations in tanker dependence.

Keywords: urban; informal; tanker; water market; India

Introduction

Context and significance of informal tanker water markets for urban water supply

In the past 60 years, India's urban population has increased twice as fast as the population as a whole. This rapid urbanization, accompanied by income growth, is placing immense pressure on water utilities in Indian cities, where infrastructure lags behind. No Indian city currently has a 24/7 water supply. Even in cities where most of the population is connected to the piped water system, households typically receive water for a few hours a day and in insufficient quantities (Water and Sanitation Program [WSP] 2003). Consumers typically supplement piped supply from the utility with water from private wells and tankers. This article addresses the problem of water provision in Indian cities, a problem with huge implications for human welfare. In particular, the focus is upon the emergence of informal water markets wherein private tanker operators purchase water from peri-urban farmers and transport the water to urban consumers in tanker trucks.

Many Indian cities have seen the emergence of informal tanker markets. Londhe *et al.* (2005) describe tanker markets in six cities in India, where tankers meet about 7% of the demand–supply gap. In a different study, Shaban and Sharma (2007) presented statistics of water supply by source in seven other Indian cities; private tanker markets were prevalent in six of the seven cities. Although the total quantity of tanker water supplied appears to be a relatively small fraction of the water supplied overall, tanker markets are prominent during droughts when supply from other sources is scarce. Moreover, tanker markets are significant in terms of overall household spending on water.

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Previous studies (Crane 1994, Baisa *et al*. 2008) elsewhere in the developing world have addressed tanker markets, noting that these informal markets allocate water very inefficiently. Municipal supply uncertainty prevents water from being allocated to consumers who value it most; some households are forced to rely on expensive emergency purchases from tankers, while others allocate water to frivolous uses. The studies suggest that this results in resource misallocation and substantial welfare losses. Other scholars (Gilbert 2003, Ruet *et al*. 2007), having investigated the external impacts of rural–urban water markets on peri-urban agriculture, have argued that tanker markets have unfortunate external consequences. They claim that while landowners who sell water profit from informal water markets, non-selling farmers suffer from falling groundwater levels, and landless labourers suffer from a loss of livelihood due to the elimination of agriculture. Londhe *et al*. (2005) claim that informal tanker markets have led to a steep fall in groundwater in peri-urban areas affecting livelihoods and causing conflicts between farmers and water sellers.

Previous explanations for reliance on tanker water

Empirical studies on informal tanker markets in the developing world are relatively sparse. However, the few existing studies explain reliance on tanker water by concentrating exclusively on inadequacies in piped water supply. They emphasize that tanker markets fill a gap between demand for water and piped supply. Two types of explanations for the emergence of tanker markets in urban areas have been offered: (1) inadequate piped infrastructure (Whittington *et al*. 1991); and (2) lack of reliable piped supply (Baisa *et al*. 2008). Thus:

(1) Tanker markets emerge when piped supply is insufficiently developed. In an early study Whittington *et al*. (1991) quantified the tanker market in Onitsha, Nigeria. The town did not have adequate piped infrastructure and 95% of the consumers depended on private tanker providers. The study showed that consumers were already paying private providers more for an inferior service than what it would cost to operate a well-run piped distribution system.
(2) Tanker markets emerge when piped supply is unevenly provided because of poor management or inadequate infrastructure. Baisa *et al*. (2008) estimated the welfare losses from unreliable piped supply in Mexico. They considered consumers' coping responses to unreliable piped supply including in-house storage and emergency water purchases from tankers. The study concluded that welfare gains could be achieved by normalizing the delivery schedules of piped water supply, specifically by making the quantity and frequency of piped water delivery uniform across households more predictable.

Main argument: tanker demand is driven by groundwater availability

In this article it is suggested that neither explanation above adequately captured the situation in the case study site, Chennai, India. Indeed, tanker markets emerged even though 95% of households had access to some form of piped supply from the public water utility. Although piped supply unreliability clearly contributes to dependence on private sources, tanker markets exhibited patterns that could not be explained by piped supply provision or non-provision alone. In this article, it is suggested that prior studies ignore the contribution of private wells and variability in water resource availability. This analysis indicates that because over 70% of households have private wells, these represent a critical supplementary source of water in Chennai. Importantly, this study reveals that tanker markets are driven primarily by limitations in groundwater availability.

Arriving at a valid explanation for tanker market reliance has important social consequences. Tanker water is expensive, costing anywhere between three to fifty times more than water from alternative sources such as municipal piped supply and private wells (Whittington *et al*. 1991, Londhe *et al*. 2005, Baisa *et al*. 2010), so tanker markets involve significant welfare losses. Importantly, if the explanation offered in this article is correct, it suggests that one way to reduce reliance on tanker water is to improve private well supply. In a related policy paper the authors argue that improving self-supply from private wells by better management of recharge in the aquifer may be a particularly low-cost way of avoiding reliance on tankers and improving welfare (Srinivasan *et al*. under review). Indeed, towards this end many Indian cities are promoting decentralized management policies to improve aquifer recharge. These include rooftop rainwater harvesting by individual households, rehabilitation of urban lakes and temple tanks, and improved storm water management.

To pursue these objectives, the paper is divided into four sections: (1) a description of the systems-modelling approach used to estimate supply and demand for tanker water; (2) a description of the characteristics of tanker markets; (3) a discussion of the caused factors determining tanker markets; and (4) the conclusion.

The systems model

To test the hypothesis, a unique systems-modelling approach is applied to the case study area, Chennai, India. The model considers in a dynamic manner the connections between private wells (i.e. self-supply) and piped supply in determining the need for tanker water. The model results support the hypothesis by revealing a very close relationship between reduced groundwater availability and demands for water from the tanker market. The model reveals the spatial and temporal variability of groundwater availability and tanker markets. Finally, the model reveals very significant differences across consumer categories, particularly across residential and commercial consumers.

Chennai was found to be a suitable case study for two reasons: (1) Chennai's water availability at 40–100 litres per capita per day (LPCD) is the lowest of all mega-cities in India; the majority of consumers rely on private wells and occasionally private water tankers to cope with the unreliability of piped water supply. Although Chennai's water problem is particularly severe, these patterns are common to all rapidly growing mega-cities in India and elsewhere in the developing world; thus (2) 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 the study timeframe, and the availability of both socio-economic survey data and physical data for both hydrological states, made it possible to study the emergence and subsequent disappearance of the tanker market. In the following sections, a brief introduction to Chennai, the case study area, and the systems approach is presented.

Case study area

Chennai, formerly Madras, with a population of 4.5 million (7 million including peri-urban areas) is located in the semi-arid state of Tamil Nadu, in southern India. The average annual rainfall of 1275 mm occurs over two seasons: the southwest monsoon (June–September) and northeast monsoon (October–November). A public water utility, Metrowater, supplies the municipal area via a piped network, using water from rain-fed reservoirs, well-fields outside the city, two inter-basin projects and some minor local sources. The water utility serves the municipal area via a piped network, where over 95% of the households within Chennai city have some sort of access to public supply: private piped connections, yard hand-pumps or taps, public standpipes, and utility-run "mobile supply" tankers. However, piped water supply is highly intermittent and available for only a few hours each day. Over two-thirds of the households supplement their water needs via private wells, which number over 420,000 within the city (Vaidyanathan and Saravanan 2004). This study was conducted over the period from January 2002 to March 2006 during which, as noted above, the city experienced one of the worst multi-year droughts followed by the heaviest rains in recorded history. In 2003–2004, the reservoirs serving Chennai went completely dry, and the piped supply system was shut down for almost a year. In response to the cessation of supply, informal private tanker markets emerged in which water was purchased from peri-urban farmers for urban supply, providing an opportunity to study the dynamics of tanker markets. This paper deals exclusively with the private or informal tanker market. However, during the drought in 2003–2004, the water utility also purchased water from farmers for city supply. A description of the "formal" market, purchases by the water utility, has been covered by other scholars and is not addressed in this paper (Moench *et al*. 2003, Ruet *et al*. 2007).

Brief description of the systems-modelling approach

This study adopted a systems-modelling approach to analyzing the tanker market in Chennai, India. Conventional "reductionist" approaches seek to test hypotheses by establishing statistically significant relationships between relevant variables: water market size, well ownership, groundwater levels, and so on. In contrast, here the system as a whole, rather than relationships between specific components, is examined. By explicitly including dynamic feedbacks between components, systems models provide explanations regarding "patterns of change rather than relationships between static snapshots" (Simonovic and Fahmy 1999).

Systems model

In developing the systems model, a "modular" approach is adopted wherein different components of an interconnected system are developed and calibrated independently, and then linked using appropriate feedbacks (Srinivasan *et al*. 2010). Both the model sub-components and the outputs of the whole model are calibrated and validated against observed data. The modular systems-modelling approach allowed consideration of explicit inclusion of dynamic feedbacks between the groundwater system, consumers and tanker operators; that is, extractions by consumers and tanker operators reduce groundwater availability, while lack of groundwater availability induces consumers to look for other sources of water. The modular model consisted of five interlinked modules (Figure 1). Simulation results were produced for three-month time periods and 10 census zones, then analyzed on a system-wide basis.

Different components of the water system were simulated using a multi-scale, dynamic, spatially explicit model of the Chennai Basin. Each system component or module was modelled using established physical and economic principles, e.g.: the groundwater equation to simulate the aquifer, cost-minimizing behaviour for consumers, and profit-maximizing behaviour for producers. Each of the five modules is described briefly below. A detailed description of the systems model, module equations, parameters, and calibration process can be found elsewhere (Srinivasan *et al.* 2010).

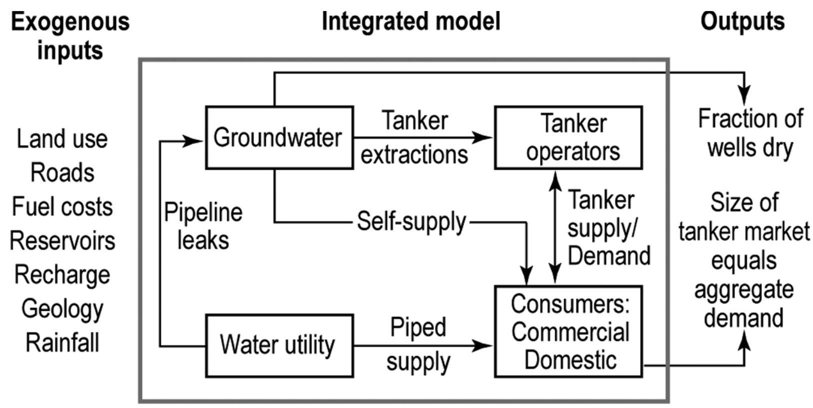

Figure 1. Conceptual model of the tanker market.

Groundwater module

The purpose of the groundwater module was to simulate the quantity of groundwater available to consumers via private wells. A 3-D groundwater flow model was used to simulate water levels in the Chennai aquifer. The model used the US Geological Survey (USGS) software, MODFLOW-2000, which solves the 3-D transient groundwater equation (1), for heads and thus depth to water (USGS 2000). Recharge and extraction behaviour were based on land use outside the municipal area. Within municipal boundaries, the quantity of groundwater extracted was input from the consumer module. Simulated heads were matched with head data published by local agencies. The outputs of the groundwater module also fed back into the consumer module. If the water table dropped below the bottom of consumers' wells the wells dry up, so the consumer can no longer use the well.

Reservoir module

The purpose of the reservoir module was to determine the quantity of water available for city supply, based on local rainfall, runoff, and inter-state imports.

Water utility module

The water utility module estimated the quantity of water supplied to consumers by the water utility in each period and neighbourhood. The water utility supplies the Chennai municipal area via a piped network, obtaining water from rain-fed reservoirs, two inter-basin projects, and well-fields outside the city. Unconnected consumers in slum neighbourhoods are supplied a lifeline quantity of treated water free, via tankers ("mobile supply"). The water utility module allocated the total quantity of water available to the utility among consumers depending on the type of connection they had access to. Consumers received water either from household taps, yard taps, public standpipes or mobile supply.

Consumer module

The consumer module simulated water consumption based on prices and quantities of supply available from different water sources using the discrete-choice model of consumer behaviour. The consumer module solves the consumers' cost-minimization problem assuming the consumer can access water at different qualities and prices from multiple sources under supply-constrained conditions i.e., the quantity available from each source is restricted. An important feature of the consumer module was that it explicitly accounted for coping investments made by consumers; i.e., the fact that consumers influence the quantity, quality and cost of water available to them. To account for differential investments, households were classified into four categories, based on different levels of coping investments and the cost-minimization problem was solved for each consumer type.

Tanker module

The tanker module estimated the demand for tanker water temporally, spatially and by consumer category. It also predicted tanker prices in each period in each part of the city. It involved several simplifying assumptions which were based on the following field observations: observations of tanker movements along major roads, phone surveys of 61 tanker operators and ten in-person interviews. Moreover:

(1) Tanker operators were assumed to be profit-maximizing and subject to perfect competition. Because the tanker market was assumed to be perfectly competitive, the price of tanker water was set equal to the marginal cost of supply (including a profit or market return on investment). The marginal cost of supply and thus the price of tanker water were found to be a function of fuel, labour, capital, raw water costs and distance to the most proximate peri-urban source villages.
(2) Tanker supply at a given price was functionally unlimited in a given period, i.e., tanker operators will always be able to purchase water from farmers as long as the groundwater is available in the shallow peri-urban agricultural wells because selling water to tanker operators is far more profitable than farming (Ruet *et al*. 2007).
(3) Tanker supply was dependent on groundwater availability in peri-urban areas. To simplify the model, consumers and tanker operators were assumed to base their extractions on the water table at the start of the period. Their collective extractions were input into the groundwater model to determine water table at the end of the period. If no groundwater were available in the areas immediately outside the city, tanker operators would go further, increasing the price to consumers.
(4) Tanker water would only be sourced from peri-urban farms (not suburbs) located with a kilometre of a major road.

A simulation of historical system behaviour (January 2002–April 2006) was used to calibrate model parameters, and develop insights into the dynamics of the urban water system. The model was formulated and calibrated based on extensive primary and secondary data including large-scale household surveys, lithologic data, water level data, reservoir data, satellite images, government statistics, census data and others.

Model results

The simulation model indicates that changes in the demand for tanker water were driven by changes in groundwater availability in private wells in addition to changes in piped supply. The model results show that demand for tanker water varied temporally as well as across consumer categories. Specifically: (1) the total size of the tanker market varied significantly between wet and dry years; and (2) tanker demand varied considerably between residential and commercial consumers. Residential tanker demand was found to emerge mainly during

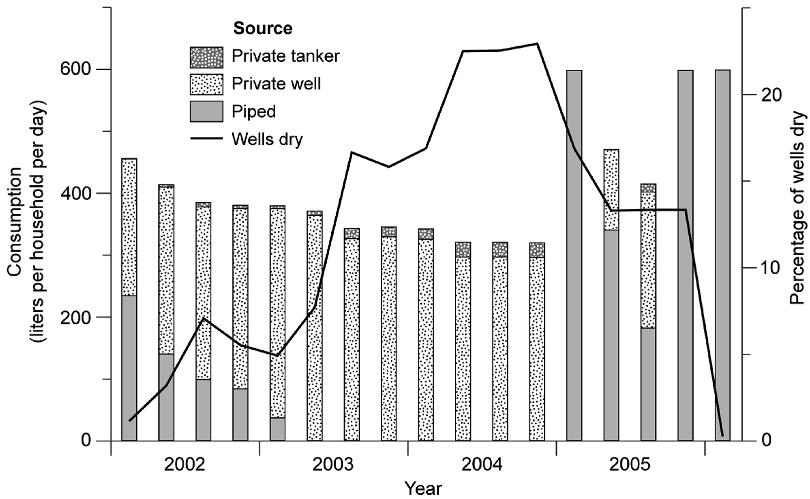

Figure 2. Simulated water consumption by source of supply in litres per household per day. Consumption is shown for a specific category of consumers: residential consumers having private wells and sump storage.

drought periods and was virtually non-existent in wet periods. In contrast, commercial demand for tanker water, though higher during droughts, persisted even in the wettest periods.

Figure 2 shows the simulated consumption of tanker water, by consumer category, plotted over time. From Figure 2, it is apparent that the simulated tanker market size correlated inversely with groundwater levels in Chennai. The residential tanker market was variable; it peaked during the drought period in 2003–2004, and virtually disappeared after the heavy rains in 2005. In contrast, commercial demand for tanker water doubled during the drought, but did not disappear completely after the rains. Commercial demand for private tanker water persisted even during wet periods.

The model outputs correlate well with field evidence. To obtain an independent estimate of the size of the tanker market, two field assistants, “tanker counters”, were stationed along each major road entering Chennai for a period of one to two days. The tanker counters were instructed to note the number of trucks entering in each one-hour interval and also phone numbers painted on the trucks used for a follow-up phone survey. The total size of the tanker market predicted by the model for the period October–December 2005 was 17 million litres per day (MLD), which compares well with the 18 MLD estimated by tanker counters’ observations. The simulated tanker market size of 50 million litres per day (MLD) during March–September 2004 also matches well with the 55 MLD reported by Londhe *et al.* (2005) during that period.

In addition to being able to replicate observed behaviour, the model provided insights into the processes that generate this behaviour. Examination of the model parameters reveals that the processes that drove residential and consumer demand for tanker water were fundamentally different. Residential tanker demand was typically driven by loss of access to piped supply and private wells. In contrast, commercial tanker demand was determined by both loss of access as well as insufficiency in the quantity supplied.

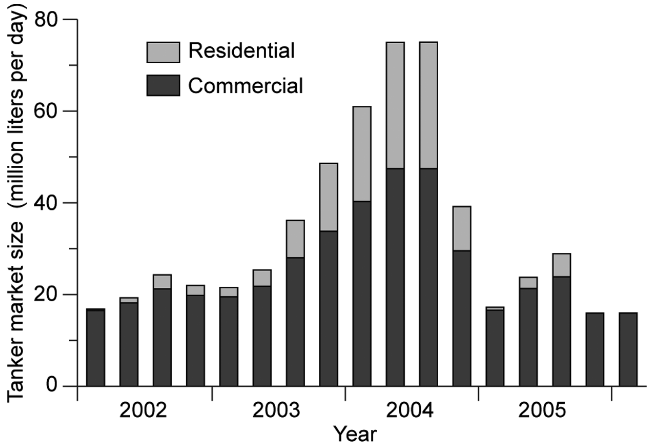

Figure 3. Residential and commercial tanker market size in Chennai in million litres per day.

Tanker demand was closely related to groundwater levels for residential consumers

The model results indicate that the changes in residential demand for tanker water were driven by fluctuations in the regional groundwater table. Specifically, residential consumers purchased tanker water when their (relatively shallow) private wells dried up. For illustrative purposes, Figure 3 shows the results of the consumer cost-minimization problem for one specific consumer category: consumers with full-service piped supply connections owning in-house storage tanks, and private wells. As per the household surveys, these represented about a third of all consumers (Srinivasan 2008).

From Figure 3, it is apparent that consumption during the historical period can be divided into three distinct phases:

(1) January 2002–March 2003: water supply in Chennai was available but at restricted levels. During this period, private wells served as a supplementary source of water supply; the tanker reliance was restricted to a few underserved areas.
(2) October 2003–December 2004: piped supply was completely shut off and groundwater levels also dropped. As consumers lost access to both utility supply and self-supply via their own wells, they began to purchase water from private tankers.
(3) October 2005–April 2006: following the heavy rains in October–December 2005, groundwater levels recovered completely and piped supply was restored. Tanker dependence among residential consumers virtually disappeared.

These consumption patterns arising from the cost-minimization behaviour of consumers can be explained by examining the relative costs of water from various sources experienced by residential consumers. For residential consumers, the cheapest source of water was piped supply from the utility (~$0.05–$0.10/kL) followed by private wells (~$0.15/kL). Private tanker purchases at $1.25/kL were an order of magnitude more expensive than piped supply or private wells. Thus private wells represented the primary supplementary or backup source. During the period January 2002–March 2003, when piped supply was available but in insufficient quantities but groundwater levels were high, consumers were able to supplement water from private wells. As piped supply was cut back from October

2003–October 2004, groundwater levels fell for two independent reasons. Firstly, extractions increased as consumers extracted more groundwater from private wells as piped supply was curtailed. Secondly, and more significantly, recharge from leaking pipelines ceased. Distribution pipeline leaks contributed more than half of the groundwater recharge of the aquifer (Srinivasan 2008), so as piped supply was halted, recharge to the aquifer dropped by half. As groundwater levels dropped, residential wells went dry. The model predicted that the five to 10 metre drop in the water table resulted in 23% of the residential wells going dry in 2004, at the peak of the drought. As consumers were forced to purchase expensive tanker water, they suffered a monthly aggregate loss in consumer surplus of almost $9 million in drought periods relative to wet periods.

Although tanker purchases contributed only 6% of the water consumed by residential consumers at the peak of the drought, the drought caused a significant the loss in consumer wellbeing. The steep losses in consumer surplus were a result of three separate factors:

(1) The cost of supply from alternative sources (wells, hand-pumps, mobile supply) was higher.
(2) Lower-income consumers simply cut back on consumption, if they could not afford tanker water. Wealthier consumers did buy tanker water but used a lot less. Average water consumption at the peak of the drought was 33% less than in subsequent normal years (Srinivasan 2008).
(3) The cost of treatment increased as consumers lost access to potable piped supply; well water and tanker supply are considered non-potable.

Following the heavy rains in October–December 2005, groundwater levels recovered, the reservoir system was replenished and piped supply was restored. As residential consumers regained access to the cheaper sources of water, they no longer needed tanker water; the residential tanker market disappeared.

In summary, as far as residential consumers are concerned, the aquifer behaved like a "bathtub" (Alley *et al*. 1999), draining out during periods of scarcity and getting replenished in wet periods. Residential consumers became increasingly tanker-reliant as they lost access to their two lowest-cost sources: piped supply and private wells. Residential tanker demand was driven by the loss of water availability from relatively shallow private wells caused by fluctuations in the water table.

Commercial tanker demand is determined by aquifer capacity

The model results show that the dynamics of commercial tanker demand differ considerably from that of residential consumers. While smaller commercial consumers behave just like residential consumers, water-intensive commercial consumers became tanker dependent because they were unable to extract enough water to meet their needs. Consumers requiring large quantities of water each day were limited by the capacity of the aquifer, and the quantity of piped supply delivered by the piped distribution system.

The patterns for commercial consumers can be explained by the relative costs of water from various sources as follows: for commercial consumers, the cheapest source of water is self-supply from private wells. This is because Chennai, like many developing world cities, has followed a policy of cross-subsidizing water. While residential water is unmetered and thus practically free, commercial consumers face metered block rate pricing starting at $0.80/kL (Metrowater 2008). As a result, piped supply is much more expensive than pumping groundwater from private wells ($0.15/kL). So commercial consumers often prefer to use their private wells to meet their non-potable needs (restroom, cooling, landscaping) in *all* periods, even when utility piped supply is plentiful, relying on utility piped supply only for their high-quality water needs.

However, the model suggests that commercial consumers requiring large quantities of water are limited by the physical properties of the aquifer. In pumping large volumes of water each day, their wells functionally dry up. This is because the urban aquifer, less than five meters thick in some locations, has a low transmissivity (the volume of water flowing through a unit cross-sectional area of an aquifer under a unit hydraulic gradient) and is simply not productive enough (Srinivasan 2008). Moreover, many wells are inefficient and poorly constructed. As a result, wells do not yield enough water to meet the daily needs of water-intensive commercial establishments. The groundwater simulation model predicted the maximum quantity of water extractable per day at a representative establishment within the city, using the analytic Theim equation (Trescott *et al*. 1976). The maximum quantity of water extractable per day was defined as that quantity that would induce a drawdown of no more 80% of the standing water column in the well assuming a 5% well efficiency, based on expert assessments. The Theim equation corrects for the impact of extractions and regional groundwater levels on individual wells. The model results predicted that the maximum quantities extractable per day ranged between 20 and 90 kilolitres per day. Although the estimated quantity extractable per day is rather sensitive to assumptions regarding the well efficiency, regardless of the parameter value assumed, the *order of magnitude* of the quantity of water extractable offers a critical insight.

Because the quantity extractable at a single well is on the order of tens of kilolitres per day, single-family homes or small residential buildings extracting about 0.5 kL/household/day are not impacted by the low transmissivity of the aquifer. However, large commercial complexes, hospitals and luxury hotels, using hundreds of kilolitres each day, are limited by the quantity they can extract from the Chennai aquifer. Thus, commercial establishments are often unable to extract as much water as they need from the aquifer.

Water-intensive commercial establishments limited by the quantity of groundwater they can extract might be expected to depend more on piped utility supply. Unfortunately, the physics of intermittent distribution systems further limits commercial establishments in the quantity of piped supply they receive. In Chennai (like most Indian cities), piped water supply is "intermittent", typically available for only a few hours each day. It has been established that intermittency is not related to the lack of sufficient water resources but rather to poor management, pipeline leakage, and excessive demand spurred by low tariffs and lack of metering (McIntosh 2003, WSP 2003). Consumers cope with intermittency by constructing underground sumps to store water for use through the day and thus convert an intermittent mains supply into a continuous 24/7 supply in household taps. Unfortunately, underground sumps provide limited benefits for water-intensive consumers who consume tens of kilolitres of water each day. They do not receive sufficient volume of water during the two hours when water is available in the piped mains.

This point can be illustrated with the following hypothetical: consider a distribution system where a "representative" medium-sized hotel using about 8000 litres of potable water daily located next to a "representative" single family home with four residents, each consuming 125 litres per capita per day. The hotel's demand is equivalent to about 20 households. In each case, the piped mains deliver water into an underground storage tank on the property. Based on the utility's prescribed piped mains connection sizes, such a hotel would be allowed to have a connection to the piped supply that can deliver five times the flow of a typical residential connection at a given pressure. In intermittent supply systems, the rate at which water is delivered to the sumps depends on the pressure head at that point in the piped system (Totsuka 2004); so if the hotel and home are located next to each other, each would experience the same water pressure and hence flow-rate from the distribution network. Because the hotel has a connection that can deliver five times the flow-rate, it will receive five times the quantity of water compared to the house next door, in the two-hour period when water is available. However, the hotel's demand is in fact twenty times that of the family. As a result, in supply-constrained situations very large users are unlikely to receive the quantity of water they need from an intermittent supply system. Finally, the model results further indicate that even if sufficient piped supply were to become available, commercial establishments have no incentive to buy water from the utility under the current tariff structure. At higher consumption blocks, the volumetric tariff is $1.35/kL. This exceeds the cost of purchasing water from private tankers, so commercial consumers may prefer to buy water from private tankers at higher consumption blocks. Thus, large commercial consumers are restricted both in terms of the piped supply and private well supply, and remain dependent on private tanker water in all periods.

These model predictions were supported by the survey of 217 commercial consumers in 2006 (Srinivasan 2008). Although the survey was not random and over-sampled larger commercial establishments, the results are illustrative. Thirteen per cent of the commercial establishments surveyed reported being dependent on private tankers in all periods despite having one or more private wells, piped supply and sufficient on-site tank storage. These findings were also verified by interviews with a facility manager at one luxury hotel and interviews with tanker operators supplying two large hospitals. In each case, it was reported that commercial establishments were buying tanker water even in the wettest periods when supply was plentiful.

In summary, for commercial consumers extracting large quantities of water each day, the aquifer resembles an "egg carton" (Alley *et al*. 1999): the wells dry up locally even if the regional water table is close to the ground surface. Tanker dependence in commercial consumers is driven by the four causal factors: (1) high commercial tariffs render private wells preferable to piped supply; (2) the poor transmissivity of the aquifer limits the quantity extractable at a single well; (3) piped supply is the secondary source of supply, but intermittency limits the quantity of piped supply available; and (4) even if piped supply were to be made available in sufficient quantities, the current tariff for higher consumption blocks exceeds the cost of purchasing water from private tankers. As a result, many commercial establishments remain tanker-dependent in all periods. In fact, tanker movement is observable in major Indian cities even in the wettest periods and even in establishments with piped mains.

Policy Implications

In previous sections, it was suggested that dependence on expensive private tanker water purchases contributed to steep losses in consumer wellbeing among urban consumers during drought periods. Moreover, tanker dependence occurred because consumers lost access to the two cheapest sources of water: piped supply and private wells. Given the joint contributions of self-supply from private wells and piped supply, it is crucial to consider both of these determinants in formulating policies to address the problems posed by reliance on the tanker market. In this section, we evaluate the relative cost-effectiveness of efforts to improve private well supply versus piped supply. In Table 1 below, the short-term and long-term costs of making additional water available from a variety of sources are presented. The costs are classified in terms of options available to consumers versus

Table 1. Estimated cost of supply.

	Cost in USD 1USD = Rs 44*	Cost in Rupees/kilolitre
Options available to consumers		
Short-term piped supply cost – residential flat rate (Pumping costs to overhead storage tanks)	\$0.06/kL	Rs 2.50/kL[1]
Short-term marginal cost of private well supply for consumers who have private wells (Extraction costs from existing wells)	\$0.13/kL	Rs 5–7/kL[2]
Short-term marginal cost – commercial piped supply (Current metered tariff for water-intensive consumers)	\$0.80 –1.35/kL	Rs 35–60/kL[3]
Short-term marginal cost of private supply (Cost of trucking water from peri-urban farms)	\$1.22/kL	Rs 54/kL[4]
Long-Run marginal cost of private well supply (Extraction + artificial recharge)	\$0.31/kL	Rs 14/kL[5]
Options available to the utility		
Short-term cost of piped supply (Average historical cost / O&M costs incurred by utility)	\$0.30/kL	Rs 13/kL[6]
Long-term marginal cost of supply: piped supply efficiency (Cost of reducing pipeline leaks)	\$0.22/kL	Rs 10/kL[7]
Long-term marginal cost of piped supply (Cost of desalination)	\$1.09/kL	Rs 48/kL[8]

*Average for 2005. O&M, operation and maintenance.
[1] Cost of pumping to overhead tank – since tariff is a single flat monthly rate, no charge to the utility was applied (Srinivasan 2008).
[2] Includes O&M costs for private wells assuming average pump/well efficiency, depth to water.
[3] Metrowater tariff schedule (Metrowater 2008).
[4] Average surveyed tanker price across Chennai based on telephone survey of 61 tanker companies in 2005.
[5] Median cost of recharge across four studies (Kumar 2004).
[6] McKenzie and Ray (2009).
[7] Estimated costs and benefits of pipeline leakage based on expert opinion (Srinivasan 2008).
[8] (*The Hindu* 2005).

supply options available to the utility both in the short run, (given existing investments and policies) and in the long run (accounting for new investments).

From Table 1, it is clear that in the short term, piped supply is the lowest-cost cost option for residential consumers – but only because the current “flat-rate” unmetered tariff structure entails a massive subsidy to residential consumers. In fact, the current tariff structure covers only a fraction of the operation and maintenance costs of the utility’s piped supply system. However, a strategy that perpetuates massive subsidies to consumers is clearly unsustainable. The problem is that if the water utility were to rectify this problem, raising tariffs to recover the average costs of piped supply (\$0.30/kl), from Table 1 it is clear that piped supply would become more expensive than extracting water via private wells (\$0.13/kL). Consequently, the majority of consumers who own private wells would switch to private wells for end-uses that do not necessitate high quality of water. So any policy promoting full-cost recovery for water utilities must promote improved aquifer management. Many Indian cities are already promoting policies aimed at enhancing aquifer recharge via rooftop rainwater harvesting by individual households, commercial establishments and institutions (Government of Tamil Nadu 2003, Government of Kerala 2004). The cost data presented in Table 1 suggest that a policy that promotes higher tariffs, in conjunction with aggressive aquifer management is a cost-effective and rational strategy. A more comprehensive case for this "dual-quality strategy" can be found elsewhere (Srinivasan 2008, Srinivasan *et al*. under review).

The concerns of commercial establishments are less easily addressed. Earlier it was shown that large commercial establishments become tanker-dependent because they receive insufficient quantity from both private wells or the piped supply system. However, the model results indicate that this is not due to a lack of aggregate water availability, but because of high tariffs, low aquifer transmissivity, and intermittency of the piped distribution system. Unfortunately, these are physical properties of the system that do not have a simple policy fix in the short term. However, in the medium to long term the authors suggest that commercial establishments can greatly reduce their own dependence on tankers by improving process efficiency. Thus:

(1) Using professional well-construction firms could improve well efficiency and boost the quantity of groundwater extractable. The model showed that well efficiency was critical in determining the quantity of groundwater available to private establishments and thus tanker dependence.
(2) Improving water-use efficiency (recycling, low-flow nozzles and so on) would reduce overall water use and thus reduce the quantity purchased.
(3) In the long term, commercial consumers will benefit from a transition to 24/7 continuous supply. The model established that commercial consumers were simply not getting enough water in the few hours that water is supplied via the piped mains to meet their needs. A few Indian cities are now in the process of implementing pilot 24/7 zones (WSP 2003, Sangameswaran *et al*. 2008). Although the impacts of a transition to 24/7 supply have not been studied and merit careful consideration, the model results provide a preliminary indication that commercial establishments will benefit from such a transition.
(4) Commercial consumers would benefit from a rationalization of tariffs. Currently, commercial tariffs are set so high that at higher block rates, commercial consumers are better off buying water from private tankers. At these tariffs even if 24/7 piped supply is guaranteed, commercial consumers have no incentive to buy water from the utility. Not only does the utility lose revenue, the negative external consequences on peri-urban farmers and environmental and congestion problems of trucking large amounts of water into the city persist. The water utility should consider a bulk commercial pricing strategy that does not exceed the cost of supply by private tankers.

In the previous sections, the options available to consumers, focusing on self-supply via private wells, were considered. But improving supply via private wells alone is clearly inadequate; consumers need treated high-quality water for drinking and cooking. The goal of any developing world city is surely to achieve high standards of service, quality, and reliability for drinking water supply. However, expanding piped supply infrastructure and developing new water sources remains a challenging proposition. Cities like Chennai, located in semi-arid environments, have few undeveloped sources of surface water to tap. Desalination is not cost-effective as can be seen from

Table 1. Instead, the cost data suggest that improving efficiency by eliminating pipeline leaks is the most cost-effective way for the utility to improve piped supply in the medium term. A more comprehensive assessment of the costs and benefits, over space and time, and trade-offs of various policy options can be found elsewhere (Srinivasan *et al*. under review).

Conclusion

In this paper, a causal relationship between groundwater availability in private wells and the informal tanker market in Chennai, India, was established. The study used a systems model to show that in addition to the unreliability of piped supply, the informal water market is influenced by two separate causal factors: the depth of water table and the transmissivity of the aquifer. The systems-modelling approach allowed consideration of dynamic feedbacks between the groundwater system, utility supply, consumers, and tanker operators. Each system component was modelled independently using established mechanistic relationships such as the groundwater flow equation to simulate aquifer behaviour, cost-minimizing behaviour of consumers, and profit-maximizing behaviour of producers. The individual modules were linked using appropriate feedbacks. Data for the historical period 2002–2006 were used to calibrate the model.

The simulation model reveals that tanker water demand in Chennai was a residual demand: it accounted for the difference between overall demand and the combination of piped-supply and private well supply. Demand for tanker water varied temporally. Moreover, residential and commercial demand for tanker water exhibited very different characteristics. Residential tanker demand was found to emerge mainly during drought periods and was virtually non-existent in wet periods. In contrast, commercial demand for tanker water, though higher during droughts, persisted even in the wettest periods. These model outputs matched well with estimates of the tanker market size obtained by field observations and interviews.

In addition to being able to replicate observations of the tanker market, the model provided causal explanations regarding the processes that generate this behaviour. Examination of the model parameters reveals that the processes that drove residential and consumer demand for tanker water were fundamentally different. In the case of residential consumers, tanker demand was shown to be related to the loss of water availability from relatively shallow private wells, caused by the decline in the water table and cutbacks in piped supply. However, for water-intensive commercial consumers, tanker demand was driven by the low transmissivity of the aquifer, which limits the maximum quantity extractable from a private well. Moreover, because commercial consumers are charged very high rates for piped supply at higher blocks, purchasing water from private tankers was cheaper than piped supply at higher consumption blocks.

Although the research presented in this paper is empirical, focusing on a single case study, Chennai, the results are applicable in many other Indian cities. In particular, these results are relevant to smaller metropolitan areas that share similar characteristics: an underlying alluvial aquifer, high penetration of private well ownership, and unreliable piped supply. High well ownership rates have been documented in other large Indian cities, which also have alluvial or partially alluvial aquifers, Madurai (81%) and Kanpur (79%) (Shaban and Sharma 2007), and Vijayawada (49%) (Zerah 2002) making recharge and partial decentralized supply via private wells a feasible option.

The current trend of rapid urbanization, accompanied by income growth is likely to continue in the twenty-first century. This will place immense pressure on already-strained water utilities in India. However, if income and population growth continue to outstrip infrastructure, urban wells will become increasingly common if the geology is favourable, as is already being seen throughout India. Once private wells are constructed, they offer a relatively low-cost supplementary source of supply. Consumers will only depend on informal water markets if both piped public supply and self-supply through private wells fail. This research suggests that integrated management of urban water resources in Indian cities must explicitly take account of urban groundwater.

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References

Alley, W., Reilly T., and Franke, O., 1999. *Sustainability of ground-water resources*. Circular 1186. Denver, CO: US Department of the Interior, US Geological Survey. US Department of the Interior, US Geological Survey.

Baisa, B., *et al*., 2010. The welfare costs of unreliable water service. *Journal of Development Economics*, 92 (1), 1–12.

Crane, R., 1994. Water markets, market reform and the urban poor: results from Jakarta, Indonesia. *World Development*, 22 (1), 71–83.

Gilbert R., 2003. *Water, water, nowhere: a case study of Palayaseevaram village regarding sharing of water with the Chennai city and its impact on the village*. WHIRL Project Working Paper 9. IRC International Water and Sanitation Centre, The Netherlands. Available from: www.nri.org/projects/WSS-IWRM/reports.htm [Accessed 9 March 2010].

Government of Kerala, 2004. Extraordinary Gazette No. 92/2004, dated 2-01-2004: amendment of Kerala Municipality Building Rules. GO.(MS) NO. 19/2004/LSGD. Thiruvananthapuram: Local Self Government Department.

Government of Tamil Nadu, 2003. Amendment to the Chennai City Municipal Corporation Act, 1919. *Tamil Nadu Government Gazette,* Chennai. Available from http://www.chennaimetrowater.tn.nic.in/rwh/tngo.htm [Accessed 9 March 2010].

Kumar, M.D., 2004. Roof water harvesting for domestic water security: who gains and who loses? *Water International*, 29 (1), 43–53.

Londhe, A.J., *et al*., 2005. Urban-hinterland water transactions: a scoping study of six class I Indian cities. *IWMI Tata water policy program working paper*. Anand, India: International Water Management Institute.

McIntosh, A.C., 2003. *Asian water supplies: reaching the urban poor*. London: IWA Publishing.

McKenzie, D. and Ray, I., 2009. Urban water supply in India: status, reform options and possible lessons. *Water Policy*, 11 (4), 442–460.

Metrowater, 2008. Metered Consumers - Tariff. Available from: http://www.chennaimetrowater.tn.nic.in/finance/financemain.htm. [Accessed June 2008].

Moench, M., *et al*., 2003. *The fluid mosaic: water governance in the context of variability, uncertainity and change*. Katmandu: Institute for Social and Economic Change, Colorado and Nepal Water Conservation Foundation.

Ruet, J., Gambiez, M., and Lacour, E., 2007. Private appropriation of resource: impact of peri-urban farmers selling water to Chennai Metropolitan Water Board. *Cities*, 24 (2), 110–121.

Sangameswaran, P., Madhav, R., and Rozario, C., 2008. 24/7, privatisation and water reform: insights from Hubli-Dharwad. *Economic and Political Weekly*, 43 (60), 60–67.

Shaban, A. and Sharma, R.N., 2007. Water consumption patterns in domestic households in major cities. *Economic and Political Weekly*, 39 (48), 2190–2197.
Simonovic, S.P. and Fahmy, H., 1999. A new modeling approach for water resources policy analysis. *Water Resources Research*, 35 (1), 295–304.
Srinivasan, V., 2008. An integrated framework for analysis of water supply strategies in a developing city: Chennai, India. Dissertation (PhD). Stanford University.
Srinivasan, V., Gorelick S.M., and Goulder, L., 2010. A hydrologic-economic modeling approach for analysis of urban water supply dynamics in Chennai, India. *Water Resources Research* (forthcoming).
Srinivasan, V., Gorelick, S.M., and Goulder, L., under review. Sustainable urban water supply in South India: desalination, efficiency improvement, or rainwater harvesting? *The Hindu*, 2005. Metrowater, IVCRL to ink water deal. *The Hindu,* Sep 13, Chennai, India.
The Hindu, 2005. Metrowater, IVCRL to ink water deal. *The Hindu,* Sep 13, Chennai, India.
Totsuka, S.N., Trifunovi, N., Vairavamoorthy, K., 2004. Intermittent urban water supply under water starving situations. Manuscript prepared for the 30th WEDC international conference on people-centered approaches to water and environmental sanitation, October 25–29 2004, Vientiane, Lao PDR.
Trescott, P.C., *et al*., 1976. Finite difference model for aquifer simulation in two dimensions with results of numerical experiments. *Techniques of water-resources investigations of the US Geological Survey*. Washington, D.C.: Department of the Interior, US Geological Survey.
USGS, 2000. MODFLOW-Modular three-dimensional finite-difference ground-water flow model. Available from: http://water.usgs.gov/software/modflow.html. [Accessed June 2006].
Vaidyanathan, A. and Saravanan, J., 2004. *Household water consumption in Chennai City: a sample survey*. New Delhi: Centre for Science and Environment.
Whittington, D., Lauria, D.T., and Mu, X., 1991. A study of water vending and willingness to pay for water in Onitsha, Nigeria. *World Development*, 19 (2/3), 179–198.
WSP, 2003. 24-hour water supply: is this goal achievable? *Fifteenth meeting of the Urban Think Tank*. Hyderabad, India, Water and Sanitation Program-South Asia (WSP-SA).
Zerah, M., 2002. Water supply and sanitation in Vijayawada: analysis of households' situation towards modes and cost of access, consumption and level of satisfaction. Research report Paris: CERNA.