# AN INTEGRATED FRAMEWORK FOR ANALYSIS OF WATER SUPPLY STRATEGIES IN A DEVELOPING CITY: CHENNAI, INDIA

A DISSERTATION
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FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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# Dissertation Abstract

This dissertation addresses the challenge of supplying water to rapidly growing cities in South Asia, using evidence from the water-scarce city of Chennai. Chennai (formerly Madras) is a rapidly growing metropolis of over 6.5 million people, whose infrastructure has not kept pace with its growing demand for water. In the year 2003-2004, Chennai experienced a severe water crisis: the piped supply for the entire city was virtually shut down for a 12-month period. Consumers became dependent on private tanker suppliers trucking in untreated groundwater from peri-urban areas.

This research effort accomplished three goals: understanding the dynamics of the recent water crisis, extending the model to project the business-as-usual trajectory of Chennai's water supply and understanding how the trajectory may be altered by various policies. The study departs from previous research studies in several respects: Firstly, this study explicitly incorporates self-supply via private wells, and private-supply via the tanker market as an integral part of the urban water system. Secondly, the research integrates bio-physical and socio-economic behavior at multiple scales: user-scale supply and demand, utility-scale management, and basin-scale water availability and allocation. Finally, the study allows policy-makers to evaluate and compare a wide-range of policy options on an apples-to-apples basis, something that cannot be done with existing frameworks.

An integrative theoretical framework and model were developed to address the research goals. The integrated model was calibrated for the historical period 2002-2006 against extensive physical and socio-economic data: groundwater heads, reservoir levels, household survey data in dry and wet years, tanker surveys, and operational statistics collected from the water utility. The calibration run of the model suggests that the 2003-2004 water crisis was precipitated by rational responses of the utility and Chennai consumers to limited reservoir capacity, unreliable inter-state water transfers, and limited capacity of the local aquifer. The research also explored scenarios of what the city's water supply may look like in 2025, using reasonable projections of population, land use and income growth. The historical rainfall record was used to generate scenarios of future rainfall. The 2025 model simulation provides two key insights. Firstly, a future drought is likely to at least as severe as the historical one. Increases in water use due to rising populations and incomes more than compensate for any reductions in peri-urban agricultural water extractions caused by to expanding urbanization. Second, a “dual-quality” approach to urban water supply may address Chennai’s water problems. The dual-quality solution involves relying on centralized high-quality (and cost) supply for drinking, cooking and dishwashing while using lower quality (and cost) self-supplied groundwater for other non-potable needs.

The research indicates that several factors contribute to making the dual-quality solution optimal. In the absence of reliable inter-state deliveries and a local perennial source, the long-run marginal cost of utility supply in Chennai is desalination, a very expensive option. Furthermore, a vast majority of consumers already have private wells; so consumers only consider the pumping costs of extracting groundwater from their wells; the capital costs are sunk costs. So, if in order to achieve full-cost recovery, the utility raises its tariffs above the cost of groundwater extraction from wells, rational consumers would switch out of using utility supply except for uses that necessitate high-quality piped water. The model results indicate this outcome will enhance social welfare if some of the revenues generated by higher tariffs are reinvested in rainwater harvesting and recharge management. Importantly, decreasing demand for utility supply within Chennai will “free” up water for supply to the rapidly-growing, underserved suburbs. Thus, the dual-quality solution can result in a system that is more efficient, equitable, sustainable and reliable overall.

Many other cities in the developing world, particularly in South Asia, exhibit characteristics similar to Chennai: high growth, limited access to new water resources, high marginal cost of new supplies, widespread dependence on private wells and consumer willingness to manage multiple qualities of water in the household. This suggests that the insights and solutions developed in Chennai may be extended to other places.

# Acknowledgments

This dissertation is the culmination of a long journey in my quest for an interdisciplinary research project that would provide both a contribution to knowledge as well as be relevant to decision makers in my home country, India. This dissertation would not be possible without the support and assistance of many Stanford faculty, students, staff, funders, and local collaborators in India.

This research has been funded by an Environmental Ventures Program (EVP) grant from the Stanford Wood's Institute of the Environment and a fellowship from the Heinz Foundation, which named me a Teresa Heinz Environmental Scholar in 2005. The Stanford School of Earth Sciences provided funding for my education and living expenses at Stanford through the Fellowship in Environment and Resources.

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# 1 Chapter One: The need for a new water paradigm

By 2025, two billion more people will live in the world's urban areas than in 2000. Much of this population growth will occur in the developing world[1]. Among the biggest challenges associated with the growth in cities is delivering safe water to all at an affordable price. This research offers an innovative framework and method to analyze and devise policies that address the imminent water crisis in developing-world cities.

## 1.1 The new urban water crisis

The global consensus on the need to provide universal access to basic services to all humans was enshrined in the UN Millennium Development Goals. As of 2004[2], over a billion people worldwide still lacked access to clean water and almost two billion lacked access to sanitation. The UN Millennium Development Goals Program aims to reduce these numbers by half by 2015. In the Indian sub-continent alone, 200 million people still lack access to safe drinking water and 800 million people lack access to sanitation[3].

Even while development agencies have focused on the problem of extending access to safe drinking water to millions of people, urban areas in the parts of the developing world have been experiencing unprecedented growth in population and income. As cities grow and incomes rise, a new challenge arises: that of supplying water reliably to rapidly growing, increasingly wealthy populations and enterprises, while ensuring that the poor are not left out. Developing cities represent both a challenge and an opportunity. Because much of the infrastructure is still being built, there is the opportunity to leapfrog to a more efficient, equitable, sustainable system. The question is what does a sustainable, equitable, efficient system look like?

This research was motivated by the concern that current narrowly focused research and policy approaches, may overlook broader linkages in the urban supply system. They may fail to consider alternative policies that could lead to the development of efficient, equitable, sustainable water supply systems. In this dissertation, we adopt a systems approach to the

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[1] United Nations, 2001
[2] World Health Organization, 2004
[3] Kulshreshta and Mittal, 2004

problem of urban water supply in one city, Chennai, in India. We examine a variety of aspects of the water supply system this Indian city: water resource availability, water supply infrastructure, and consumer behavior over a period of time. Even though this research specifically addresses Chennai, the frameworks, issues and solutions may be applied more generally.

In this chapter, we argue that current frameworks for thinking about urban water supply are fragmented and inadequate for addressing Chennai's water problem. We begin by introducing our case study city. We describe the nature of Chennai's water supply problem and discuss the policies being considered. Then we show why existing frameworks cannot be used to evaluate and compare different policies. We show how existing frameworks are reflected and perpetuated in current fragmented research approaches. We present the case for a new integrated framework. Finally we present the roadmap to the rest of the dissertation.

## 1.2 Chennai's water crisis

This dissertation is a case study of the city of Chennai (formerly Madras) in South India. Chennai is a particularly water-scarce city. It has the lowest water availability per capita of any large metropolitan area in India[4]. We selected Chennai as our case study area in part because of the severity of its water problem and the pressing need for innovative solutions. However, the choice of Chennai as a case study city was also opportunistic. At the start of this research, 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 socio-economic survey data and physical data for both events, made an integrated analysis possible.

### *1.2.1 Background on Chennai's water supply*

Chennai is a large metropolitan city located in the state of Tamil Nadu, in South India (shown in Figure 1.1). As per the 2001 census[5], 4.3 million people lived within incorporated municipal boundaries; 6.4 million lived in the Chennai urban agglomeration, which includes peri-urban towns, suburbs and villages.

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[4] Asian Development Bank, 2007

[5] Metrowater, 2008 (b)

Source: Image downloaded from Google Earth : http://earth.google.com

**Figure 1.1: Location of Chennai**

A public water utility, the Chennai Metropolitan Water Supply and Sewerage Board (called "Metrowater"), serves the municipality area via a piped network. Almost all households in Chennai have some sort of access to public supply: private piped connections, yard handpumps or taps, public standpipes or utility-run "mobile supply" tankers. Outside city limits, peri-urban towns and villages are served by a patchwork of town and village supply schemes, and are mostly dependent on groundwater.

Metrowater obtains most of its water for city supply via three interconnected rain-fed reservoirs, along with well-fields located to the north of the city. In addition, Metrowater also gets water from two inter-basin projects: the inter-state Telugu Ganga Project, whose water is delivered into the city's reservoir system, and the newly commissioned intra-state Veeranam Project. Veeranam water is treated and delivered directly to water distribution stations in Chennai via smaller storage facilities, so the water does not enter Chennai's reservoir system. Between 2002 and 2006, the quantity available from all these sources varied significantly from month to month. Total supply at the source varied between 30 and 140 LPCD[6] (liters per

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[6] Metrowater, 2006 (b)

capita per day). The quantity available to households ranged from 20 to 100 LPCD[6] after pipeline losses and industrial/commercial needs were accounted for.

### *1.2.2 Chennai's recent water crisis*

In 2003-2004, Chennai's reservoirs went completely dry; the piped supply system was virtually shut down for almost a year[7]. The entire city was supplied by "mobile supply": utility-run tankers that went from neighborhood to neighborhood delivering a lifeline supply of water of about 20 liters per capita per day, to be collected by residents in 15-liter pots. A household survey conducted during the drought showed that over two-thirds of households reported supplement this with water from their private wells. Over 6 percent purchased private tanker water. Bottled water use was widespread at 35 percent of all surveyed households[8]. In fact in 2003-2004, utility supply contributed less than a third of the total water used in Chennai.

The cessation of piped supply for almost a year in a large Metropolitan area represented a crisis of such magnitude that it prompted speculation that the city might have to be evacuated if no water were made available soon[9]. However, this option was not exercised. By the end of the 2004, Metrowater was able to commission the Veeranam water supply scheme and also set up a formal water market to purchase emergency supplies from peri-urban farmers; evacuation was averted. The heavy rains in the following year resulted in the reservoirs getting replenished and daily piped supply was resumed. In the next section, we identify and describe some commonly offered policies to address Chennai's water problem.

## 1.3 One Crisis: Three Policy Approaches

As Chennai was suffering a severe water crisis, three very different policy approaches emerged to address Chennai's water problems: Supply Augmentation favored by the water utility, Efficiency Improvement suggested by economists at the development banks, and decentralized recharge management or "Rainwater Harvesting" promoted by environmental NGOs. In the following section, we discuss each approach in detail.

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[7] Metrowater, 2006 (c)
[8] Vaidyanatha and Saravanan, 2004
[9] Rao, 2004.

### *1.3.1 The traditional utility solution: Supply Augmentation*

Supply Augmentation approaches involve increasing the total quantity of water available by building new water supply projects like dams and reservoirs, or desalination plants. These approaches are usually favored by water utilities. Unfortunately, cities like Chennai have no local, undeveloped sources. Therefore, the only options available to augment water supply involve the construction of large inter-basin transfer projects. However, we will show in later chapters that inter-basin transfers particularly across state-boundaries have been unreliable. An urban area that runs out of local water supply sources has very few options barring desalination, an expensive solution. In fact, Chennai Metrowater has recently commissioned one desalination plant to the north of the city, and is proposing a second plant to supply the rapidly growing IT industry to the south of the city[10].

### *1.3.2 The development bank solution: Reallocate water, charge more, fix pipes*

Economic solutions are usually favored by economists at development banks among others. Rogers et al., (2000) summarize this approach to the world's urban water problems as three simple solutions: reallocate water from agriculture, charge more, and conserve.

1. **Reallocate water** from low-value agriculture to high-value urban uses. In the developing world, urban water consumption, both domestic and industrial, is small relative to irrigated agricultural consumption. Because urban water demands are small, it is generally accepted that enough water can be made available to cities by modest improvements in inefficient irrigation systems. Thus, growing cities could have large quantities of water available relatively cheaply by modest changes in irrigation practices.
2. **Charge more** to pass on the cost of supply to consumers**.** Charging at the margin, a rate equal to the long-run marginal cost, allows the water utility to maintain and develop water infrastructure to keep pace with growing demand. Even in Chennai, despite the frequent shortages, less than 5 percent of households are metered and charged on a volumetric basis. Economists argue that charging more for water is an important tool to manage demand for water; the only way to match supply and demand in the long-run.
3. **Improve efficiency** by conservation, reducing pipeline leaks and wastewater recycling. Most developing world cities, suffer from pipeline losses as high as 50 percent compared

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[10] The Hindu, 2008.

to as low as 5 percent in the worlds best run utilities[11]. Reducing high rates of pipeline leakage will result in the delivery of more water to consumers with existing infrastructure.

### *1.3.3 The Collective Action/NGO Solution: Rainwater Harvesting*

The "Rainwater Harvesting" solution involves increasing the amount of groundwater recharge by installing rooftop rainwater harvesting structures, and rejuvenating urban ponds. Currently, only an estimated 9 percent of rainwater in Chennai makes it to the aquifer; the rest runs off into the ocean. NGOs argue that Chennai' aquifer could be used to harvest and store rainwater and thus increase the quantity available to consumers. In Chennai, the term "Rainwater Harvesting" refers mainly to recharge management; rather than collection in cisterns for end use, the more common usage of the term. Throughout this dissertation Rainwater Harvesting will be used to refer to collection of rainwater for aquifer recharge.

Recharge management efforts may be conducted at any scale. They may be led by individuals, communities, or the water utility. A number of local and national environmental groups (Centre for Science and Environment, New Delhi, Akash Ganga in Chennai, Pammal community near Chennai, Rainwater club in Bangalore, Siruthuli in Coimbatore, DHAN Foundation in South India, etc.) have emerged which are promoting various forms for recharge management to protect critical groundwater reserves in urban areas. In one well-known case, a women's group in the peri-urban town of Pammal near Chennai, collectively raised funds and voluntary labor to rehabilitate the local pond by clearing the garbage blocking the storm water inlets into the pond and desilting the pond. The pond serves as a recharge structure to improve local groundwater conditions. In areas where private groundwater use is common, such interventions provide relief particularly when utility-supplied piped water is non-existent or heavily curtailed during droughts.

A major problem is that these interventions, though innovative and useful, have not made significant inroads into the policy-making arena. Although the city of Chennai recently passed pioneering Rainwater Harvesting regulation, requiring every house to capture rooftop rainwater to recharge the city's aquifer, implementation lags behind. Informal surveys by local NGOs[12] indicate that the vast majority of the structures were not properly constructed. There

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[11] Tortajada, 2006. The Public Utilities Board (PUB), Singapore, one of the worlds best utilities has consistently reported an "unaccounted for water" rate at 5 percent in recent years

[12] Ahmed, 2004

are no associated revenue streams to the utility or government from Rainwater Harvesting. So while government agencies have encouraged these practices, actual resources devoted to enforcement have been (not surprisingly) limited[13]. Within the academic and development community too, no comprehensive attempt has ever been made to quantify the costs and benefits of such efforts. No large-scale scientific studies quantifying improvements in aquifer recharge has been undertaken.

### 1.4 Research Questions

Three very different solution approaches have been offered to tackle future water problems in Chennai. The goal of this research is to figure out which policy or policies are most efficient, equitable, and sustainable in solving Chennai's water problems.

We address these research goals by asking the following research questions

**Explain currently observed and historical trends**

- How much water has been consumed from different sources, for what purpose, and by whom?
- What is the state of consumer well-being, given these consumption patterns?
- What factors contributed to the 2003-2004 Chennai water supply crisis?

**Develop a baseline forecast**

- How much water will be consumed from different sources, for what purpose and by whom in 2025, given expected growth in population, income, and water infrastructure?
- What is the baseline future state of consumer well-being?

**Evaluate policies**

- How will the three different policies affect the quantity of water consumed by different consumers from different sources?
- What is the expected state of consumer well-being under different policies?

## 1.5 No framework for comparison along multiple dimensions

The challenge in comparing the three policies is that no framework currently exists to compare the costs and benefits of these interventions on an "apples-to-apples" basis. In this section we argue that the reason no basis for comparison exists is because the three policies operate along

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[13] Currently the "Rainwater Harvesting" cell at Metrowater is staffed by two people. Their job description is monitoring groundwater levels, providing technical assistance and public education, not enforcement and ensuring that the structures are properly installed.

different dimensions. The four dimensions in urban water supply are defined as ***investment agents, water quality, time, and modes of supply***.

Firstly, the three policies involve interventions by different ***decision agents***. Different agents make investments in resource management and abstraction. In the Supply Augmentation and Efficiency Improvement policies, the utility[14] is the decision-maker regarding investments in abstraction and resource conservation in a centralized manner. In contrast, Rainwater Harvesting is a decentralized solution involving actions by millions of consumers, on how to recharge, extract and manage water resources. Secondly, the policies may have different effects on the ***temporal variability*** of supply, i.e., the timing of the water generated may be different for each. Some policies might be more effective during droughts, while others may provide no benefits during droughts when consumers are hardest hit. Thirdly, the water reaches consumers via different ***modes of supply***. Supply Augmentation involves making more water available in the utility piped supply system. Likewise, the Efficiency Improvement policy involves controlling demand by raising prices. The policy induces consumers to use less water, perhaps by investing in water saving devices like low-flow taps. The utility also invests in fixing pipeline leaks. In each case, utility supply in the piped supply system is enhanced. In contrast, Rainwater Harvesting makes more water available via private or community wells by keeping the aquifer recharged. Finally, the ***quality*** of the water generated is different for each of the proposed policies. While Supply Augmentation and Efficiency Improvement focus on increasing the availability of potable piped utility piped supply, the Rainwater Harvesting policy focuses on recharging groundwater to improve availability of untreated groundwater or untreated rainwater.

Because the three policies differ along different dimensions, there is a level of complexity that currently existing policy-evaluation frameworks cannot accommodate. Current frameworks for thinking about the urban water problem are centralized or utility-centric.

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[14] Although under efficiency improvement, the end-users make the actual conservation investments, the level of investment is determined by the utility's policies on pricing and conservation incentives. Thus, the utility can be considered the key decision-making agent. Thus, traditional models of centralized water supply, are able to account for conservation behavior fairly well. In contrast, for rainwater harvesting the utility has little leverage to influence investment behavior by consumers.

## 1.6 Current “centralized” paradigm is inadequate

Conventional wisdom dictates that cities are best served by regulated urban water utilities. We refer to this as the “centralized water paradigm”. In this section we argue that the centralized water paradigm does not allow for variability along the four dimensions identified in the earlier section. Furthermore, the centralized water paradigm is not representative of the water supply situation in Chennai. It also overlooks opportunities to recognize and promote decentralized interventions that are already taking place.

### *1.6.1 The centralized water paradigm is a utility-centric one*

In the centralized water paradigm the water utility[15] is the optimal water planner. The utility forecasts demand and makes investment decisions on behalf of the population it serves. The utility is the primary extractor of water resources needed for the urban area. It is the only intermediary between the water resource and the consumer. The water utility manages supply and demand by building reservoirs or managing demand so that it can supply water reliably in all periods. The water utility then treats the water centrally, and distributes the water via pipes to consumers. Figure 1.2 depicts the conceptual model of the centralized water paradigm.

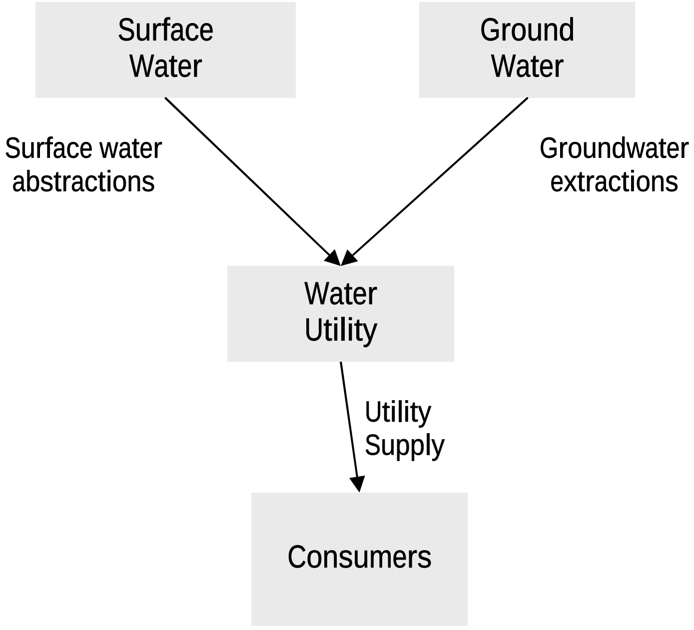

**Figure 1.2: Utility-centric conceptual model of the centralized water paradigm**

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[15] Note: that is a claim about how the centralized water paradigm is conceived. Reality may of course be very different.

In the centralized water paradigm, the water utility performs the following major functions: management and abstraction of raw water resources, storage and diversion to maintain a reliable level of supply to urban consumers, treatment to potable standards and delivery to consumers.

***Water resources management and abstraction:***

In the centralized water paradigm, the water utility is the sole ***decision-making agent*** that plans and ***manages investments*** in water resources conservation and infrastructure. In planning investments, the utility employs rules of thumb to forecast the water demand: depending on the number and types of connections, demand is assumed to range from 40 and 150 LPCD (liters per capita per day). Then adjustments are made to account for industrial and commercial needs, distribution pipeline losses, and conservation. The water utility may meet the projected demands of the population it serves by developing new water resources projects, improving technical efficiency or instating conservation programs.

***Storage and diversion:*** To overcome seasonal and inter-annual variability in rainfall, the utility must build storage infrastructure, like reservoirs. The utility manages the reservoirs so as to maintain a constant, less variable level of supply across seasons and years i.e., storage infrastructure reduces ***temporal variability*** in supply.

***Water Treatment:*** The utility then treats the raw water to ***potable quality*** to meet drinking water standards. Conventional engineering wisdom for urban water systems requires that ALL piped water is treated to drinking water quality.

***Water delivery:*** The utility delivers water via pipes or standpipes to consumers. In the centralized water paradigm, utility piped supply is the only (excluding bottled water) ***mode of supply*** by which a consumer obtains water.

In theory, to remain economically viable, the water utility meters and prices water so that it can recover costs and remain financially viable. The utility manages this by charging a marginal rate equal to the long-run marginal cost so it is able to match demand and supply in the long-term. Thus, in the centralized water paradigm, the utility makes all planning and abstraction, storage, treatment, delivery and pricing decisions. The consumer can decide how much to consume at the price set by the utility, if supply is insufficient. However, users do not abstract water resources independent of the utility. In this sense, users are “passive” end-of-pipe recipients of what ever the utility delivers to the tap. If the utility does not deliver enough water, the consumer “copes”. In the centralized water paradigm, all coping actions by the consumer are exogenous to the system.

### *1.6.2 The centralized water paradigm overlooks non-utility modes of supply*

In Chennai, a significant fraction of water is sourced from non-utility sources. Far from being passive end-of-pipe recipients of water, consumers get water from alternative. Figure 1.4 shows the fraction of water used from utility and non-utility sources for two years in Chennai.

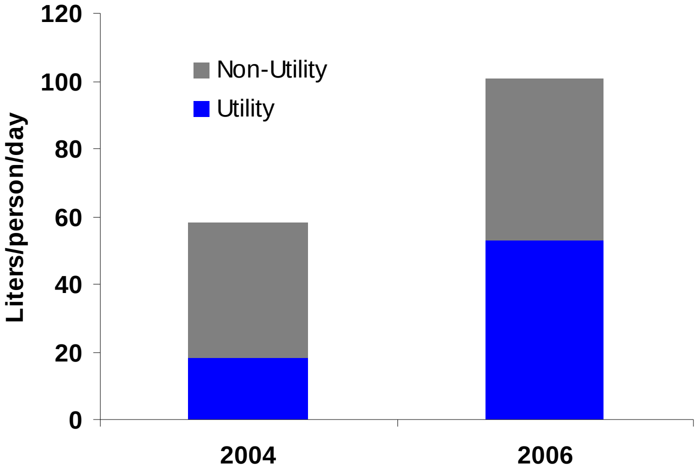

**Figure 1.3: Average water obtained from utility and non-utility sources**

The statistics presented in Figure 1.4 are based on recent household surveys in Chennai presented in detail in Appendix F. These showed that between a third and two-thirds of the water supplied to consumers was from non-utility sources. Consumers abstract groundwater directly (self-supply) from their own or community wells or indirectly by purchasing it from private tanker operators (private supply) who in turn extract groundwater from peri-urban wells and truck it to consumers' homes[16].

### *1.6.3 The centralized water paradigm ignores effects of temporal variability*

The centralized water paradigm also does not account for significant differences in availability in supply from year to year and the coping behavior it may induce. Figure 1.3 shows the actual gross utility supply (before losses) to Chennai over the last 20 years.

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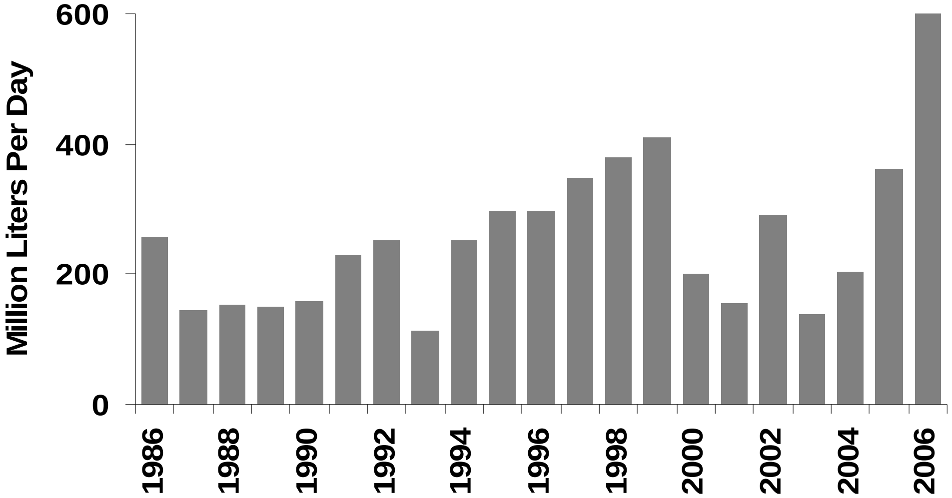
[16] Moench et al., 2003 discuss the tanker market in Katmandu, Nepal. Vaidyanathan and Saravanan, 2004 showed that over half of the water supply in Chennai was sourced via private wells. Shaban and Sharma, 2007 present data from 8 Indian cities showing a significant amount of private groundwater extraction.



**Source: Metrowater, 2006 (a)**

**Figure 1.4: Total utility supply to Chennai**

Total utility supply to Chennai varied significantly from one year to the next, primarily because of differences in water resource availability. Even if non-utility modes of supply are included (as suggested in the earlier section) in a static manner, i.e., by fixing the fraction of consumption accessed from non-utility sources, the formulation would be incomplete. Instead Figure 1.3 indicates that fluctuations in utility supply may cause fluctuations in non-utility modes of supply.

### *1.6.4 The centralized water paradigm overlooks non-utility investments*

The centralized water paradigm assumes that the utility is the only institution by which policy is implemented. It is the only agency that can make investments in abstracting, storing, treating and preserving water resources. Thus, the centralized water paradigm overlooks opportunities for non-utility actors to invest in storing and preserving scarce water resources, including community-based recharge management schemes, decentralized wastewater recycling, and individual rooftop rainwater harvesting.

In this section, we argued that the prevailing utility-centric centralized water paradigm doesn’t allow for variability along multiple dimensions. Moreover, it ignores important elements of the water supply system in Chennai. In subsequent sections, we argue that the centralized water paradigm mindset has evolved as a direct consequence of the fragmented nature of current research tools, frameworks, and methods. In the next section we offer a critical review of current research.

## 1.7 Critical review of the literature:

**Current research efforts are fragmented, and may lead to incorrect conclusions:**
We classify the broad range of research efforts underway in the area of urban water supply. We show how current research efforts tend to focus on components, relationships, or units of analyses of the centralized water supply cycle and in doing so researchers make implicit or explicit assumptions about the other components of the water supply system that may be incorrect. This critical review of the literature is organized as follows: We begin by explaining how the literature is fragmented. For, each area of the literature, we summarize the high-level conclusions about the urban water problem.

### *1.7.1 Studies have multiple scales and foci of analyses*

The scholarly literature has tended to split the problem of urban water supply into two separate problems: managing and storing the raw water resources (the "water resources" problem) and treating and delivering it to the final consumer ("the water delivery" problem) each addressing a different goal. Studies addressing these problems tend to be fairly independent. These literatures typically engage different research communities, and disciplines. They may even target different journals.

The focus of the water resources management literature is the fair and optimal allocation of water resources between agriculture, industry, urban and ecosystem needs. In contrast, the goal of the water (and sanitation) delivery literature is to improve public health, and the quality of life in urban areas. Moreover, these different foci address different spatial scales and use different units of analyses. Figure 1.5 shows the different scales and foci of current studies.

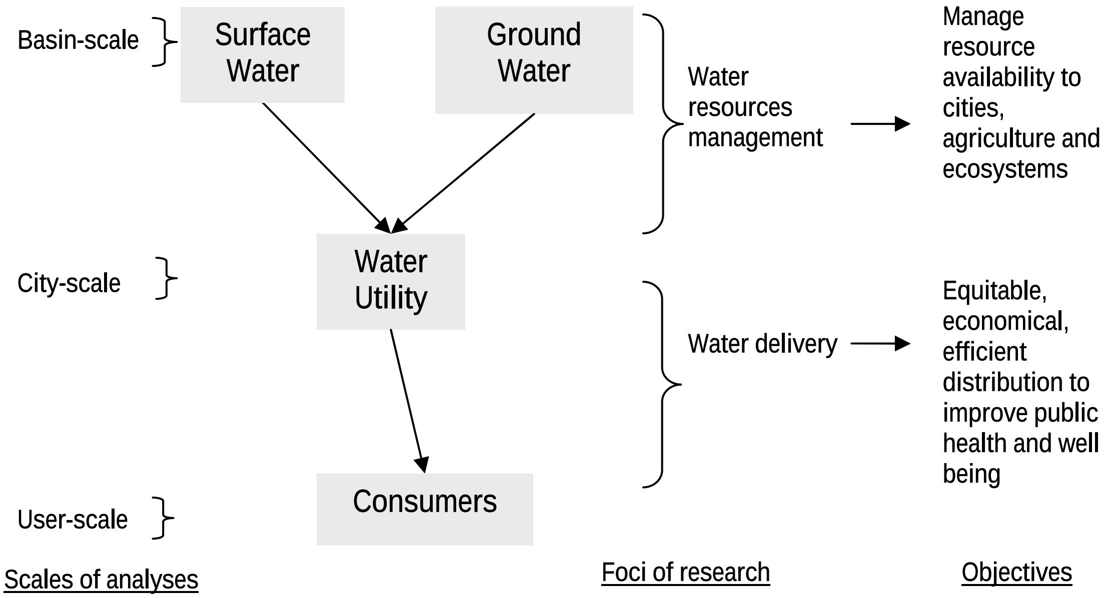


**Figure 1.5: Scales and foci of analyses**

Of these different scales and foci, it is often assumed that the water resources management component i.e., basin-scale problem of the urban water supply problem in the developing world is relatively easily solved. The utility-scale and user-scale problem is considered the more challenging problem.

### *1.7.2 Basin-scale studies*

Basin-scale studies[17] are aimed at evaluating optimal or feasible intersectoral allocation of water among agriculture, urban (utility), industrial and ecosystem needs. Basin-scale analyses indicate that the problem of supplying water to cities is not major. The research methods might include linked or separate hydrologic and economic models. A conceptual model for basin-scale studies is shown in Figure 1.6.

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[17] Maddaus, 1976, Meizen-Dick and Appasamy, 2002

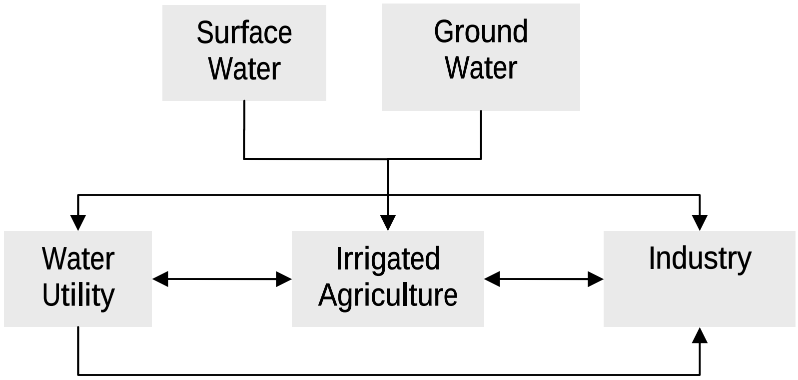

**Figure 1.6: Inter-sectoral allocation of water**

#### *1.7.2.1 Summary of basin-scale studies: urban water demand can be met by modest improvements in agriculture at relatively low costs*

Basin-scale studies in the developing world argue that urban water needs, both domestic and industrial, are small relative to agricultural needs and can be met at relatively low-costs by reallocation of water from agriculture. It is technically feasible, economically efficient and politically possible to effect transfers[18]. Urban water uses constitute only 10 to 20 percent of the water of total use in basins, in most developing countries[19]. Furthermore, urban water uses, unlike agricultural uses, are largely non-consumptive. Most of the water is returned to the watershed (albeit at a diminished quality). Because urban water needs are small, it is generally accepted that enough water can be made available to cities by modest improvements in inefficient irrigation systems. Thus, urban needs are not a considered significant in the larger water resources problem. It is economically efficient to transfer water from low-value agricultural uses to high-value urban uses via modest improvements in irrigation efficiency. Many cultures also accord high priority to drinking water provision. Moreover, urban areas often constitute a significant fraction of the total economic tax-base. So it is often also politically feasible to reallocate water from agriculture to urban areas either via water markets (if property rights to water exist) or policy mandates (if water is centrally allocated)[20].

Basin-scale studies of inter-sectoral allocation of water conclude that, except for a few arid areas, most urban areas have access to low cost (relative to what consumers are willing to pay

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[18] Meizen-Dick and Appasamy, 2002
[19] Rosegrant 2000, Gleick et al., 2002
[20] Meizen-Dick and Appasamy, 2002

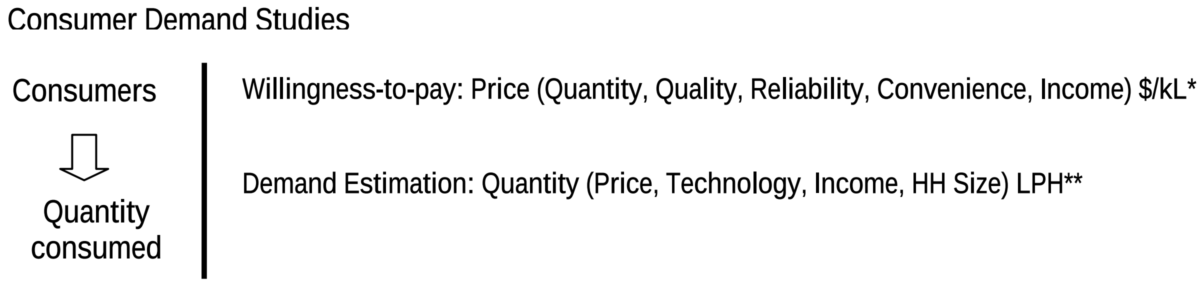
for reliable, high-quality water piped water supply) water resources, by reallocating water from agriculture or urban uses.

### *1.7.3 Consumer-scale analyses*

Consumer-scale studies aim to assess user behavior, how much they currently pay, how much users are willing to pay, and how they cope with shortages or lack of connectivity to the piped water supply system.

#### *1.7.3.1 Consumer-scale demand modeling*

These studies forecast user demand for water. They aim to identify how much demand will materialize under different tariff regimes or assess if certain investments should be made. The literature here has developed in two directions[21]. The first uses regression models to quantify the demand (for water or connectivity) as it relates to observable parameters like household size, income, price, and weather[22]. The second uses contingent valuation and revealed preference techniques to assess willingness-to-pay[23] as depicted in Figure 1.7.



*kL= 1000 liters
**LPH = Liters/household/day

**Figure 1.7: Consumer-scale demand studies**

#### *1.7.3.2 Coping strategy studies*

Other user-scale studies explain how users deal with the absence of reliable piped water supply. Users cope by relying on alternative supply sources such as bottled water, private tankers, and private or community wells. One branch of research (usually economic) estimates costs of investments in storage, treatment, and self-supply[24]. Another strand of

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[21] Rosenberg et al. 2007

[22] Basani et al. 2008, Hewitt and Hanemann 1995. Strand and Walker 2005, Nieswiadomy 1992, Arbues et al. 2002

[23] Whittington et al. 2002, Anand and Perman, 1999, Van Houtven et al. 2006

[24] Yepes et al. 2002

research is directed to studying private providers such as water vendors or private tanker truck operators or use water from communal water bodies[25]. Water from these alternative sources costs anywhere from 5 to 100 times more than piped supply[25]. These studies consistently show that consumers are able and willing to pay for water. However, the quality and quantity of water obtained from alternative sources is much poorer than that obtainable by piped supply. Coping mechanisms are inefficient and at best temporary solutions to water service delivery. These studies usually conclude that consumers would benefit greatly from centralized provision and can afford to pay for it.

#### *1.7.3.3 Summary of consumer-scale studies: consumers are willing to pay*

In the absence of reliable supply, consumers buy water from alternative sources, private tanker operators, water vendors, neighborhood resellers, packaged water, private or communal wells, or direct use of (often polluted) local rivers and lakes. The overwhelming consensus is that these alternatives cost more than piped supply, so consumers in effect pay more for lower quality, less reliable source of supply. While these alternatives may be tolerated or even supported as a necessary interim solution[26], they are expensive and entail health risks. The studies conclude that price that the poor already pay is evidence of their willingness-to-pay for water. In the long run, metered, properly priced, centrally treated piped supply is a feasible and desirable solution for the urban poor.

### ***1.7.4 Utility-scale analyses***

Utility-scale analyses argue for expansions in centralized supply of water, citing public health benefits. However, most studies show developing world utilities are currently managed extremely inefficiently and can be improved significantly to the benefit of consumers.

#### *1.7.4.1 Rationale of utility-scale investments:*

These studies argue that providing high quality centralized piped supply has public health benefits. One set of utility-scale studies make the case for investments in water utilities in light of competing uses of public funds. Arguments rely on methods that include cost-benefit analyses[27] or regression analyses showing reductions in morbidity and mortality associated with improved access to high quality water (and sanitation) services[28]. Studies suggest that

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[25] Kjellan 2000, Pattanayak et al. 2005

[26] Kjellan 2000, Strand and Walker 2004, McIntosh 2003

[27] Stober and Falk 1967, Whittington et al., 2004

[28] Kulshreshta and Mittal 2003, Jalan and Ravillion 2003, Merrick 1985

public health gains from improved piped supply alone are positive though small; but expanding centralized provision of high-quality water supply is cheaper than what consumers currently pay for water[29].

### *1.7.4.2 Utility systems analysis:*

Another set of utility-scale studies are systems' analyses applied to water utilities, with the objective of comparing short-term and long-term options to acquire water[30] such as, supply augmentation, conservation, and water transfers. The analyses may consider aspects of external costs, inter-annual reliability of supply, stakeholder issues, and economic efficiency. Based on such analyses, utilities rank the available options and choose the most cost-effective alternatives as shown in Figure 1.8.

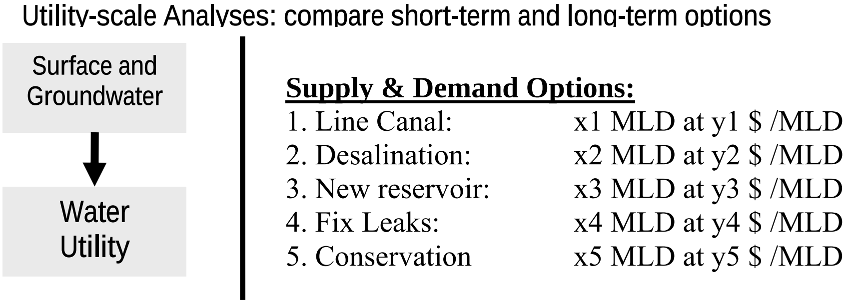

**Figure 1.8: Example of utility-scale systems' analyses studies**

As shown in Figure 1.8, utilities will typically compare various options available to them based on price and quantity in order to asses the most cost-effective method meet future demands. In the figure, price is specified in $/ Million liters/day.

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[29] Yepes et. al 2002, Whittington et al. 1991

[30] Wilchfirt and Lund 1997

### *1.7.4.3 Utility-scale institutional change to improve efficiency:*

The vast majority of utility-scale studies focus on institutional change[31]. These studies focus on utility ownership, alternative management models, incentives to employees and consumers, customer service, corruption, tariff structure, efficiency improvements, and monitoring mechanisms. The studies use one or more metrics to measure benefits, such as improvement in coverage, utility profits, quantity of water delivered, consumer satisfaction, and reduced incidence of water-borne diseases. Regression analyses or qualitative case study analyses are common analytical tools. Figure 1.9 shows a conceptual model for this class of studies.

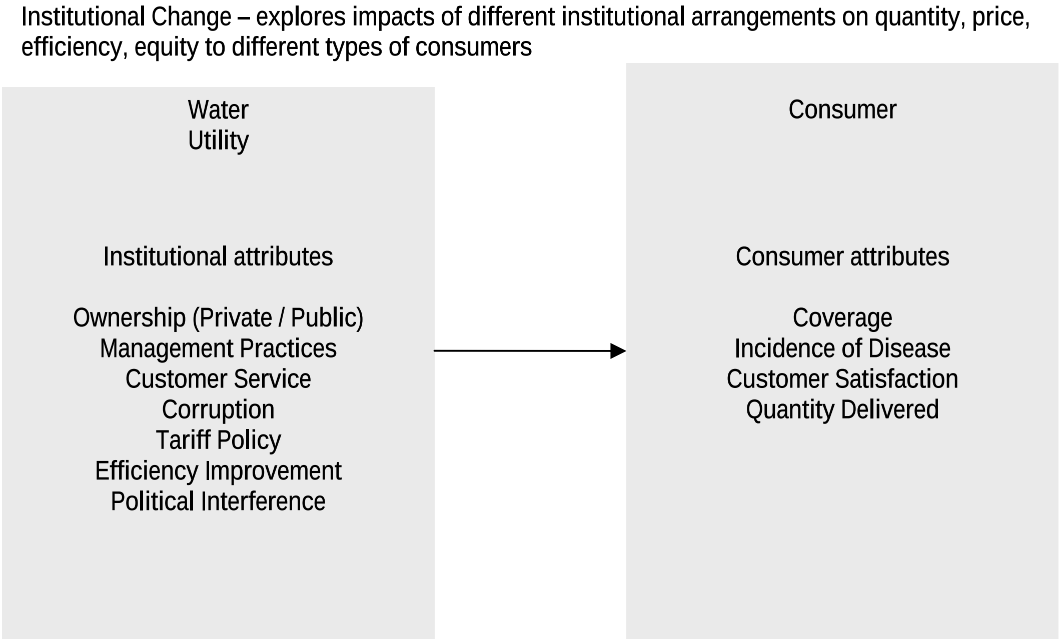

**Figure 1.9: Utility-scale efficiency improvement studies**

### *1.7.4.4 Summary of utility-scale analyses: The urban water supply problem is one of institutional failure*

Most utility-scale studies[32] argue that the problem of water supply in the developing world is neither due to non-availability of water resources (at a reasonable cost) nor due to inability to pay on the part of users. The problem is one of poor management by utilities and political interference. Many developing country utilities offer highly subsidized, even un-metered water services. Assuring free water and electricity is a way for politicians to win popular support. Unfortunately, only a small fraction of consumers, usually upper and middle-class,

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[31] Clarke et al. 2002, Singh et al. 1992, Davis 2004
[32] Singh et al. 1992, Walker et al. 1997, McIntosh 2003

have piped water access; so the subsidized water is ironically captured by the wealthy. The poor, lacking access to the piped supply system, pay more for water as they are left to “cope” with less reliable, labor intensive, poor quality sources like public standpipes, community wells and ponds and pay more for water. Because of the low rates charged, water utilities are often unable to recover costs. Over time the water infrastructure becomes leaky, incurring higher operational costs, decreasing the water available to consumers and revenues to the utility. The deteriorating financial state of the water utility makes it impossible to extend the infrastructure or service poor or new peri-urban communities.

Building piped water and sanitation infrastructure involves big, long-term capital investments. This requires confidence on the part of investors that demand will materialize and consumers will pay. So raising funds to build the infrastructure is a major hurdle. To make matters worse, water infrastructure is also characterized by economies of scale – fewer connected consumers imply higher costs for all, perpetuating the negative cycle or “low-level equilibrium”. In the next section, we argue that taking this fragmented view of the problem misses key linkages in the water supply system.

## 1.8 Gaps in current research approaches

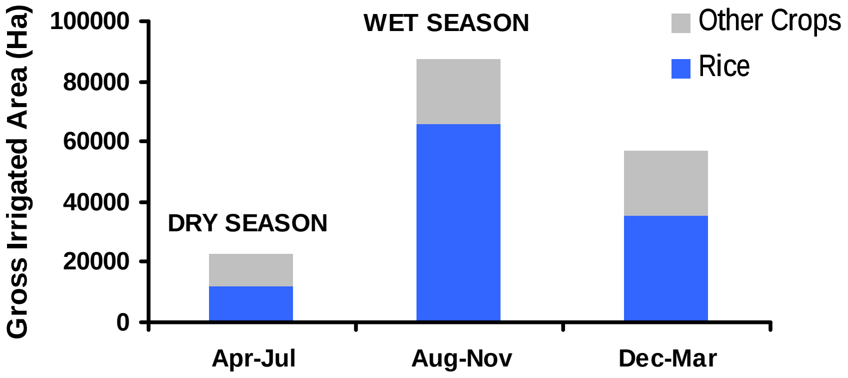
Taking a fragmented view of the urban water problem misses key linkages or involves assumptions about the water supply system that do not hold for Chennai. We identify some gaps in current research approaches. We identify key assumptions that are made in current research studies in terms of the four dimensions identified earlier: agents, temporal variability, quality, and modes of supply. Finally, we offer a broader framework for urban water supply that could overcome these problems.

### *1.8.1 Basin-scale analyses under-estimate time and costs of reallocation*

One of the conclusions of both utility and basin-scale analyses is that water can be cheaply and easily reallocated from low-value agricultural to high-value urban uses so urban water utilities have ready access to a low-cost source of water. This is the reason that much of the focus on urban water supply in the developing world is on user and utility-scale analyses. However, the costs of reallocation of water from agriculture to urban uses and hence the water resources component of urban water supply may be much higher than commonly assumed.

Basin-scale studies overlook the fact that urban water supply can tolerate much lower variability than agriculture. While cropping patterns in the Chennai basin vary seasonally, domestic (urban) demand is mostly uniform; consumers need about the same amount of water to drink, wash and bathe everyday regardless of the season particularly since outdoor water use (garden and landscaping needs) comprise only a small component of total water use in Chennai[33].

Figure 1.10 below shows the gross irrigated acreage by season in the Kancheepuram and Tiruvallur districts adjacent to Chennai. From the figure below it may be seen that both total irrigated acreage, as well as the fraction of acreage under water-intensive rice varied by as much as a factor of four across seasons. Most of the rice cultivation occurs in the wet season. Very little rice is grown in the dry summer months.



**Source: Government of Tamil Nadu, 2006**
**Figure 1.10: Gross irrigated acreage: Kancheepuram District**

Crop water needs also change from year to year and season to season by altering cropping patterns, and thus adjust somewhat to variability in water resource availability. Consequently, agricultural water uses have a much lower need for storage when compared to urban water uses. While a comparison of the marginal value of water to agriculture and urban uses demonstrates that it is economically efficient to transfer water from agriculture to urban areas, in practice the reallocation often entails construction of new expensive storage and transportation facilities. The time and monetary costs of building new water resources infrastructure may be prohibitive. When the water is simply reallocated without building additional storage, cities end up receiving highly variable water supply in the short-term or

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[33] Vaidyanathan and Saravanan, 2004

even in the long-term (i.e., in effect the city is treated like a large farm!), a possibility that has received insufficient attention.

In the short-term, the difference in the time-scale of developing water resources projects to reallocate water, and the pace of urban growth can cause developing world cities to face resource scarcity, while these problems are resolved. Dams and reservoir projects involve resettling displaced populations, resolving stakeholder claims, and mitigating environmental concerns. In democratic settings, conflicts can take years even decades[34] to resolve. This can occur even while many cities in the developing world are facing unprecedented urban growth. In the long-term, it is conceivable that some new storage projects will never be built. Resettlement of populations to build reservoirs close to densely populated urban areas may be too expensive.

An example from Chennai is instructive. After failing to augment reservoir capacity and get consistent deliveries of water from inter-state water projects, the water utility, Metrowater, recently commissioned a desalination plant to guarantee a minimum level of supply to meet the needs of the growing urban population. The city is now considering commissioning a second desalination plant. This step is significant because it is partly an acknowledgement that the political and economic costs of resettling populations may actually be higher than the cost of desalination. The problem is that the long-run marginal cost of water supply (LRMC) via desalination is higher that even the most optimistic estimate of willingness-to-pay for piped water supply in a developing country setting.

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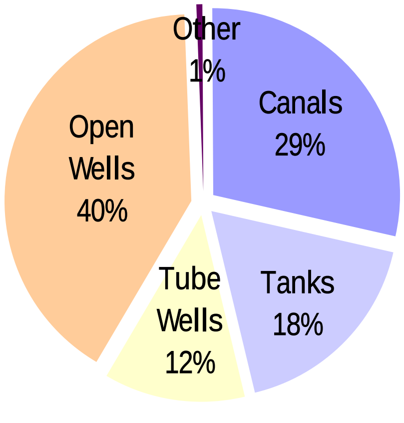
[34] An example is the dispute over the inter-state Cauvery River in South India, which would ultimately provide water to the metropolitan areas of Chennai and Bangalore in the riparian states of Tamil Nadu and Karnataka, respectively. The Cauvery water tribunal, which was set up by the central government in 1990 took 17 years to arrive at a ruling. In the meantime, both resource development projects and scientific research in the Cauvery Basin were severely restricted

The Telugu Ganga project which was to bring water to Chennai from the Krishna River was first conceived in the 1950s. The inter-state agreement on sharing of the Krishna waters and allocation to the Telugu Ganga Project occurred in 1976. The project took another 20 years till 1996 to achieve completion, and even after commissioning Chennai received only a third of the planned quantity and none in some years (Nikku 2004)

The arguments presented here challenge long-held assumptions that the water-resources component of urban supply, in the developing world, can be easily solved as it will always be possible to access low cost sources to meet the demand of centralized piped supply systems.

### *1.8.2 Irrigation water use is distributed*

In Tamil Nadu water used for irrigated agriculture is not met from reservoir/canal irrigation but instead small distributed water bodies such as tanks and groundwater irrigation wells. Thus, even though a large fraction of the total water in the state continues to be used by agriculture, the water extracted for agriculture is distributed in nature and not amenable for aggregation into a centralized urban supply utility. Figure 1.11 shows the source-wise break-up of water use by irrigated agriculture in Tamil Nadu state. In may be seen that less than 30 percent is canal irrigated. For the districts of Tiruvallur and Kancheepuram surrounding Chennai, canal irrigation accounts for less than 5 percent of agricultural water use.



**Source: Government of Tamil Nadu, 2006**
**Figure 1.11: Net irrigated area by source: Total for Tamil Nadu state**

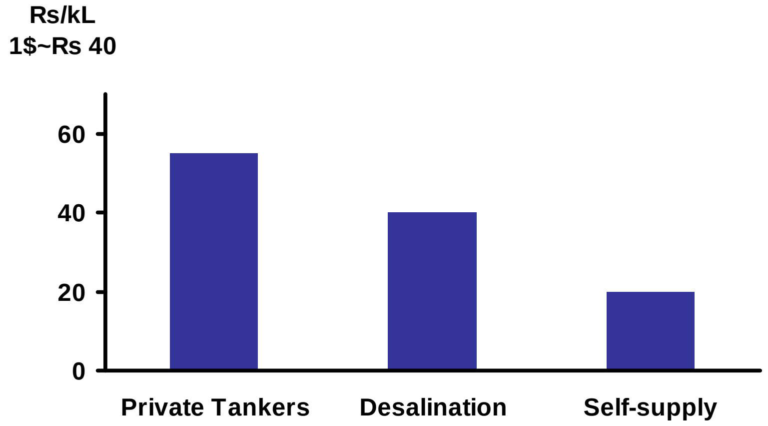
The lack of large perennial rivers close to Chennai is well understood and acknowledged by the utility and policy-makers. However, the converse argument is not acknowledged; lacking a large perennial source of water, the de facto process by which water is reallocated from agriculture to urban uses is the natural process of urbanization: Cities grow and develop new suburbs. If centralized utility supply is not expanded, the main source of water to new suburbs arises from the substitution of a distributed network of agriculture wells by a distributed network of peri-urban domestic wells.

Thus, while policy-makers focus exclusively on utility-based urban water supply, opportunities to build decentralized community-based, private or self-supply systems have been neglected. Expanding urbanization in semi-arid South India indicates that it is probable that the distributed water sources used by irrigated agriculture will naturally evolve into a patchwork of decentralized urban supply systems. The centralized water paradigm does not allow for such a progression.

### *1.8.3 Centralized supply may not be the least-cost mode of supply*

Chennai's decision to build a desalination plant calls into question a long-held assumption: that urban water supply via a centralized piped supply system is always the least cost alternative. When the full costs of acquiring the raw water are factored in, the long-run marginal cost of supply from a centralized utility could, exceed the cost of local/community or private supply (own wells, local rainwater collection) alternatives.

Figure 1.12 below depicts representative long-run marginal costs of supply (including capital costs and operation and maintenance costs) from various modes of supply: private supply via tankers (bringing in water from peri-urban wells), utility supply (assuming desalination is the marginal source) and self-supply (via consumers' motorized wells).



* Private tanker costs from household survey, self-supply costs estimated based on borewell cost of construction and extraction amortized over a 15 year lifetime.

**Figure 1.12: Comparison of the long-run marginal cost of urban water supply**

Thus if the long-run marginal cost of utility-supply is desalination, the cost of self-supply via wells (not accounting for water quality differences) is clearly cheaper. If the costs of treating and delivering water through pipes are included then centralized supply via desalination is much more expensive. It is possible that some developing cities will face an extended transition phase. Consumers today are not able and willing to afford full-cost piped supply, preferring instead to depend on cheaper lower-cost local alternatives (private or community wells) for their non-potable needs.

### *1.8.4 Non-utility resource abstractions may be underestimated*

Basin-scale studies often focus on allocations to cities, equating the city to the utility. However, self-supplied water may be underestimated in basin-scale studies. Consumers in Chennai abstract water in large quantities independent of the water utility. Recent surveys as part of this study and previously by other groups indicate that a large fraction of urban consumers in India cope by accessing water from multiple sources: the public supply system, wells, private water tankers and packaged water. In a recent study of 8 Indian cities[35], the fraction of households resorting to self-supply varied from 4 percent to 77 percent, averaging 39 percent. The same study revealed that up to 11 percent of households used tanker water in some cities.

Although use of water from multiple sources is known in the context of consumer-scale "coping strategy" studies, it has not been explicitly included in the policy literature in utility-scale or basin-scale policy analyses. The impacts on the water resources at the basin-scale are assumed to be negligible. Even in cities where private groundwater extraction is significant, contributing to a large fraction of city water supply, it is explored only in the context of the coping costs imposed on consumers in the absence of full-scale piped supply[36] or as a upper bound on how much water can be charged.

### *1.8.5 Consumers' ability to manage multiple qualities of water is underestimated*

Consumer-scale analyses often report a single "willingness-to-pay" value or function, without recognizing that willingness-to-pay may differ greatly by quality of water; depending on the costs of the source and perceived risks of using it. One of the motivations for development of centralized piped water systems was to control water quality to meet potable standards and thus prevent water-borne diseases. However, various studies have shown that <u>non-potable</u> end-

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[35] Shaban and Sharma 2007

[36] Yepes et. al 2001, Solo 1999

uses of water, such as flushing, gardening and clothes washing, constitute the major component of domestic water use[37].

The focus of researchers and policy-makers on expanding high-quality centralized piped supply to meet all urban water needs misses the opportunity to promote use of lower quality, low-cost, grey water and groundwater for non-potable needs. The "grey" non peer-reviewed literature offers a variety of options like rainwater harvesting, and community based recharge management as alternatives to meeting non-potable needs. Mckensie and Ray (2004) discuss some of these alternatives. In Chennai, much of the water is sourced from outside the public supply system. Over two-thirds of households have their own private wells. An estimated 40 percent of households get non-potable water from private borewells (supplementing drinking water from handpumps). In fact, in Chennai, the number of sewage connections in Chennai actually exceeds the number of private water connections[38] indicating that a sizeable fraction of households are dependent exclusively on private borewells. Interestingly, our household survey in Chennai (described in Appendix F) indicate that consumers have the ability to match quality of supply to end-use. These alternatives to expansion of centralized-supply have not gained much traction in the mainstream development literature.

### *1.8.6 Simultaneous heterogeneity in all dimensions has never been attempted*

Most current studies deal only with heterogeneity in only one or two dimensions[39]: Consumer-scale studies focus on heterogeneity of users (types of agents and their ability to pay) and quality of water accessed. Utility-scale studies might focus on heterogeneity of users and modes of supply (standpipe supply versus piped supply, rich and poor consumers). Basin-scale analyses usually only consider inter-annual variability in water availability, treating the city or utility as a black-box. No studies have simultaneously addressed heterogeneity in agents, temporal variability, quality of water, and modes of supply. However, as discussed earlier the three policies differ from each other in each of the dimensions. They involve

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[37] Vaidyanathan and Saravanan, 2004.

[38] Metrowater 2006 (a)

[39] Some recent studies explore variability along two dimensions. For instance, Rosenberg et al. (2007) offer a multi-scale model of water supply in Jordan linking variability in utility supply and consumer responses. The model offers a systems' analysis of options available to the utility, integrated over dry and wet periods. However, the model doesn't explicitly include multiple modes of supply or basin-scale processes or differentiate between water qualities. Nauges and Strand (2005) in their demand estimation study explicitly include multiple modes of supply, but ignore inter-annual variability and differing qualities.

different decision-making agents, different temporal effects, different water qualities and different modes of supply. Ultimately, any framework comparing the policies will need to integrate all these elements of urban water supply.

### 1.9 Summary of dissertation

This dissertation attempts to address the question of what an efficient sustainable and equitable water supply system would look like. Using a case study of Chennai, India we develop an integrated approach to water supply systems in the developing world. We offer a theoretical framework that overcomes many of the gaps in research identified in the previous section, by allowing for multiple agents, temporal variability, multiple qualities of water and multiple modes of supply. The theory is applied to develop a model and simulate the state of Chennai's water supply. We show that expanding centralized supply may not always be the least-cost option. Instead, a combination of high-cost high-quality continuous piped supply and low-cost, low-quality decentralized self or community supply could address Chennai's water supply problem.

The research indicates that several factors contribute to making the dual-quality solution optimal. In the absence of reliable inter-state deliveries and a local perennial source, the long-run marginal cost of utility supply in Chennai is desalination, a very expensive option. Furthermore, a vast majority of consumers already have private wells; so consumers only consider the pumping costs of extracting groundwater from their wells; the capital costs represent sunk costs. So, if in order to achieve full-cost recovery, the utility raises its tariffs above the cost of extraction from private wells, rational consumers would switch out of using utility supply; except for uses that necessitate high-quality piped water. The model results indicate this outcome will enhance social welfare if some of the revenues generated by higher tariffs are reinvested in rainwater harvesting and recharge management. Importantly, decreasing demand for utility supply within Chennai will "free" up water for supply to the rapidly-growing, underserved suburbs. Thus, the dual-quality solution can result in a system that is more efficient, equitable, sustainable and reliable overall.

### 1.10 Layout of dissertation

The dissertation is organized as follows. Chapters 2, 3 and 4 discuss the theory and development of the integrated model. In Chapter 2, we develop our theoretical framework, the “integrated water paradigm”. We show how the theoretical framework can be implemented as an integrated model of urban water supply using a systems’ dynamics approach. In Chapters 3 and 4, we describe the development of the transient integrated model for Chennai, explaining the assumptions and data sources used to build the model. We describe the integrated model simulation of the historical period from Jan 2002- April 2006. We calibrate the model outputs against a variety of observed data: household survey data, groundwater heads, reservoir storage, and tanker prices, and total tanker market size.

The research questions laid out in Chapter 1 are addressed in Chapters 5, 6 and 7, respectively. In Chapter 5, we discuss the results for the historical run. We derive insights from the historical simulation to explain the nature of the biophysical and human responses in Chennai. We also present the consumer surplus for various categories of consumers in 2004 (drought year) and 2006 (surplus year). In Chapter 6, we run the model to 2025 to predict what the city’s water supply might look like, using reasonable assumptions about income, population, and land use change. This produces a “baseline” of Chennai’s water future. In Chapter 7, we simulate several policies over the period to 2025. Using reasonable estimates of policy costs, we then evaluate against multiple criteria how these different policy options compare. Finally, in Chapter 8, we present our summary conclusions, and scope for future work.

# 2 Chapter Two: The Integrated Water Paradigm

In Chapter 1, we argued that the centralized urban water paradigm was inadequate to explain the water supply situation in Chennai. In this chapter, we offer an alternative conceptualization of water supply in supply-constrained cities, which we refer to as the “integrated water paradigm”.

The chapter is organized as follows: We begin by describing the integrated water paradigm. Next we develop the theoretical framework. We explain how our theoretical framework allows researchers to consider heterogeneity along each of the four dimensions (agents, temporal variability, quality and modes of supply) identified in Chapter 1. Then we present our research method: development of a transient, integrated, simulation model. Finally, we show how our model will help us compare different policy options presented in Chapter 1.

## 2.1 The integrated water paradigm

The integrated water paradigm is an alternative framework for urban water supply in the developing world. The integrated water paradigm extends the centralized water paradigm, by allowing for multiple agents, qualities of water, modes of supply, and temporal variability in supply. We begin with the conceptual model of the centralized water paradigm described in Chapter 1. Then we extend the conceptual model to develop the integrated water paradigm. We do this by extending the centralized paradigm one dimension at a time, so that the final result is the integrated water paradigm.

### *2.1.1 Conceptual model of centralized water supply*

In Chapter 1, we described the existing utility-centric framework for urban water supply. The conceptual model of the centralized water supply system is shown in Figure 2.1.

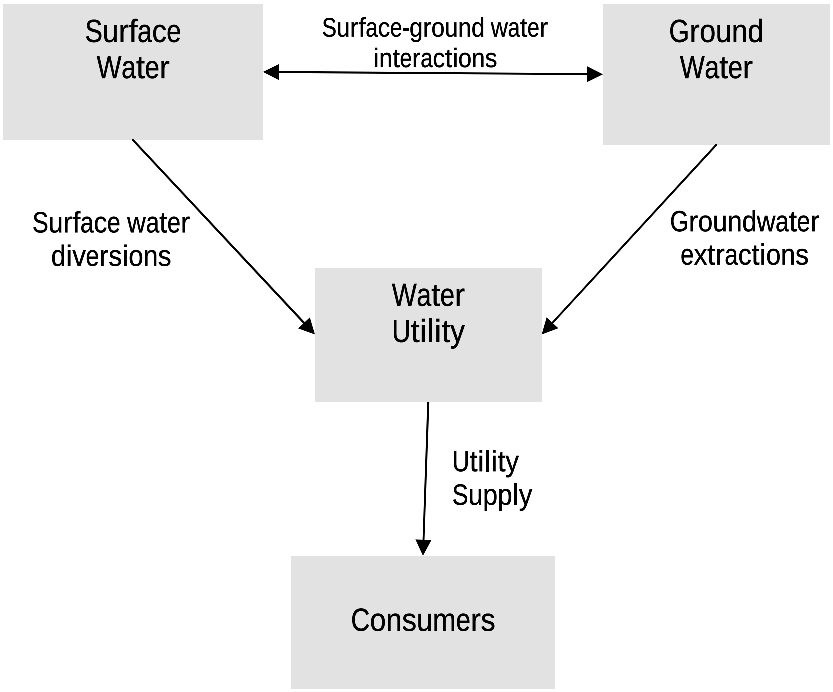

**Figure 2.1: The centralized water system – "Utility-centric"**

In the centralized water paradigm, the utility obtains water from the basin by extraction from surface water and/or groundwater sources. The utility then distributes the water to consumers. The consumer is a "passive" end-of-pipe recipient of water. If utility supply falls short, the consumer simply consumes less. Figure 2.2 shows the "theory of the consumer" under the centralized paradigm.

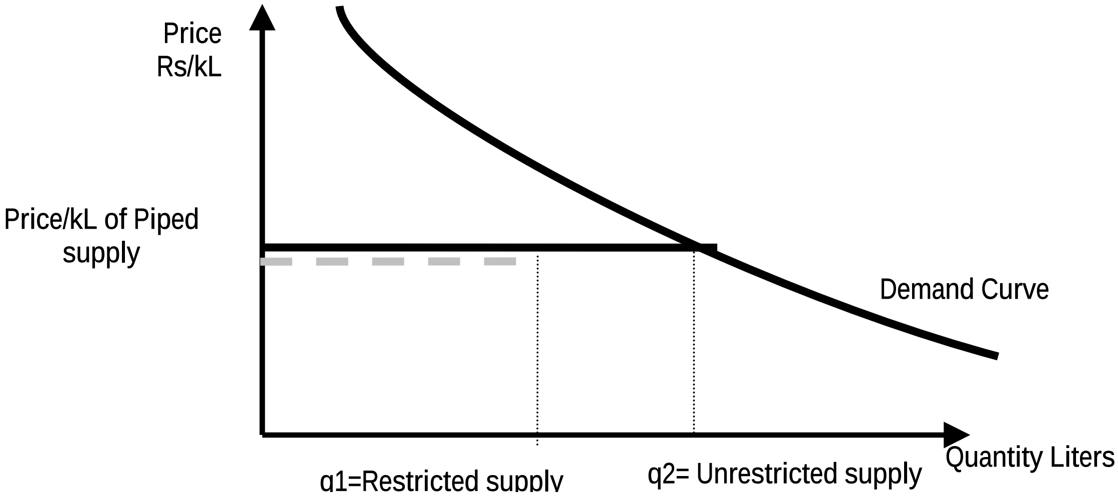

**Figure 2.2: Demand and supply curve under the centralized paradigm**

In the centralized water paradigm, the consumer is assumed to have access to only one mode of access to water, the water utility, one type of water quality, potable water. Many studies also assume only one type of user or a constant level of supply.

In subsequent sections, we will extend the centralized water paradigm. To keep the development logical, we will extend the centralized water paradigm by adding one dimension at a time in the following order:

- Modes of supply
- Quality
- Consumer categories as investment-making agents
- Temporal variability

For each dimension, we will show how the conceptual model of the system as a whole changes. For each, we will introduce how the theory of the consumer is extended.

### *2.1.2 Conceptual model with multiple modes of supply*

In Chennai, the utility is one of several modes via which consumers' access water. Figure 2.3 shows a generalized conceptual model in which the consumer can obtain water via multiple modes of supply. Some of these linkages are eliminated later to simplify this general model for the specific situation in Chennai.

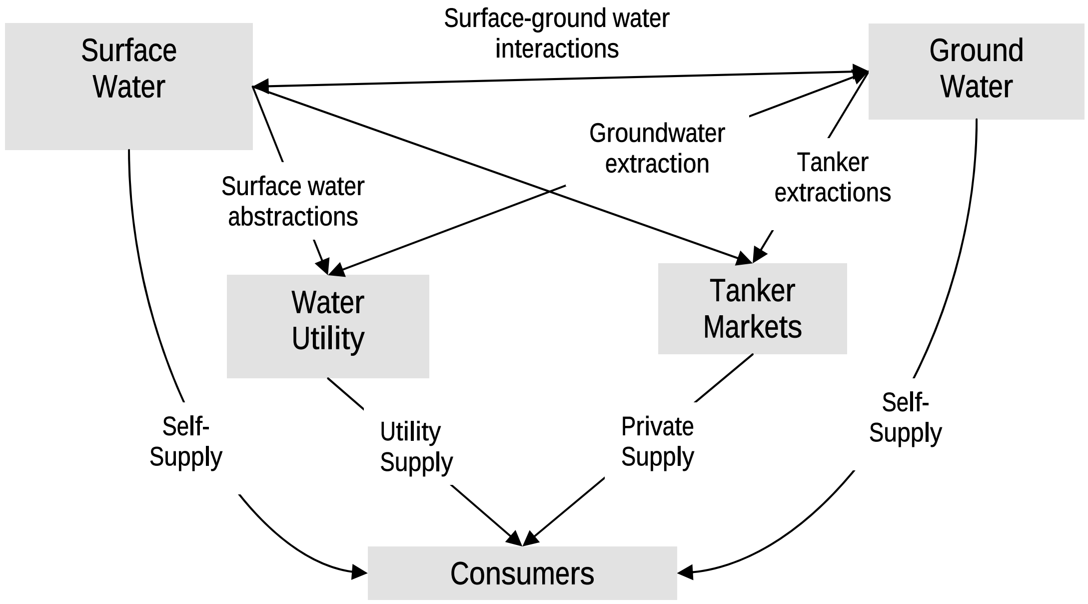

**Figure 2.3: Multiple modes of supply**

Figure 2.3 shows a conceptual model where the consumers can obtain water via multiple modes of supply. There are two differences between Figures 2.2 and 2.3.

1) In the integrated water paradigm, the consumer may access water from multiple sources. This is a departure from the conception of the consumer in the centralized water paradigm as a passive end-of-pipe recipient of utility supply.
2) The tanker market is explicitly included as an avenue by which consumers may indirectly obtain peri-urban groundwater or surface water.

In the conceptual model shown in Figure 2.3, like the centralized water paradigm, the consumer may receive water from the utility which in turn abstracts water from ground and surface water sources. Consumers may also extract groundwater or surface water directly (self-supply) from their own wells or surface water from nearby rivers/ lakes. Consumers may also access water from the water market by purchasing water from private suppliers (tankers, vendors, kiosks, packaged water, etc.). The private suppliers in turn abstract surface water or groundwater.

#### *2.1.2.1 Theory of consumer choice with multiple modes of supply*

We need a new theory of the consumer to allow the consumer "freedom of choice" in mode of supply. In developing this theory, we assume consumers are rational and have perfect information regarding the price of water from different sources. Solving the consumer's cost-minimization problem results in a solution wherein the consumer faces a "tiered supply curve". In other words 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 cheapest source. A hypothetical tiered supply curve is shown in Figure 2.4.

Figure 2.4 shows the demand and supply curves for a hypothetical consumer. For this consumer, the cheapest source of water is piped supply. When the consumer has used up the piped supply amount available, the consumer turns on his/her private well, and if the well goes dry, the consumer will call a private tanker supplier to deliver water. The total quantity consumed is determined by the intersection of the tiered-supply curve with the consumers demand curve. The "tiered-supply" curve is the solution to the consumers' cost-minimization problem presented in mathematical form is derived in Appendix A.

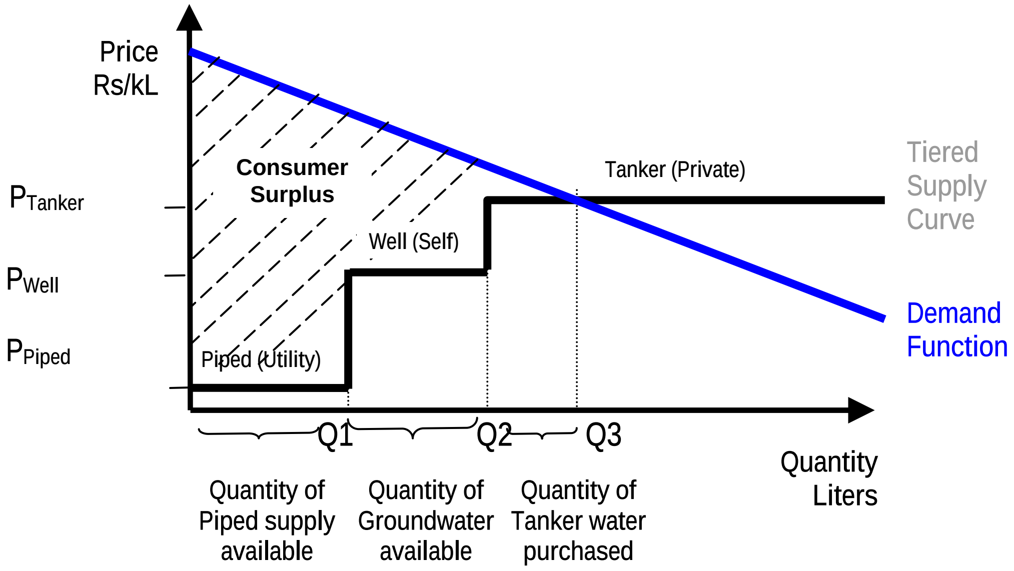

**Figure 2.4: Representative tiered supply curve**

Thus, the consumer faces a “tiered supply curve” and has a downward-sloping demand curve. The intersection of the two determines the total quantity consumed and the marginal source accessed. The area between the two curves, indicated by the shaded portion in Figure 2.4, is the consumer surplus, a measure of consumer well-being commonly used by economists. The expression for the consumer surplus is obtained by integrating the demand function and subtracting the costs. The mathematical expression for consumer surplus is derived in Appendix A.

### *2.1.3 Conceptual model with multiple qualities of supply*

In this section we extend the framework to account for the fact that the quality of water obtained from different modes of water is different. To keep the analysis tractable, we assume that consumers have the ability to distinguish between two qualities of water; potable and non-potable. They will strictly use potable water[40] for their drinking, cooking and perhaps rinsing needs (“potable uses”), for other purposes they are indifferent about the quality of water (“non-potable uses”). In Figure 2.5, the different modes of supply are differentiated based on the “quality” of water.

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[40] We do not define the exact parameters of “potable quality water” at this juncture, but instead broadly define it as whatever consumers accept to be water meeting their drinking or cooking quality standards. It could be a culturally accepted standard or a strict legal definition.

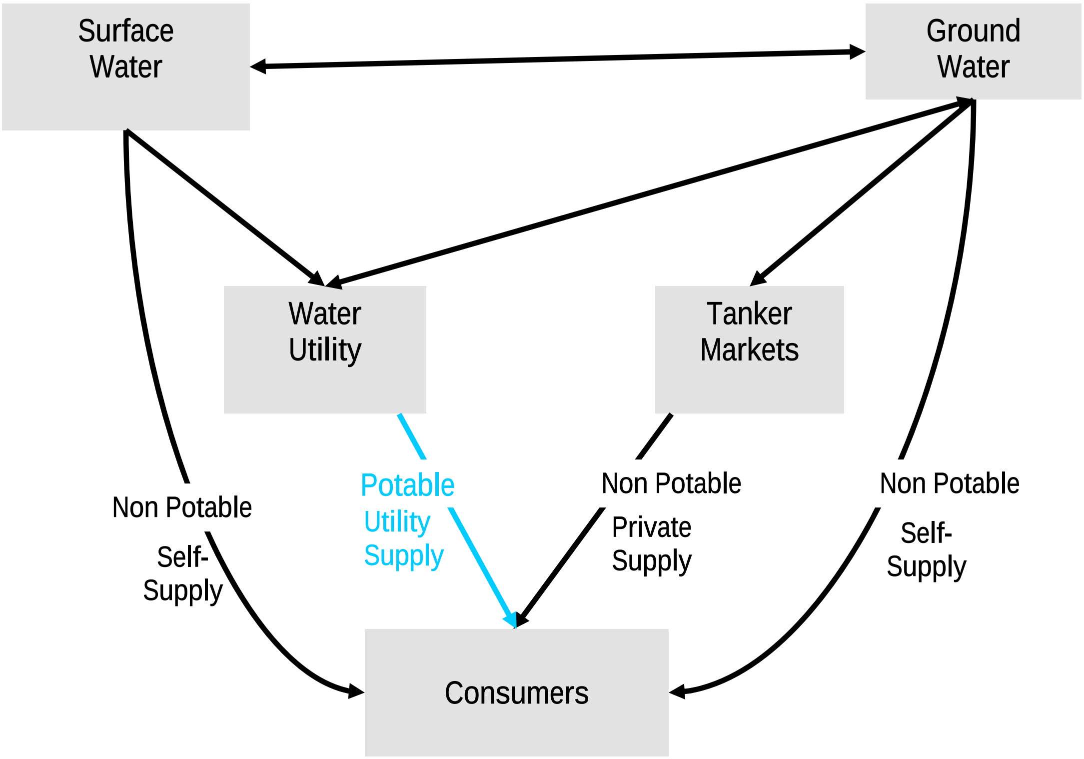

**Figure 2.5: Multiple qualities of supply**

Only water obtained from the utility is treated and thus considered to be of potable quality. Self-supply and private supply, are assumed to be of non-potable quality because they are untreated sources.

#### *2.1.3.1 Theory of consumer choice with multiple qualities of supply*

We extend the theory of choice developed in the previous section to include the two basic qualities of water. We propose the following assumptions

1. Consumers will use only potable quality water for potable needs (drinking, cooking, and rinsing).
2. Demand for potable water is inelastic and hence fixed.
3. Consumers may use potable-quality water for non-potables uses (flushing, bathing, gardening and washing) if available and cheaper to do so. Otherwise, they will use non-potable quality water.
4. Consumers derive a higher marginal benefit from the potable end-uses (drinking, cooking, rinsing) and these will be the last uses to be eliminated during shortages. Thus, if availability of both qualities of water is limited, consumers will assign the potable water to meet the potable requirements first.

In effect, we separate potable and non-potable uses of water into two demand supply curves. However, the supply curves are linked. The water available for non-potable uses from a particular mode of supply is equal to the total water available from that mode of supply, less the quantity needed for the potable end-uses.

Figure 2.6 shows the tiered-supply curves for non-potable needs.

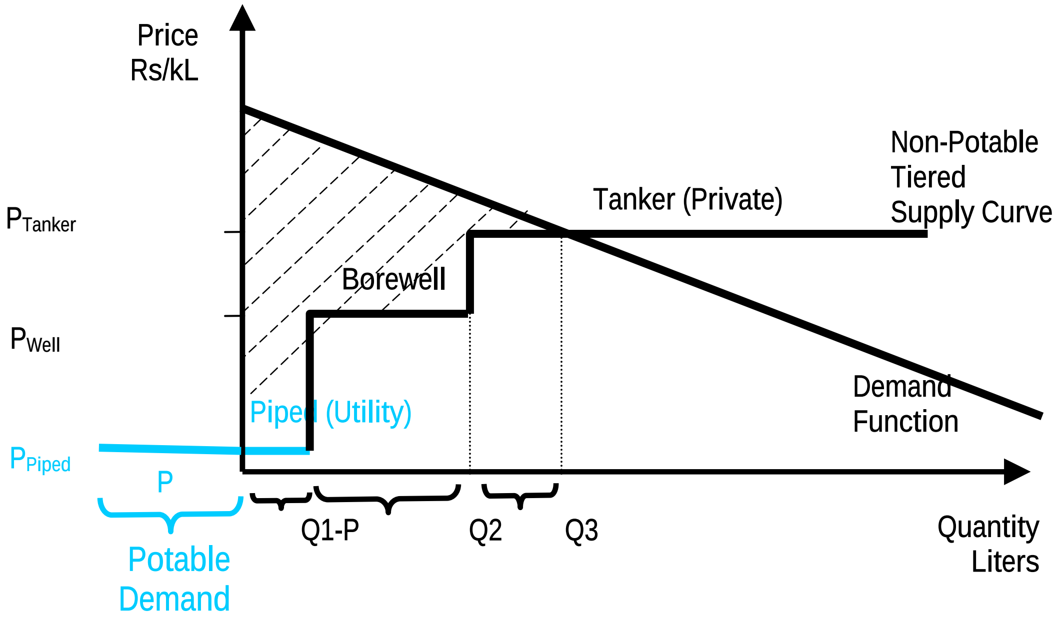

**Figure 2.6: Tiered supply curve with potable and non-potable sources and uses**

In the figure, the potable demand, P, is subtracted out from the total quantity available from the least-cost potable source. In the specific hypothetical example chosen, it so happens that the least-cost source overall, is also the least-cost potable source of water. This need not always be the case.

To avoid the confusion in interpreting the graphs, in the rest of the dissertation the potable and non-potable supply and demand curves will be presented separately in Figure 2.7.

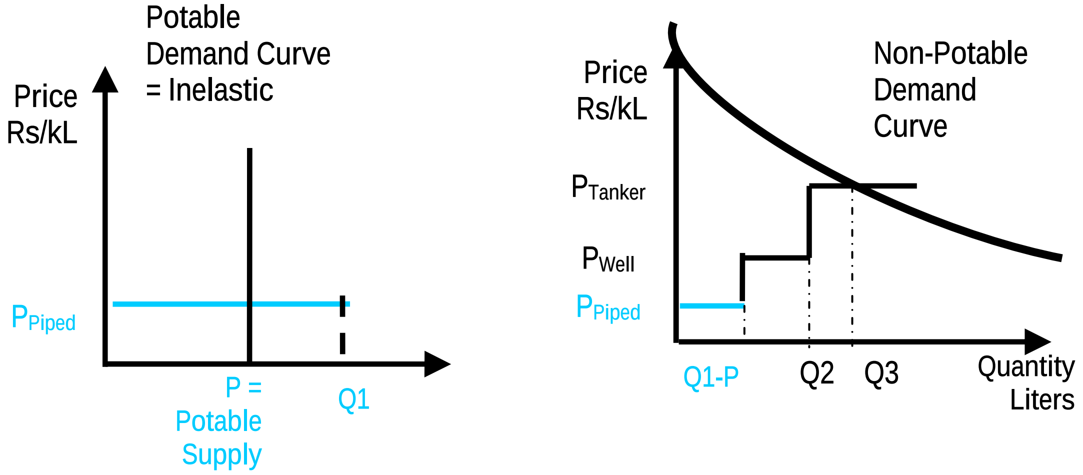

**Figure 2.7: Separated potable and non-potable demand and supply curves**

The potable demand P is subtracted from the quantity of piped supply available (Q1), in developing the non-potable tiered-supply curve. Thus the quantity of piped supply available for non-potable uses is Q1-P.

For the remainder of the dissertation, the potable portions of the supply curve will be shown in light blue. Also the consumer surplus will be estimated only for the non-potable portion of supply, since potable demand is inelastic. For economic policy analysis, benefits and costs of policies are always measured relative to a baseline. Because the potable component of consumption is considered inelastic (representing the minimum quantity a consumer can use) consumption is constant. Consequently, in all periods, for all consumers, the gross-benefit derived from potable consumption is identical. However, the cost of potable water is considered. Therefore, in estimating benefits to consumers only the consumer-surplus for the non-potable tiered supply curve, and the cost of potable supply are considered relevant.

### *2.1.4 Conceptual model with consumers with different levels of investment*

In the integrated water paradigm we want to be able to distinguish between different decision-making agents, other than the water utility. Investments made by consumers are explicitly incorporated into the framework, by categorizing consumers based on investments in infrastructure.

In the centralized water paradigm, the consumer's decision is limited to whether to connect to the utility, and what type of connection to get. Connection choices might include full-service piped supply, yard handpumps or taps, "mobile supply", remaining un-served, etc. However, once connected, the consumer has little control over the quantity or quality supplied[41]. Under the centralized water paradigm, the nature of connectivity to the utility mains and the operations of the utility system are the main determinants of the quantity and quality of supply and therefore, consumer well-being.

In the integrated water paradigm, consumer well-being is dependent on the quantity, quality and price of water available from multiple modes of supply. However, these factors are in turn contingent on prior long-term investments made by the consumer in connectivity, abstraction and storage. For example, a consumer can only have a "well" as a tier in the tiered supply curve if the consumer has made a prior investment in drilling a well.

To keep the analysis manageable, we make two simplifying assumptions regarding consumer investments.

Firstly, we assume that consumers only make the following types of investments:

- **Connectivity:** A consumer may choose to pay the "connection" fee to the utility to get a yard tap or handpump and receive utility supply.
- **Borewell:** A consumer may invest in a private motorized borewell to extract groundwater via self-supply
- **Storage:** A consumer may install an underground sump to store water.

Secondly, we assume that the investment made by a consumer only depends on the consumer's household income. The level of investment does not depend on external variables such as how wet or dry the year is, the quality of supply, or local geology.

To extend the framework to accommodate consumer investments, we divide consumers into categories based on the investments made. The tiered supply curve is constructed separately for each consumer category. The tiered supply curve is different for each consumer category, because the tiers or choices available to consumers are contingent on prior investments. The

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[41] Again there is some grey area here. Consumers do have avenues such a political action, activism, bribing the operators etc. to influence the quantity of water supplied. However, these are largely ignored in this research because they are so hard to model.

major advantage of classifying consumers based on prior investments is that only the short-run marginal cost (only O&M costs) and not the long-run marginal cost of supply are considered in the tiered supply curve. Figure 2.8 below shows the consumer categories suggested for Chennai.  These categories may need to be expanded or reduced for other urban areas.

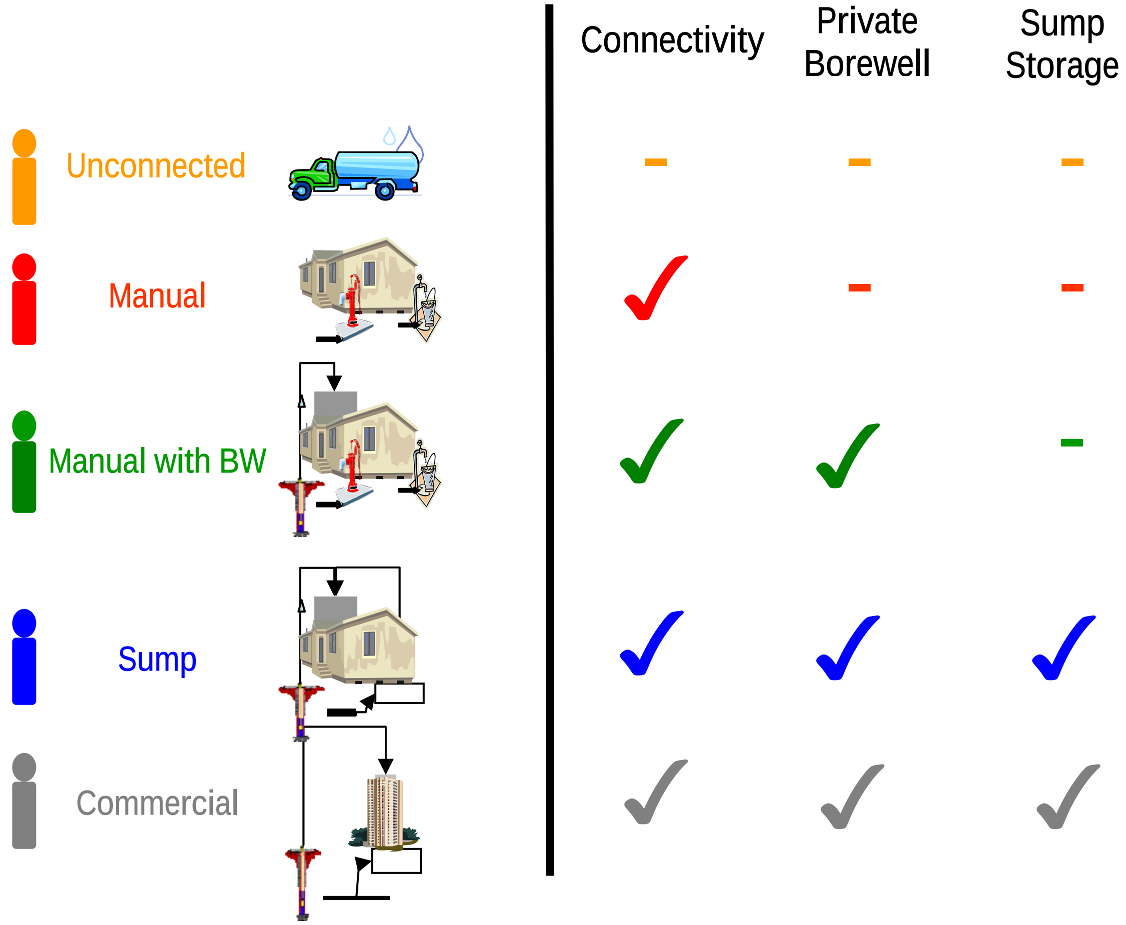

**Figure 2.8: Multiple consumer categories**

The categories shown in Figure 2.8 above are

***Unconnected:*** These consumers constitute the lowest income group and have no connectivity to the utility. They represent the poorest category of consumers. These consumers usually depend on public standpipes or community ponds or wells for their water.

***Manual Only:*** These low-income consumers have private in-house handpumps or yard-taps and are thus "connected" to the utility's piped distribution system but they lack indoor plumbing. These consumers must still collect water manually in pots from the yard tap or handpump and carry it into the house albeit over a shorter distance; but they do not have to wait in line and are not restricted in how many pots they can fill.

***Manual with Borewell:*** These are middle-income consumers with private handpumps or yard taps to access the utility piped network. However, these consumers have made investments in indoor plumbing and borewells. They receive water in their taps at home, but it is of non-potable quality and from a non-utility mode of supply. To receive potable supply, they must walk out to the yard-tap or handpump and collect water in pots.

***Sump consumers:*** These are upper-middle class to wealthy consumers living in single family homes or apartments. They have invested in an underground sump to receive water from the piped mains. They pump this water to a rooftop-tank and allow it to flow by gravity to the taps in the house. So they have plumbed in-house potable supply.

Most Indian utilities, including Chennai, have highly intermittent supply[42], with piped supply available for only a few hours each day. Instead of collecting the water in pots during the brief window it is available, and hauling it to the point of end-use when needed, underground sump storage allows consumers to "convert" an intermittent utility supply into a 24*7 piped supply system. This has tremendous implications on the "price" of the water to the consumer and hence the quantity consumed. This is because when water has to be collected manually, consumers must factor in the cost of time and effort of collection. Even at relatively low opportunity costs of time (a sixth of the minimum wage), hauling water manually is expensive.

***Commercial consumers:*** Commercial consumers face different tariffs and consume water in different ways than residential consumers. They also have a different demand function for water (different willingness-to-pay), which is why they merit a separate category. However, we assume they resemble sump consumers in terms of their investments in infrastructure.

For the remainder of this dissertation the color scheme used below will be used to represent these four consumer categories: unconnected consumers in orange, manual consumers in red, manual with borewell consumers in green, sump consumers in blue, and commercial

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[42] McIntosh, 2003

consumers in gray. Figure 2.9 shows the conceptual model of the system, with the different categories of consumers shown explicitly.

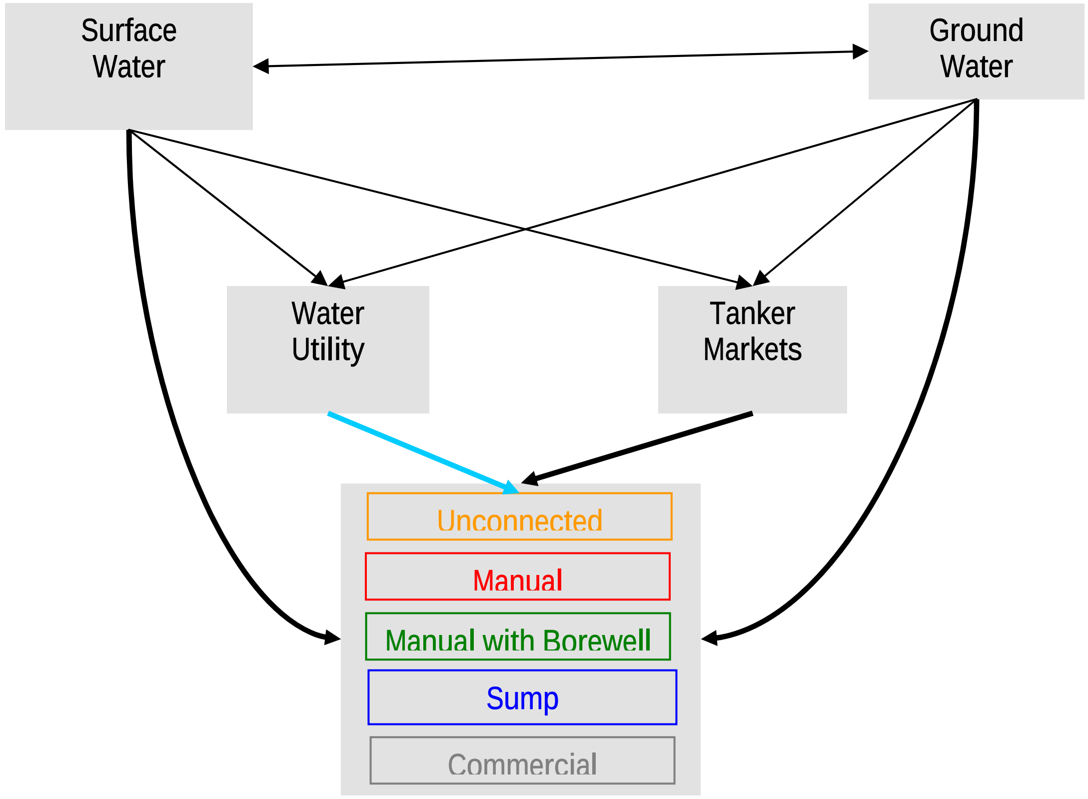

**Figure 2.9: Conceptual model of integrated water paradigm**

### *2.1.4.1 Theory of consumer choice with multiple consumer categories*

When developing the tiered supply curves for each consumer category, we link the tiers available to consumers based on prior investments made. In Figure 2.10 we show hypothetical potable and non-potable tiered supply curves for two sample consumer categories; Manual and Manual with Borewell. It is assumed that there is enough water available, whichever mode of supply the consumer chooses.

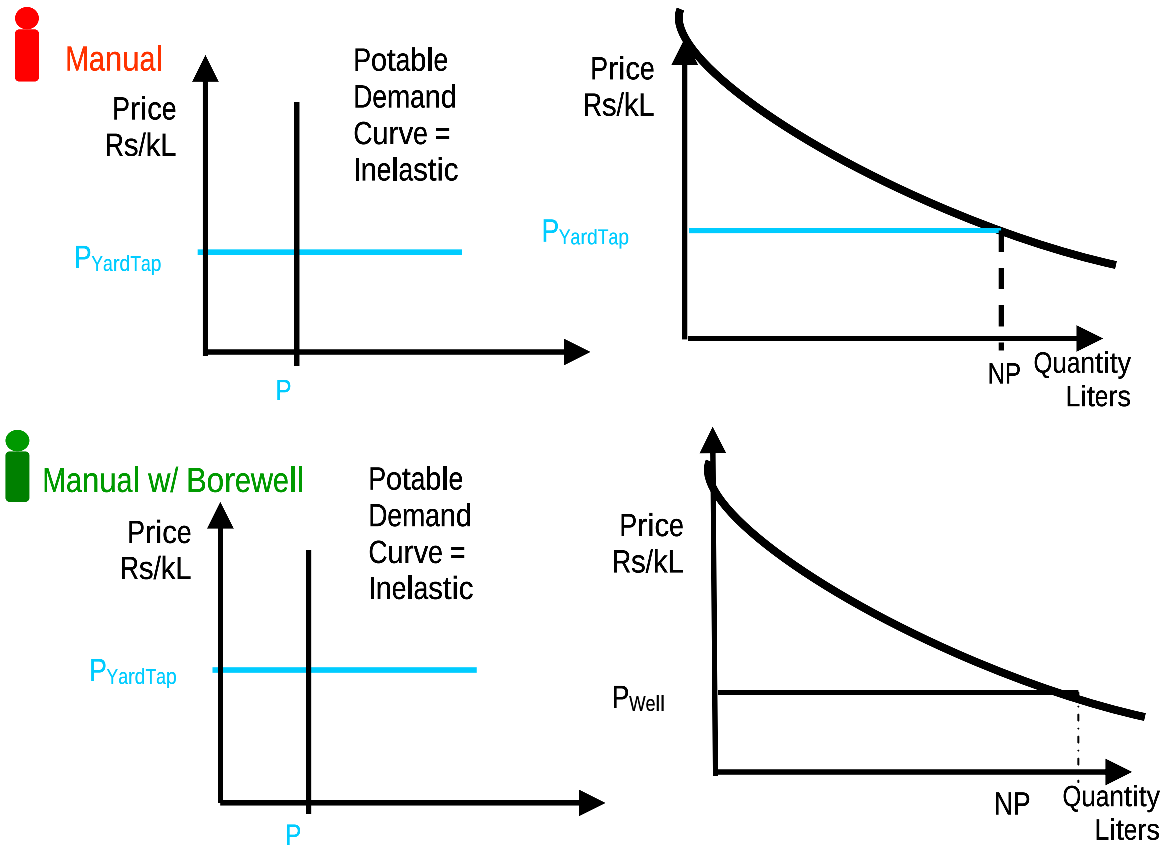

**Figure 2.10: Comparison of tiered supply curves across consumer categories**

From Figure 2.10 we see that because of differences in investments in abstraction, storage and connectivity, consumers may have different tiered supply curves. For manual consumers the yard tap is the cheapest source of supply for all needs. On the other hand, for Manual with Borewell consumers, yard-taps are the least cost potable source, but for non-potable uses, they prefer to use their private borewells.

### *2.1.5 Conceptual model with variability in water availability*

No additional changes to theory or the framework were necessary to incorporate variability in supply. For instance, Figure 2.11 shows the key system linkages in a situation where no-surface water is available via the city's reservoir system and utility supply is severely restricted.

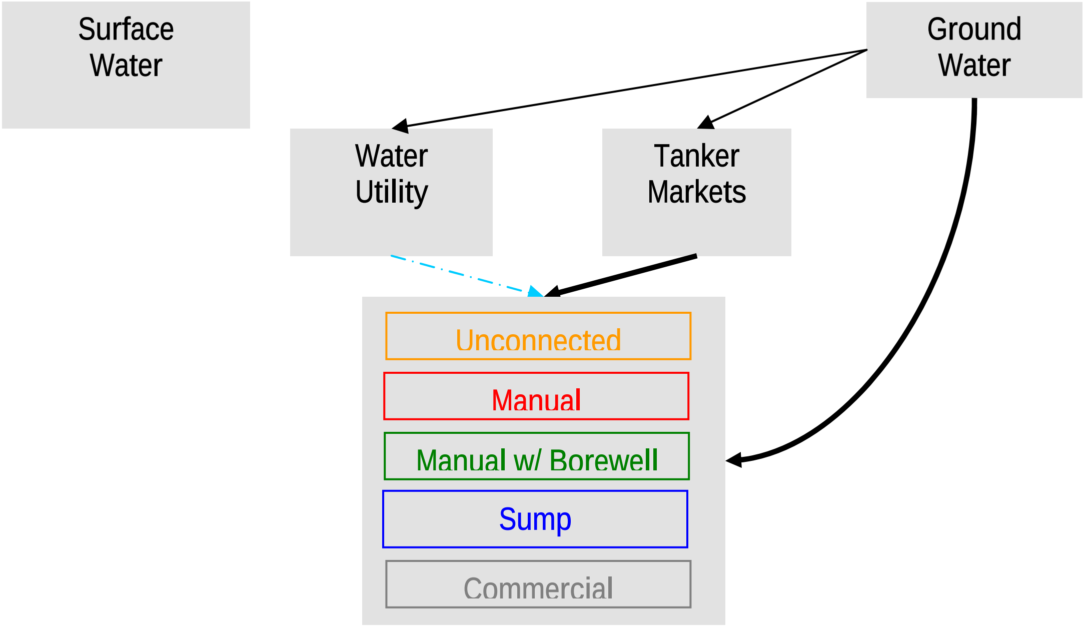

**Figure 2.11: System linkages in a drought year**

### *2.1.6 Conceptual model of integrated water paradigm*

Figure 2.12 shows the conceptual model of the integrated water paradigm with all dimensions.

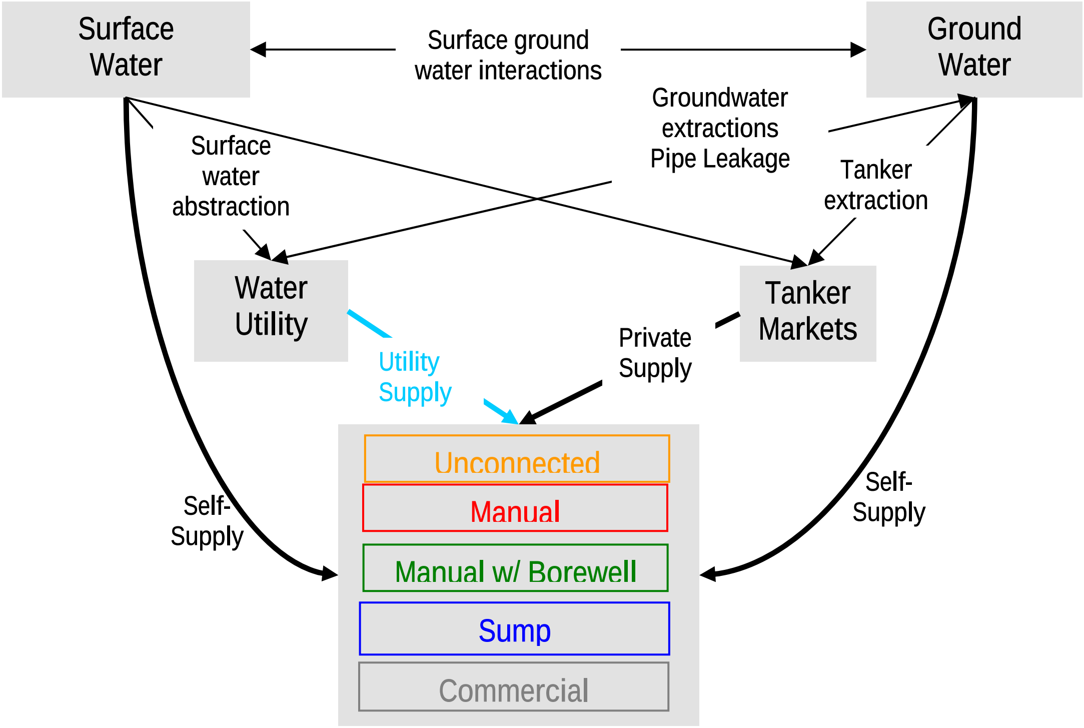

**Figure 2.12: Conceptual model of the Integrated Water Paradigm**

## 2.2 Research approach: Development of an integrated model

We addressed the research questions laid out in Chapter 1, by developing a systems' dynamics integrated model of water supply in Chennai, our case study area. In this section, we discuss how our research approach of developing a simulation model addressed the research questions. Then we present the modular structure of the model. We discuss the spatial extent and the units of analyses of the model. We list the main inputs, transformation equations and outputs for each module. We briefly discuss our calibration method. Finally, we describe the model outputs.

### *2.2.1 The integrated model addresses the research questions*

Table 2.1 shows how our research approach addresses each research question set out in Chapter 1.

**Table 2.1: Matching modeling simulations to research goals**

| **Research Goal** | **Modeling Simulation** |
|---|---|
| **Explain current and historical trends** | We developed and calibrated the integrated transient model to replicate current and historically observed patterns of water availability, and consumption. |
| **Develop a baseline forecast** | We forecasted model parameters out to 2025 to establish the state of Chennai's water system under a "baseline" or business-as-usual welfare level. |
| **Examine policy solutions** | We examined and compared the model outputs for each policy simulation. |

### *2.2.2 Modular structure of the integrated model*

The following Chennai-specific simplifying assumptions were made to the integrated water paradigm conceptual model:

1) Self-supply from surface water sources was eliminated as household surveys showed that it was insignificant.
2) Tanker operators in Chennai, when interviewed, did not show any evidence of abstracting surface water. Most depended on peri-urban wells. So the link between the tanker market and surface water bodies was eliminated.
3) Because there were no direct links between surface water bodies and consumers or tanker markets, only the reservoir system was modeled as part of the surface water module. Other

surface water bodies, like Chennai's seasonal rivers and peri-urban lakes, were only included exogenously as far as they impacted the groundwater recharge, since there was little direct abstraction from them within Chennai.

4) The link between the surface and groundwater module was eliminated, because leakage from the reservoir system was estimated to be negligible.
5) As the utility did not extract any groundwater from within the Chennai basin, the link between the Chennai groundwater and the utility was eliminated. Extractions from the well-fields were exogenous inputs into the model.

In building the integrated model we adopted a modular approach. Each component of the conceptual model presented in Figure 2.12 earlier became one "module" of the integrated model. Thus, the integrated model has 5 modules: the Reservoir Module, the Groundwater Module, the Utility Module, the Tanker Module and the Consumer Module.
Figure 2.13 shows the integrated model linkages for Chennai. Thus, Figure 2.13 is similar to generalized conceptual model presented earlier in Figure 2.12 except for the deletion of some links.

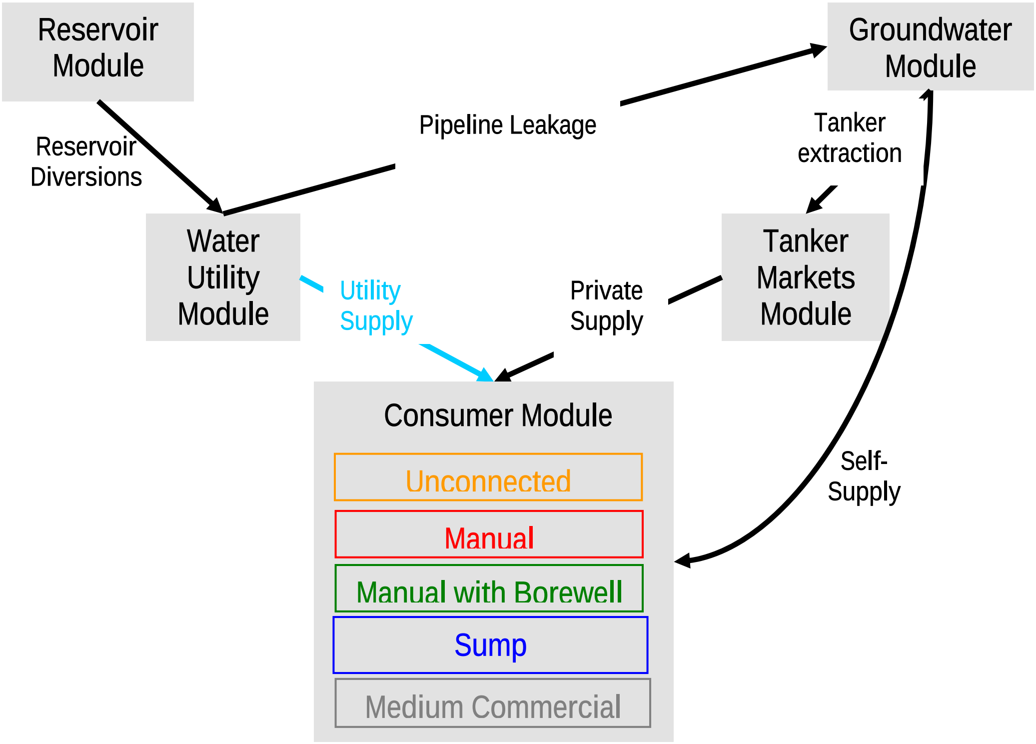

**Figure 2.13: Modular structure of integrated model**

The inputs, transformations, and output variables for each module are listed in Table 2.2. Table 2.2 shows the main function (or transformation) of each module. All the variables listed under "Inputs" are either known policy variables (known for historical period but may be set to different values in the future), calibrated parameters, or outputs of other modules.
In the table, calibrated parameters are in purple, variables for which surveyed or observed data are available are shown in gray, while endogenous variables are in black.

**Table 2.2: Function of each module**

| Module | Inputs | Transformation | Outputs |
|---|---|---|---|
| Reservoir Module | Rainfall,<br>Reservoir Evaporation,<br>Reservoir capacity,<br>Telugu Ganga water transfers | Rainfall-inflow relationship<br>Reservoir operational rules | Water diverted from city reservoirs for city supply |
| Groundwater Module | Land use<br>Geology,<br>Aquifer properties,<br>Recharge,<br>Extraction<br>Initial Conditions ( Heads)<br>Boundary Conditions | 3-D Transient Groundwater Model | Groundwater head as a function of space and time |
| | Geology,<br>Aquifer Properties<br>Well depths,<br>Groundwater head | Theim Equation | Maximum quantity of water that can be drawn from a well.<br>Fraction of dry wells |
| | Groundwater head<br>Pre-drawdown lift<br>Electricity price<br>Pump efficiency | Pumping cost calculation | Price of groundwater = cost of extraction |
| Water Utility Module | Water diverted from city reservoirs for city supply<br>Pipeline Losses<br>Water abstracted from other sources | Distribution rules | Water supply by utility to different consumer categories |

|  |  |  |  |
|---|---|---|---|
| Tanker Market Module | Demand for tanker water<br>Location of source areas<br>Cost of transportation | Competitive market pricing of tanker water | Price of tanker water<br>Size of tanker market |
| Consumer Module | Water demanded by consumer, by source: utility, groundwater, surface water and tankers<br>Price of utility supply<br>Price of groundwater<br>Price of tanker water<br>Opportunity cost of time<br>Collection time from private handpumps<br>Collection time from standpipes<br>Consumer demand function<br>Population, Income | Consumer choice algorithm | Water consumed by consumer category, by mode of supply, and quality |
|  | Water consumed by consumer category, by mode of supply, and quality | Welfare estimation | Consumer welfare |

## 2.3 Units of analysis

The integrated model is a transient, spatially explicit simulation of water supply in the city of Chennai. The model is spatially explicit, because variables are allowed to vary spatially across the basin. The model is transient, because it “marches forward in time.” All variables are recalculated at the end of each time period. The values of the variables in a given time period depend on the values in the previous period. Thus, a variable may take on a different value for a representative consumer in each consumer category, within each spatial unit, for each time period.

In this section, we first describe the model area and introduce the spatial units of analyses. The choices of the model extent and spatial discretization were motivated by the need to have a “sufficient” model, while allowing the model to run in a reasonable amount of time. We then introduce the assumptions specific to Chennai regarding temporal variability, modes of supply consumer categories, and water quality.

### *2.3.1 Spatial extent of model*

The model spatial extent was selected based on two criteria: Firstly, the model needs to capture future land-use and population changes and peri-urban growth. Secondly, the model needs to provide for reasonable boundary conditions in the groundwater module. Accordingly, the model covers an area of about 50 km * 50 km incorporating the entire Chennai Metropolitan Area[43] between latitudes 12° 86' N to 13° 32' N and longitudes 79° 92' E to 80° 38' E.

### *2.3.2 Spatial unit*

The integrated model uses two different spatial units within the model area. The groundwater module is spatially explicit. The groundwater flow model used is the USGS's MODFLOW-2000, computer software program that employs finite differences to numerically solve the 3-D transient groundwater equation. The inputs and outputs into the groundwater model were therefore specified for each grid cell. In contrast, the Utility, Consumer and Tanker modules use the census unit of a "municipal corporation zone."[44] For these modules, the input data (population and housing census data[45], were available for census units. Chennai city is divided into 10 zones, each about 10-20 sq. km in area. For reasons explained in Appendix C, zone 12 was split into 3 zones: 10A, 10B and 10C. So the model had 12 spatial units or zones.

The inputs and outputs of the groundwater model; groundwater head, recharge, extraction, and hydrogeologic parameters were specified for each grid cell. Initial and boundary conditions are also specified. For the groundwater module, the model area was divided into 231 rows and 231 columns, so that each grid cell is approximately 220m on the side[46] (or 0.002°) and 0.048 sq km in area. There are 3 model layers varying in thickness from 0.5 m to 108 m. In total there are 115,806 active cells in the model. The grid resolution selection was based on the need to maintain model tractability; we found that increasing the resolution greatly increased computational requirements. Moreover, a higher grid resolution was not justifiable

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[43] The choice of model boundaries was mainly based on the need to have reasonable boundary conditions for the groundwater model, a process which will be described in detail later.

[44] We actually collected data at the level of the smallest census unit available in Chennai, the corporation ward. Chennai has 155 corporation wards. The model was initially developed at the ward level, but was found to be unnecessarily cumbersome as most wards yielded very similar results. Other than corporation zone 10,which was split into 3 zones 10A, 10B and 10 C because there were big differences in geology and consumer base within it, all other zones were left intact.

[45] Government of India 2001

[46] Because Chennai is close enough to the equation, there was very little difference between the x and y lengths.

given the quality of data available. For instance, the groundwater head ranged from 30 m (above MSL) to 0 m from west to east across the model area or an average variation of about 0.12 m per grid cell. The groundwater level measurements were only found to be accurate within +/- 0.1 m, so choosing a smaller cell size was not justified.

A different unit was chosen for the consumer and utility modules, because they involve agent based models simulating a "representative consumer" defined as a median household. Demand and supply are estimated for each representative consumer. Using a census unit allows us to capture differences in consumer characteristics across census units. For instance, one zone may have a higher proportion of slums, another may have more commercial establishments, yet another may have a higher incidence of wells and so on. Fortunately, the zone also corresponds (more or less) to a Metrowater administrative division called an "Area." Metrowater aggregates and publishes statistics by "Area". The spatial unit used by each module is shown in Table 2.3.

**Table 2.3 : Spatial unit of analysis**

| **Module** | **Spatial Unit** |
|---|---|
| Consumer | Zone (i = 1, 12) |
| Utility | Zone (i = 1, 12) |
| Tanker Market | Zone (i = 1, 12) |
| Surface Water | N/A (Only models the reservoir storage in each period) |
| Groundwater | Grid Cell ( x ε{1,..,231} , y ε{1,..,231} ) |
| Land use Map | Grid Cell ( x ε{1,..,231} , y ε{1,..,231} ) |

Figure 2.14 shows how the spatial units were mapped across modules. On the left is the "census map" showing the 12 spatial units or zones within the city and the census blocks outside the city. On the right is a land-use map which depicts the land use in each groundwater model grid cell, with the borders of the census blocks overlaid on it. Both maps were developed in MS Excel. Any given grid cell can be mapped uniquely to one census unit. Similarly, any given census unit can be mapped uniquely to the set of grid cells that fall within its boundaries.

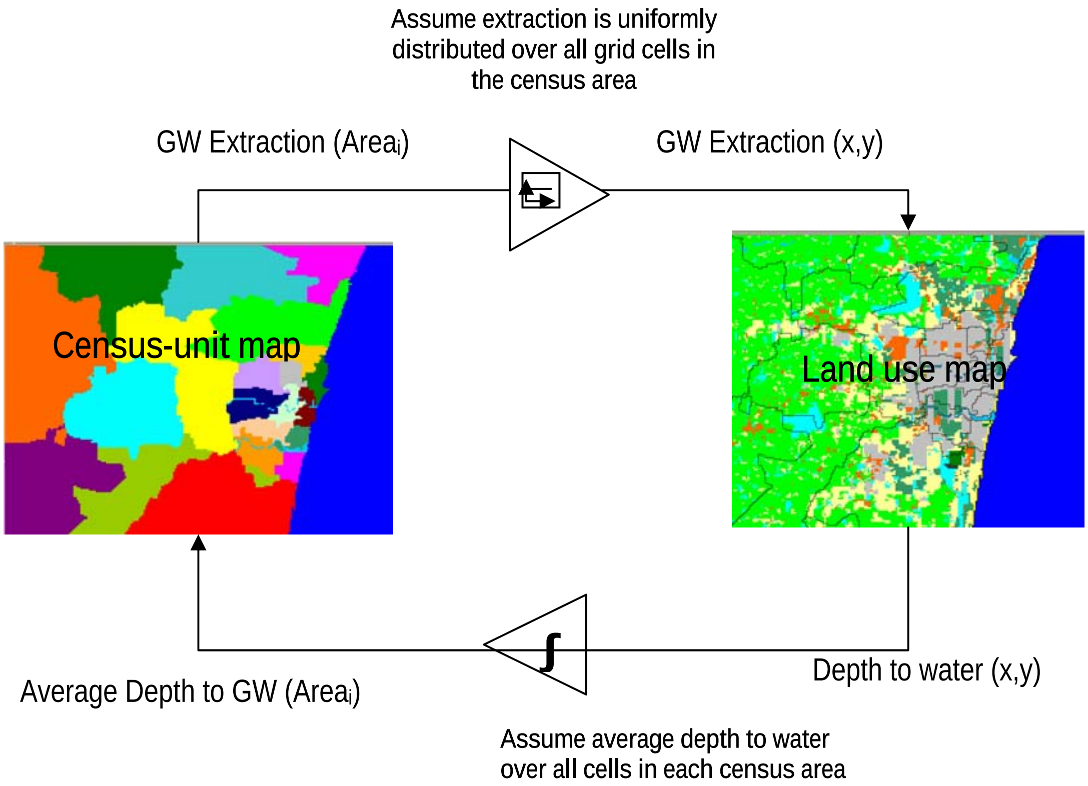


**Figure 2.14: Mapping spatial units**

### *2.3.3 Temporal Unit*

The temporal unit or "time step" of the integrated model was selected to be three months (i.e., one quarter). Three month periods (Jan-Mar, Apr-Jun, Jul-Sep, Oct-Dec) were found to be a reasonable time period to allow us to capture seasonal variations, while still allowing the overall model to run in a reasonable amount of time. The choice of temporal unit at three months is important because it defines the level of temporal variability of the model. A period of one year would miss seasonal effects; a period of one month would take too long to run.

The three-month sequences were chosen based on considerations of growing seasons (there is a considerable amount of irrigated agriculture in parts of the Chennai basin) and Chennai's rainfall and groundwater patterns. Chennai receives rainfall mainly in the months from Oct-Dec from the northwest monsoon and to a lesser extent from Jun-Sep from the Southwest monsoon. Groundwater levels are highest in January, and lowest in July. However, to improve accuracy of solution, some sub-modules were run at shorter time-steps. The groundwater model operates on much shorter time-steps, each 3-month period is divided into

50 time steps. The surface water model, being a mass-balance, was run with a time-step of one month.

### *2.3.4 Consumer categories*

The consumer categories were chosen based on differences in demand, supply, and investments by residential consumers as described earlier in the chapter. Additionally, we had two types of commercial consumers, medium commercial (restaurants, hotels, educational institutions) and water-intensive commercial (e.g. hotels, hospitals). The water use of very small commercial establishments (most of which do not even have restrooms) was assumed to be negligible. Based on these criteria we identified six distinct consumer categories. In the model, the consumers' problem is solved for a "representative agent" in each consumer category, within each spatial unit, in each time period. The categories are

1. ***Unconnected consumers:*** These, the poorest of consumers, do not have private in-house Metrowater connections. They also lack indoor plumbing. They depend on Metrowater "mobile" supply (free tankers operated by Metrowater to supply neighborhoods receiving little or no piped supply), public standpipes, and community wells. When no other source is available they may purchase water by the pot from water vendors or private tankers. All unconnected consumers must manually collect water in pots from a communal source, and carry it back home. Because they collect water from a communal connection, they usually also have to stand in line and may be restricted by community norms in how many pots they are allowed to collect. Unconnected consumers constituted about 15 percent of the households in Chennai in 2001.
2. ***Manual consumers:*** These low-income consumers have private in-house handpumps or yard-taps and are thus connected to the utility's piped network. However, they lack indoor plumbing. These consumers must still collect water manually in pots from the yard tap or handpump and carry it into the house (a shorter distance), but do not have to wait in line and are not restricted in how many pots they can fill. In addition to Metrowater supply, they may have open (shallow dug) wells or community wells from which they draw water manually, or purchase water by the pot from street vendors. Manual consumers constitute 21 percent of the households in Chennai.
3. ***Manual with Borewell consumers:*** These moderate-income consumers have private handpumps or yard taps to access the Metrowater piped network. However, they have made investments indoor plumbing and borewells. They use borewell water for most of their non-potable needs, relying on the handpumps only for potable quality water. They

may also buy private tanker or vendor water during a drought. This category constitutes about 35 percent of the population.

4. ***Sump consumers:*** These are upper-middle class to wealthy consumers living in single family homes or apartments. They have "full-service" piped water access and indoor plumbing. Almost all also have borewells and sumps. So they can buy and store private tanker water during a drought. These consumers constitute about 30 percent of the population.
5. ***Medium Commercial:*** These are mid-sized commercial consumers, typically offices, retail stores, etc., whose main consumption of water is for restroom use. Like single family homes, they have piped access to Metrowater, but they pay higher commercial rates. In our model, we only consider commercial establishments with Metrowater connections[47]. They invariably also have borewells and commonly purchase tanker water. There are about 44,000 such consumers in Chennai
6. ***Water Intensive Commercial:*** These are large hotels, hospitals, or small-scale industries which use a lot of water. Metrowater classifies them as "water intensive commercial." Many are also "bulk consumers." They often have dedicated mains from the pumping station and are charged exorbitant rates (about 30 times the volumetric domestic price). In general, these establishments pump a lot of groundwater and routinely purchase water from tankers. In fact, water intensive commercial consumers constitute a significant fraction of the tanker market in all years.

Table 2.4 shows how the residential consumer categories described above, map to household incomes for Chennai. The values are based on the 2006 household survey data presented in Appendix J. Unfortunately the household survey data asked consumers to select income brackets rather than report actual household income, so only average incomes could be ascertained.

---

[47] The 1998 Economic Census data indicate that there are close to a million commercial establishments in Chennai but most are small establishments no water use using shared restroom facilities. So decide to not use the census data instead focusing on

**Table 2.4: Map between income and consumer category**

| **Category** | **Median Income Bracket** | **Average Household Income (2005)** |
|---|---|---|
| **Unconnected** | 1 | Rs 1500/ Month |
| **Manual** | 1 | Rs 3500/ Month |
| **Manual with Borewell** | 2 | Rs 7500/ Month |
| **Sump** | 3&4 | Rs 12,500/ Month |

The fraction of households belonging to each consumer category was estimated from the 2001 Housing Census data and is explained in Appendix C. The number of medium and water-intensive commercial consumers was obtained from Metrowater to be about 44,000 and 1,100, respectively. Figure 2.15 displays the fraction of households in each residential consumer category.

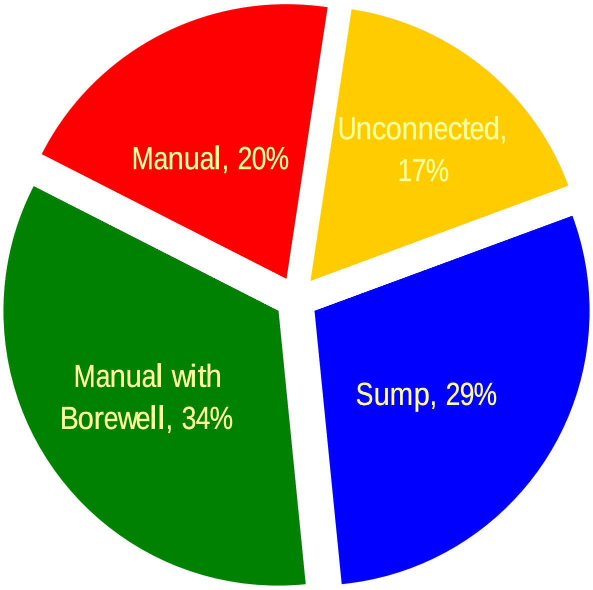


**Figure 2.15: Percentage of households in each consumer category**

In our model, the consumers' problem is solved for a "representative agent" in each consumer category, for each spatial unit, in each time period.

## 2.4 Calibration methodology

The purpose of calibration is to estimate model parameters.

Variables in a model may be classified into three types

1. ***Known inputs***. These are independent variables that are known for an historic period. Population, rainfall, prices are examples. These variables can usually be assumed to lie within a certain range during future periods.
2. ***Known outputs***: These are dependent variables that are calculated or endogenous to the model. For which observation data are available for past periods
3. ***Parameter inputs***: These are model inputs that are not easily observable (e.g., well efficiency, number of water-intensive commercial consumers, irrigation water needs, opportunity cost of time, aquifer hydraulic conductivity), and therefore few or not necessarily representative data exist for historical periods. However, these parameters are required in the equations in the model.

The calibration process is one of estimating parameter values that allow calculated model outputs (dependent variable) to match data. The challenge in calibrating complex models is that very different parameter values may coincidentally produce the same result. For instance, we might find that assuming high well-efficiencies and a low number of water-intensive commercial establishments produces the same result as a low well-efficiency and large number of water-intensive commercial establishments. This is called the "parameter correlation" problem. To address this problem, we use the notion of the "smallest independently calibratable component." The advantage of breaking up a big model into smaller components that can be calibrated independently so that the problem of unexpected parameter correlation is minimized i.e., we minimize the chance of several combination of parameters producing the same result.

The criterion for selecting the "smallest independently calibratable component" is that within each, all variables other than the parameter to be calibrated were known (census data, rainfall data, land use maps, etc.) or were observed at some time (household survey data, prices, size of tanker market) during the historical record. Fortunately, most sub-modules in the integrated model met this criterion, and so could be calibrated independently. Each sub-module in the integrated model typically only had one unknown parameter value. All other inputs were either know variable values, policy parameters or had observed values for past years. In a few cases, we only had "expert assessments" not observations or measurements. In these cases, these values have been cited accordingly and sensitivity analysis was conducted over the range suggested by the experts.

## 2.5 Model outputs

The integrated model produces the following outputs

1) Quantity of water consumed
    a. by quality (potable and non potable)
    b. by mode of supply
    c. by consumer category
    d. in each time period
2) Consumer surplus for each consumer category in each time period

## 2.6 The Integrated Water Paradigm and the three solutions

In the previous sections of this chapter we introduced a new theoretical framework. We showed how the framework could accommodate each of the important dimensions of water supply. We also showed how we planned to implement our theoretical framework as an integrated simulation model.

In this section we show how our approach will allow comparison of the three policies: Supply Augmentation, Efficiency Improvement and Recharge Management, on a consistent "apples-to-apples" basis. We do this by identifying the main parameter changes required to the model, to implement each solution. In each case we show that the model produces a constant measure, "net social benefits" (gross social benefits[48] less implementation costs). Thus we argue that the integrated model can answer the research questions set up in Chapter 1.

### *2.6.1 Supply Augmentation*

The Supply Augmentation solution involves increasing the quantity of surface water availability by expanding reservoir storage, developing an inter-basin transfer project, or building a desalination plant. For this solution, the main parameter changes would occur in the surface water, and utility modules as shown in Figure 2.16. These parameter changes would be expected to impact the consumer module as shown in Figure 2.17.

---

[48] Gross social benefits is definted as the sum of producer and consumer surplus

The parameter changes expected under Supply Augmentation are indicated as dashed boxes in Figure 2.16. For instance, the utility might consider increasing reservoir capacity or adding a desalination plant. This would alter the amount of surface water available to the utility.

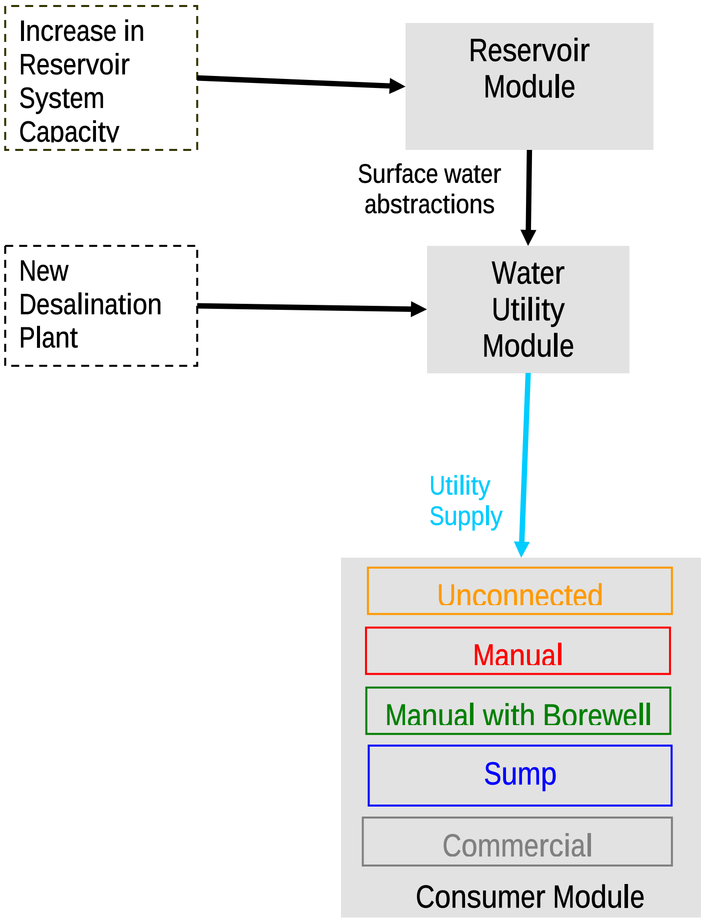


**Figure 2.16: Parameter changes in Supply Augmentation Scenario**

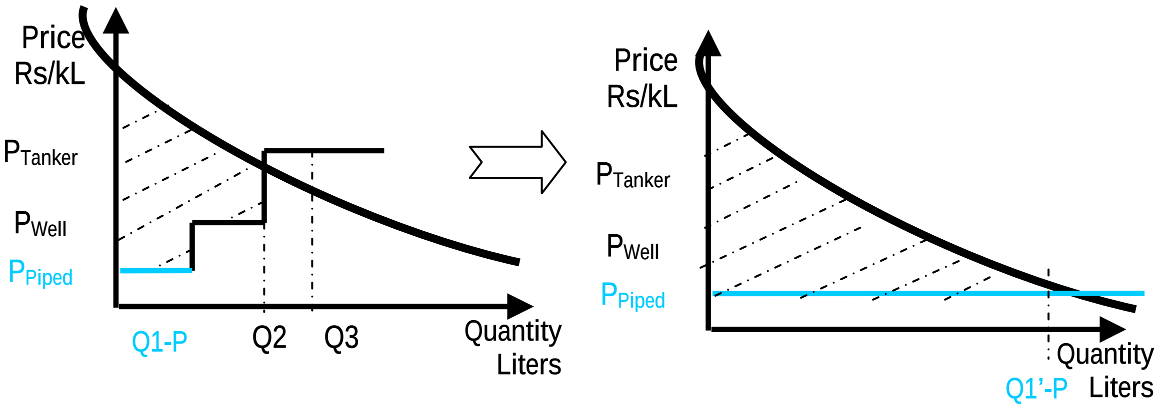


**Figure 2.17: Likely change in consumer surplus changes from Supply Augmentation**

Thus, increase in the availability of utility supply would result in increasing consumer surplus. For this policy, the change in gross social benefits is the total increase in consumer surplus per household aggregated across all households. Net social benefit would be the gross social benefit, less the costs of implementing the policy.

### *2.6.2 Efficiency Improvement*

The Efficiency Improvement solution involves increasing tariffs and reducing pipeline leakage. For this policy, the main parameter changes would occur in the Consumer and Utility modules as shown as dashed boxes in Figure 2.18. Pipeline losses would be entered as an input parameter in the Utility module. Higher utility tariffs would be entered as an input parameter in the Consumer module.

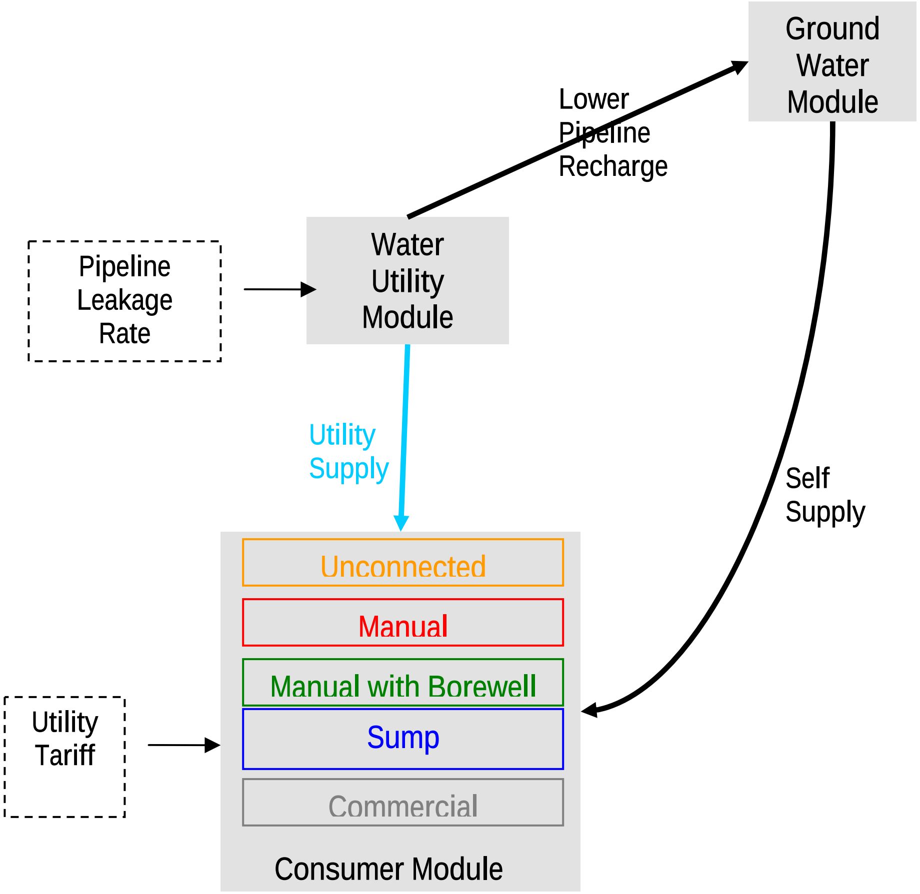
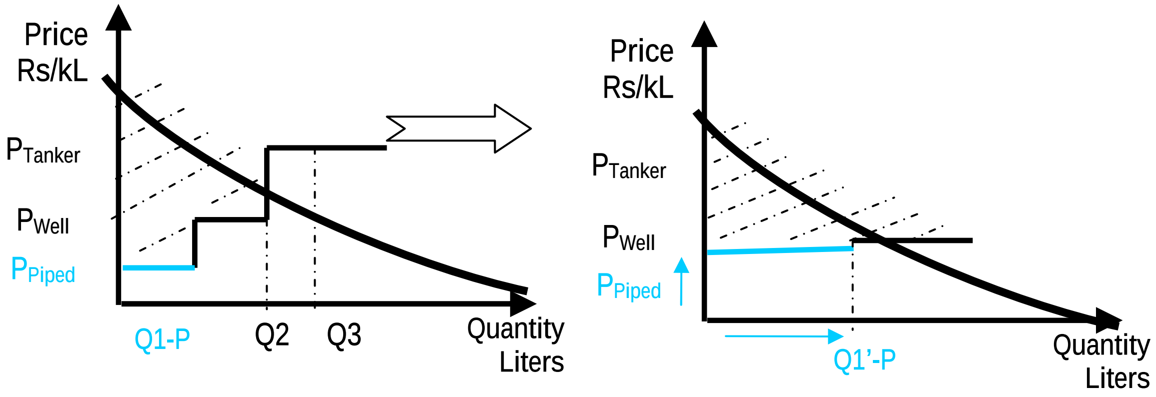


**Figure 2.18: Parameter changes under Efficiency Improvement scenario**

These parameter changes would be expected to impact the consumer module as follows:

The decrease in pipeline results in more water being available via piped supply to households, increasing consumer surplus. Increase in tariff would shift the utility supply component of the supply curve upwards, decreasing consumer surplus. Furthermore, the decrease in pipeline losses might lower water levels in the aquifer and decrease the groundwater available in consumers' wells. It is difficult to predict how these factors would balance out a priori. The changes in the tiered-supply curve are shown in Figure 2.19.



**2.19: Effect of parameter changes under Efficiency Improvement scenario**

### *2.6.3 Rainwater Harvesting*

For this policy, the main parameter changes are in the Groundwater module as indicated by the dashed box in Figure 2.20.

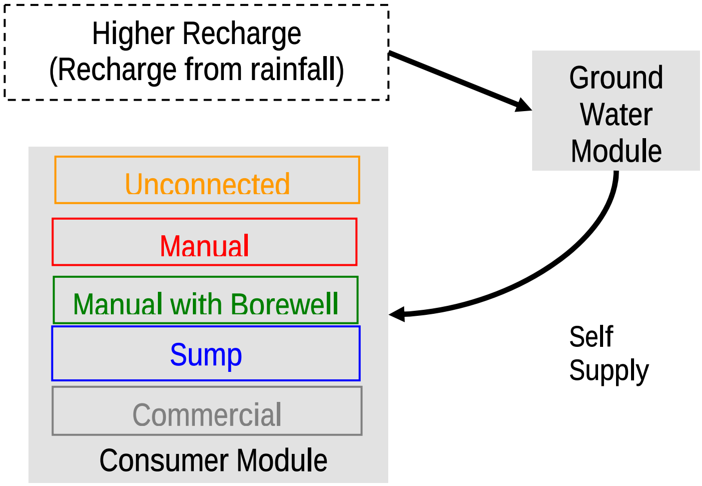


**Figure 2.20: Parameter changes under Rainwater Harvesting policy**

The expected impact of the parameter changes due to Rainwater Harvesting, on consumer surplus is as follows: Increasing rainfall recharge raises groundwater levels, preventing wells from going dry during a drought. This allows consumers to avoid purchase of tanker water during the drought. Possible changes in the tiered-supply curve are shown in Figure 2.21.

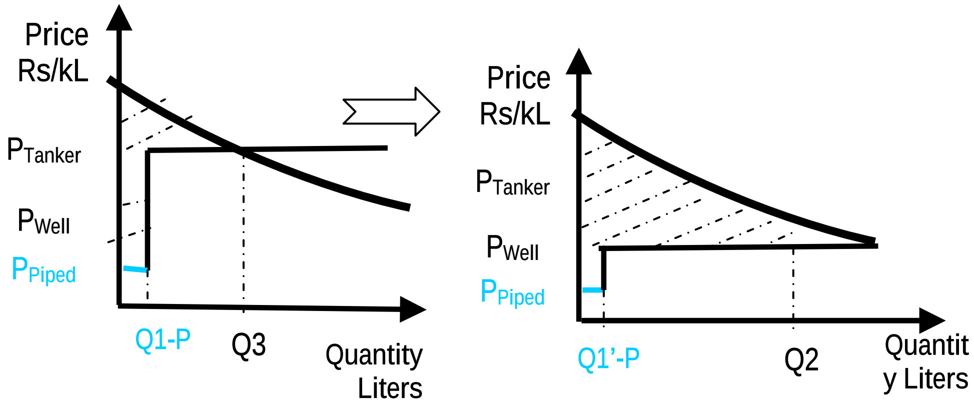


**Figure 2.21: Effects of parameter changes under the Rainwater Harvesting policy**

Rainwater harvesting measures would increase consumer surplus by putting water in consumers' wells. The net benefits from the solution would be the total increase in consumer surplus across all consumers, less the costs of implementing the policy.

### *2.6.4 Comparison of policies*

In the preceding sections, we have shown that in theory, for each policy we will be able to generate a consistent measure, net social benefits, of how the policy contributes to improving economic efficiency. Because we estimate the benefits for each consumer category, we can also compare the distributional effects of each solution. Similarly, because we estimate the benefits for each time period, we can also evaluate the effectiveness of the three solutions in sustaining consumer welfare in dry and wet periods.

## 2.7 Chapter Summary

In this chapter, we presented our theoretical framework and showed that it addresses the gaps in the literature identified in Chapter 1. By implementing the framework as a simulation model, we can compare the three policies using a consistent set of evaluation measures.
In the next Chapter we will present the development and calibration of three modules of the integrated model.

# 3 Chapter Three: Model Development – Part I

In this chapter, we describe the development and calibration of the three modules of the integrated model introduced in Chapter 2; the Reservoir module, the Groundwater module, and the Tanker module. For each module we explain the data sources, variables, parameters, and outputs. The remaining two modules (Utility and Consumer) are presented in Chapter 4. A detailed description of each of the three modules is provided in this chapter. For each module, we show a diagram of the key linkages, list the transformation equations and identify the sub-modules. Then each sub-module is described in detail; the input variables, calibrated parameters, equations, outputs, etc. Wherever appropriate only the outcome of the calibration process is included in the main text of the chapter, the details are presented in an Appendix.

## 3.1 Reservoir Module

The purpose of the Reservoir module is to simulate the city's reservoir system. In our model we only focus on the three main reservoirs serving Chennai. Surface flows that do not contribute to the reservoirs are not modeled[49]. Chennai has traditionally depended on three rain-fed reservoirs, the Poondi, Cholavaram and Red Hills. The three main reservoirs (shown in Figure 3.1) are interconnected and located fairly close to one another, so for practical purposes are treated as a single reservoir system. The three-reservoir system also receives and stores water from the Telugu-Ganga Project (interstate transfer from the Krishna River). These sources combined contribute the bulk of the surface water supply to Chennai.

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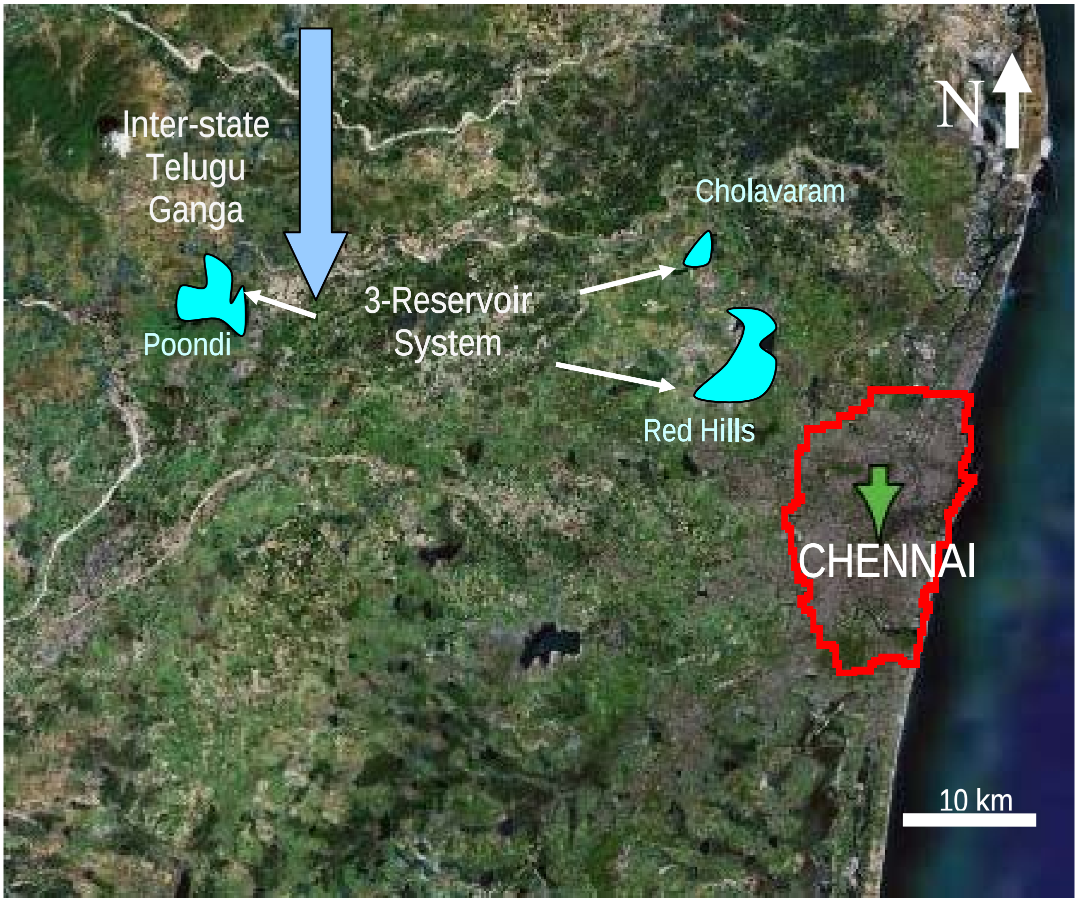
[49] We believe this is justifiable for three reasons. Firstly, although two rivers, the Adayar and the Cooum flow through Chennai, household surveys showed no evidence of in-situ use of river water (Vaidyanathan and Saravanan, 2004). Thus, there are no inputs from the surface water module to the consumer module. Since both rivers are dry for over most of their course for most of the year, there is also little interaction with the aquifer, except for a few days each year, when the interaction is modeled exogenously. Secondly, although Chennai receives a small amount of water from the peri-urban Chembarambakkam lake; it contributes only a small component of Metrowater's supply. Moreover, as it is located in the same watershed, we can assume that water availability from these lakes is correlated to that of the three-reservoir system. Thirdly, although the landscape is dotted by numerous tanks (ponds or small lakes are referred to as "tanks" locally), these are used largely for irrigation or as serve as infiltration structures. Thus, while recharge from tanks and their contribution to irrigation use is considered in the Groundwater module, we do not explicitly model storage, inflows or outflows into any surface water bodies other than the three main reservoirs.



Source: Google Earth: http://earth.google.com

**Figure 3.1: Map of Chennai region showing three reservoir system and model area**

The Reservoir module models the stocks and flows of the city's reservoir system. The Reservoir module uses one month time-periods. The outputs are aggregated to three-months to link to the other modules. The Reservoir module has two sub-modules with different functions: estimation of the inflows into the reservoirs based on local rainfall, and estimation of the volume of water available for diversion by Metrowater. Each of the two sub-modules has one equation. Each sub-module is enclosed in a dashed box shown in Figure 3.2.

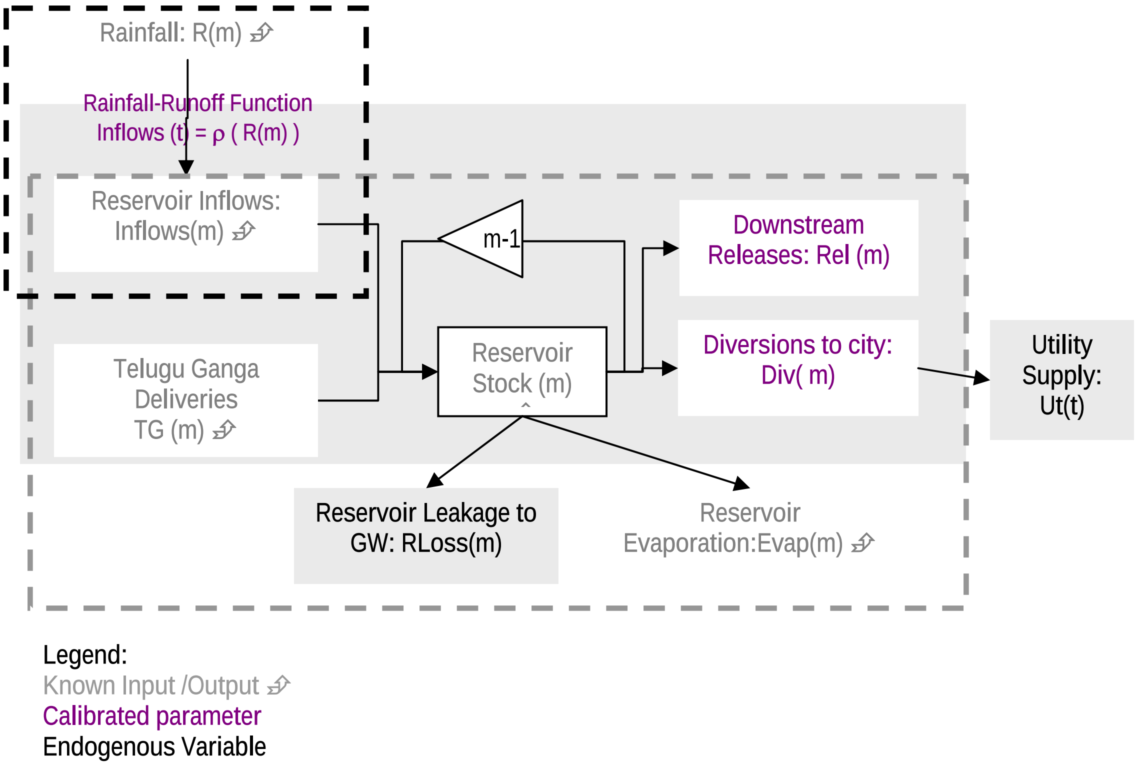


Figure 3.2: Linkages in Reservoir module

**Table 3.1: Sub-modules and equations in Reservoir module**

| Sub Module | Eqn. | Input | Transformation | Output |
|---|---|---|---|---|
| Reservoir Inflows | 3.1 | Rainfall ✍ | Rainfall-Runoff Equation | Inflows into reservoirs ✍ |
| Reservoir Diversions | 3.2 | Inflows into reservoirs ✍<br>Reservoir evaporation ✍<br>Reservoir capacity ✍<br>Telugu Ganga deliveries ✍<br>Reservoir storage ✍ | Reservoir-Water Balance Equation | Quantity of water diverted from city reservoirs for city supply |

### *3.1.1 Reservoir Sub-Module – Estimating reservoir inflows*

The purpose of this sub-module is to estimate the inflow into the city reservoirs deriving from rainfall in the local watershed. Data on total inflows into the city's reservoir system, and average monthly rainfall at the three reservoirs were downloaded from the Metrowater website[50]. Isolating inflows from local watershed runoff was challenging because the city's

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[50] Data accessed between Jan. and March 2007 from http://www.chennaimetrowater.com/lakemain.htm

reservoir system receives water from both the inter-state Telugu Ganga project as well as from surface runoff generated by rainfall in the watershed. In order to isolate the flows contributed from the local watershed, we downloaded reservoir inflows reported on the Metrowater website[51]. Metrowater reports deliveries of Telugu Ganga water at "zero-point" at the state boundary. Flows at zero-point and transfers between the reservoirs were subtracted to isolate the contributions from the local watershed[52]. The break-up of contributions of local watershed inflows and the Telugu Ganga Project to the reservoir system are presented in Figure 3.3

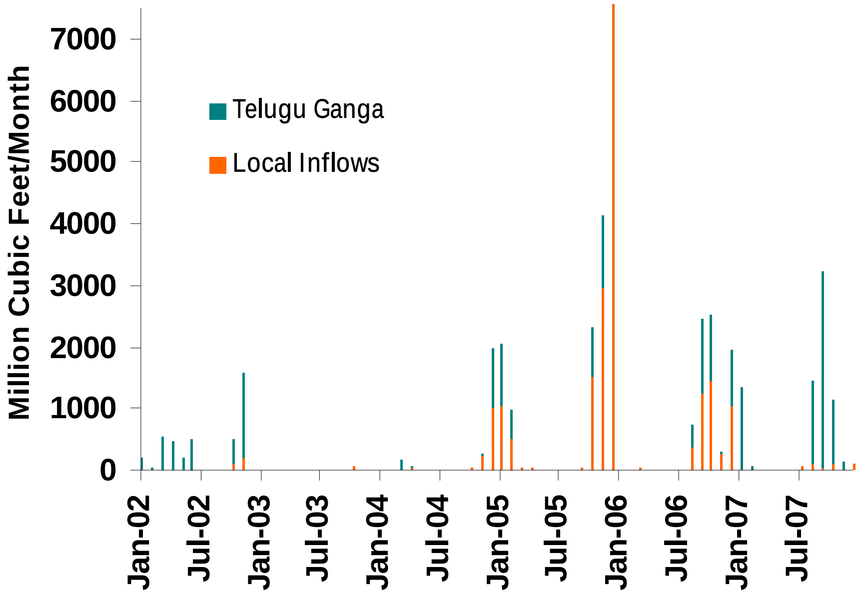

**Figure 3.3: Monthly inflows into reservoir system**

Once we isolated the inflows into the reservoir system, the next task was to determine the relationship between the local inflows and rainfall. After experimenting with different functional forms, we found that a log-linear relationship provided the best fit. A simple regression between Log (Inflows) and Rainfall yielded an $R^2$ of 77%. Figure 3.4 depicts the estimated log-linear relationship between rainfall and inflows into the 3-reservoir system due to rainfall in the local watershed.

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[51] Metrowater 2007

[52] Based on conversations with local academics, in our model, we only considered inflows into Cholavaram and Poondi; i.e., assuming that direct inflows into Red-Hills are small particularly because the Red Hills watershed is highly urbanized.

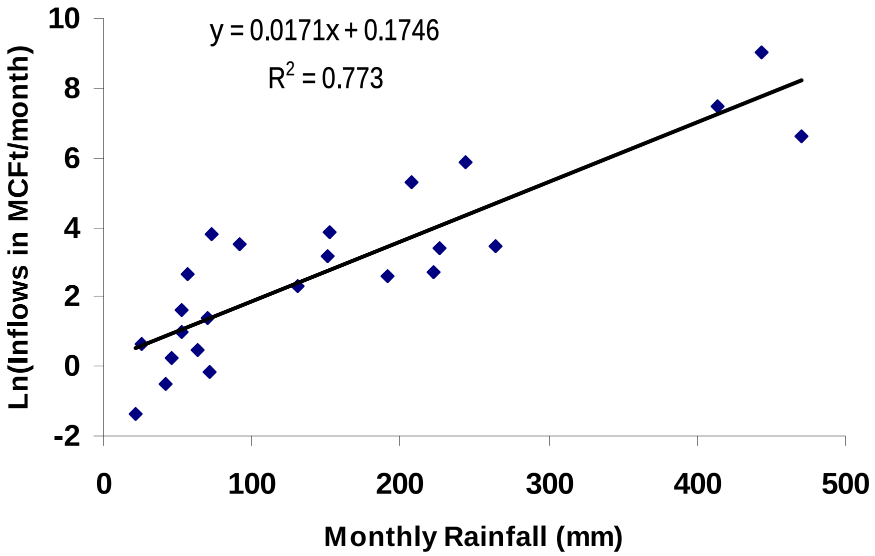

**Figure 3.4: Rainfall-Inflow relationship**

Thus, the monthly inflow from the local watershed can be expressed as a function of monthly rainfall.

$$\textbf{Inflows(m)} = \alpha\, e^{\beta\, \text{Rainfall (m)}}$$

$$\textbf{where } \beta = 0.0171 \textbf{ and } \alpha = \text{Exp}(0.1746) = 1.19$$

**Equation 3.1**

Inflows(m) is the total monthly inflow into the city's reservoirs from the Chennai watersheds.
Rainfall (m) is the monthly rainfall into the city's reservoirs
The qualifier "m" refers to month. A different temporal subscript was used for the Reservoir module because the Reservoir module uses a time-step of a month versus the other modules which have a time-step of 3-months.

### *3.1.2 Reservoir Sub-Module – Estimating reservoir operation rules*

In this sub-module we simulate Metrowater's operation of the city's reservoir system, specifically, how much water is diverted in a given period for utility supply. Since diversions are dependent on the stock of water available in the reservoir system, the main equation in this model is a water balance for the three-reservoir system. Reservoir stock (refers to total stock in three reservoirs combined) is represented by the following equation.

**Reservoir_Stock (m)**

**= Reservoir_Stock(m-1) + Inflows(m) +TG (m) –Evap(m) –Div (m) –Rel (m) – RLoss(m)**

**Equation 3.2**

where Reservoir_Stock(m) is the total combined storage in the three reservoirs in any given period in Million Cubic Feet. Initial Reservoir_Stock is known.

TG(m) is the water received from the Telugu Ganga water scheme in Million Cubic Feet/Month, an inter-state water transfer project. The quantity of water delivered from this project is rather unreliable and variable and only a fraction of the promised quantity has ever been received[53]. For future years, we assume that the quantity received is a function of the total rainfall in Chennai[54], but we cap the total receipts to the maximum quantity received historically.

Evap (m) is the reservoir evaporation less direct rainfall, a function of surface area of the reservoirs and potential (seasonal) lake evaporation rate averaged over a 40 year monitoring period.

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

Rel(m) is the quantity released when reservoir storage levels are dangerously high.

Div(m) is the quantity diverted for utility supply to Chennai

The values for each of the variables in the equation above are discussed below.

The values of TG(m), the quantity delivered at "zero-point" at the inter-state border in MCFt (Million Cubic Feet) each month from January 2002 to Dec 2006 are shown in Figure 3.5. For the historical period actual inflows are used. The total receipts never exceeded 3.5 TMC (Trillion CubicFeet), even though the quantity promised by the tribunal is 12 TMC (after accounting for en-route losses).

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[53] Nikku (2004) documents the politics of water receipts from the Telugu-Ganga Project. See Appendix L for details of Telugu Ganga Project

[54] A justification for this assumption is provided in Appendix L

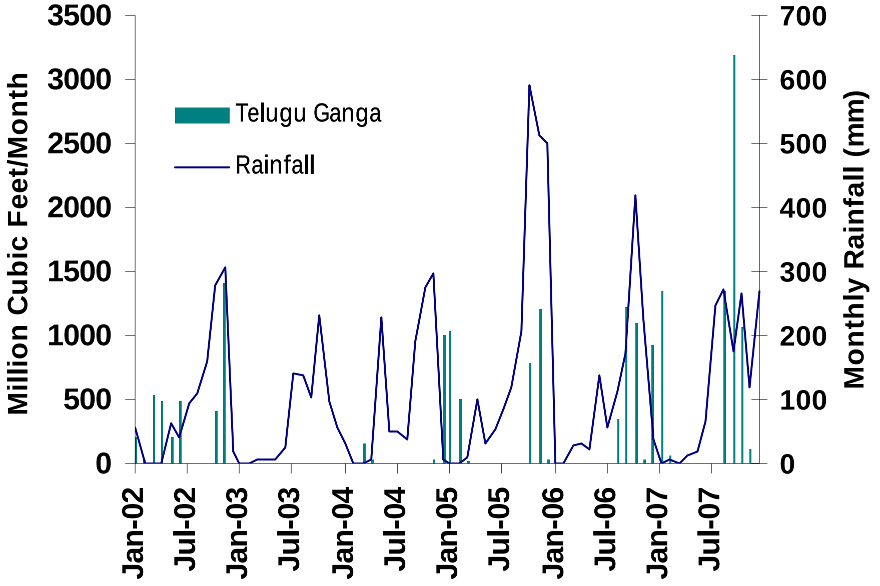


**Figure 3.5: Monthly receipts from Telugu Ganga Project**

The quantum of water delivered from the Telugu Ganga project has been very variable. Since the project was commissioned in 1996, only a fraction of the promised quantity has ever been delivered[55]. The total inflows into the reservoir system, including both Telugu Ganga and inter-state receipts are shown below.

We assumed that the annual Telugu Ganga deliveries are proportional to total annual rainfall in the Chennai basin. A description of the Telugu Ganga Project and the rationale for this assumption is provided in Appendix L.

$$\begin{aligned} TG(m) &= Annual\_TG\,(Year) * TG\_Frac(Month(m)) \text{ if Month = Sep to Feb} \\ &= 0 \text{ otherwise} \end{aligned}$$

**Equation 3.3**

$$\begin{aligned} &Annual\_TG(Year(m)) \\ &\quad = 3.5\text{ TMC} * Annual\_Rainfall(Year)\,/30Year\_Annual\_Rainfall \\ &\qquad \text{if } Annual\_Rainfall(Year)\,/30Year\_Annual\_Rainfall \geq 75\% \\ &\quad = 0 \text{ otherwise} \end{aligned}$$

**Equation 3.4**

---

[55] Chennai was offered water from the Krishna water based on an award by the Krishna Water Tribunal. However, the award is not underpinned by a legal agreement. Moreover, to receive the water flows through an open canal running hundreds of km through a highly drought-prone area. Nikku (2004) documents the politics of water receipts from the Telugu-Ganga Project. The paper cites how farmers and town along the canal have agitated to divert Krishna water to satisfy their own needs first before allowing the water to flow across state lines. The paper cites numerous instances of villages breaching the canal temporarily to fill local ponds as well as instances of lift pumps installed on the canal.

The Telugu Ganga deliveries are allocated over the months in proportion to the average fraction actually received historically in that month. And TG_Frac(Month(m)) is as shown in the Table 3.2.

**Table 3.2: Assumed distribution of Telugu Ganga deliveries in different months**

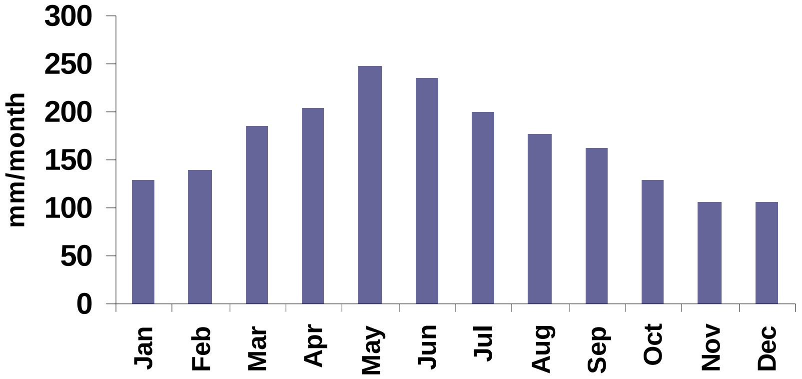
| Month | Fraction (Month) |
|---|---|
| September | 5% |
| October | 10% |
| November | 25% |
| December | 25% |
| January | 20% |
| February | 10% |

Evap (m) is net evaporation in Million Cubic Feet/Month, a function of reservoir surface area

**Evap(m) = (Avg_Evap – Rainfall(m)) * Reservoir_Surface_Area(m)**

**Equation 3.5**

Where Avg_Evap is the potential lake evaporation averaged over a 40 year monitoring period in mm/month (Figure 3.6).



**Source: Indian Meteorological Department, cited in UN, 1987**

**Figure 3.6: Average Lake Evaporation Meenambakkam, Chennai (1959-1982)**

Reservoir_Surface_Area(m) in Million Square Feet, is the surface area of the reservoir. It is simply a function of the total water in the reservoir system. Fortunately Metrowater reported the height as well as the total volume of the lake surfaces for each of the three reservoirs, so we were able to derive the reservoir surface area as a function of reservoir stock.

**Reservoir_Surface_Area(m) = 0.00465 * Reservoir_Stock(m) + 5.99**

**Equation 3.6**

RLoss(m) in Million Cubic Feet/Month is the leakage from the reservoir system to the groundwater. All the Chennai reservoirs are lined by a thick layer of clay (~3 meters. The head difference between the reservoirs and the local groundwater table varied but was about 5-10m. Using a clay leakance of 0.000008 m/day

**RLoss(m) = Reservoir_Surface_Area(m) *ΔHead * Clay_Leakance / Clay_Thickness**

**Equation 3.7**

Reservoir leakage to groundwater turns out to be negligible (~0.0005 McFt), so it could be neglected for all practical purposes.

The last two variables are diversions, Div(m) and downstream releases, Rel(m). Although these are based on reservoir operational rules and should technically be "known", we were unable to get clear explanations from Metrowater officials. Instead, we had to calibrate these. The calibration process is described below.

From conversations with local academics we applied three simple rules:

1) The utility uses a simple rule to decide how much water is diverted for utility supply – a simple fraction of total storage each month.
2) The reservoirs are used exclusively for Metrowater utility supply. They do not serve local irrigation needs.
3) Flood control functions of the reservoirs are minimal. Chennai is so water-starved that downstream releases only occur when the reservoirs are filled to capacity.

Rel(m) is the quantity released downstream when reservoir storage levels are dangerously high. Since the reservoir system is maintained primarily for water supply, we assume that these releases occur only when the reservoir system is at almost at capacity.

**Rel(m) = MAXIMUM (0,**

**Reservoir_Stock(m-1) + Inflows +TG(m) –Evap(m) – Div(m)-Reservoir_Cap)**

**Equation 3.8**

Where Reservoir_Cap = 96 percent of maximum storage = 7110 McFt

This figure was simply the highest monthly storage reported in the record

Div(m) is the quantity of water diverted to the utility in Million Cubic Feet/Month.

For this historical period, actual diversions was effectively known since the values of all other variables are known; the "residual" is the quantity diverted for city supply needs to make the water balance work out. However, we needed a “rule” to relate this variable to reservoir stock, so that we could forecast this variable for future periods.

**Div(m) = Op_Rule (Reservoir_Stock(m))**

**Equation 3.9**

We found the following rule could explain reservoir diversions: Metrowater diverted 170 McFt plus about 7 percent of total storage until the Veeranam project came online in late 2004. The fraction was increased to 10 percent of total stock each month plus 170 Mcft after that. In months when Telugu Ganga water is available, Metrowater diverts 25 percent of total reservoir storage to make space available for the Telugu Ganga water as shown in Figure 3.7.

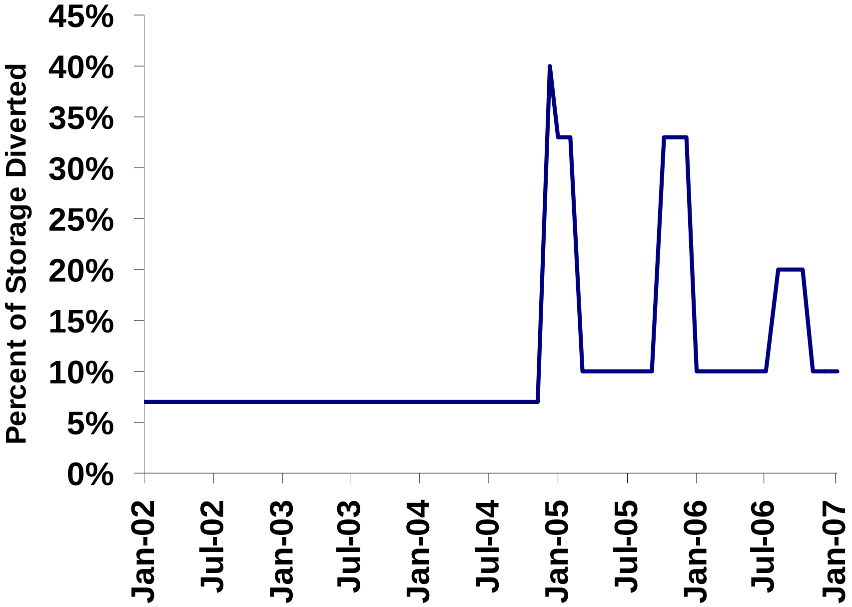


**Figure 3.7: Calibrated diversion rule from reservoir-system**

**Div(m) = 25% * (Reservoir_Stock(m)+ 170) if TG(m) > 100 Mcft and**
**= 10% * (Reservoir_Stock(m)+ 170) otherwise**

**Equation 3.10**

Based on this diversion rule and the evaporation, rainfall, leakage and release data presented earlier, we were able to replicate reservoir storage almost perfectly as shown in Figure 3.8.

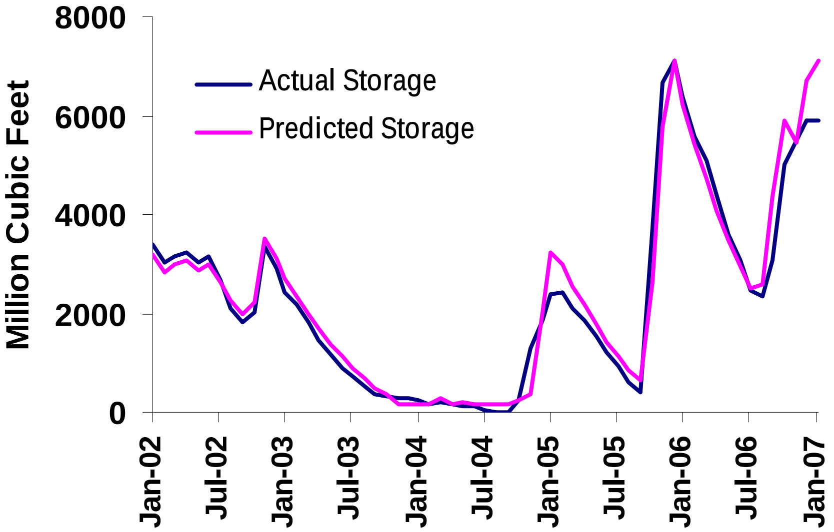


**Figure 3.8: Match of actual and predicted reservoir storage**

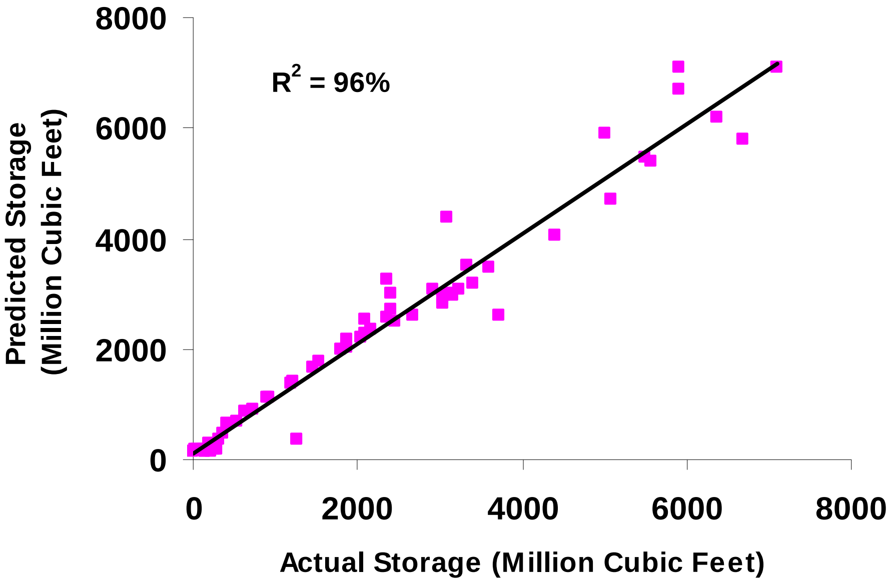


**Figure 3.9: Scatter plot of actual and predicted reservoir storage**

The Reservoir storage calibration run produces an $R^2$ of 96% in matching predicted and actual reservoir-system storage

## 3.2 Groundwater Module

Chennai has a complex hydrogeological system consisting of alluvium, weathered rock, shale and sandstone. As a result, there is considerable variation in both the quality and quantity of water available across the city. The purpose of the groundwater module is twofold:

1) To determine how extractions by consumers affect groundwater levels
2) To determine the quantity of water available to consumers via private and public wells.

While the link between extractions and groundwater levels is well established via the groundwater field, the feedback, determining how aquifers constrain individual consumers is not as well understood. We allow three possible feedback mechanisms or ways in which the aquifer limits pumping.

1) ***Cost of pumping:*** Pumping becomes too expensive as water levels fall
2) ***Drying of wells:*** The regional water table drops below the depth of the well, making it dry
3) ***In-well drawdown:*** Pumping causes drawdown (i.e., cone of depression) at the well so the well may go locally dry.

Figure 3.10 shows the linkages within the Groundwater module

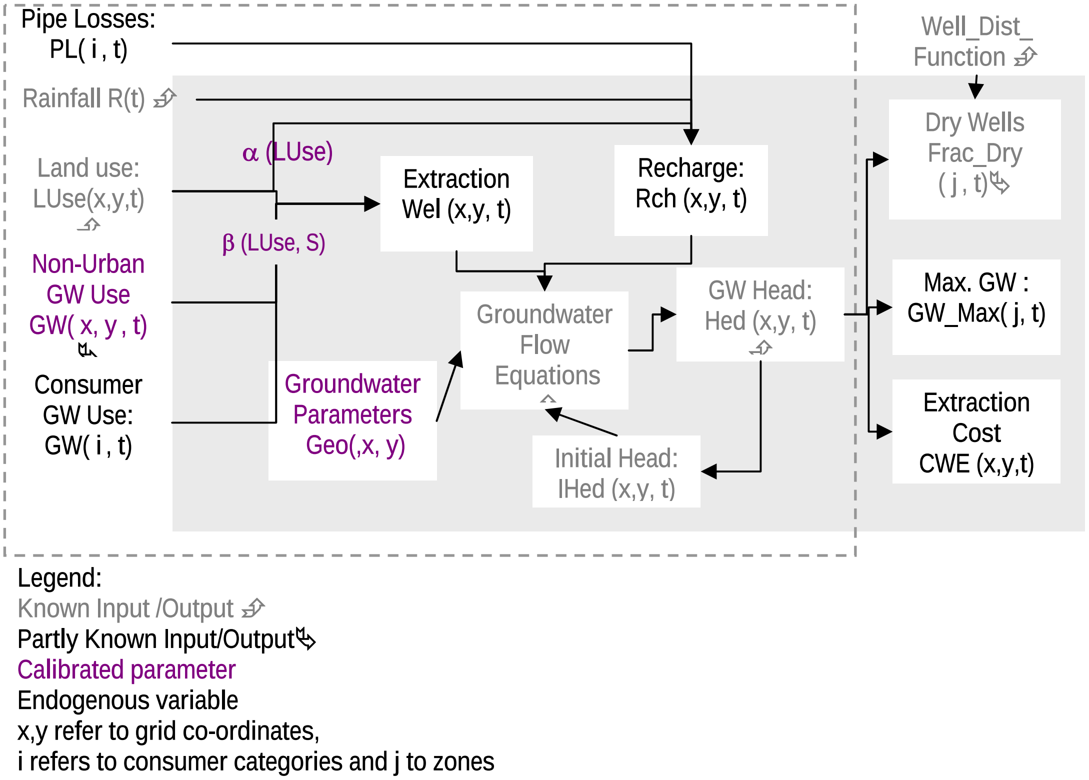


**Figure 3.10: Linkages in Groundwater module**

**Table 3.3: Equations in Groundwater module**

| Sub Module | Eqn. | Input | Transformation | Output |
|---|---|---|---|---|
| MODFLOW | 3.11 | Geology,<br>Aquifer properties,<br>ICs and BCs,<br>Recharge,<br>Extraction | Transient Groundwater Equation ⇗ | Groundwater head ⇗ |
| Fraction of dry wells | 3.14 | Groundwater head<br>Elevation⇗<br>Well-Distribution ⇗ | Distribution of well depths ⇗ | Fraction of wells dry ⇘ |
| Maximum Quantity Extractable | 3.16 | Groundwater head<br>Aquifer properties,<br>Well-efficiency ⇗ | Theim Equation ⇗ | Maximum quantity of water that can be drawn from a well |
| Cost of groundwater | 3.17 | Groundwater head ⇗<br>Electricity price ⇗<br>Pump efficiency ⇗ | Pumping cost calculation | Price of groundwater = cost of extraction |

A description of each sub-module of the Groundwater module follows

### *3.2.1 MODFLOW*

The purpose of this sub-module is to estimate groundwater heads using a groundwater flow model. We developed a 3-D aquifer simulation model using MODFLOW-2000 (USGS, 2000). From the data we collected, the Chennai basin was modeled as a 3-layer aquifer, with an upper unconfined sand layer, a confining clay layer, and a lower confined sand layer. The description of Chennai's geology and the development and calibration of the groundwater model is described in detail in Appendix D. MODFLOW approximates the 3-D transient flow groundwater equation, to solve for groundwater heads.

**Head (x, y, z, t) =**

**f (Recharge(x, y, z, t), Extraction(x, y, z, t) , Hydraulic Conductivity(x, y ,z, t) , Storage Coefficient(x, y, z, t ))**

**Equation 3.11**

where x,y represents a grid cell and can be translated easily into Lat-Long co-ordinates. x and y each range from 1 to 231. Since the model has three layers z =1,2 or 3, where the upper unconfined layer has z=1, the aquitard has z=2 and the lower confined layer has z=3.

i represents a census unit

Head (x, y, z, t) is the groundwater (hydraulic) head in a particular cell in meters above MSL
Recharge (x, y, t) is the vertical recharge into the uppermost aquifer layer in M/day.

In the groundwater model, Recharge and Extraction were specified as a function of land use. This approach was beneficial because it allowed us to greatly reduce the number of parameters in the groundwater model to a few: one value of extraction and recharge for each major land use category. This ensured that the groundwater model was not over-parameterized.

**Recharge(x,y,t) = Rainfall(t) * Recharge_Rate(Land Use (x,y,t))**

**Equation 3.12**

Where Rainfall (t) is the rainfall in period t, and Recharge_Rate is the fraction of rainfall that recharges. Recharge_Rate was calibrated to be 18% in rural areas and recharge was assumed to be half of this (or 9%) in urban areas.
Extractions (x, y, z, t) is the quantity extracted from a grid cell in $M^3$/day.

**Extraction(x,y,t) = f(Land Use (x,y,t))**

**Equation 3.13**

No extraction was assumed in water bodies and forest areas like the Guindy national forest area (green area in land use map within Chennai south of Adyar river) are excluded.
Within the city of Chennai, the extraction is derived from the consumer module. The consumer module generates the quantity actually extracted by individual households or establishments. The total extraction per grid cell is obtained by aggregating the groundwater extraction over all households and commercial establishments in that grid cell.
Extraction outside the city is a function of land use. Irrigation consumptive (net of return flows) and industrial use were calibrated parameters. Domestic extractions were based on density of population. Hydraulic conductivity, thickness, and storage coefficients are aquifer characteristics. The groundwater equation outputs groundwater heads (hydraulic head above mean sea level).

### *3.2.2 Fraction of wells going dry*

Shallow wells are more likely to dry up because the water table drops below the bottom of the pump inlet near the well bottom (i.e., the first mechanism described above). If the water table drops below the bottom of the pump inlet, the well goes dry, and quantity extractable is zero. This presented a modeling problem because, in consumer module models the decision process of a “representative” consumer with median characteristics, a 1-HP pump and 4.5 family members. So if all consumers were endowed with a well of "median depth", then all either all wells in the city would go dry simultaneously or none would. To surmount this problem, we needed to account for the fact that consumer well-depths are distributed over a range.

If the groundwater level is lower than the depth of the well, the well would go dry. Thus, by combining the well-depth distribution with groundwater level data, we could determine what fraction of the wells would be dry in any given period, assuming that this distribution is the same all over Chennai. The distribution of well-depths based on household survey data in Chennai is shown in Figure 3.11. Figure 3.12 shows the cumulative distribution.

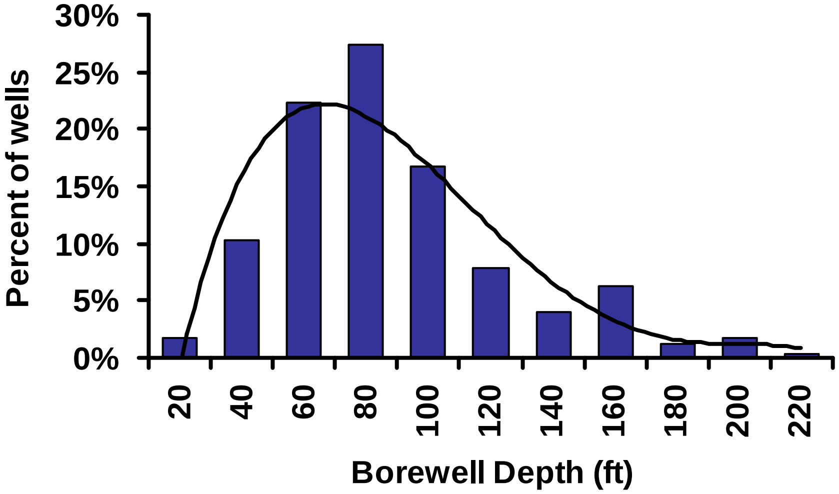


**Figure 3.11: Frequency distribution of depth below ground surface of domestic wells**

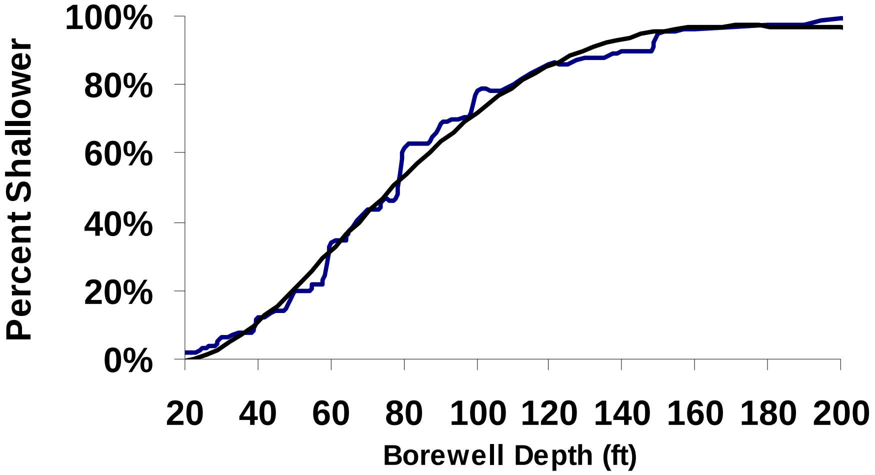


**Figure 3.12: Cumulative distribution of depth of domestic wells**

For instance, reading Figure 3.12, if the depth to the water table is 50 ft about 20 percent of the wells would be shallower than this and therefore dry. By fitting a polynomial curve to the graph above, we get the equation for fraction of wells that would be dry at any depth to water. For any given period, we estimated what fraction of consumers' domestic wells went dry.

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

**Equation 3.14**

Fraction_dry is the fraction of wells that are dry in a particular census area

X(j,t) = Depth(j,t), the average depth to the water table in zone j, defined as

$$Depth(j,t) = \frac{\sum_j Elevation(x,y) - Head(x,y,1,t)}{Noofgridcells(j)}$$

**Equation 3.15**

### *3.2.3 In-well drawdown*

Establishments that extract large amounts of water daily may find their wells go dry locally because of an in-well drawdown problem. The model calculates the $Q_{MAX}$, the maximum quantity that can be drawn from a well, at any location and inputs it into the consumer model. We determine the maximum quantity of water extractable using the Theim equation.

$$\Delta H = \frac{1}{Well\_Eff} * \frac{Q}{2\pi T} Ln(\frac{R_E}{R_W})$$

**Equation 3.16**

Where, ΔH is the allowable drawdown, or the height of the water column in the well above the pump under non-pumping conditions[56]. Transposing Equation 3.16 we obtain the maximum quantity extractable so the drawn down in the well is limited to no more than 80 percent of the standing water column.

$$GW\_Q_{MAX} = \frac{\Delta H * 2\pi T * Well\_Eff}{Ln(\frac{R_E}{R_W})}$$

**Equation 3.17**

$GW\_Q_{MAX}$ is the quantity of water extracted each day. $R_E$ is the grid cell size/4.81 and $R_W$ is the radius of the well. Well efficiency is the efficiency of the well, defined as the drawdown

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[56] We assume pumps are installed a meter above the well bottom.

outside the well divided by the drawdown immediately inside the well. Well efficiencies in Chennai are reported to be very low at around 5%. Using the typical ΔH values observed in Chennai, we found that the quantities that could be drawn without drying up the wells were typically quite large, ranging from 20 up to 90 kilo liters per day. This implies that the in-well drawndown limitation is only likely to affect the water-intensive commercial establishments, but unlike to affect domestic establishments.

### *3.2.4 Cost of groundwater extraction*

In theory, one of the reasons consumers may limit groundwater extraction is that it becomes too expensive to pump groundwater. The third sub-module of the groundwater module is to compute the cost of groundwater extraction. Cost of pumping groundwater is estimated as follows:

**GW_Cost (x, y, t) (Rs/kL) =**

$$ElecPrice(\frac{Rs}{kWh}) * PumpkW * \frac{1000}{RatedFlow}(\frac{\min}{kL}) * \frac{1}{60}(\frac{hours}{\min})$$

**Equation 3.18**

Where GW_cost is the cost of extraction in Rs/kL

*Elec_Price* is the price of electricity in Rs/kWh. A value of Rs 4/kWh was assumed

PumpkW = Pump power in kW. The vast majority of domestic pumps in our household survey were 1 HP (1HP= 0.746 kW). So this was the value assumed for all representative households. Apartments and commercial consumers were assumed to have 3 HP pumps based on the most common pump-size for those categories.

*RatedFlow* as a function of dynamic head is published as pump-rating curves for most standard pumps. Standard rating curves for a family of pumps manufactured by two popular local manufacturers, Suguna and CRI Pumps, were examined. The head in the (upper) aquifer beneath Chennai ranges between 25 and 40 m above mean sea level. The flow rate for most pumps ranged around 25 L/min in this head range.

Depending on the assumed pump maintenance and other O&M costs, groundwater extraction costs vary between 2 and 7 Rs/kL. The pumping cost difference between the highest and lowest groundwater levels is equivalent to a total difference of 30 Rs/month in the monthly electricity bill, small enough to not influence consumer behavior for consumers who have private borewells. This indicates that the cost of groundwater extraction is probably not an important factor limiting groundwater extractions by consumers. Therefore, to keep the model simple, rather than varying the cost of extraction dynamically with groundwater head we assumed a value of Rs 5.50/kL[57]. Sensitivity analysis to groundwater costs are presented in Chapter 4.

GW_Cost (x, y, t) (Rs/kL) = 5.50 Rs/kL

**Equation 3.19**

In summary, using reasonable parameter ranges from the calibration run, it was established that extraction cost is probably not a limiting factor. It does not vary enough within the relatively small head changes observed in Chennai to be noticeable. Domestic and commercial extractions are limited for different reasons, a phenomenon explained in detail in Chapter 5.

Domestic wells tend to be shallow and are more likely to dry up because the water table drops below the bottom of the well (i.e., the first mechanism described above). If the water table drops below the bottom of the pump inlet, the well goes dry, and quantity extractable is zero. However, most households extract 1 kL or less each day they are unlikely to be affected by the in-well drawdown problem. In contrast, commercial wells tend to be deep and rarely dry up completely. Instead, consumers will likely be limited by in-well drawdown, as they extract large amounts of water.

## 3.3 Tanker Module

A small fraction of consumers in the city get their water from private tanker trucks (not to be confused with the utility-run “mobile supply” tankers described later in Chapter 4). These private tanker operators buy water from peri-urban farms and transport the water to the city. The main purpose of the Tanker module is

1) to estimate the price of tanker water within Chennai as an input into the Consumer module
2) to estimate tanker extractions as an input to the Groundwater module

Additionally, we also explain how we estimated the size of the tanker market empirically.

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[57] This flow-rate was corroborated by an independent measurement at one house in the field, where we measured the time to fill a 2000 L overhead tank on the rooftop of a 2-storey building to be about 120 min.

In estimating the price of tanker water, we assume that the tanker market is perfectly competitive; no single tanker operator has market power[58] or controls the market. Moreover, the supply of tanker water available at a given price is infinite (i.e., the tanker market is not supply constrained), as selling water in the city is always more profitable than agriculture and agriculture still accounts for most of the water use in the peri-urban areas. Furthermore, we assume the tanker source areas (villages from which tanker groundwater is extracted, and usually close to highways just on the outskirts of the city) are known. The key linkages are shown in Figure 3.13.

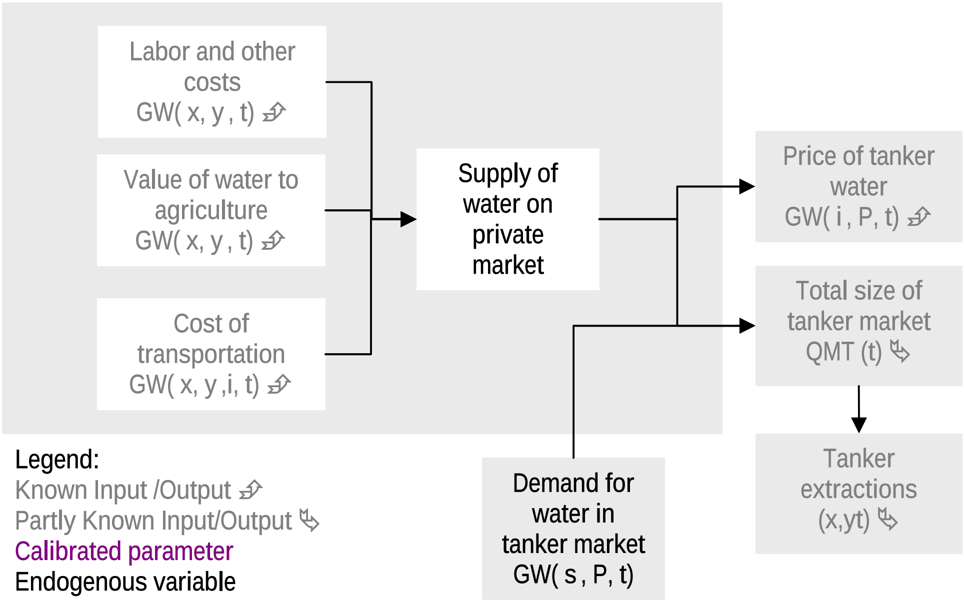

Figure 3.13: Linkages in Tanker module

**Table 3.4: Sub-modules and Equations in Tanker module**

| Module | Eqn. | Input | Transformation | Output |
|---|---|---|---|---|
| Tanker Prices | 3.12 | Demand for tanker water<br>Tanker source areas☞<br>Cost of transportation☞<br>Labor and Capital Costs☞ | Tanker costing equation | Price of tanker water |
| Tanker Extractions | 3.13 | Size of Tanker Market | Tanker source area distribution | Tanker Extraction (x,y,t) |

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[58] About 60 tanker companies were surveyed. Most operated 1-2 trucks. Only two companies reported operating 50 trucks. Each supplied housing colonies of large corporate customers.

### *3.3.1 Tanker price estimation*

The module estimates tanker water prices based on the cost of transportation.

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

**Equation 3.20**

where,
PLabor = Wage rate to driver and helper ~ Rs 100/12 kL Tanker load
PFuel ~ Cost of fuel = Rs 30/liter
PWater ~ Price paid to farmer = Rs 50/12 kL Tanker load
PProfit ~ Profit to tanker operator = Rs 100/12 kL Tanker load
Fuel_Eff ~ Fuel efficiency = 2.5 km/liter
(based on interviews with tanker operators)
"j" is the spatial unit within city limits.

All prices and costs given above were based on interview data collected in 2005-2006. Distance is multiplied by a factor of two because the tanker makes a round-trip from the city, to the source-collection point and back to the consumer.

The estimation for the southern suburb of Adyar is as follows: For the suburb of Adyar, the closest source area is the Medavakkam village area 15 km away. So, the price of a 12 kL tanker works out to be Rs 610/ 12 kL tanker or Rs 51/kL

$Price(i,t) = (2 * Distance\ (i,t) * 30/2.5 + 100+100+50) \quad = \text{Rs } 610\ /\ \text{tanker}$

Thus, more than half the cost of the tanker water is transportation cost.

The main calibrated parameter in the tanker module is the fuel-efficiency of the tankers. To calibrate the equation, estimated and surveyed tanker prices were compared. The other unknown variable in the equation is distance transported. The process of estimating distance over which tanker water was transported was as follows.

Based on over 60 phone interviews with tanker operators we established the locations of tanker source areas to be limited to four locations:

1) the Medavakkam- Chitlapakkam area to the south along Velachery High Road,
2) the Naenam-Poonamalle-Thirumazhisai area to the west along Poonamallee High Road and the Avadi-Poonamalle Highway
3) the Sriperambadur area to the west along Grand Truck Road
4) the Red-Hills-Gummudipundi area to the north along Red Hills Road

For each spatial unit within the city, the closest source area was identified to obtain the lowest tanker price in that part of the city. Figure 3.14 depicts a spatial map of estimated tanker prices within Chennai. These were found to match surveyed prices in Chennai reasonably well.

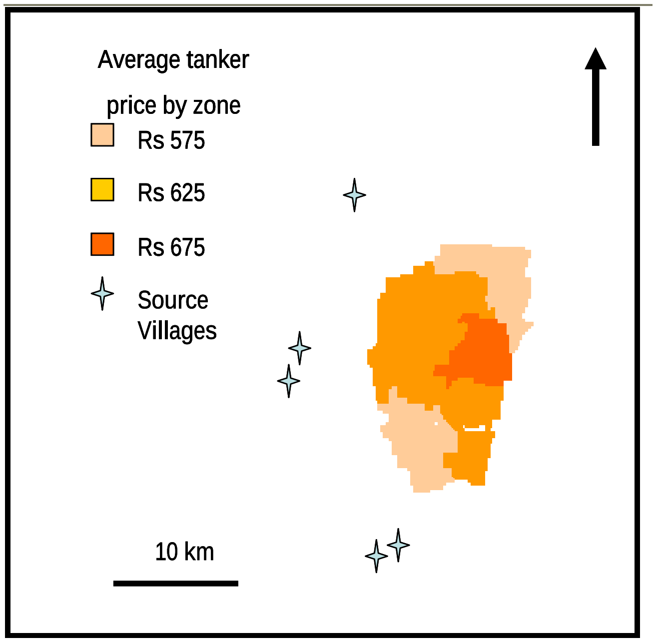


**Figure 3.14: Map of estimated tanker prices in Chennai**

### *3.3.2 Empirical estimation of tanker market size*

The tanker market was empirically estimated based on observation as follows. Tanker observers were stationed at each major highway entering Chennai. The number of tankers entering the city was counted over for 8 hour time-slots. Figure 3.15 shows the number of tankers observed entering Chennai per hours along each major highway.

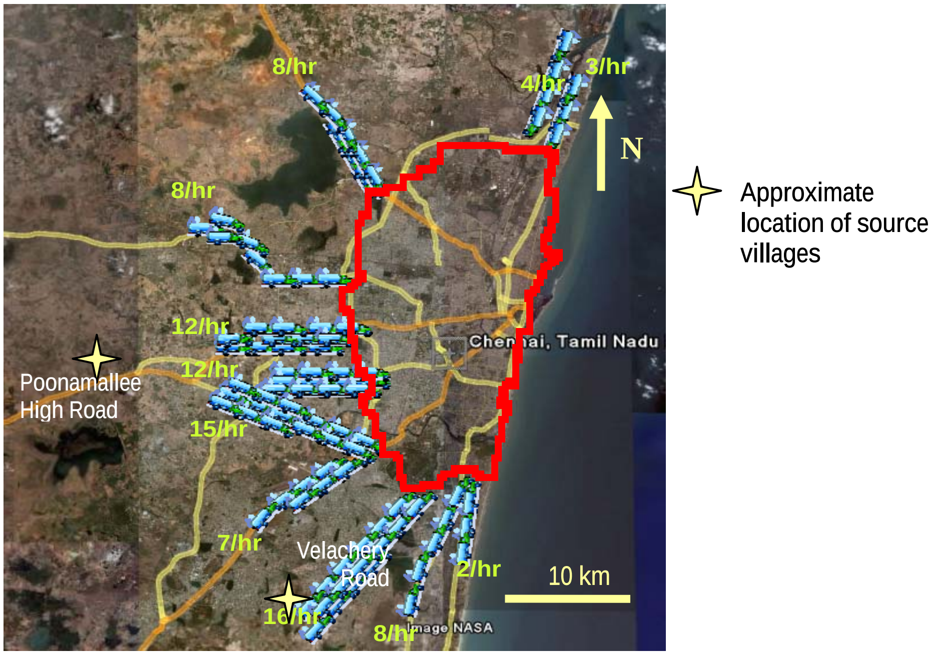


**Figure 3.15: Tanker movement into Chennai**

Figure 3.15 indicates that most of the tanker traffic was along Poonamalle High Road and Velachery High Roads to the west and south-west of Chennai. This observation corroborates the phone survey results in locating the majority of source villages just beyond Poonamalle in west-Chennai and Medavakkam in South-west of Chennai (depicted as stars in the figure). Figure 3.15 also shows the number of tankers observed to be entering the city per hour for each major highway. Since tanker entry into the city is restricted during working hours, tanker movement is assumed to occur for only 16 hours each day. So we were able to estimate the tanker market at 17 million liters per day.

### *3.3.3 Tanker extraction estimation*

To input peri-urban tanker water extractions to the groundwater model, tanker source area grid cells were first identified. Grid cells that were "eligible" for tanker extraction were identified using the following criteria.

- The depth to water in the grid cell was shallower than 10 m,
- The land use classification was agriculture or suburban
- The grid cell was located within 1 km of a major road (Figure 3.16).
- The grid cell was located in census blocks Tambaram, Poonamalle, Avadi or Manali. Specifically no extraction was allowed from distant areas or within Chennai.

The total tanker market size estimated from the consumer module was assumed to be uniformly distributed among all “eligible” source areas. The tanker extractions were then added to other extractions and input into the groundwater model.

$$\mathbf{Tanker\_Extractions(x,y,t)} = \frac{\mathbf{Tanker\_Source\_Area\ (x,y) * Tanker\_Market\_Size(t)/10^{\wedge}3}}{\mathbf{Source\_Area}}$$

**Equation 3.21**

Where Tanker_Extractions(x,y,t) is the extraction per grid cell in M$^3$/Day

Tanker Market Size is the total size of the tanker market in MLD

Tanker_Source_Area (x,y) =1 if the grid cell is a source area

=0 otherwise

Source_Area = Total number of grid cells that are source areas

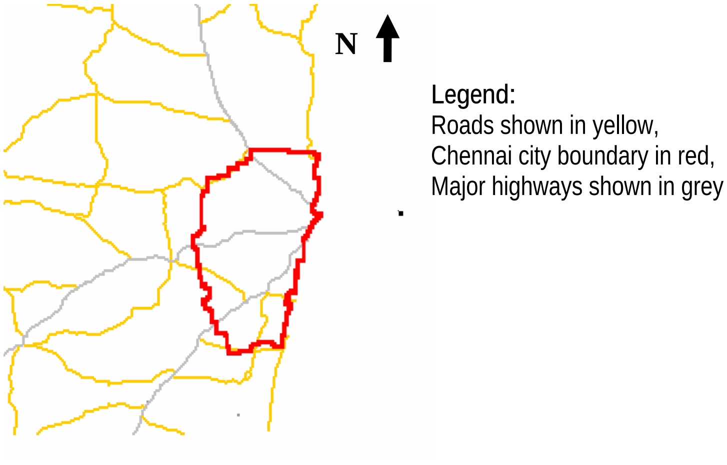


**Figure 3.16: Network of roads in model area**

## 3.4 Chapter summary

In this chapter we have described in detail how three modules were developed: the Reservoir module, the Groundwater module and the Tanker module. In the next chapter, we will describe the two remaining modules; the Utility module and the Consumer module.

# 4 Chapter Four: Model Development –Part II

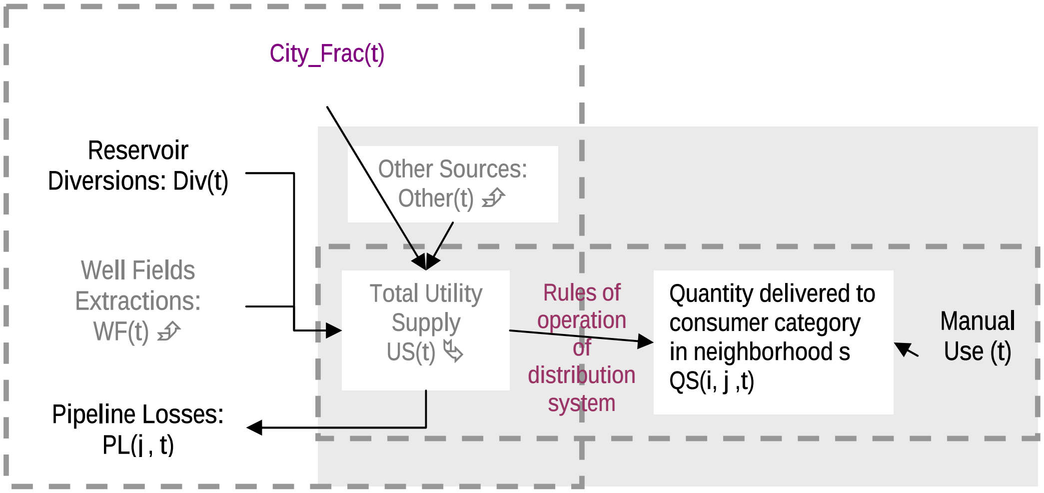
In this chapter, we describe the development and calibration of the remaining two modules of the integrated model described in Chapter 2; the Utility module, and the Consumer module. This chapter is organized as follows: For each module, the linkages, sub-modules, and parameters are described in detail. The Utility module could not be calibrated separately because the module outputs are not observable. Instead the Utility and Consumer modules are calibrated together. Finally, sensitivity analysis on the major parameters in the integrated model is presented.

## 4.1 The Utility Module

The purpose of the Utility module is to simulate how much water is delivered to consumers via the public water distribution system. The Chennai water supply system is run by the public water utility, Metrowater, which serves the incorporated (municipal) urban area of 4.3 million people (2001 census). Within Chennai, almost all the people in the city have some sort of access to the public supply system.

The peri-urban areas (about 1.4 million people in 2001) are served by a patchwork of town and village water schemes. These schemes, developed by a separate state-level agency, "The Tamil Nadu Water and Drainage Board," are supplied by water sourced from borewells. The water is chlorinated and delivered via pipes to local neighborhoods. In our model we do not distinguish between self-supply from individual borewells and piped supply from groundwater-based village schemes. We simply assume that most domestic and commercial needs in peri-urban areas are primarily met via groundwater extraction. The water utility module is comprised of two sub-modules, each of which simulates an important function of Metrowater: obtaining raw water from the various supply sources and delivering the treated water to consumers.

Figure 4.1 depicts the linkages between the variables in the utility module. The two sub-modules are shown in an enclosed dashed box.



Legend:
Known Input /Output ☞
Partly Known Input/Output↳
Calibrated parameter
Endogenous variable

The subscript j denotes the zone and i denotes the consumer category

**Figure 4.1: Linkages in Utility module**

**Table 4.1: Sub-Moduless in Utility Module**

| Sub-Module | Equation | Input | Transformation | Output |
|---|---|---|---|---|
| Total utility supply available to Chennai | 4.1 to 4.6 | Quantity available from various sources | Distribution between Chennai, industry and neighboring towns | Total utility supply available |
| Quantity of utility supply available by consumer category | 4.7 to 4.16 | Total utility supply | Distribution rules | Quantum of utility supply available to households in consumer category in each zone |

### *4.1.1 Sub-Module: Total utility supply available to Chennai*

The total utility supply available to Chennai is the total quantity available from all sources less commitments to industries and neighboring municipalities. The purpose of this module is to estimate the total supply available within the city of Chennai. To do this, we first summed the water availability from the various sources; then derived the fraction allocated water to industries and adjacent municipalities.

The Chennai utility, Metrowater, receives water from both surface and groundwater sources. In addition to the reservoir-system covered in Chapter 3, the city also extracts water from the Araniyar-Koratilaiyar (A-K basin) well-fields to the north of the city. Additionally, since 2004 the city has been receiving water from Veeranam Lake located in the Cauvery River Basin to the south. A small amount of water is abstracted from local sources including the Chembarambakkam lake and the Southern Coastal Aquifer.

Total supply available to Chennai is estimated by the equation:

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

**Equation 4.1**

Where

Utility_Supply(t) is the total water supplied within Chennai in Million liters per day (MLD)

Div (t) is the quantity total diverted from the three-reservoir system as defined in Chapter 3 over the three-month time-step in the Utility module.

$$\textbf{Div(t)} = \sum_{m=1 to 3} \textbf{Div (m)}$$

Veeranam(t) represents water available from the Veeranam Project. We used a simplified assumption to model deliveries from the Veeranam Project. We assume that the city receives 180 MLD, the maximum amount the project can deliver, in all periods. The quantum is assumed to be constant in all 3-month model periods. This is a conservative assumption, as the Veeranam project did in fact fail to deliver for water several months in 2006 and 2007. However, the complexity of that project[59] makes it very difficult to model.

**Veeranam(t) = 180 MLD**

**Equation 4.2**

Well_Fields(t) is the quantity of water extracted from well-fields located in the Araniyar-Koratalaiyar (A-K) basin to the north of Chennai. Extraction data from the well-fields indicate

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[59] Simulating actual diversions from the Veeranam project was impossible for several reasons. Firstly, the Veeranam Lake is located in the Cauvery River Basin and is filled by diversions from the Cauvery River, a highly controversial inter-state river (shared with Karnataka state). Chennai's share of the Veeranam Lake is relatively small; the lake is still largely used for local irrigation. Modeling storage in the Veeranam Lake would require entail understanding the politics of irrigation as well as the complex management of the inter-state Cauvery River. Secondly, until the Cauvery Water Tribunal reached its decision on the sharing of Cauvery waters between the riparian states of Karnataka and Tamil Nadu in 2007, all data for the basin was kept confidential and was unavailable to model. Thirdly, since the Cauvery River is fed mainly by the Southwest monsoon (as opposed to the northeast monsoon which fills the Chennai reservoir system), flows into the Veeranam lakes are uncorrelated with the Chennai reservoir system. Finally, since the project has been around only for three years, long-term data on diversions to Chennai are unavailable, so we cannot deduce the operation rules by calibrating against historical data as we were able to do for the other reservoirs.

that the actual withdrawals ranged from 56 MLD to about 100 MLD in the recent past. However, withdrawals have been restricted following severe salt-water intrusion problems along the coast near Minjur in the A-K aquifer. For historical years, we use actual extractions. For future years, we use the reported "safe yield" of 68 MLD for the A-K basin aquifer (Metrowater, 2004). We further assume that the utility will not exceed the safe yield except during a crisis in which case up to 100 MLD will be extracted.

**Well_Fields(t) = 68 MLD if Reservoir_Stock> 5% of Reservoir_Capacity**
**=100 MLD otherwise**

**Equation 4.3**

Other_Sources(t) is water available from three local sources: the Southern Coastal Aquifer to the south of Chennai, Chembarambakkam tank, and Porur lake. We assume that these local sources (the Southern Coastal Aquifer, and Chembarambakkam tank) combined provided 30 MLD (Metrowater, 2006).

**Other_Sources(t) = 30 MLD**

**Equation 4.4**

Emergency_Imports(t) represent the amount of water that is imported during extreme water scarcity situations. In years when the reservoir system was dry, Metrowater imported water from distant sources, increased pumping from well-fields and also signed water purchase agreements with peri-urban farmers. This component contributed about 100 MLD in the years when the reservoir system was dry.

**Well_Fields(t) = 0 MLD if Reservoir_Stock> 5% of Reservoir_Capacity**
**=100 MLD otherwise**

**Equation 4.5**

City_Frac is the percent of water available for distribution within Chennai after Metrowater meets its obligations to the industrial areas to the north and adjacent municipalities.
This fraction was estimated by dividing city utility supply by the total water available from various sources for the historical period. It is assumed that the rest of the water is supplied to the water-intensive industries to the north, adjacent municipalities or lost in transit. This parameter was adjusted so that observed total utility supply to Chennai would match statistics reported by Metrowater. The data sources used and estimation process used to arrive at the fraction are explained in Appendix E.

**City_Frac = 65%**

**Equation 4.6**

For future periods, Chennai's share of total available supply was maintained at the historical average share of 65 percent.

### *4.1.2 Estimating quantity of utility supply available to each consumer category*

The purpose of this sub-module is to allocate the total water available for utility supply across consumer categories. The output of this sub-module is the maximum amount that would be *theoretically* available to a household in each category each day. The actual quantity consumed would be estimated by Consumer module. In general, the quantity available to consumers depends on the type of connection consumers have, the pressure at the point in the distribution system where the consumer is located, etc. In our simplified model of the distribution system, however, we ignore spatial variations and assume that the quantity available to a consumer is determined primarily by the type of connection.

To determine the quantity available via various types of utility supply connections, we first define the types of connections by which people access the utility supply system. Then we explain the conceptual model, both of the physics and management, of the water distribution system and describe how this results in different types of connections receiving different levels of supply. Next, we present the variables and key linkages of the sub-module. Finally, we explain the operational rules followed by Metrowater and the quantity of water available to each household.

#### *4.1.2.1 Types of utility supply in Chennai*

There are four different ways in which consumers can get utility supply: mobile supply, private handpumps/taps, public standpipes/street taps and in house connections with sumps. ***Mobile Supply:*** Metrowater runs tankers to slum areas where there are no piped mains or if the pressure is too low to practically deliver water. This type of supply is called "mobile supply". Among the consumer categories described earlier, only unconnected consumers are assumed to have regular access to mobile supply. In most Chennai slums the Metrowater tanker fills large steel "Sintex"[60] tanks installed in each street. So slum residents typically do not have to wait in line to collect mobile supply water. A typical street in a slum might have

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[60] "Sintex" is the name of the company that manufactures these storage tanks. However, they are locally referred to as such and we use this term to distinguish between other types of storage tanks.

several 3000-liter tanks on each street, each shared by about 20-25 households. The exact quantity of water allocated to each household is set by community norms and varies considerably[61]. The households are each assigned to a specific Sintex tank and are free to collect water any time of day. Although mobile supply is free, in practice slum residents tip the tanker driver to insure regular service. The tip amount is sometimes shared between a driver and a trusted elder, who stays around when the tanker comes in each day and enforces the allocation. The elder ensures that the street tanks are filled to the brim and no household "cheats" by taking more than their allowable share. In the model, we simply assumed every unconnected household received six pots or 90 Liters/Day.

Additionally, during water crises resulting in a shut down of the piped supply system, mobile supply will be made available (but not necessarily availed) to all households[62] at 6 pots or 90 liters per household per day. We refer to this special case of mobile supply as ***"Emergency" Mobile Supply.***

***Private Handpump/Tap:*** A large fraction of consumers have only have "manual" access to the Metrowater piped system, i.e., they do not have piped supply and indoor plumbing within the home. They have to pump the water out using a handpump connected to the piped mains, during the few hours when supply is available, usually 3-4 hours each morning Other than this restriction on the time for which water is available each day, consumers with private connections face no restrictions on how much water they can collect.

***Public Standpipe:*** Unconnected consumers, lacking private connections, use public standpipes (handpumps) or street taps. A public standpipe is identical (connectivity-wise) to a private handpump, except it is a located in a public space and a single standpipe may be

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[61] For instance in interviews in Odai Kuppam (slum) in the Besant Nagar in South Chennai while entitlements were generally proportional to the number of members in the household, renters got fewer pots than owners, married daughters got less than married sons etc. A family of four typically received four pots. In neighboring Orur-Olcott Kuppam (slum) the quantity supplied was reported to be much higher at ten 15-liter pots/day for a family of four. These differences were despite the proximity and identical ethnic make-up of the two slums. Residents attributed the differences to better political clout of some of the residents in the latter.

[62] In years like 2003/2004 when the reservoirs went dry, the per-capita availability in the system was so low that the piped system had to be shut down according to newspaper reports. Our model simulated this shutdown when the quantity of water available to Chennai dropped below 50 LPCD, a level at which it becomes impracticable to supply water via pipes. Below this threshold, the entire city was supplied via "mobile supply."

shared by 10-20 households. Consumers often have to stand in line to access the public standpipe to obtain water during the short period each day when water is available. Furthermore, consumers may be subject to community norms on how many pots they are allowed to collect, to ensure everybody gets a chance to collect some water before it runs out.

***Sump Supply:*** These consumers receive piped water in underground sumps and pump the water to overhead tanks via electric pumps. The water is allowed to flow by gravity to in-house taps from the overhead tanks. As per the 2006 household survey conducted (See Appendix F), sump sizes in Chennai varied between 1kL and 15 kL, averaging about 4 kL (4kL or 4000 liters represents about a week of supply for a typical household).

Each consumer category defined in Chapter 2, may access one or more modes of utility supply. For instance, unconnected consumers may have access to mobile supply in addition to accessing public standpipes. Table 4.2 maps the consumer categories and the type of utility supply typically accessed. Emergency mobile supply is assumed available to all consumer categories if the piped supply system shuts down is therefore not shown in the table.

**Table 4.2: Mapping consumer categories to types of utility supply**

| **Category** | **Modes of supply** |
|---|---|
| **Unconnected** | Mobile, Public Standpipe |
| **Manual** | Private handpumps |
| **Manual with Borewell** | Private handpumps |
| **Sump** | Piped |
| **Medium Commercial** | Piped |
| **Water Intensive Commercial** | Bulk Supply |

In the next section we describe how the water available to the utility is distributed among the different types of connections.

### *4.1.2.2 Physics of the distribution system*

Ideally, we would like to have developed a complete physical model of the distribution system. However, this would involve a model of a complex physical system involving thousands of pipes. Time, budgetary constraints, and quality of data available did not justify developing a full-scale model of the distribution system. Instead, we use a highly simplified conceptual model of the distribution system. A description of some features of the Metrowater water distribution system relevant to our simplified model follows.

The Metrowater supply system is an intermittent supply system. Unlike the continuous systems in the developed world, water is only available for a few hours each day. The water distribution system is divided into 16 distribution zones, each served by a major distribution (pumping) station. Water is pumped to the distribution stations via transmission trunk mains from the treatment plant. Each distribution station has a large storage tank, which can hold a day or two of supply. Each distribution station has a "filling point" from which Metrowater mobile supply tankers fill water to deliver to slum neighborhoods through the day.

Every morning, the pumping stations turn the pumps and pump water for about 3-6 hours. The pipes get pressurized and deliver water to sumps and handpumps. From informal interviews most residents were aware about when the water becomes available. We assume that they keep a watch out for the water so it can be collected before it runs out. In any case, the pumping stations are turned on at about the same time each day. Residents access the system via handpumps or yard taps. Handpumps are ubiquitous in Chennai partly because they yield water even at low pressures or when the piped mains are only partially full. This phenomenon can be explained by examining this cartoon of water delivery in Figure 4.2.

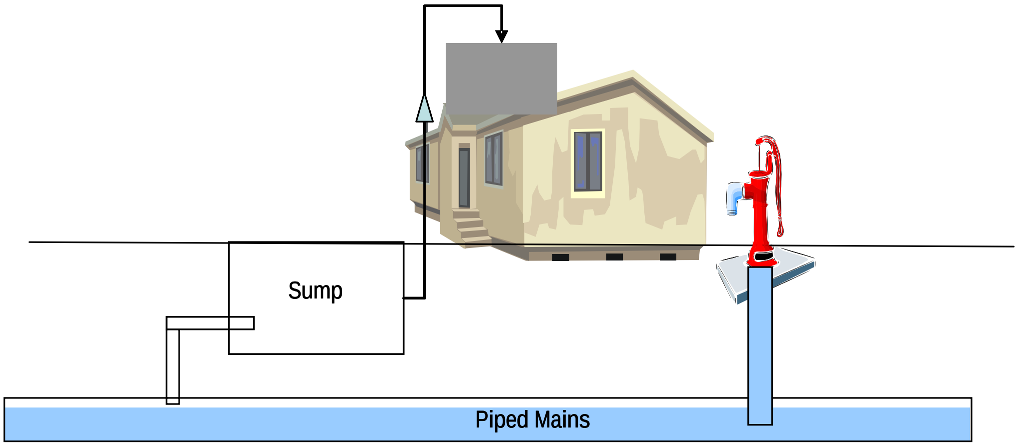


**Figure 4.2: Water delivery by handpump and sumps**

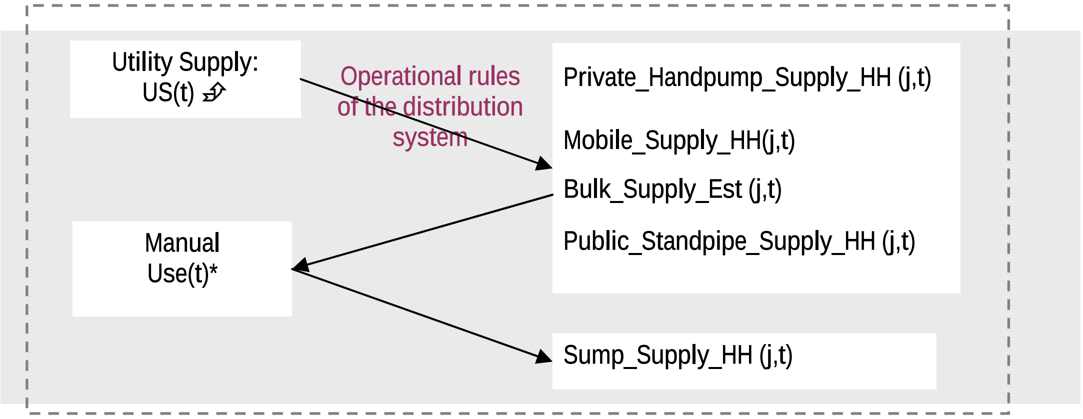
Figure 4.2 depicts a house with a sump and a handpump. Outlets to sumps are typically required to be placed above the distribution mains pipe (although residents do violate this norm on occasion based on informal interviews with households). Consequently, the sump receives water only if the pressure in the pipe is sufficient for the water to rise up into the sump inlet (a pressure of 1-2 meters above atmospheric pressure). In contrast, a handpump may be able to pump water out of the piped mains even when the mains are only partially full (at atmospheric pressure). To simulate this in our model we assumed that the needs of consumers with handpumps are satisfied first. Sump consumers are treated as passive consumers who get whatever is left after manual consumers have met their needs.

Metrowater's stated policy is that the water distributed to the pumping stations is in proportion to the population served. However, based on the data on quantities of water delivered to each pumping station, we were unable to confirm this or deduce an alternative rule for how the distribution system is operated. In our model, we simply assumed that all sump consumers get the same amount of water even though there are in fact significant variations in pressure within the Metrowater system. These variations result in high pressure "head-end" areas close to pumping stations and low-pressure "tail-end" areas away from pumping stations. Thus, while our model results may be reasonable for the "representative" household assumed for each spatial unit or zone, the results are not accurate at the neighborhood, street, or individual household level.

In the model, sump consumers are assumed to be passive. They get whatever is left after manual consumers have satisfied their demand, the quantity of water delivered to sump consumers depends on the quantity *actually used* by manual consumers. However, the Utility module simulates only quantity *available*; quantity *used* is estimated in the Consumer module. To resolve this, the Utility and Consumer modules were run iteratively in the following order. First, the Utility module was run for all manual consumers. Next, the Consumer module was run for manual consumers to determine how much water is actually used by manual consumers given the price and supply constraints they face. Then, the Utility module was run for sump consumers, followed by the Consumer module for sump consumers.

### *4.1.2.3 Variables and key linkages*

Let Public_Standpipe_Supply_HH, Private_Handpump_Supply_HH, Mobile_Supply_HH, Sump_Supply_HH, and, Bulk_Supply_Est be the daily quantities supplied to each household (or establishment) via public standpipes, private handpumps, mobile supply, sump or bulk connections respectively. The number of households/establishments in each consumer category were derived from 2001 Census data and are presented in Appendix C. Then the quantities delivered at a given location j, in period t, are a function of total available supply, the rules of operation and physical nature of the distribution system as shown in Figure 4.3**.**



Legend:
Known Input /Output
Partly Known Input/Output
Calibrated parameter
Endogenous variable

The subscript j denotes the zone and i denotes consumer category

**Figure 4.3: Linkages in water distribution sub-module**

#### *4.1.2.4 Equations governing water distribution*

Based on conversations with city officials, we assume that Metrowater manages supply in the following order of priority: mobile supply, supply to industries outside Chennai followed by piped supply. Note that this is a crude characterization of how the system works out not necessarily the utility's policy.

***Mobile supply:***

We assume unconnected consumers are provided with water at a rate of 20 liters per capita per day or 90 liters (=6 pots) per household per day, for an average Chennai household of 4.5 people. These consumers (often low-income housing colonies or slums – locally referred to as kuppams) tend to be highly politically active in Chennai and typically have few alternatives to tanker water. They readily agitate to ensure that these minimum needs are met[63]. From interviews with slum residents, we found a wide variation in per capita supply even between neighboring slums with similar socio-economic characteristics. However, the reasons for

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[63] Interviews with kuppam residents indicate that these residents tend to be very politically active and able and willing to mobilize to ensure they get a minimum lifeline supply. In the few kuppams where we interviewed residents, residents were able to describe strategies of when and how they would approach the local depot manager to agitate, how to split the transport costs, etc.

these differences are complex[64] and beyond the scope of this research. Coelho's (2004) ethnographic analysis of Metrowater, provides an explanation of the processes involved, but these are not readily translatable into an integrated model. Thus, we did not model spatial variability in mobile supply across Chennai. Instead, the model uses an average figure in all zones.

**Mobile_Supply_HH(j,t) = 90 LPHD**

**Equation 4.7**

**Mobile_Supply(t) = Mobile_Supply_HH(j,t) * Unconnected_HH(t)**

**Equation 4.8**

where Mobile_Supply(t) is the total amount of water supplied by utility-run tankers Unconnected_HH (t) represents the number of unconnected households. These are households that receive mobile supply regularly.

***Bulk Supply***

Commercial and industrial consumers, called bulk consumers, have dedicated pipelines from pumping stations. They are charged at a rate which is 25 times the residential rate and are crucial to the Metrowater's financial viability. We assume that meeting the demand of bulk commercial and industrial consumers is accorded high priority and amounts to about 10% of the total utility supply.

**Bulk_Supply (t) = MIN (40 MLD, 10% of Utility_Supply(t) )**

**Equation 4.9**

After the two above categories' needs are met, the rest of the water is pumped from pumping stations and taken up by handpump and piped consumers.

**Piped_Supply(t) = Utility_Supply (t) – Mobile_Supply(t) – Bulk_Supply (t)**

**Equation 4.10**

where Piped_Supply (t) represents the total quantity of supplied input into the piped system.

The quantity of water available in the piped system is distributed to public standpipes, private handpumps and sumps.

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[64] Political clout, presence of liquor manufacturers who were siphoning off water by bribing the tanker drivers, were some of the reasons cited but not investigated fully.

***Private Handpumps:***

We assume that the maximum quantity of water available to hand pump consumers is restricted by the time it takes to pump the water, and the number of hours during which water is available in the piped mains. This quantity may be too much or too little to meet the consumers' demand. It does not represent the actual consumption, merely the maximum available to the consumer. We did not model spatial variability in utility supply across Chennai. Only temporal variability was modeled.

$$\text{Private\_Handpump\_Supply\_HH}(j,t) = \text{Hours\_Supply}(t) * (60\ \text{min/hr}) * \text{Pot\_Time} * 15$$

**Equation 4.11**

where Private_Handpump_Supply_HH(j,t) is the quantity available to each HH having manual access to the piped supply system.

Pot_Time is the pots that can be filled per minute. We assume that it takes about one minute to fill a 15-liter pot of water (and 30 seconds to fetch it or 1.5 minutes in collection time). However, only the filling time is relevant as far as the utility system is concerned.

$$\therefore\ \text{Pot\_Time} = 1\ \text{pot/minute}$$

Hours_Supply(t) = Number of hours daily for which water is available. The number of hours for which water is available is dependent on the quantity of water available to the city. We use a simple correlation between the hours for which water is available and the city supply.

$$\text{Hours\_of\_Supply}(t) = \text{Piped\_Supply}(t) * \alpha$$

**Equation 4.12**

Empirically, since piped supply varied between 2 and 8 hours each day, and quantity of water supplied varied between about 200 and 800 MLD, we used $\alpha = 0.01$. The model was not very sensitive to our choice of $\alpha$.

***Public Standpipes***

For consumers accessing water via public standpipes, we assume that the quantity available is divided by the number of households sharing the connection. Again, we did not model spatial variability in utility supply across Chennai. Only temporal variability was modeled.

$$\text{Public\_Standpipe\_Supply\_HH}(j,t) = \frac{\text{Private\_Handpump\_Supply\_HH}(t)}{\text{Sharing\_HH}}$$

**Equation 4.13**

Public_Standpipe_Supply_HH(j,t) is the quantity of water available via public standpipes

Sharing_HH is the number of households that share the connection; assumed to be 10 for street taps and 1 for a private connection.

We found that manual consumers were "demand-constrained" (limited by time and effort of collection) and not "supply-constrained" (availability in the piped system) for most periods. So the model is fairly insensitive to the number of households the hours of supply.

***Emergency Mobile Supply***

Emergency mobile supply is made available to all residential if the piped supply system shuts down

$$\text{Emer\_Mobile\_Supply\_HH}(j,t) = \begin{cases} 90 & \text{if Piped\_Supply} = 0 \\ 0 & \text{if Piped\_Supply} > 0 \end{cases}$$

**Equation 4.14**

***Piped supply to sumps***

Full service consumers receive water in their underground sumps and are "passive" consumers. Sump consumers receive water from the piped mains until their sumps are full[65]. The quantity of water delivered into the sumps depends on the flow rate and connection size, which is dependent on the pressure at that point in the system and the diameter of the piped mains connection. As with mobile, private handpump and public standpipe supply, we did not model spatial variability in utility supply across Chennai. Only temporal variability was modeled.

$$\text{Sump\_Supply\_HH}(j,t) = \frac{\text{Piped\_Supply}(t) - \text{Manual\_Use}(t)}{\text{Sump\_HH}}$$

**Equation 4.15**

Sump_Supply_HH(j,t) is the quantity available to each HH that has a sump

Manual_Use(t) is the quantity of water actually consumed by consumers with handpumps, yard taps and other forms of manual access to the piped supply system.

Sump_HH is the total number of households with sump connections

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[65] Automatic valves are quite rare. Most consumers appear to have manual valves, so they can turn the inlet off if the sump overflows. More commonly, if the water level rises above the inlet of the piped mains, it flows back into the mains. Thus, the maximum sump capacity is the sump volume below the inlet.

$$\text{Manual\_use}(t) = \frac{1}{10^6}\sum_{j=1}^{12} \text{Public\_Standpipe\_Use\_HH}(j, t) * \text{Unconnected\_HH}(j, t) + \text{Private\_Handpump\_Use\_HH}(j, t) * \text{Manual\_HH}(j, t) + \text{Private\_Handpump\_Use\_HH}(j, t) * \text{Manual\_\_w\_BW\_HH}(j, t)$$

**Equation 4.16**

### *4.1.3 Calibration of Utility Module*

The output of the Utility module is the quantity of utility water available to a representative household in each consumer category in each time period. Figure 4.5 below shows the quantity of water available in each period to each mode of supply. i.e., the values of Mobile_Supply_HH, Private_Supply_HH, Public_Supply_HH, and Sump_Supply_HH. These represent the maximum amount that would be *theoretically* available to a consumer in each category. The actual quantity taken would be estimated in the Consumer module.

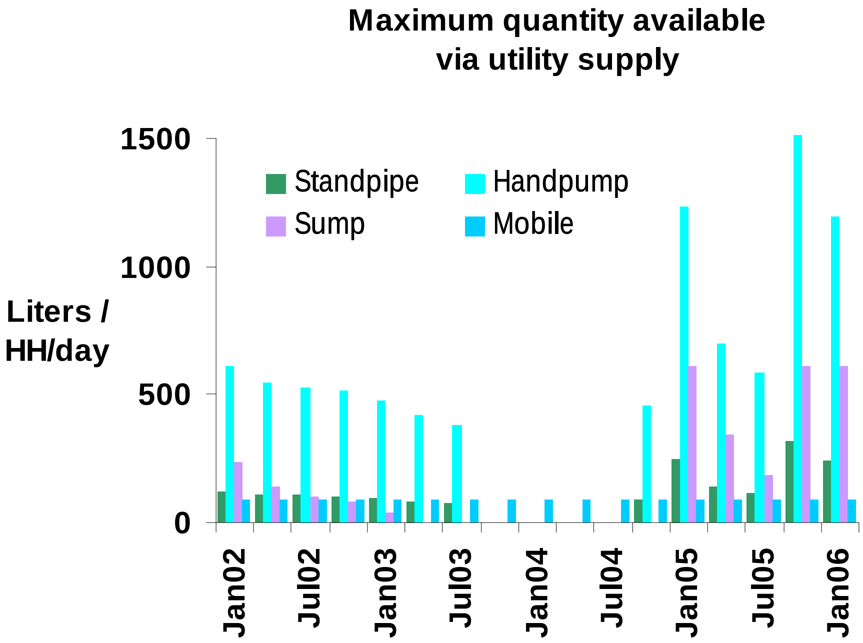


**Figure 4.4: Quantity delivered to different connection types**

The maximum quantity available to a consumer via each mode of supply, i.e., the supply constraint on the consumer, shown in Figure 4.4, is not an observable entity; this quantity is impossible to measure how much water would be theoretically available to each household. The only observable entity is the quantity actually consumed. As a result, the utility module was not calibrated independently. Instead, it was calibrated jointly with the consumer module as discussed in the subsequent section.

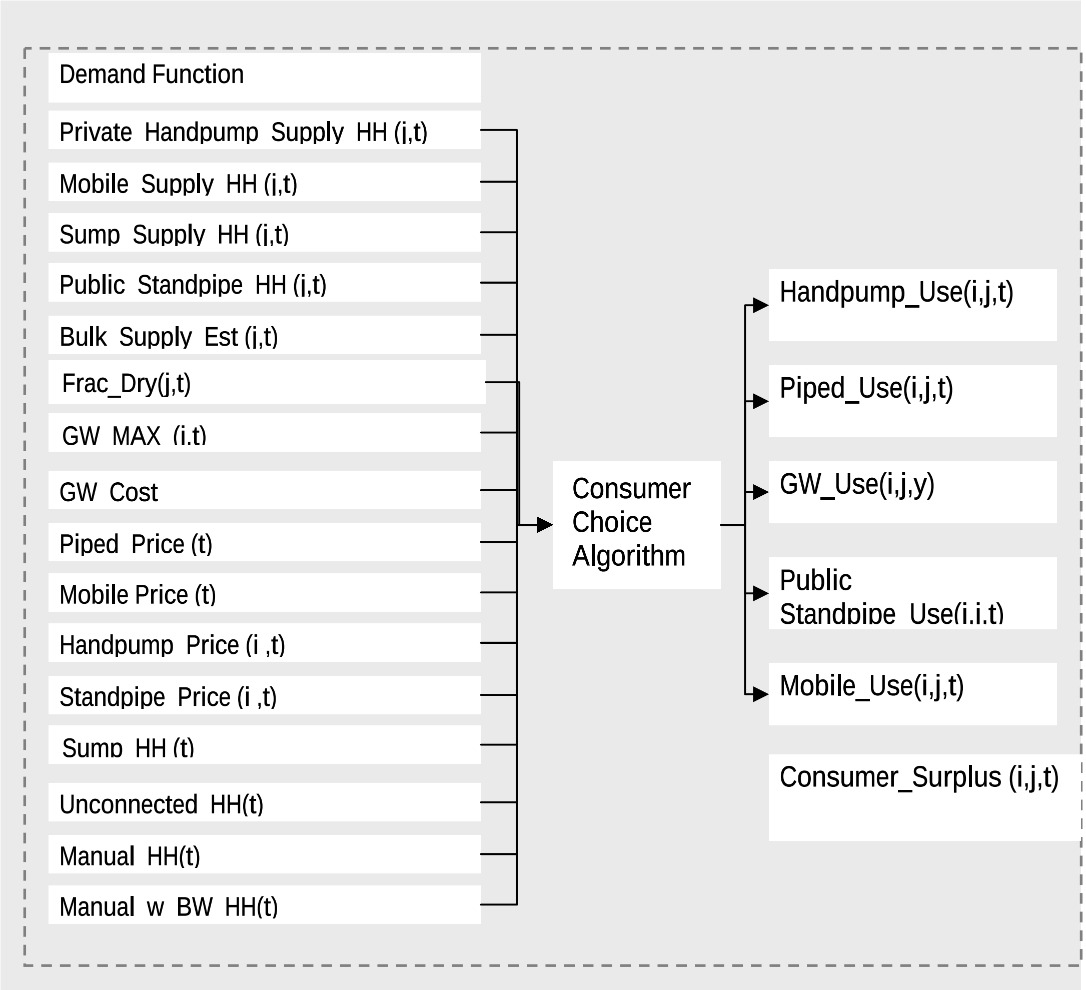
## 4.2 Consumer Module

The purpose of the Consumer module is to simulate how much water consumers actually use from each of the supply options available to them. As defined in earlier chapters, a "consumer" refers to a "representative" household headed by a rational decision-maker, who makes decisions about investment and consumption for the entire household. The consumers' choice problem is solved for each consumer category, zone and time period. Table 4.3 shows the sub-modules and equations in the consumer module. In the Table, variables or relationships labeled in purple are calibrated.

**Table 4.3: Sub-modules and Equations in Consumer Module**

| Module | Equation | Inputs | Transformation | Outputs |
|---|---|---|---|---|
| Demand Estimation | 4.17<br>4.18 | Household and commercial survey data<br>Income | Regression | Residential and commercial demand functions |
| Creation of tiers | N/A | Water availability by source<br>Water quality by source<br>Price by source:<br>Price of utility piped supply<br>Price of groundwater<br>Price of tanker water<br>Opportunity cost of time<br>Collection time from private handpumps<br>Collection time from public standpipes | Ranking algorithm | Tiered supply curves by consumer category |
| Consumer Choice | N/A | Residential and commercial demand functions<br>Tiered supply curves by consumer category<br>Population | Consumer choice algorithm | Water consumed by consumer category, by mode of supply, and quality |
| Consumer Surplus Estimation | 4.19 | Water consumed by consumer category, by mode of supply, and quality | Welfare estimation | Consumer surplus |

The integrated water paradigm framework developed in Chapter 2 was used to determine how consumers make choices when the quantity of water available from various sources is limited. Consumers minimize costs by using as much as possible of the least-cost source before they move on to the next source; i.e., consumers face a “tiered supply curve”. The total water consumed is determined by the demand function. The area between the supply and demand curves is a measure of the consumer surplus, a measure of consumer well-being. The main inputs into the Consumer module are the supply restrictions, the quality and the price of water of each source. The key linkages are shown in Figure 4.5.



Legend:
Known Input /Output
Partly Known Input/Output
Calibrated parameter
Endogenous variable
The subscript j denotes the zone and i denotes consumer category

**Figure 4.5: Linkages in Consumer module**

The Consumer module consists of four sub-modules; estimation of the demand function, development of the tiered supply curve, the choice algorithm, and welfare estimation.

### *4.2.1 The residential and commercial demand function*

The total quantum of water consumed by consumers is obtained by the intersection of the demand and supply curves. Knowledge of the consumers' demand function is therefore a key input into the Consumer module. The estimation of residential demand has been a subject of intensive research for many decades now. However, studies aimed at demand estimation in the developing world have been plagued by four problems; quantity estimation, the supply constraint problem, the price estimation problem and the income-effect problem.

1) **Quantity Estimation Problem:** Estimating quantity consumed is often challenging because metering coverage may be sparse, and water meters often do not work.
2) **Supply Constraint Problem:** Because of the unreliable nature of public supply, even if metered data is widely available, the quantity consumed may reflect supply conditions rather than consumer demand. Furthermore, consumers often get water from multiple sources. Failing to account for other sources may result in severly underestimating total quantity consumed.
3) **Price Estimation Problem:** Often in developing countries, poorer consumers tend to depend on manual collection of water from public standpipes or community sources such as wells, ponds or rivers. Although water from these sources may be free, consumers still pay a "price" in terms of time and labor costs of hauling water.
4) "**Income-Effect" Problem:** Because utility supply is unrealiable, many households rely heavily on coping mechanisms such as private wells and tankers or vendors to satisfy their needs. So even if the most expensive or dominant source is considered, the marginal price is not correctly reflect the lower price paid for infra-marginal units.

In this research, we used an alternative approach to estimating the household demand function that addresses these challenges. Using the integrated water paradigm framework developed in Chapter 2, the tiered supply curve is treated as a special case of an increasing block rate tariff[66]. The method suggested by Nieswiadomy and Molina (1988) for increasing-block rate tariff schedules, which uses the "difference variable" to account for the fact that infra-marginal (i.e., initial or non-marginal) units are purchased at cheaper rates, was employed.

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[66] Since by definition the tiered supply curve must always be an increasing block-rate tariff, we did not concern ourselves with the literature addressing more general tariff structures.

The difference variable is a measure of benefit that accrues to the consumer from getting the initial units cheaper. A large difference variable indicates a large difference between the price paid for infra-marginal units and the marginal unit, and thus implies a larger "income-benefit". So the coefficient of the difference variable must therefore be positive.

By using the difference variable and tiered supply curve formulation, we were able to overcome the income-effect problem by taking into account the extent to which infra-marginal units were cheaper than the marginal price. Likewise the tiered supply curve formulation addresses the supply constraint problem. A more detailed discussion of how the price estimation and quantity estimation problems were overcome is presented in Appendix H.

In Chapter 2, we defined the difference variable mathematically as follows: For a consumer who has consumes water from M sources of water, where the price of the $k^{th}$ source is $p_k$ such that $p_1 \leq p_2 \leq ..... \leq p_M$ and $q_k$ is the quantity consumed from the $k^{th}$ source in each time period.

$$Difference = p_M q_M - \sum_{k=1}^{M} p_k q_k$$

**Equation 4.17**

Figure 4.6 shows the value of the difference variable graphically.

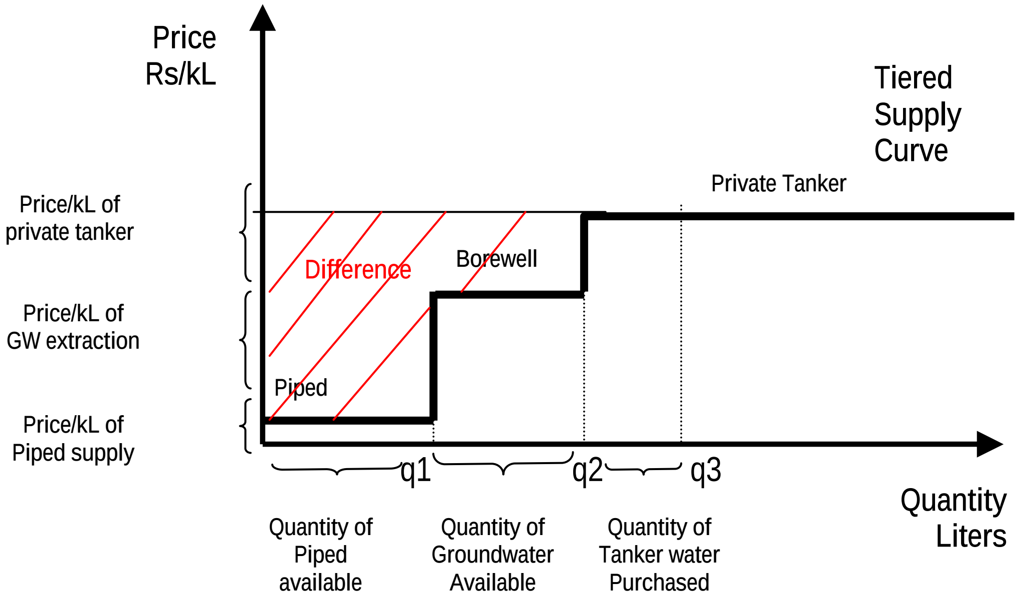

**Figure 4.6: The difference variable**

A pooled data set of 1488 households in Chennai the January 2006 household survey and 1510 households from the January 2004 survey was used in demand estimation. The description of the survey, questionnaire and demand estimation methodology are presented in Appendix F, G, and H, respectively.

Residential water demand is usually expressed as a function of price, income, household size, season, garden size etc.

$$Q = C\ P^{\alpha} N^{\beta} D^{\gamma} I^{\delta}$$

where

Q= Total quantity consumed in liters per HH per week (Note: need to divide by 7, to obtain consumption in liters/HH/day)

P = the marginal price or price in Rs /kL of the marginal source

$\alpha$ = Price elasticity of demand (assumed constant)

N = Total number of members in the household

I is a discrete variable that indicates if household income > Rs 10,000 / month

Thus, I = 1 if household income > Rs 10,000 / month,

I = 0, otherwise

D or Difference = Income effect to account for the fact that the infra-marginal sources are cheaper. i.e., it accounts for the fact than much of the water was purchased at a price lower than the marginal price.

Based on the regression function on the survey data set, the regression coefficients were estimated as C=4.6, $\alpha = -0.46$, $\beta = 0.44$, $\gamma = 0.27$, $\delta = 0.19$

Thus, the residential demand function was specified as follows.

$$\mathbf{Q = 4.6 * P^{-0.46} * N^{0.44} * D^{0.27} * I^{0.19}}$$

**Equation 4.18**

All coefficients had t-statistics that were significant at the 1% level.

We estimated a price elasticity of demand of -0.46. The price elasticity had 95% confidence interval of -0.41 to -0.51. Moreover, the estimate of Q was quite robust to changes in assumptions such as the opportunity cost of time, cost of groundwater extraction and pump efficiency. All the variables had highly significant coefficients. The $R^2$ for the regression was about 55%. Given the source and quality of the data, we believe that this $R^2$ is acceptable, especially given that this price elasticity of -0.46 was well within the range specified in literature[67].

### *4.2.2 Estimating the commercial demand function*

We derived the commercial demand function from our survey data set of 217 establishments in January 2006. The description of the survey, questionnaires and demand estimation methodology are presented in Appendices F,G, and H, respectively.

Commercial water demand is usually expressed as a function of price, establishment size, or industry type. The functional form chosen to estimate the commercial demand function was

$$Q = C \;\; P^{\alpha} FE^{\beta} D^{\gamma} WI^{\delta}$$

where

Q = Total quantity consumed in liters per establishment per week (Note: need to divide by 7, to obtain consumption in liters/establishment/day)

P = the marginal price or price in Rs /kL of the marginal source. As can be seen in equation 4.10, we estimated a price elasticity of demand of -0.21.

FE = Total number of full time employees. An exponent of about 0.85 implies water use does not scale linearly with increase in number of employees.

D or Difference = (Same a residential demand function) Income effect to account for the fact that the infra-marginal sources are cheaper. i.e., it accounts for the fact than much of the water was purchased at a price lower than the marginal price.

WI is a discrete variable used to capture water-intensive establishments. Establishments that uses water for purposes other than restrooms use, e.g., cooling, cafeteria, laundry, process use, are defined as water intensive. Examples include large hotels, hospitals, and restaurants. WI= 1 for these establishments. Office buildings and retail establishments are considered non water-intensive, so WI=0 for these.

The regression coefficients were found to be C=6.17, $\alpha$ = -0.21, $\beta$ = 0.85, $\gamma$ = 0.06, $\delta$ = 0.19

Accordingly, the demand function was specified as follows.

$$\mathbf{Q = 6.17 * P^{-0.21} * FE^{0.85} * D^{0.06} * WI^{1.9}}$$

**Equation 4.19**

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[67] Arbues et al., 2003 provide a comprehensive meta-data analysis of price elasticity of demand in developed world settings. Most estimates ranged between -0.3 and -0.7.
Nauges and Strand, 2005 estimated the residential price elasticity of demand for Latin American countries at -0.3.

All the variables had highly significant coefficients. Although the $R^2$ for the regression at 39% was not as high as the residential case, the estimated price elasticity of demand, -0.2, is consistent with other estimates of price elasticity of commercial demand. These results indicate that commercial demand is less elastic to price than residential demand.

### *4.2.3 Constructing the tiered supply curve*

To develop a tiered supply curve we used the following inputs

1) Quantity of water available to a representative household in each category
2) Average price of water in Rs/kL from each source
3) Quality of water from each source (potable or non-potable)

#### *4.2.3.1 Quantity supplied from different sources*

The volumetric quantity limits in the tiered supply curve are input to the consumer choice module from the three supply-side modules. The variables from the different sources are assembled in Table 4.4.

**Table 4.4: Quantitative limits on water available from different sources**

| Consumer Category | Mobile (LPHD) | Utility Supply (LPHD) | Community well (LPHD) | Borewell (LPHD) | Number of HH |
|---|---|---|---|---|---|
| Unconnected | 90 | Public_Standpipe_Supply_HH | 0 or $\infty$* | N/A | Unconnected HH |
| Manual | 0 | Private_Handpump_Supply_HH | 0 or $\infty$* | N/A | Manual HH |
| Manual with borewell | 0 | Private_Handpump_Supply_HH | 0 or $\infty$* | GW_$Q_{MAX}$ | (1-Frac_Dry) * Manual_w_BW_HH |
| Manual + with borewell (well dry) | 0 | Private_Handpump_Supply_HH | 0 or $\infty$* | 0 | (Frac_Dry) * Manual_w_BW_HH |
| Sump | 0 | Sump_Supply_HH | 0 or $\infty$* | GW_$Q_{MAX}$ | (1-Frac_Dry) * Sump HH |
| Sump (well dry) | 0 | Sump_Supply_HH | 0 or $\infty$* | 0 | (Frac_Dry) * Sump HH |
| Commercial | 0 | Sump_Supply_HH | N/A | GW_$Q_{MAX}$ | (1-Frac_Dry) * 44,450 |
| Commercial with dry wells | 0 | Sump_Supply_HH | N/A | 0 | Frac_Dry * 44,450 |
| Water-Intensive | 0 | $\infty$ | N/A | GW_$Q_{MAX}$ | 1,130 |

*Manual and unconnected consumers are assumed to have access to shallow wells (open community wells, or manual handpumps connected to wells) about 40 feet deep. They have access to as much water as needed as long as shallow wells in an area have water, otherwise they have 0.

It is assumed that an unlimited amount of water can theoretically become available from private tankers, as the value of water to urban users will always exceed that to agriculture, i.e., there will always be enough farmers willing to sell water.

### *4.2.3.2 Prices of different sources*

Actual prices were used for utility, mobile and tanker supply. The cost of groundwater extraction was obtained from the Groundwater module. For consumers accessing manual supply, however, the cost of water involved the cost of time spent in collecting water defined as follows.

$$\mathbf{P_{Manual}\ (Rs/kL) = Coll\_Time\ (}\frac{hours}{pot}\mathbf{)\ *\ Op\_Cost\ (}\frac{Rs}{hour}\mathbf{)\ *\ (}\frac{1000}{15}\ \frac{kL}{pot}\mathbf{)}$$

**Equation 4.20**

Where

$P_{Manual}$ is the price of manual supply in Rs/kL

Coll_Time is the time spent in collecting water in hours per pot

Op_Cost is the opportunity cost of time in Rs/hour

While the average time spent in collecting water was known from the household survey data, opportunity cost of time was not. Unfortunately, opportunity cost of time is not a directly observable entity. Usually it is estimated indirectly based on choices made by consumers, i.e., consumers' willingness to pay to for time and labor saving options. However, the household survey was not designed to elicit this. Lacking comprehensive data on consumers' preferences, the opportunity cost of time was a calibrated parameter in the integrated model. To obtain the initial values and a reasonable range for the opportunity cost of time parameter, the following data and logic was applied.

1) Average collection times were estimated at 4.5 minutes/pot for public standpipes and 1.5 minutes/pot for private handpumps based on reported times in the household survey.
2) At Rs 12/hr (about the minimum wage) the cost of a pot of water works out to Re 1/pot, the price typically charged by water vendors. Since, not a single household purchased vendor water when standpipe water was available, we might conclude that the average opportunity cost of time had to be considerably lower than Rs 12/hr.
3) The household survey indicated that 75 percent of the water collected from public standpipes was fetched by unemployed women in the household, so the average opportunity cost of time is likely to be much lower than the Rs 12/hr minimum wage rate.
4) Wealthier households with sumps and borewells must have a higher opportunity cost of time than manual consumers to justify these capital-intensive investments. For instance, at

an opportunity cost of time as low as Rs 2/hr, the cost of a borewell is not justifiable; it would be cheaper for consumers to fetch water manually.

5) No household has an opportunity cost exceeding Rs 12/hr as beyond this it would be cheaper to hire someone to perform the tasks, or purchase vendor water.

Based on this information, it was surmised that the opportunity cost of time had to be between 0 and 12 Rs/hr (the minimum wage. The calibration process established the opportunity cost of time parameter value to be Rs 2/hour for the poorest consumers, earning Rs 5000/month or less. The opportunity cost of time was calibrated to be Rs 10/hr for the highest income households. Table 4.5 displays the price of water from different sources using the opportunity cost of time and collection times presented in this section.

**Table 4.5: Price of water from different sources**

| **Source of Supply** | **Price** (1$= Rs 40) | **Basis of assumption** |
|---|---|---|
| **Utility -Manual Supply** | | |
| Public Standpipe Handpump Supply (Low Income) | Rs 10/kL | The time spent in collection from public standpipes was assumed to be 4.5 minutes to fill the pot. The opportunity cost of time for low-income consumers was assumed to be Rs 2//hr<br>$\therefore$ Price of standpipe supply for low-income consumers<br>= Price $_{\text{Standpipe\_LI}}$<br>= Coll_Time * Op_Cost<br>$= (\frac{4.5}{60}\frac{hours}{pot} * \frac{Rs\,2}{hour} * \frac{1000}{15}\frac{pots}{kL})$<br>=Rs 10/kL |
| Private Handpump Supply (Low Income) | Rs 3.30/kL | The time spent in collection from private yard taps was assumed to be half a minute to fill the pot, a minute to fetch it into the house.<br>The opportunity cost of time for low-income consumers was assumed to be Rs 2//hr<br>$\therefore$ Price of handpump supply for low-income consumers<br>= Price $_{\text{Handpump\_LI}}$<br>= Coll_Time * Op_Cost<br>$= (\frac{1.5}{60}\frac{hours}{pot} * \frac{Rs\,2}{hour} * \frac{1000}{15}\frac{pots}{kL})$<br>=Rs 3.30/kL |

| | | |
|---|---|---|
| Private Handpump Supply<br>(High Income) | Rs 15/kL | The time spent in collection from private yard taps was assumed to be half a minute to fill the pot, a minute to fetch it into the house.<br>The opportunity cost of time for high-income consumers was assumed to be Rs 10//hr<br>$\therefore$Price of handpump supply for high-income consumers<br>= Price $_{\text{Handpump\_HI}}$<br>= Coll_Time * Op_Cost<br>$= \left(\frac{1.5}{60}\frac{hours}{pot} * \frac{Rs\,10}{hour} * \frac{1000}{15}\frac{pots}{kL}\right)$<br>=Rs 16.67/kL |
| **Utility -Mobile Supply** | | |
| Mobile Supply<br>(Low Income) | Rs 20/kL | The cost of mobile supply to slums was based on the average "cost" of a pot of tanker water. This cost consists of two components: the "tip" to be paid to the tanker driver plus the cost of fetching the water.<br>The tip to be paid to the tanker driver was reported at about to Re 1 four 15-liter pots or Rs16.67/kL<br>Price $_{\text{Tip}} = \left(\frac{1}{4}\frac{Rs}{pot} * \frac{1000}{15}\frac{pots}{kL}\right) = 16.67$<br>The cost of collection was assumed to be the same as that of private handpump = Rs 3.30/kL<br>$P_{\text{Mobile\_LI}} = P_{\text{Tip}} + P_{\text{Handpump\_LI}} =$<br>Rs 16.67 /kL + Rs 3.33/kL = Rs 20/kL |
| Mobile Supply<br>(High Income) | Rs 33.33/kL | Likewise for high income consumers, the price of mobile supply<br>$= P_{\text{Mobile\_HI}} = P_{\text{Tip}} + P_{\text{Handpump\_HI}} =$<br>Rs 16.67 /kL + Rs 16.67/kL = Rs 33/kL |
| **Utility- Sump Supply** | | |
| Sump Supply | Rs 2/kL | Piped supply in Chennai is largely unmetered, and therefore the marginal cost of supply is essentially the cost of pumping the water from the sump to the overhead tank in-house which is about Rs 2/kL |
| Commercial Sump Supply | Rs 15/kL | This price was obtained from the Metrowater Tariff Schedule[68] |
| Commercial Bulk Supply | Rs 60/kL | This price was obtained from the Metrowater Tariff Schedule |

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[68] Metrowater, 2008. Metrowater tariff schedule Accessed online July 10, 2008 http://www.chennaimetrowater.com/finance/finance_tariff.htm

| | | |
|---|---|---|
| **Groundwater Supply** | | |
| Shallow community wells | Rs 10/kL | The cost of water from shallow community wells was based on the average “cost” of collecting a pot of water from a public standpipe |
| Private motorized borewells | Rs 5.50/kL | Price of borewell water is estimated in the groundwater module (Equation 3.13 in Chapter 3.) |
| **Private Tanker/Vendor Supply** | | |
| Manual with well and sump consumers | Rs 50-55/kL | Price of tanker water is estimated in tanker market module. See Equation 3.12 in Chapter 3. |
| Unconnected and Manual consumers | Rs 66/kL | Based on the reported price of Re 1/ 15L pot.<br>Price $_{\text{vendor}}$= $(1\frac{Rupee}{pot}*\frac{1000}{15}\frac{pots}{kL})$ = Rs 66/kL |

#### *4.2.3.3 Quality of water supplied from different sources*

The following assumptions regarding water quality were made. Consumers can only distinguish between two qualities of water; potable and non-potable. The demand for the potable component was assumed to be inelastic and also accorded the highest priority by consumers. Thus consumers would first use any potable-quality water for potable needs. Potable water needs were set at 90 liters per household per day (LPHD) to be used for drinking, cooking and to some extent dishwashing and hand-washing[69]. Also utility supply from all modes (piped, handpump, mobile supply) is the only source of potable quality water. Bottled water is only used when no other source is available, and is capped at 2 LPCD for drinking purposes only.

Once the sources, the quantity available, quality, and the price available to a consumer are known, the tiered supply curve can be constructed by ranking the sources from cheapest to most expensive. For potable needs, 90 liters per household per day (LPHD) was consumed from the cheapest potable source. In developing the non-potable tiered supply curve, 90 LPHD is subtracted from the cheapest available potable source. For instance, by combining the information from Table 4.4 and Table 4.5 as shown in Table 4.6, the tiered supply curve for unconnected consumers could be constructed (Figure 4.7).

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[69] We initially considered assuming potable water would be used only for drinking and cooking amounting to about 5 LPCD. However, we were unable quantities that were being used in households with handpumps. The only way we could explain extensive preference for handpump water in households who had access to other non-potable sources was by requiring potable water use of other kitchen uses like dishwashing. In some slum areas particularly where groundwater is salty, we found households would use potable quality water for the final rinse.

**Table 4.6: Tiered Supply Curve Inputs**

| **Source** | **Quantity Available** | **Price** | **Quality** |
|---|---|---|---|
| **Mobile** | 90 | Rs 20/kL | Potable |
| **Public Standpipe** | Public_Standpipe_Supply_HH | Rs 10/kL | Non-Potable |
| **Community well** | 0 or ∞* | Rs 10/kL | Non-Potable |
| **Water Vendor** | ∞ | Rs 66/kL | Non-Potable |

*0 if shallow community wells of 40 ft depth are dry, ∞ otherwise

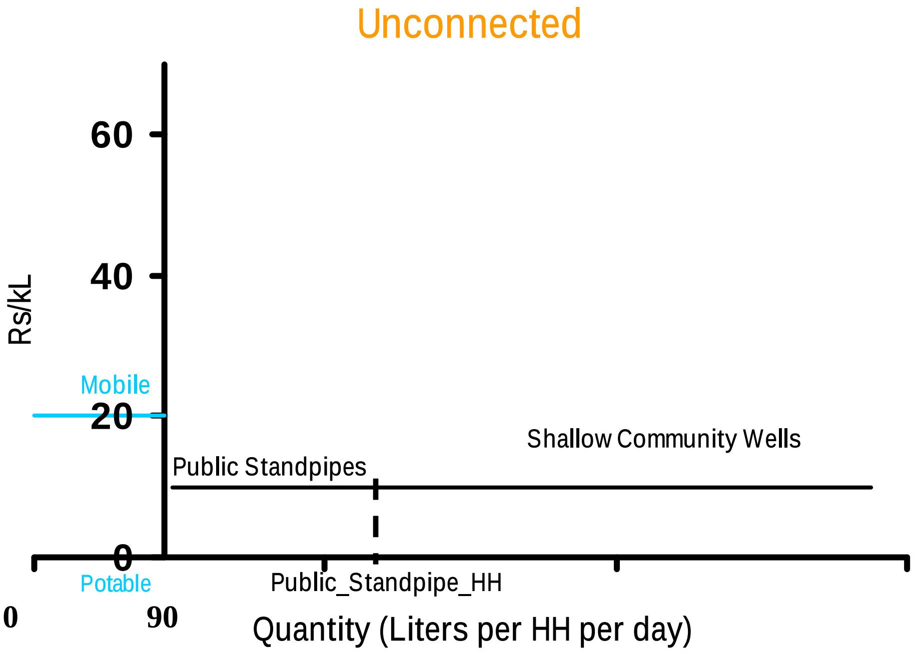

**Figure 4.7: Tiered Supply Curve for Unconnected consumers**

### *4.2.4 Choice Algorithm*

Once the demand function and tiered supply curve have been constructed, the next step is to estimate the quantum of water consumed. This is not entirely straightforward, because of the specific functional form of the demand function, which determines that the total consumption is governed both by the marginal price as well as infra-marginal prices. In effect, each time the consumer reaches a quantitative limit, the consumer must decide if it is worth moving on to the next most expensive source or just stop. The consumers-choice algorithm is used to determine which the marginal source should be. The flowchart of the consumer-choice algorithm is shown in Figure 4.8.

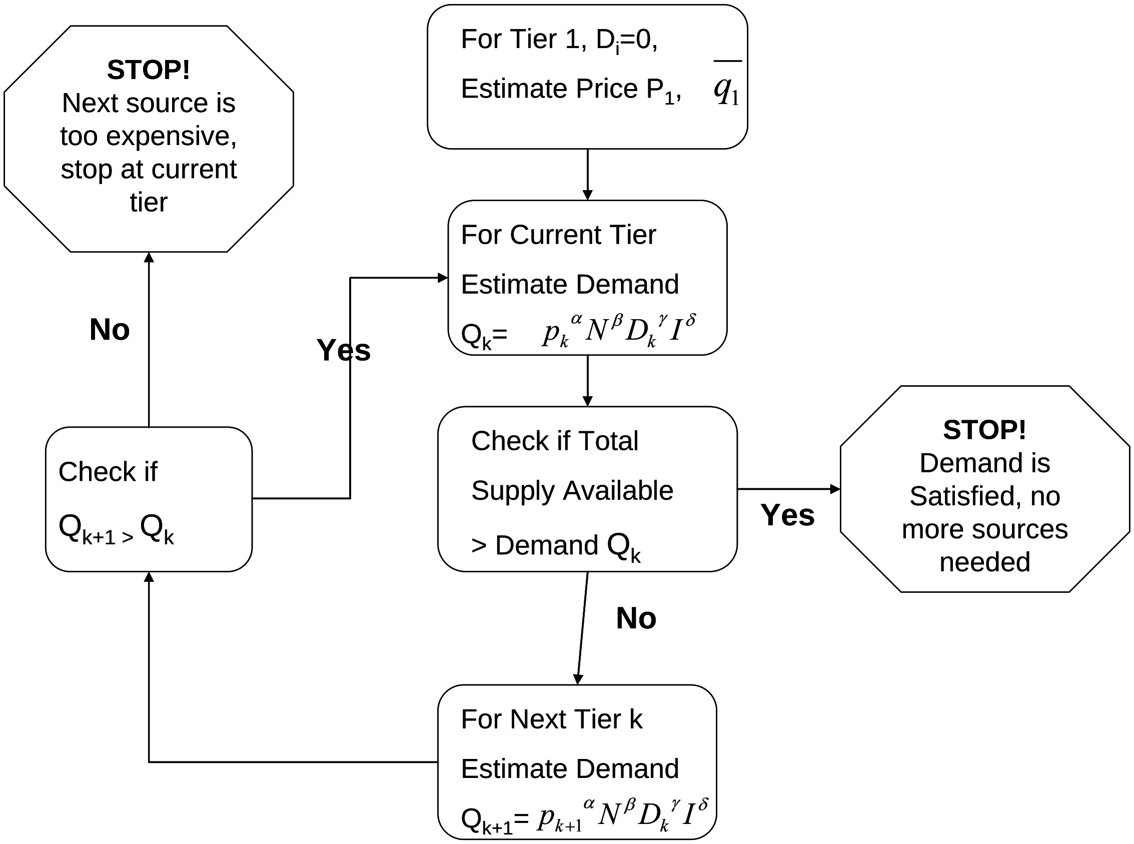

**Figure 4.8: Consumer-Choice Algorithm**

The consumer-choice algorithm can be described as follows. For each tier, we determine the marginal price ($p_k$), supply available ($\overline{q_k}$), and difference ($D_k$) variable. Then we use the demand function to estimate total demand ($Q_k$) and compute residual demand (total demand less demand satisfied from cheaper sources). If supply available from that source exceeds residual demand, then that tier is the marginal tier; i.e., the consumer meets all remaining demand from that source. However, if residual demand exceeds supply, then the consumer will choose to go on to the next source, repeating the process once more. The Consumer module yields for each consumer category, area, and time period, the quantum of water consumed from each source. By multiplying this by price, we can obtain economic variables of interest such as monthly spending on water, consumer welfare, etc.

### *4.2.5 Consumer-Surplus Estimation*

Based on the formulae obtained on Chapter 2, we were able to estimate consumer surplus in Rs/HH/day.

$$CS(Q) = \frac{1+\alpha}{7 * C^{\frac{1}{\alpha}} N^{\frac{\beta}{\alpha}} I^{\frac{\delta}{\alpha}}} \sum_{1}^{M} \frac{1}{D_i^{\frac{\gamma}{\alpha}}} \{ Q_i^{\frac{1}{1+\alpha}} - Q_{i-1}^{\frac{1}{1+\alpha}} ) - \sum_{1}^{M} C_i q_i$$

**Equation 4.21**

Where

CS(Q) is the consumer surplus for the demand function assumed.

C, N, I, D, Q, α,β,γ and δ are defined as in Section 4.2.1. The factor of 7 is because the of the unit conversion. The demand function was defined in liters/HH/week, while the consumer surplus is in Rs/day. The consumer surplus per household by consumer category is shown in Figure 4.9.

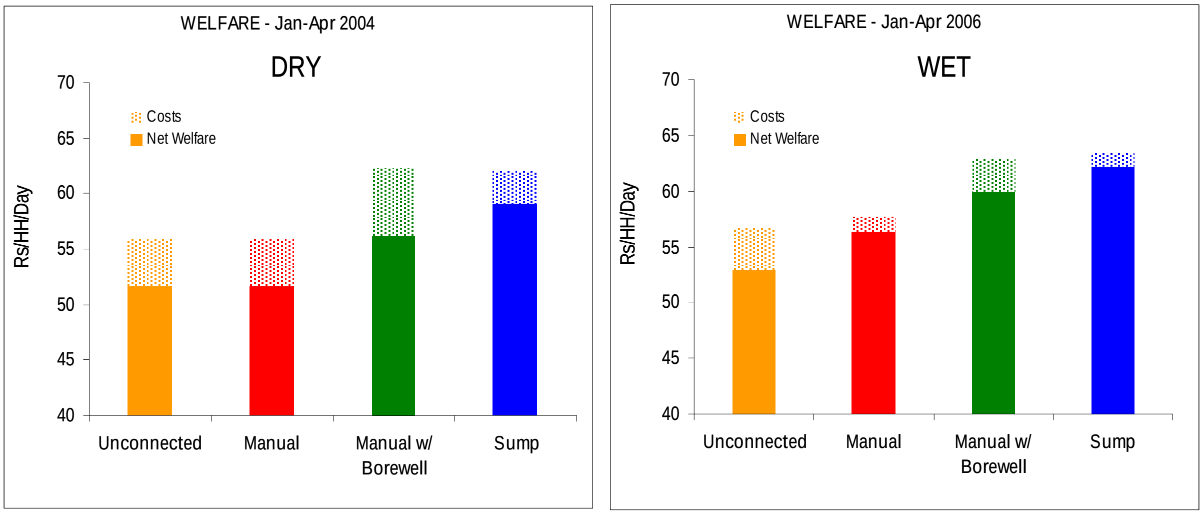

**Figure 4.9: Consumer Surplus by consumer category during the dry and wet years**

Figure 4.9 shows the consumer surplus for each consumer category in the two reference periods: Jan 2002 (dry) and Jan 2006 (wet). The figure should be interpreted as follows. The solid area is the net consumer surplus, the measure of consumer well-being. The shaded area represents the amount spent (including opportunity cost of time). The sum of the two is the gross benefit.

The rationale for displaying the figure in this way is as follows. A drop in consumer surplus occurs for two reasons: consuming less water, and paying more for water. Gross benefit decreases when the quantity consumed decreases. Cost increases when the amount paid by the consumer increases. Change in consumer surplus occurs due to the combination of both effects. In general, all consumer categories were worse off during the Jan 2004 drought period, they consumed less, paid more and enjoyed a lower consumer surplus. So for each category the consumer surplus in Rs/HH/day was less. In both periods higher income consumers, who invested in coping mechanisms, enjoyed a higher consumer surplus than low income consumers who did not.

### *4.2.6 Joint calibration of the Consumer and Utility modules*

Earlier in the chapter we argued that the Utility module could not be calibrated independently because its outputs were not directly observable. Moreover, the Utility and Consumer modules are run in a coupled manner, because the quantity of water consumed by some categories of consumers determined how much was available for others.

The main model parameters that were calibrated were

1) Groundwater price
2) Opportunity cost of time
3) Well efficiency

In the subsequent sections, we describe how we used two sets of observations, household survey data and tanker observation data, to calibrate these parameters. Although sensitivity analyses were conducted on a variety of minor parameters, the model was relatively insensitive to the other parameters.

Figure 4.10 shows the conceptual model for the joint calibration process.

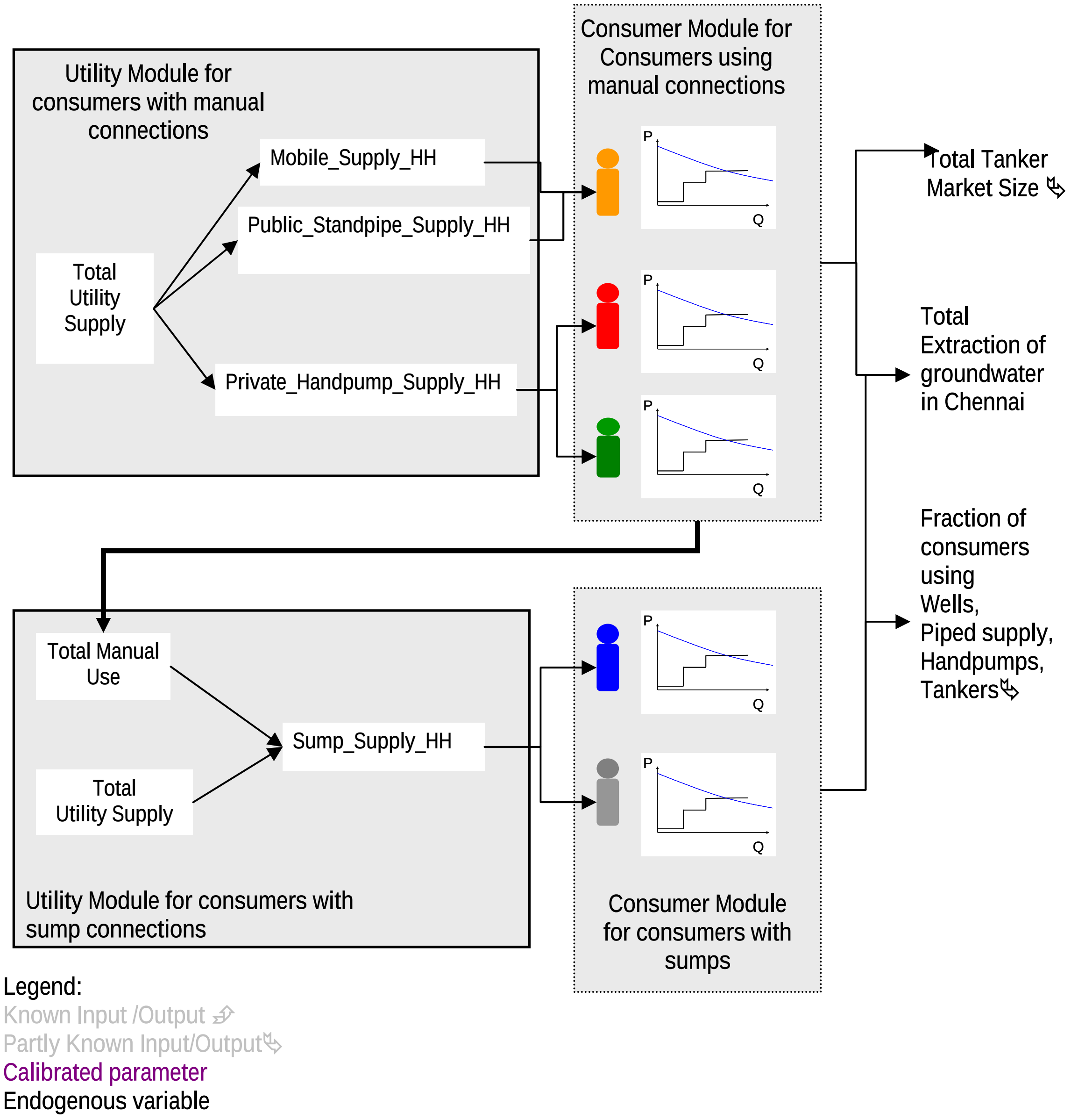

**Figure 4.10: Joint Calibration**

### *4.2.7 Household Survey*

Groundwater price and opportunity cost of time were calibrated against the statistics from the household survey described fully in Appendix F. The parameters were calibrated against two types of statistics compiled from the survey: the fraction of households accessing a particular source and the average quantity of water used per capita by source. These statistics were used because they could be used in a comparable manner between both data sets in the dry and wet years, respectively. The results from our best calibration run are shown in Figure 4.11, Figure 4.12, Figure 4.13 and Figure 4.14.

Figure 4.11 and Figure 4.12 compare the fraction of households accessing each source from the calibrated model and the household survey data, for the periods Jan-Apr 2004 and Jan-Apr 2006, respectively. In the figures, potable (utility) sources are shown in blue, while non-potable sources (self-supply and private supply) are shown in gray.

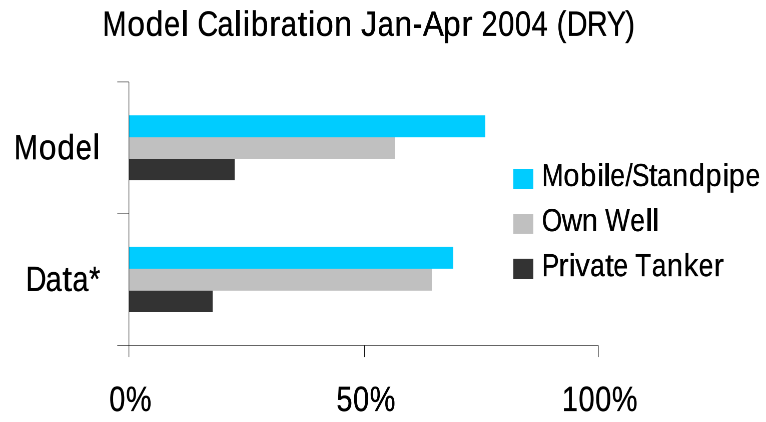

**Figure 4.11: Calibrated versus observed percent of HH by source accessed (2004)**

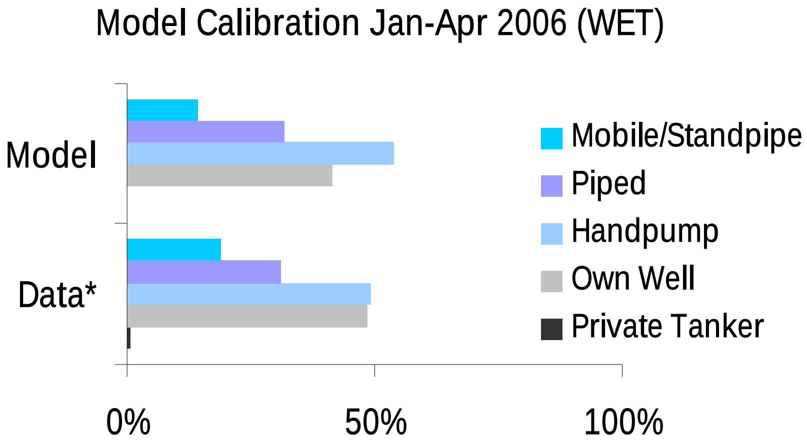

**Figure 4.12: Calibrated versus observed percent of HH by source accessed (2006)**

From Figure 4.11 and Figure 4.12, it may be seen that the model was able to match the fraction of households accessing different sources within 10%, in both wet and dry years for each source. Since utility supply was shut-down in 2004, the fraction of households is not reported. Figure 4.13 and Figure 4.14 compare the average quantity of water from each source from the calibrated model and the household survey data, for the periods Jan-Apr 2004 and Jan-Apr 2006, respectively. In the figures, potable (utility) sources are shown in blue, while non-potable sources (self-supply and private supply) are shown in gray.

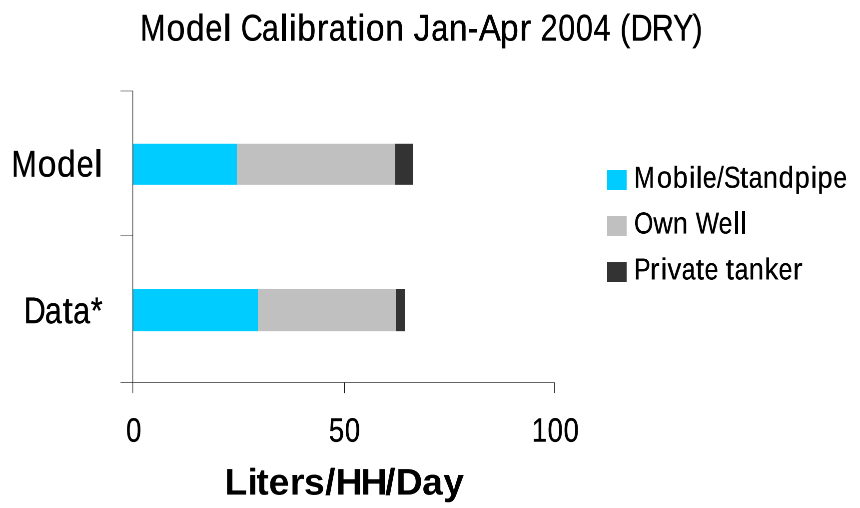

**Figure 4.13: Calibrated versus observed quantity consumed by source in Jan 2004**

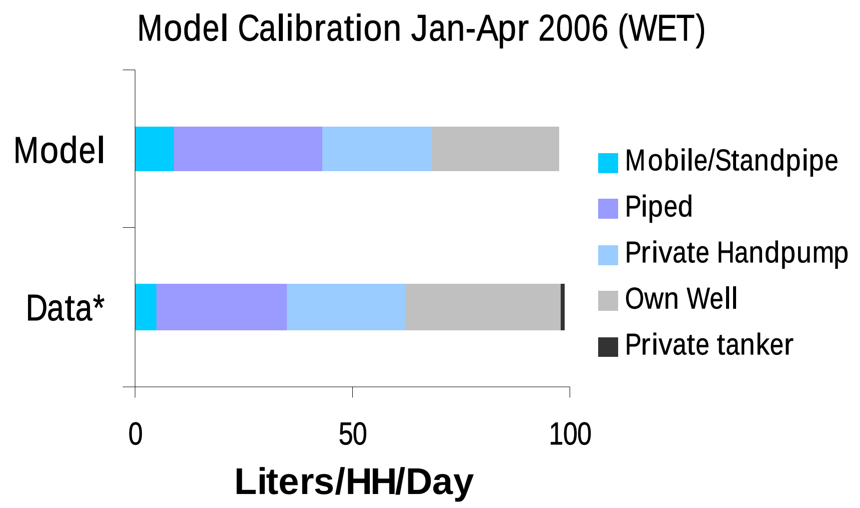

**Figure 4.14: Calibrated versus observed quantity consumed by source in Jan 2006**

From Figure 4.13 and Figure 4.14, it may be seen that the model was able to match the quantity consumed by source reasonably well in both wet and dry years for each source. In the next section we present the sensitivity analyses on the parameters that were calibrated.

### 4.2.8 *Sensitivity Analysis on cost of groundwater extraction*

In Chapter 3, we presented our estimation of cost of groundwater. The cost was estimated based on average well and pump efficiency. Groundwater price affects the quantity demanded per household in the Consumer module, and consequently the total groundwater extracted in the Groundwater module. Since the cost of groundwater extraction is not easily observable, we needed to conduct sensitivity analyses to test our parameter assumption. Figure 4.15 and Figure 4.16 show the quantity of own-well supply (averaged across all households in Chennai) predicted by the model versus the household survey data in 2004 and 2006, respectively.

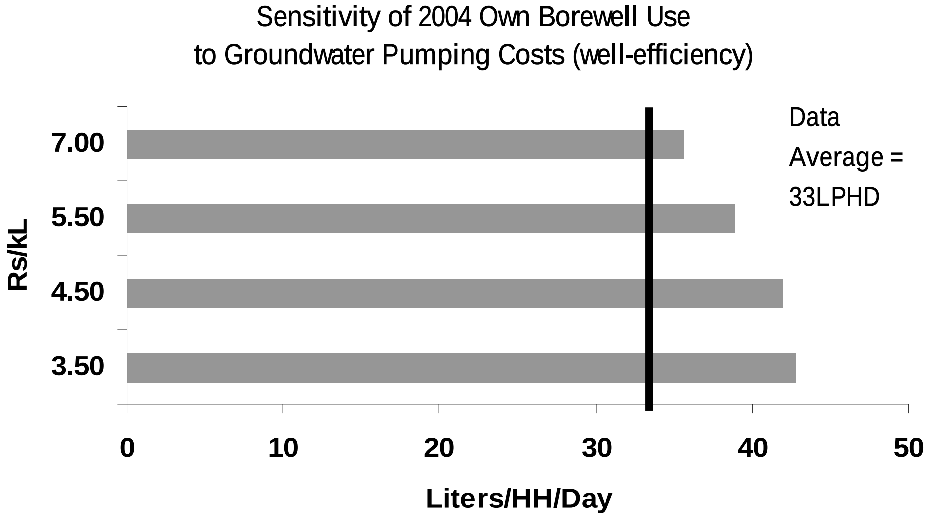

**Figure 4.15: Sensitivity of model result to groundwater pumping costs (Jan 2004)**

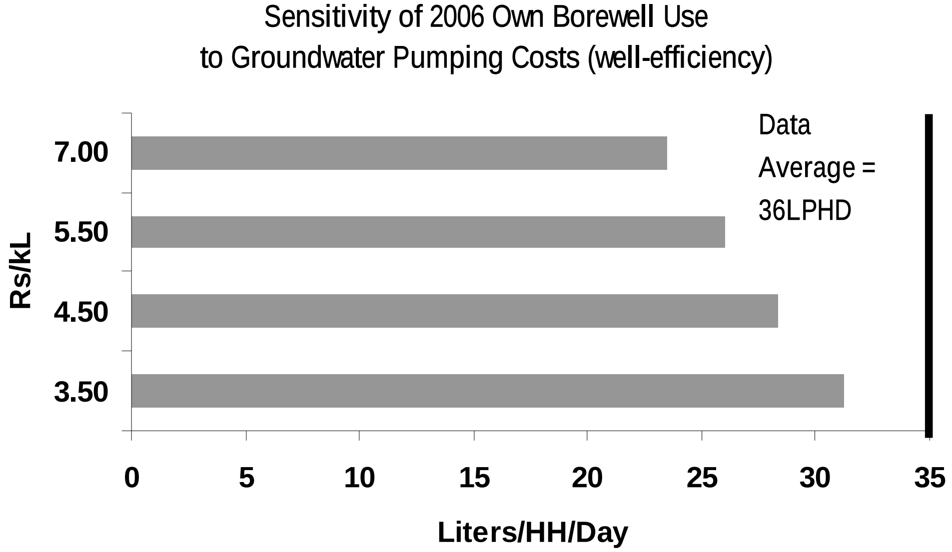

**Figure 4.16: Sensitivity of model result to groundwater pumping costs (Jan 2006)**

From figures 4.15 and 4.16, it may be seen that for the period Jan-Apr 2004, we consistently overestimated groundwater use over the entire range of pumping costs, while for model period Jan-Apr 2006 we underestimated groundwater use over the entire range of pumping costs. From this one might infer that groundwater pumping costs were higher during drought because of the lower water table, so consumers used less groundwater and use of an average constant groundwater price (independent of groundwater head) is faulty. However, examination of the groundwater head maps does not lend credence to this explanation. Groundwater heads dropped only about 10-15 m at the peak of the drought, not enough to increase pumping costs sufficiently for consumers to notice the difference in their electricity bills and adjust behavior. An alternative more likely explanation is that water quality was poorer during the drought as consumers were forced to pump from the deeper (lower quality) aquifer. Because of the poorer water quality encountered at depth, consumers avoided extracting groundwater for some uses they might normally have used it for (such as clothes washing), instead preferring to buy tanker water. So although the fractions of households predicted was correct, the model may be over-predicting groundwater use during the drought. However, since we have not modeled water quality in the aquifer, or included a quality variable in the demand function, we could not formalize this. In the wet year, it is possible the model assumption of 25% pipeline losses is in fact too optimistic. It is possible that if pipeline losses were higher, groundwater extraction (and recharge) might both be more. To avoid complicating the model, it was decided to use an average groundwater price of Rs 5.50/kL, which would minimize the variability between the modeled and observed groundwater use for the two years.

### *4.2.9 Sensitivity Analysis on Opportunity cost of time*

The opportunity cost of time parameter affects the cost of water collected manually from private handpumps, and public standpipes. As discussed earlier, the opportunity cost of time is another parameter that is not directly observable. In our model, it was a calibrated parameter. Figure 4.17 shows the sensitivity of the average quantity of water consumed from private handpumps to the opportunity cost of time. Private handpump use is only presented for Jan-Apr 2006 because for the period Jan-Apr 2004, the piped supply system was shut-down and use was zero.

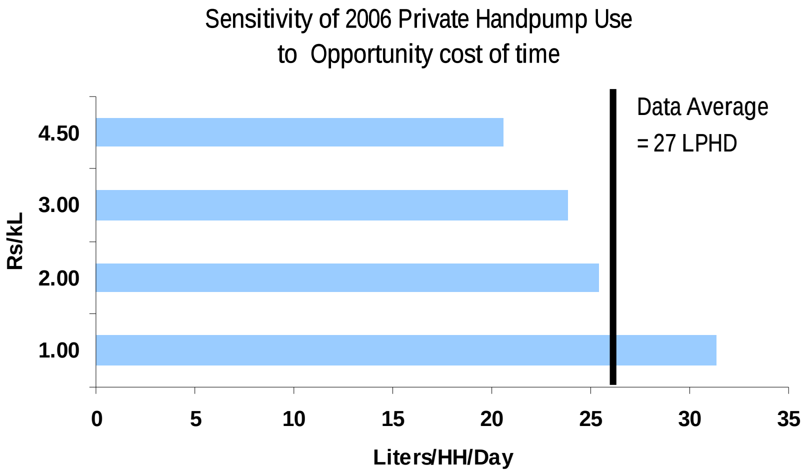

**Figure 4.17: Sensitivity of model result to opportunity cost of time**

We observe that an opportunity cost of time of Rs 2/hr for low income consumers produces the best match. We were initially surprised at how low the estimate for the opportunity cost of time was. However, we could not explain the quantity of water consumed from private handpumps by any other means, particularly since the collection time of 1.5 minutes per pot from private handpumps was fairly reasonable and verified by simple field test.

### *4.2.10 Tanker Market Size*

The third calibrated parameter was the average well-efficiency used in the Theim equation in Equation 3.16. The well-efficiency parameter is the main determinant of in-well drawdown. Therefore the well-efficiency parameter affects the tanker dependence of large commercial establishments, which draw large quantities of tanker water each day; lower the well-efficiency, lower the groundwater availability to commercial establishments, larger the size of the tanker market.

In Chapter 3, we described how the size of the tanker market was estimated for the period Oct-Dec 2005 by observing tanker movement into Chennai. By calibrating well-efficiency, we were able to match the observed and simulated size of the tanker market for the period Oct-Dec 2005. Figure 4.18 shows the simulated and observed size of the wet-period tanker market in Chennai for a well-efficiency of 3%. The calibrated well efficiency turned out to be lower (but in the general ballpark) of the estimate offered by experts.

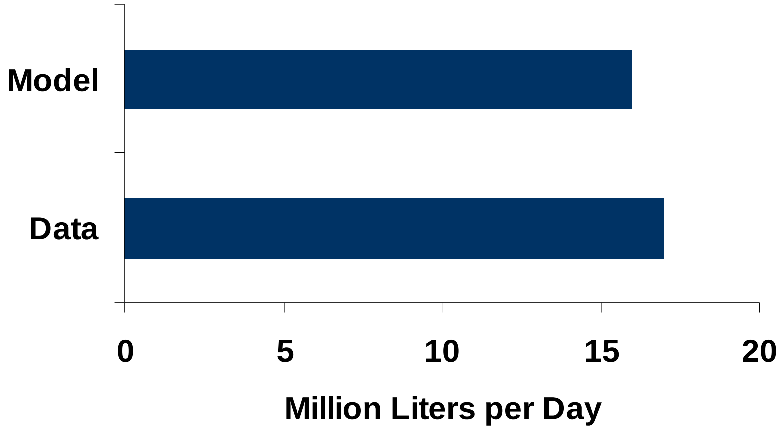

**Figure 4.18: Total tanker market size in Chennai**

### *4.2.11 Chapter Summary*

The Utility and Consumer modules were run iteratively. First both modules were run for manual consumers, and then both were run for sump consumers. The modules were jointly calibrated based on three parameters: groundwater price, well-efficiency and opportunity cost of time. The module outputs were matched against 2004 and 2006 household survey data and estimated tanker market size.

In the next chapter, we will analyze the simulation results of the calibration run from 2002-2006 for the model as a whole.

# 5 Chapter Five: Chennai's water system from 2002-06

In this chapter we present the analysis of the simulation results over the 4- historical year period from Jan 2002- Jan 2006. This historical period was used both for calibration as described in Chapters 3 and 4, as well as to develop insights on the nature of the water problem in Chennai. The period included a multi-year drought (2003-2004) as well as a year (2005) in which Chennai received the highest rainfall in recorded history. Through this chapter we offer comparisons using the two climatic extremes as reference periods: Jan-Apr 2004 (dry) and Jan-Apr 2006 (wet) following the record rains.

This chapter is organized as follows: We begin the chapter with an analysis of the dynamics of the system in the wet and dry periods, respectively. The dynamics of the Chennai water supply system is described as being governed by the interlinkages between water resources availability, utility management, and consumer responses. Then we present the main factors determining outputs for each module. The integrated model linkages are shown in Figure 5.1.

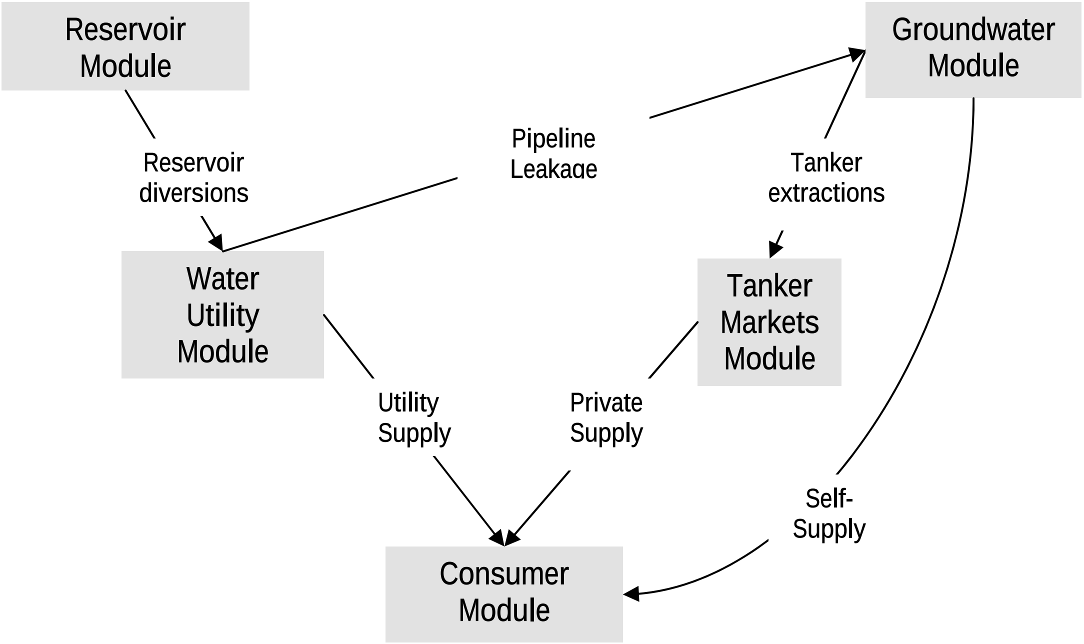

**Figure 5.1: Integrated Model Linkages**

The outputs that best describe the state of each module sub-system are presented in Table 5.1.

**Table 5.1: Output variables of each module**

| **Module** | **Main Output Variable** |
|---|---|
| Reservoir Module | Reservoir Storage |
| Groundwater Module | Fraction of wells dry |
| Utility Module | Total Utility Supply<br>Max. quantity of standpipe, handpump, piped supply available |
| Consumer Module | Quantity consumed by mode of supply, and consumer category, consumer surplus |
| Tanker Module | Total demand for tanker water (size of tanker market) |

## 5.1 Dynamics of the system as a whole

### *5.1.1 Dynamics in the dry period*

Chennai's reservoir system dried up during the 2003-2004 period. This triggered a shut-down of the piped supply system as the total water available to the utility (including non-reservoir sources) was too small to make delivery via the piped distribution network feasible. While poorer consumers depended on mobile supply (utility-run tankers), and community wells[70] to meet their needs; wealthier consumers with private wells relied heavily on self-supply via their wells. As extractions increased and recharge (from both rainfall recharge and pipeline leakage) dropped, groundwater storage was depleted. Groundwater levels began to fall, causing wells in Chennai to dry up. As their wells dried up, consumers became more and more dependent on expensive tanker water. In effect, consumers used less water during the drought, and suffered losses in consumer surplus.

### *5.1.2 Dynamics in the wet period*

During the wet period (Jan-Apr 2006), the city's surface-water reservoir system was filled to capacity. The utility was able to divert large quantities of water for city supply. The aquifer was completely replenished following the record rains in Oct 2005. So groundwater was readily available in consumers' wells, even shallow community wells. As residential consumers were able to meet most of their needs via utility supply and self-supply, the residential tanker market mostly disappeared. The results were similar for medium and small

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[70] Community wells includes borewell based standpipes locally called "Indian Mark Pumps"

commercial establishments. Only large water-intensive commercial consumers remained partially tanker-dependent because of a combination of high utility tariffs, low capacity of the aquifer, and insufficient supply from the utility. Thus, a "residual" commercial tanker market remained even during the wet period.

## 5.2 Reservoir Module:

In this section, we show that water available to the utility from the reservoir system varied considerably, both seasonally, as well as inter-annually. This occurred due to variability in rainfall, limited reservoir capacity, and the politics of inter-state transfers (via the Telugu Ganga Project).

### *5.2.1 Chennai's utility supply varies temporally*

The total water available for utility supply in Chennai varies seasonally and inter-annually. This variation is primarily a consequence of fluctuations in reservoir storage. Figure 5.2 shows the quantity supplied to Chennai when all sources are included over the period 2002-2006.

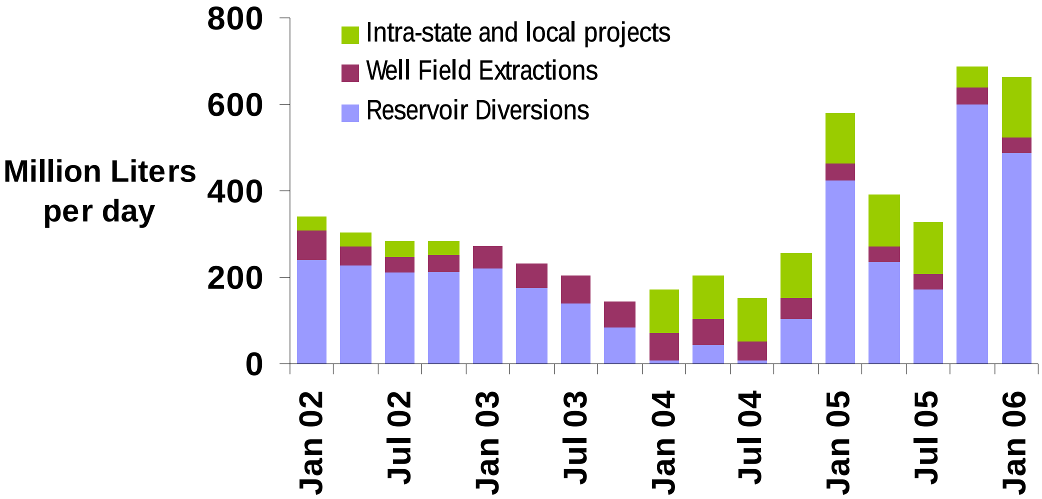

**Figure 5.2: Utility Supply (Modeled)**

Water available via the utility has varied considerably in the last five years: from over 650 MLD in Oct-Dec 2005, to less than 200 MLD in Jul-Apr 2004. Consequently, total utility supply also varied seasonally. Furthermore, that variability in reservoir diversions contributed the most to variability in total supply available to Chennai. Since diversions from the reservoir system in Chennai are a simple fraction of storage, total utility supply in Chennai was found to be proportional to reservoir storage.

In the following sections, we show that fluctuations in reservoir storage are a consequence of Chennai's rainfall patterns, limited reservoir capacity and unreliable deliveries from the inter-state Telugu Ganga Project.

### *5.2.2 Reservoir system is capacity constrained*

Given the rainfall patterns and current diversion rates, the reservoir capacity is insufficient. At median diversion rates and median inflows, the reservoir system[71] can only hold about two years of the city's water needs. The calibration process explained in Chapter 3 indicated that the inflows into the reservoirs vary exponentially with rainfall. Consequently, the reservoir system is dependent on big-storms every few years, during which the reservoir system gets completely filled. In other years the reservoir system is gradually drawn down as inflows are far lower than outflows.

Historical evidence corroborates this. Reservoir storage was "back-cast" for 45 years using the monthly rainfall, evaporation and the diversion rule derived in Chapter 3. The back-cast of reservoir storage is explained in detail in Appendix I. The storage in the Chennai reservoir system since 1965 is shown in Figure 5.3. Historically, the reservoir dried up on average every 6 years.

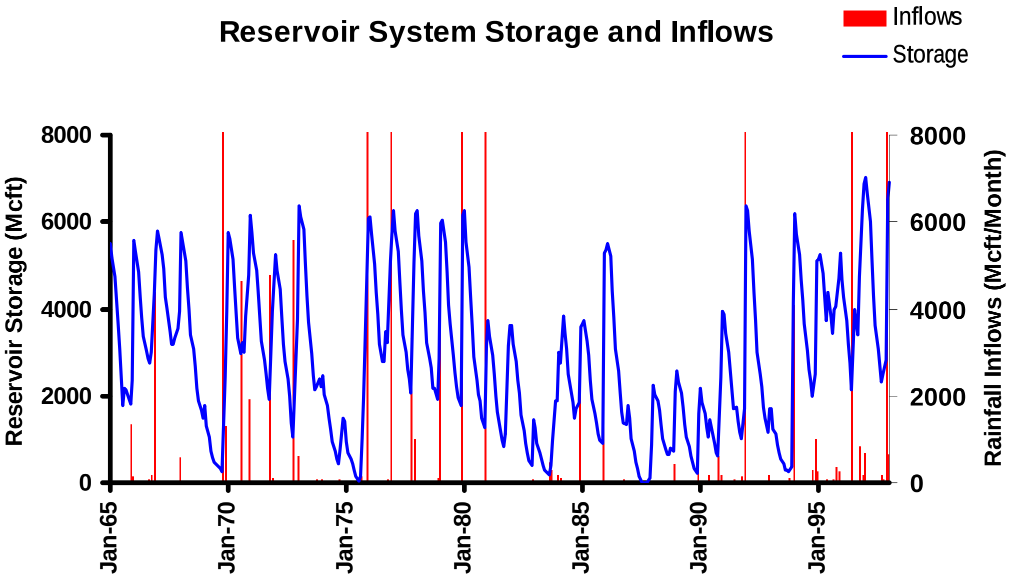

**Figure 5.3: Chennai's reservoirs storage and inflows from 1965**

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[71] As described in Chapter 3, the "reservoir system" storage or inflows refer to the combined storage or inflows of the three reservoir system including the Poondi, Cholavaran and Red Hills Reservoirs. Chembarambakkam lake is not included.

Historical reservoir data reveal that Chennai's reservoir system has dried up completely every five years; dry reservoir episodes are defined as periods when reservoir storage was less than 5 percent of the total storage. Moreover, every few years, the area experienced a big storm during which the reservoir system was completely replenished.

***Reasons for reservoir-drying patterns***

The reason for the erratic inflow patterns is that inflows into the city's reservoir system vary exponentially with rainfall. Thus, over the historical period, major storms generated most of the inflow into the reservoir system. Figure 5.4 shows the exceedance probability curve for reservoir inflows into Chennai. This exceedance probability curve was generated from the back-cast of inflows, also described in Appendix I.

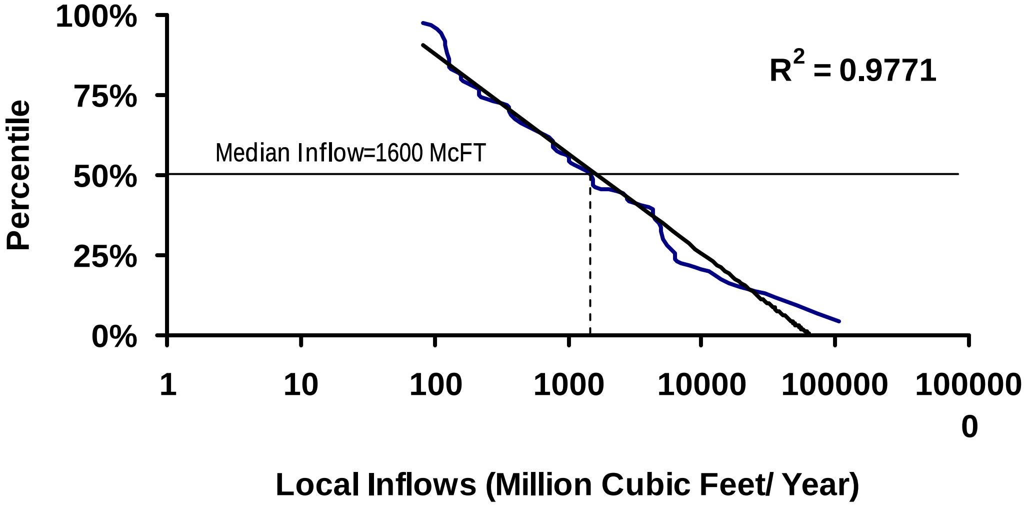

**Figure 5.4: Exceedance probability curve for local inflows**

From Figure 5.4, it can be seen that the distribution of monthly reservoir inflows and monthly rainfall is log-normal. Table 5.2 below summarizes the simulated inflows, and outflows into the reservoir system averaged over the 45-year historical period.

**Table 5.2: Inflows and outflows into the reservoir system**

| Inflows | Storage | Diversions |
|---|---|---|
| **Local inflows(exceedance probability)**<br>25th percentile ~ 280,000 ML/Year<br>50th percentile ~ 45,000 ML/yr<br>75th percentile ~ 3,000 ML/Yr<br>**Telugu Ganga**<br>50th percentile ~ 100,000 ML/Yr | 201,000 ML | 400 MLD ~ 150,000 ML/Yr |

Chennai's reservoir system has a maximum storage of about 7100 Mcft or about 201,000[72] ML (Million Liters) (excluding dead storage). From the table we can see that the "median annual inflow" is about 1,600 Mcft or 45,000 ML/Year, a little over a fifth of maximum storage. On the other hand, at a constant diversion rate of about 400 MLD (Million liters per day), 150,000 ML/Year, about three-quarters of maximum storage is drawn. Given these flows, the reservoir system would dry up within two "median rainfall" years. This accounts for the frequent drying up of the Chennai reservoir system prior to 1997.

After 1997, water from the Telugu Ganga Project became Chennai's lifeline. The annual receipts of 3,600 Mcft or 100,000 ML/Year of water from this project, though lower than anticipated, was sufficient to sustain the city's diversions of 400 MLD[73] (Million liters per day), without drawing down reservoir storage significantly. However, if the Telugu Ganga Project were to fail to deliver water for two consecutive normal or dry years as it did in 2003-2004, then the reservoir system would dry up within a year.

In summary, the reservoir system as it is currently operated has very little capacity to smooth inter-annual or seasonal variability in supply. The Telugu Ganga Project does not rectify this basic problem of insufficient storage capacity. Instead, it has exacerbated supply variability because the Telugu Ganga water is delivered just after the rains, when the reservoirs are full. In fact, since resumption of the Telugu Ganga water in 2005, Chennai supply has become even more variable, with reservoir levels varying from 25 percent to full capacity within a year creating a "feast or famine" situation.

### ***Summary of constraints on reservoir module***

In this section, we showed that insufficient reservoir capacity, variability in reservoir inflows from both rainfall and the Telugu Ganga Project resulted in the available reservoir supply to Chennai being highly variable.

In the next section we explore the constraints on consumers due to use of the groundwater system as a supplemental source of supply.

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[72] 1 cubic feet = 28.3 liters

[73] Average diversion rate sustainable with Telugu Ganga = (99000 + 45000)/365 ~ 395 MLD

## 5.3 Groundwater Module

In this section, we show that the groundwater system constrained consumers in two ways. Firstly, all consumers were affected by regional groundwater level fluctuations caused by the common pool effect of extractions by all consumers. Moreover, the groundwater level fluctuations were correlated with utility supply. This is because when utility supply was decreased, groundwater recharge from pipeline leaks decreased; at the same time extractions from private wells increased as consumers turned to their wells to make up for short-falls in utility supply. Secondly, large (usually commercial) consumers were further limited by their own extraction as they induced cones of depression around their wells. This "in-well drawdown" effect occurs due to the limited transmissivity[74] of the aquifer.

### *5.3.1 Groundwater fluctuations affect domestic consumers*

The historical run from 2002-2006 showed that groundwater levels in Chennai fluctuated both seasonally and inter-annually. These water level fluctuations were caused by the common pool effect of simultaneous extraction from the approximately 420,000[75] wells of individual households and commercial establishments in Chennai. In periods when consumers collectively extracted more than seasonal recharge, the groundwater level dropped as water stored in the aquifer was depleted. The Chennai aquifer was found by calibration to have a very low specific yield of less than 5%[76]. So, relatively modest extractions induced significant drops in water levels.

All consumers, except large commercial consumers with deep borewells, were impacted by regional variations in groundwater. If the water table dropped below the bottom of the consumer's well, the well dried up. To use an analogy offered by economists in describing groundwater, the aquifer resembled a "bath tub"; periodically filling up and drying out. Figure 5.5 shows a conceptual diagram of how the fraction of dry wells is a function of the groundwater level.

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[74] The transmissivity is low, because the aquifer is "thin" in parts of the city, not because the hydraulic conductivity is small.

[75] Vaidyanathan and Saravanan, 2004

[76] Specific yield is the volumetric fraction of the bulk aquifer volume that a given aquifer will yield when all the water is allowed to drain out of it under the forces of gravity

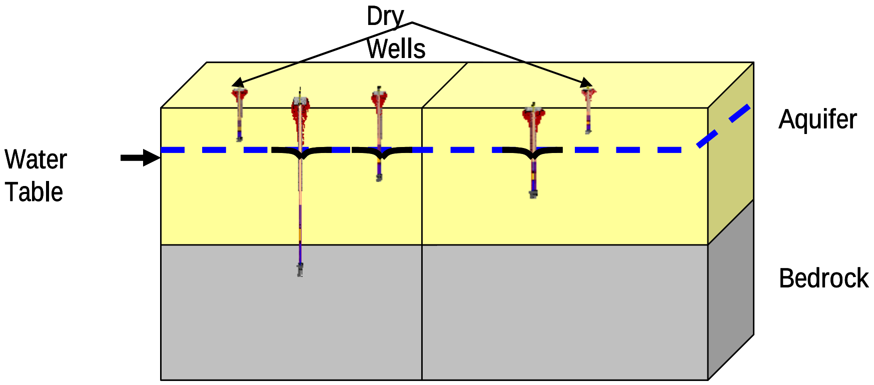

**Figure 5.5: The aquifer as a bathtub**

The fraction of wells that are dry could be used a proxy for the average water level in Chennai. This can be done using the distribution of well-depths introduced in Chapter 3.

### *5.3.2 Groundwater level fluctuations follow utility supply*

Groundwater levels in Chennai are correlated with total utility supply. When utility supply was plentiful, groundwater levels were also high and vice versa. Figure 5.6 displays utility supply to Chennai in million liters per day (MLD) versus the fraction of dry wells. Fraction of dry wells varies inversely with the quantity of water supplied by the utility.

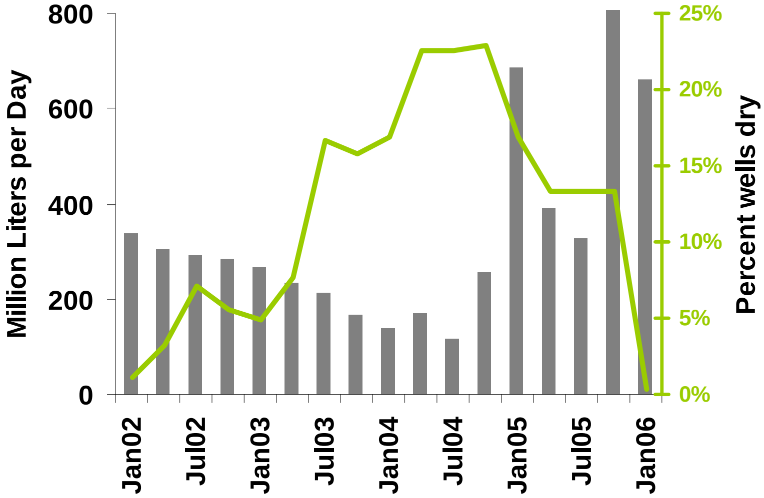

**Figure 5.6: Groundwater levels follow total utility supply**

Groundwater levels in Chennai closely followed utility supply for two reasons. When utility supply was curtailed, recharge decreased because distribution pipeline leaks were a major source of the aquifer recharge. Simultaneously, there was more extraction as households were unable to meet their needs from utility supply.

### 5.3.2.1 *Pipeline recharge is significant and varies with utility supply*

Groundwater recharge is closely correlated with total pipeline supply. Pipeline (including sewage) losses are a fixed proportion of city supply. As piped supply increases, so does recharge. Figure 5.7 displays the quantity of recharge from different sources estimated using our model: pipeline leakages and rainfall recharge in million liters per day (MLD). Pipeline recharge contributes about half the total recharge in Chennai.

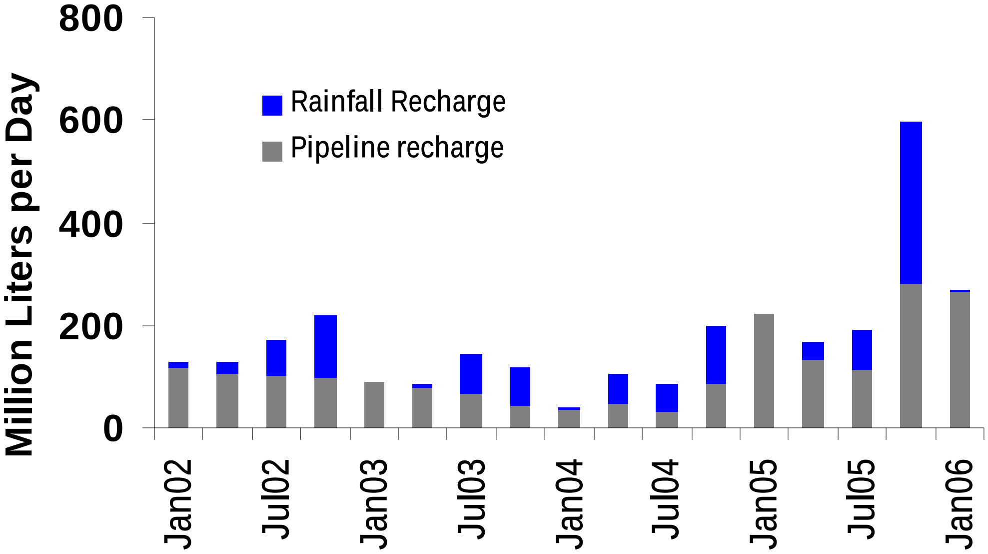

**Figure 5.7: Modeled Recharge by Source**

While recharge due to rainfall was significant during the monsoon months (Jul-Dec), pipeline losses dominated in the spring and summer months (Jan-Jun). In most periods, pipeline recharge accounted for at least half of the total recharge within the city. The only exception was in October 2005 when rainfall recharge spiked following record rains. During the drought period when piped supply virtually shut down, there was still some pipeline recharge from sewage pipes. Sewage flows decreased during the drought but did not reduce to zero, because consumers continued to use water procured from wells and private tankers.

### 5.3.2.2 *Groundwater extraction varies inversely with piped supply*

The model also suggests that groundwater extractions are inversely proportional to piped supply. Figure 5.8A depicts total extraction by consumer category within the Chennai city area as estimated in our model.

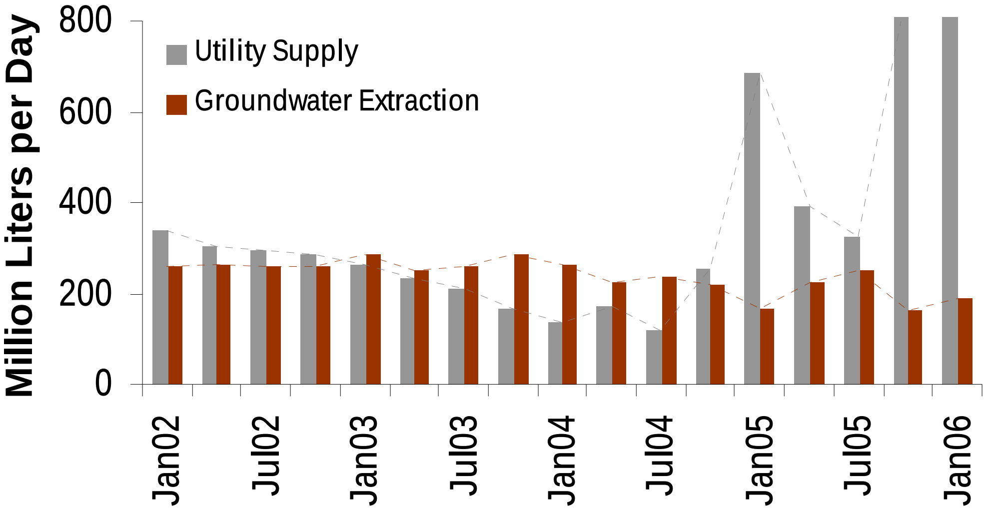

**Figure 5.8: Modeled groundwater extraction versus utility supply**

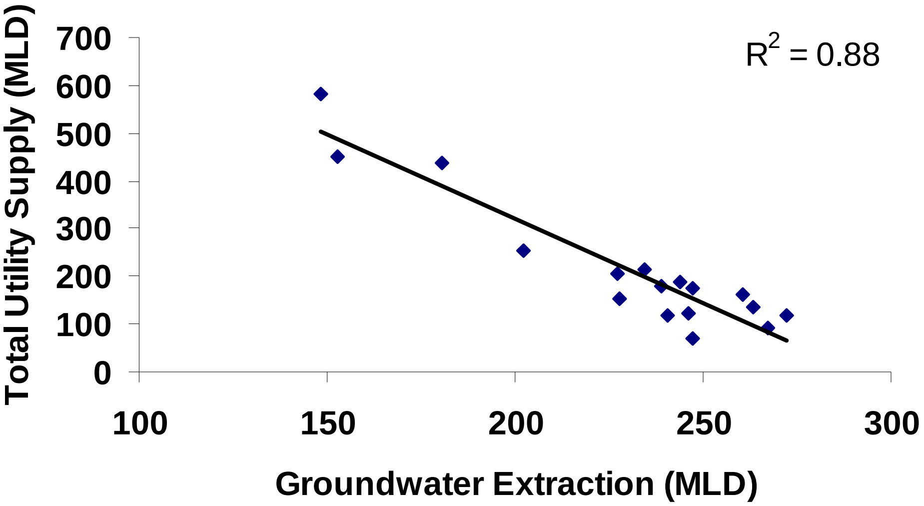

**Figure 5.9: Scatter plot of groundwater extraction versus utility supply**

Total groundwater extraction within Chennai was inversely correlated with total utility supply. The correlation between groundwater extractions and utility supply arises as a direct result of the tiered-supply curve: when utility supply is insufficient, consumers in turn depend on their borewells. Between 2002 and 2004, groundwater extractions increased as piped supply decreased. After the commissioning of the Veeranam (intra-state) water scheme in late 2004, total utility supply increased overall but also became more variable. Therefore, groundwater extractions were lower in periods when utility supply was plentiful and higher in periods when utility supply was insufficient. Following the record rainfall recharge in October 2005 groundwater levels in Chennai recovered completely.

### *5.3.3 Aquifer capacity limits large consumers – the "egg-carton" effect*

Commercial consumers who pump at high rates were limited by the physical properties of the aquifer. For commercial consumers, who needed large quantities of water each day, the aquifer resembled an "egg-carton": drying up locally even when the regional groundwater levels were high. The aquifer is not very thick or productive within the city limits. As a result, consumers cannot extract large quantities of water from their wells. High rates of extraction cause wells to dry up locally (Figure 5.10) even if the wells are deep. Commercial wells that extract large quantities of water are limited by the in-well drawdown caused by their own extraction.

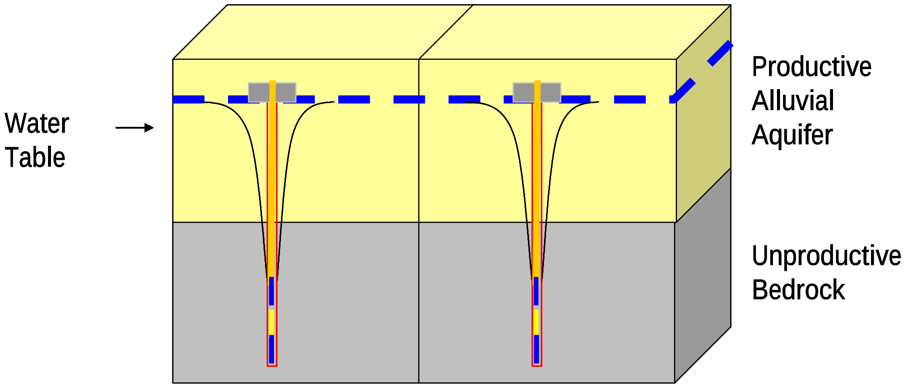

**Figure 5.10: Commercial consumers see the aquifer as an "egg carton"**

Figure 5.10 shows the spatial distribution of the maximum quantity of water that could be extracted from a single large commercial well per day as predicted by our model[77] without the

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[77] The maximum extraction figures are somewhat sensitive to our assumptions of well-efficiency, which were based on expert opinion to be 5% (low by western standards). However, the basic conclusions still hold.

These results are also consistent with survey data, interviews and visual observations. In our survey of 200+ commercial establishments in Chennai, many commercial establishments purchased tanker water in addition to extracting water from their wells. On average, commercial establishments were able to extract a maximum of 22kL/day before their wells ran dry and they had to call tankers. This quantity is in the correct order of magnitude predicted by the model.

In unstructured interviews, facilities managers at two commercial establishments revealed that they were "groundwater limited" in that they were unable to extract enough water from their wells to meet their needs. We also interviewed and photographed private tanker operators while they were filling water table falling to 20% of its full thickness. The quantity varies spatially across Chennai. These values were obtained using the Theim equation as explained in Chapter 3. The maximum quantity extractable from any single well varies spatially across Chennai.

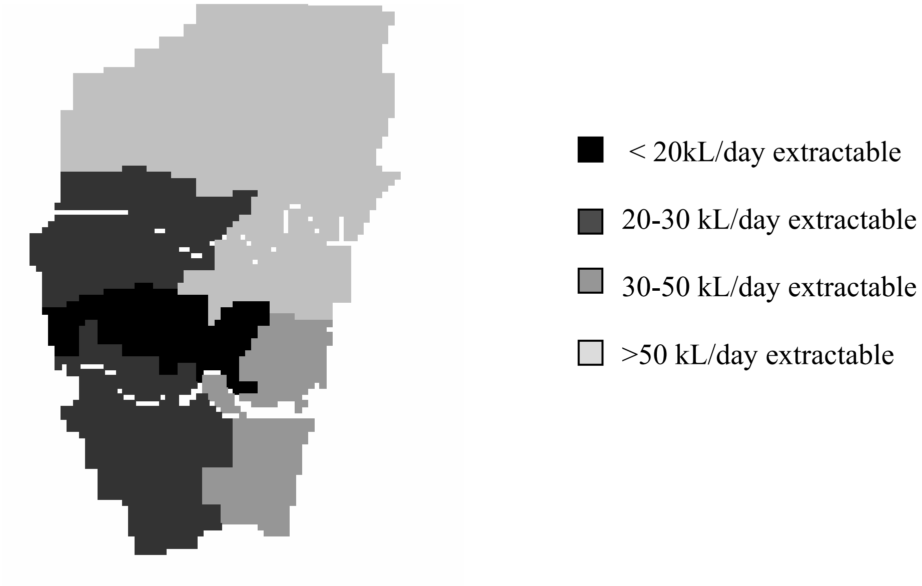

**Figure 5.11: Maximum extractable quantity from the groundwater aquifer in Chennai**

The maximum extractable quantity is on the order of tens of kiloliters per day (kL/day). So, residential consumers who extract relatively small quantities of water (e.g., <1 kL/day) are unlikely to be affected by the low productive capacity of the aquifer. Large commercial consumers on the other hand, are likely to be restricted in the quantity of water they can extract.

### *5.3.4 Summary*

In this section, we showed that aquifer storage properties limited extraction by water-intensive commercial and industrial consumers. In contrast, fluctuating groundwater levels affect extraction by domestic consumers by drying up shallow domestic and community wells as groundwater levels dropped.

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sumps at large hospitals and hotels. The tanker operators asserted that they were continuing to sell several tankers a day to large commercial establishments even in months when piped supply was copious and the groundwater levels were high.

## 5.4 Utility Module

In previous sections, it was shown that the Chennai water utility faces a high degree of variability in resource availability. In this section, we discuss how the utility deals with this situation by managing the distribution system intermittently, and the implications of intermittent supply.

The historical run of the model indicates that the total water available for utility supply in Chennai was highly variable during the period from 2002-2006. When faced with a reduction in available water, the utility's response to the variability in supply was to cut back the number of hours of supply. This form of supply, where water is available for only a few hours each day, is called intermittent supply[78]. During the historical period from 2002-2006, water was typically available for only a few hours each day. Supply was available for up to 12 hours each day during the wet periods, when utility water was plentiful. During drier periods, piped supply was available for fewer hours (2-3 hours) every day or alternate days.

In this section, we discuss two effects of intermittency. Firstly, intermittent supply affects consumers with different types of connections and demand differently. Consumers with manual connections are least affected when supply is available for only a few hours and the distribution system pressure is low, when compared to sump consumers. Consumers needing large amounts of water, such as large commercial complexes, are most impacted when supply is restricted to a few hours each day. Secondly, intermittency in supply also introduces two additional types of variability: spatial variability (head and tail end areas) and changing frequency of supply (number of days/week that water is supplied) that we discuss in Appendix K. However, our model does not simulate either of these and we do not address the effects of these in this dissertation.

### *5.4.1 Manual consumers are least affected at low supply levels*

In this section we discuss our claim that at low levels of supply: Manual consumers are less supply constrained than Sump consumers for a given location within Chennai. Figure 5.11 shows the modeled quantity of water supply available from two types of utility supply: standpipes, and handpumps over the historical period. The figure also depicts the average

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[78] The reasons for intermittency are complex and are not the subject of this dissertation. For purposes of our argument herein we simply accept that Chennai's water supply system is highly intermittent.

quantity that would be demanded by a representative household for the each type of supply, at average time and labor costs.

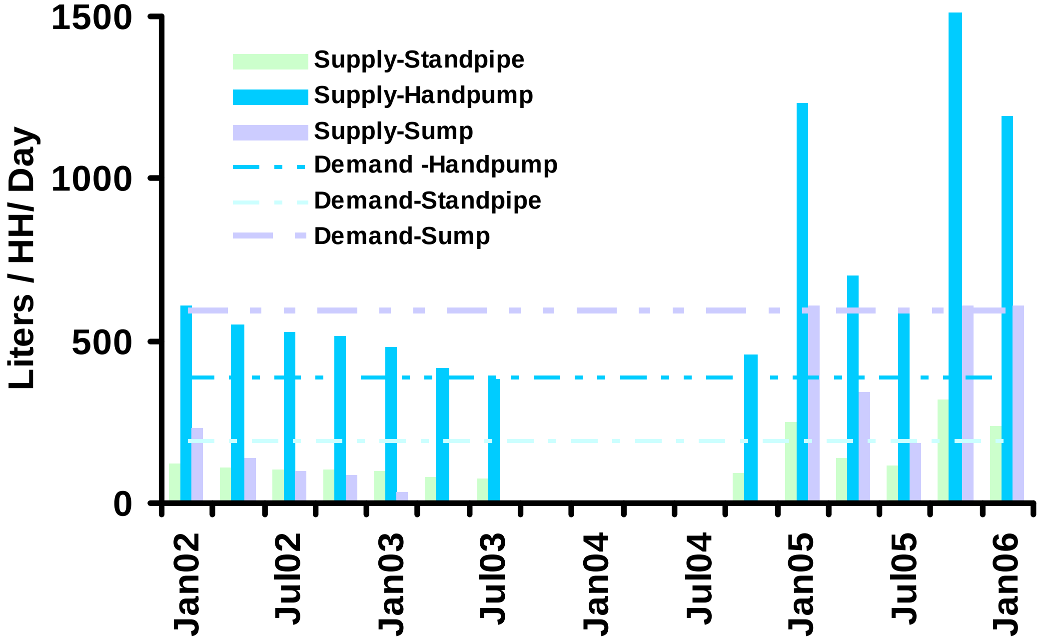

**Figure 5.12: Liters/HH/Day available via various types of utility supply**

Unconnected consumers who use public standpipes have the lowest demand because of the time and effort of collection, but they also had the least access to water because the water had to be shared among many households during the brief window of time when it was available. Thus, Unconnected consumers were able to meet their demand through standpipes only in the wettest periods, but not in other periods. So they were largely supply limited.

Manual consumers using private handpumps had the next lowest demand, but were able to satisfy their demand in most periods. I.e., the theoretical maximum obtainable via handpumps was greater than the quantity demanded in most periods. In fact, the model results indicate Manual consumers using private handpumps were affected only when there was a complete shut-down of the piped system. In other periods, they were able to meet their demand for water. However, demand was limited by of the time and effort of collecting water manually. Thus, these consumers were largely demand (not supply) limited.

Finally, Sump consumers had the highest demand, both because of the low marginal cost of piped supply and because these consumers were wealthier with a high willingness to pay. However, because of the intermittent nature of the water distribution system, the model results indicate they were able to meet their demand only in the wettest period. In most periods, demand exceeded supply and was not met. Thus, Sump consumers were largely supply limited.

These results arise in part from the assumptions made regarding water distribution. Manual consumers are assumed to extract as much as they can get in the few hours of supply because they are pro-active; they keep a look-out for when water becomes available and manually pump their daily requirement within 15-30 minutes. In contrast, Sump consumers are passive; they do not have much control over the pressure in the system and for the most part receive whatever water is "left". To summarize these results: Unconnected consumers were both supply and demand constrained, Manual consumers were primarily demand constrained, while Sump consumers were primarily supply constrained during the historical period.

### *5.4.2 Intermittency in supply impacts large consumers disproportionately*

Large consumers are disproportionately affected by intermittent supply in being able to meet a smaller fraction of their requirements from the utility. This can be explained as follows: Consider the demand for a "representative" hotel with 50 employees. The daily water demand estimated for this hypothetical hotel using the commercial demand function (shown in Chapter 4, Equation 4.10) is about 33,000 liters (equivalent to about 55 households). About 25 percent of the total water demanded (8250 liters) is assumed to be for potable-quality water and derived from utility supply. The hotel was allowed to have a connection to the piped supply that can deliver five times the flow of a typical residential connection, for a given pressure. This was based on pipe connection sizes prescribed by Metrowater[79]. Now compare a single family home and a large hotel located right next to each other as shown in Figure 5.12.

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[79] Metrowater specifies the size of the mains allowable in terms of equivalent dwelling units http://www.chennaimetrowater.gov.in/newcondn.htm
For an establishment of up to 6 dwelling units, the bore size is 15 mm. For an establishment equivalent to 41-70 dwelling units (our hypothetical hotel), the bore size is 32 mm ~ five times larger in terms of the volume of water it can deliver.

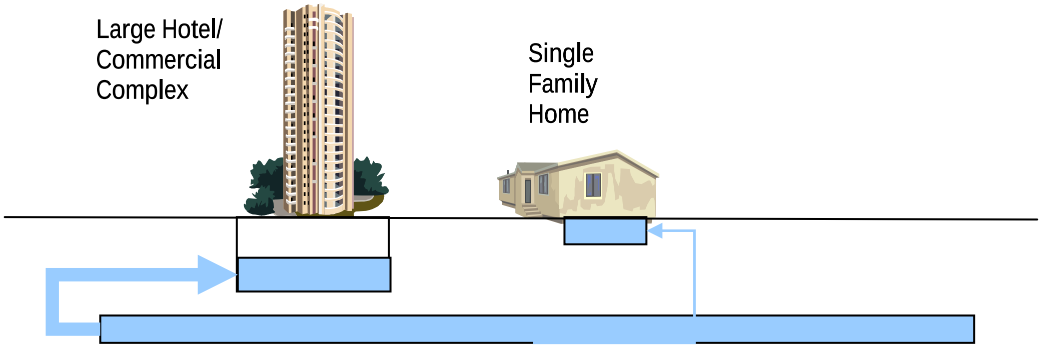

**Figure 5.13: Large consumers are disproportionately affected by intermittency**

In Figure 5.13, the hotel and single family home located next to each other experience the same water pressure in the distribution network. Each has a sump and receives water at an identical flow-rate proportional to the pressure at that point in the distribution network. Since the hotel has a connection that can deliver five times the flow-rate, it will receive only five times the quantity of water compared to the single-family home in the short period when water is available in the piped distribution network. However, the hotel's potable demand was about twenty times that of a typical household. Thus, large commercial users and large apartment complexes are unlikely to receive the quantity of water they need, from an intermittent supply system. In contrast, single family homes are likely to have proportionally a greater fraction of their water requirements met. Figure 5.14 depicts the quantity of sump supply to households and large commercial establishments, versus quantity demanded by over the historical period.

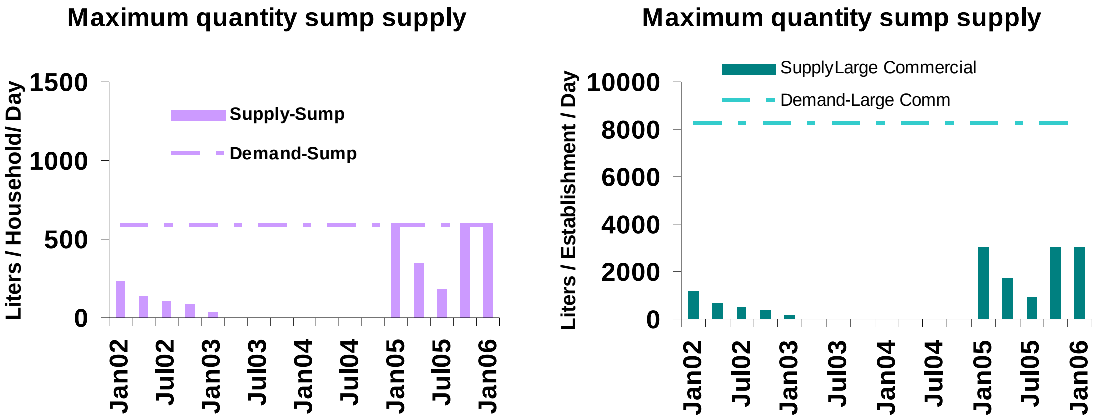

**Figure 5.14: Supply available and demanded for large and small consumers**

For this hypothetical example, while the commercial establishment could not meet its demand for potable quality water even in the wettest periods, a single family sump consumer could. Although we used a simple hypothetical example to demonstrate this, the basic result is held up by observation. Throughout cities in India, Bangalore, Mumbai, and Chennai, where water supply is intermittent, private tankers supplying water to large commercial complexes even when utility is plentiful is a common sight. In Chennai, Metrowater counteracts this problem by offering some large commercial consumers “bulk connections” or direct connections from the pumping station, so supply to them can be made independent of pressure elsewhere in the system. However, bulk connections are capital intensive and not all commercial consumers are able or willing to avail themselves of the facility at the high bulk-supply tariffs charged.

### *5.4.3 Summary*

In this section we showed that total utility supply in Chennai varied seasonally and inter-annually. The water utility responded to the supply variability by managing the piped distribution system intermittently. Intermittency further translated to variability in the quantity delivered to different consumer categories.

## 5.5 Tanker Module

In this section we discuss the dynamics of the tanker module. In the model, the tanker market was comprised of two distinct components: the residential and the commercial tanker markets. The residential tanker market was ephemeral; the tanker market arose whenever groundwater levels within Chennai dropped and disappeared when groundwater levels recovered. In contrast, the commercial tanker market was relatively stable and contributed to the existence of a residual tanker market that persisted even in wet periods.

From Figure 5.15 we can see that the size of the residential tanker market is directly correlated with the fraction of city wells that go dry. In contrast, the commercial tanker market is relatively constant. The model’s predicted market size of 17 MLD in October 2005, matches well with the estimated size of 15-20 MLD of the tanker market from surveyors stationed on the major highways outside Chennai.

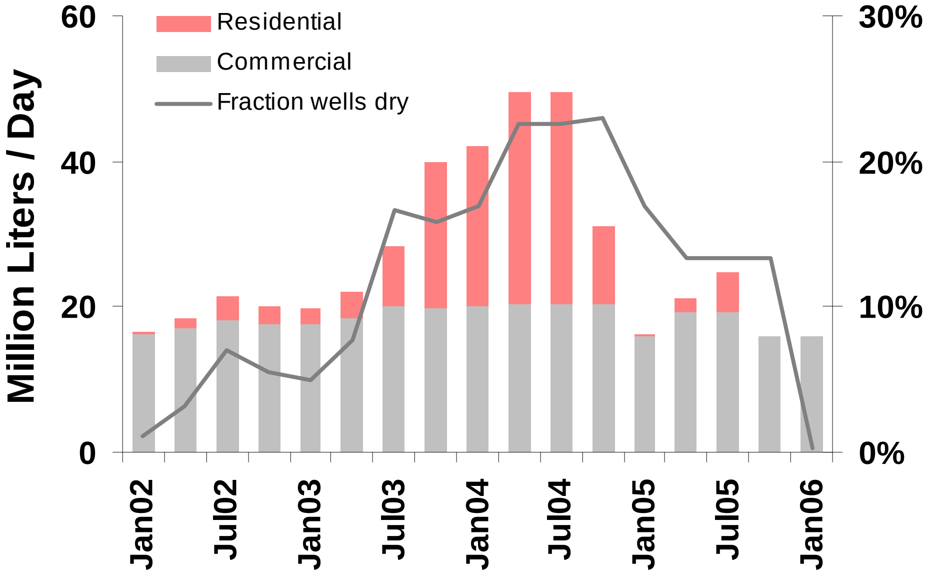

**Figure 5.15: Correlation between tanker market and city wells dry**

In the next section, we will explore the responses of consumers to these three dimensions of supply variability: utility supply, groundwater availability and tanker supply.

### 5.6 Consumer Module

In developing the integrated water paradigm theoretical framework in Chapter 2, two types of consumer responses to uncertain supplies were considered: short-term by switching to alternate forms of supply, long-term responses in making coping investments. In this section, we present the quantity and source of potable and non-potable water consumed by each consumer category, during the wet and dry period, respectively. These quantities varied by consumer category i.e., by prior investments in connectivity, storage and wells. The results indicate that each of these investments provided benefits in different periods. When piped supply was curtailed consumers with manual connections fared better than sump consumers. When the piped supply system was completely shut-down, consumers with access to deep borewells fared best, when utility supply was plentiful, (8-10 hours of supply), consumers with sumps benefited the most.

We begin by analyzing the quantity of water consumed in the wet, dry and medium supply periods, using a representative household in each consumer category. By comparing how consumers *within* a consumer category fared in the wet and dry years, we attempt to understand short-run responses to supply variability. By comparing how consumers *across* categories fared in the wet and dry years, we can analyze the effects of long-run responses or investments in coping mechanisms. The analysis in this section is presented separately for the residential and commercial consumer categories because the constraints faced are very different.

### *5.6.1 Residential consumers*

The quantity of water consumed by residential consumers varied considerably among domestic consumer categories and between the two reference periods: Jan 2004 and Jan 2006. We further note that different consumers were affected differently in the two years. Figure 5.16 shows the quantity consumed in liters/household/day for the two reference years across consumer categories.

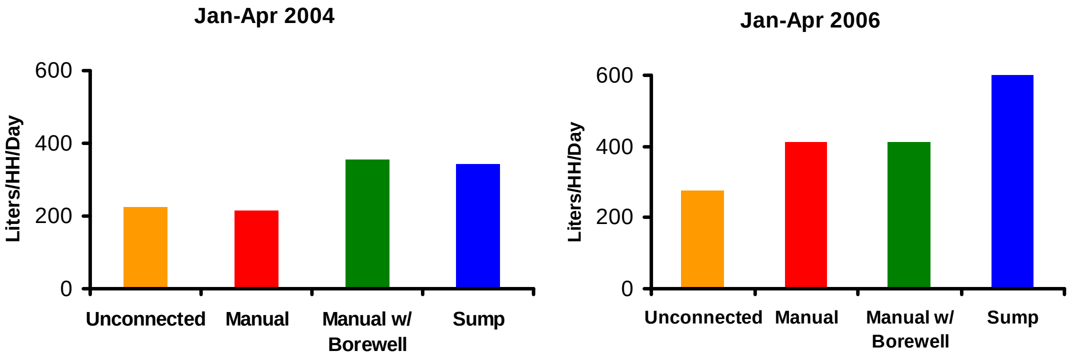

**Figure 5.16: Modeled quantity consumed in liters/HOUSEHOLD/day**

In the dry year, Manual and Unconnected consumers comprising a third of all households, were at the basic lifeline demand of 220 LPHD (or 50 liters per capita per day). In the wet year, only Unconnected consumers comprising a tenth of all households, were at this minimum level. Furthermore, different consumer categories responded differently to the dry and wet period. For instance, while Unconnected consumers remained more or less at subsistence levels, Manual and Sump consumers were able to increase consumption significantly in the wet period.

### *5.6.2 Short-run response: multiple source dependence*

We analyze the short-run responses to supply variability by comparing consumption and consumer surplus in the wet and dry year for each consumer category. In each case, the quantity consumed and consumer surplus can be derived directly by examining the tiered supply curves for each category.

Figures 5.17 to 5.20 depict the quantity accessed by source as well as the consumer surplus for each consumer category. The consumer surplus is to be interpreted as follows. The solid area is the net consumer surplus, the measure of consumer well-being. The shaded area represents the cost of the water (including opportunity cost of time) per day. The sum of the two is the gross benefit to the consumer from consumption of water.

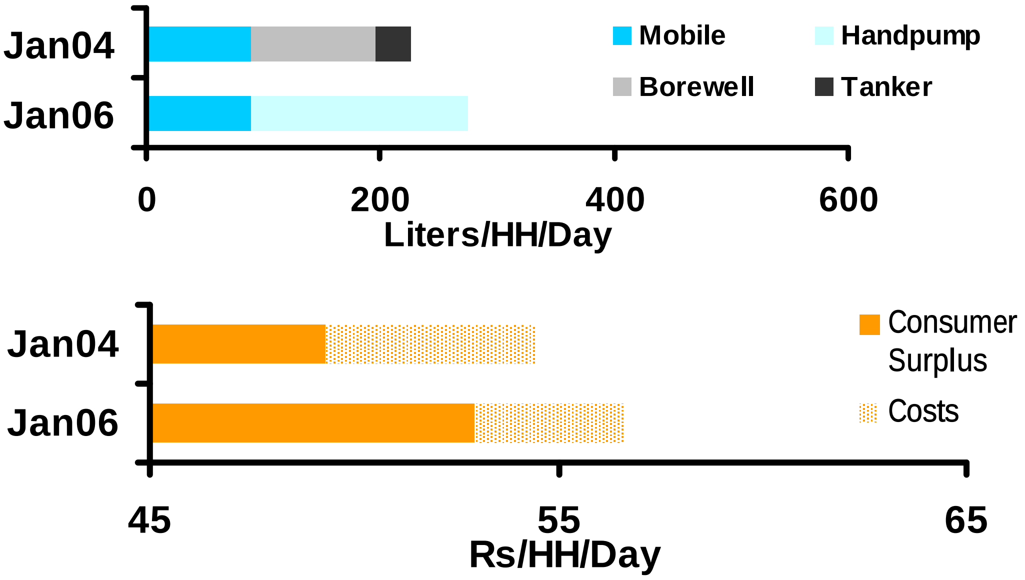

**Figure 5.17: Modeled quantity and consumer surplus for Unconnected consumers**

In the wet-year, Unconnected consumers used public standpipes for their non-potable needs, and mobile supply for their potable needs.

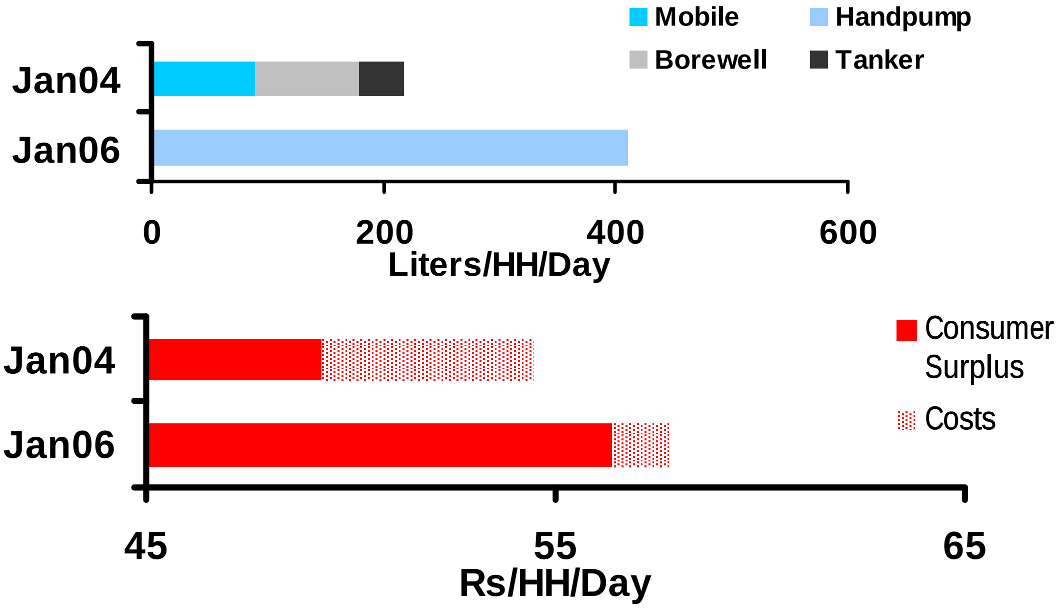

Figure 5.18: Modeled quantity and consumer surplus for Manual consumers

In the wet-year, Jan-Apr 2006, Manual consumers used private handpumps for all their needs. In the dry period, Jan-Apr 2004, Manual consumers depended on a combination of shallow community wells, mobile supply from the utility and private vendors to meet their needs.

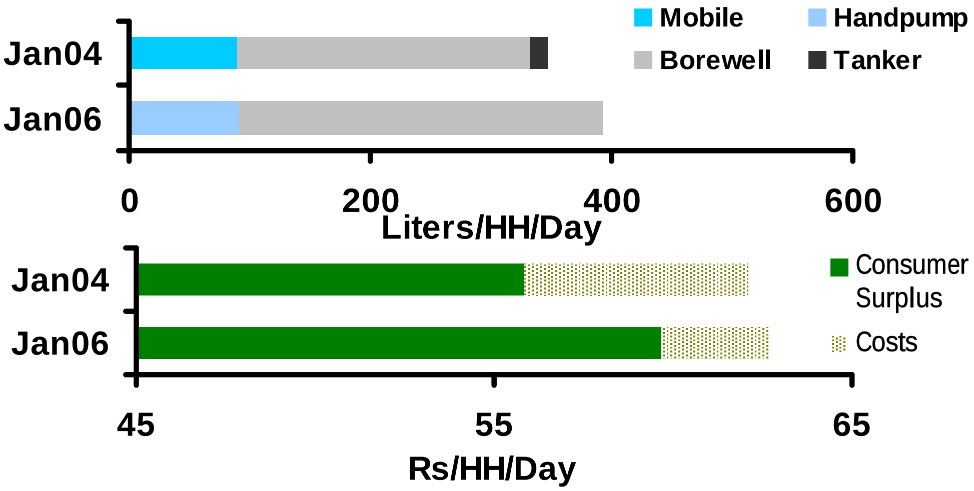

Figure 5.19: Modeled quantity and consumer surplus for Manual with borewell

In the wet-year, Jan-Apr 2006, Manual with Borewell consumers used private handpumps for their potable needs. They used motorized borewells for their non-potable needs. In the dry period, Jan-Apr 2004, these consumers depended on a combination of wells, mobile supply from the utility and tankers.

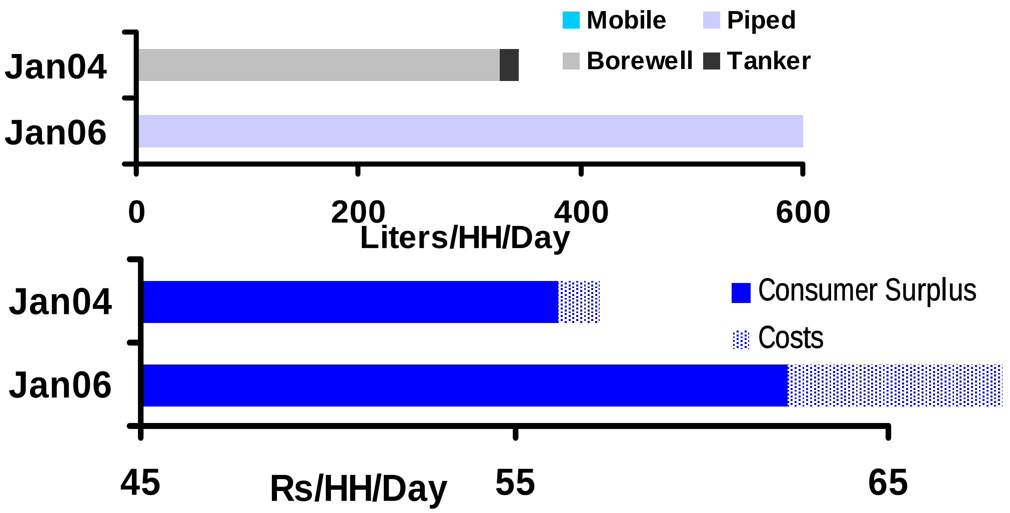

**Figure 5.20: Modeled quantity and consumer surplus for Sump consumers**

In the wet-year, Jan-Apr 2006, Sump consumers were able to meet all their needs from piped supply. In the dry period, Jan-Apr 2004, they depended on a combination of wells, and private tanker supply.

In summary, consumers used less water, from more sources and paid more for each unit of water in the dry period (Jan-Apr 2004). The quantities and welfare results presented in this section derived directly from the tiered supply curves. The tiered-supply curves for all other consumer categories are presented in Appendix J.

### *5.6.3 Long-run response*

We analyze the long-run responses to supply variability by comparing consumption in the wet and dry year across consumer categories. We find that we can best explain the consumption patterns observed across consumer categories in terms of prior investments in connectivity, storage and wells as described in Chapter 2.

#### *Residential consumers*

Residential consumers benefit from different investments under different supply conditions. During the dry year, consumers benefited mainly from having wells. Consumers with deep private borewells consumed 50 percent more water as compared with consumers who did not. As utility supply was virtually non-existent, improved connectivity to the piped supply system made no difference. In contrast, in the wet period, consumers benefited from having improved utility supply: connectivity and storage. Consumers with private manual connections used 60 percent more water than unconnected consumers. Consumers with sumps consumed 50 percent more than consumers lacking sumps.

Table 5.3 shows the five consumer categories classified by the type of prior investments in connectivity, storage, and deep wells, and the average quantity consumed by each consumer category in the wet and dry year.

**Table 5.3: Quantities used by consumer categories with different prior investments**

| Category | C | W | S | Jan-Apr '04 (Dry) L/HH/Day | Jan-Apr '06 (Wet) L/HH/Day |
|---|---|---|---|---|---|
| **Unconnected** | - | - | - | **225** | **275** |
| **Manual** | ✓ | - | - | **225** | **410** |
| **Manual+BW** | ✓ | ✓ | - | **350** | **410** |
| **Sump** | ✓ | ✓ | ✓ | **350** | **590** |

***C=Connectivity, W=Deep Well, S=Sump**

### *Commercial consumers*

Commercial consumers demonstrated significantly different patterns than domestic consumers. Within this commercial category there were no major differences in prior investments in coping mechanisms –all had borewells and large sumps. Despite these significant investments, many commercial consumers were tanker dependent at all times. Almost all were groundwater dependent.

Our survey of 217 commercial establishments (presented in Appendix F) showed that over 70 percent of commercial establishments used their wells in the wet year, in addition to receiving utility supply. Significantly, many commercial establishments were unable to meet all their needs from wells and utility supply. About 17% of surveyed establishments used private tankers to meet part their water requirements even in Jan 2006. Although this high fraction is biased by the inclusion of many larger establishments in our sample, the data support the idea of a "residual" tanker market that persists even when public supply was plentiful. Thus, despite having excellent connectivity, large storage sumps and deep borewells, many commercial establishments continued to purchase water from private tanker operators.

**Finding**

Based on our model results we found that there are three reasons for the continued tanker dependence of commercial establishments in all periods: one economic, and two physical. Commercial consumers are influenced by Metrowater's tariff policy, which makes private water use more attractive. They are also affected by the physical constraints of the aquifer and the distribution system.

#### *5.6.3.1 Tariffs*

An economic explanation of water-supply preferences was offered by establishments at which we conducted detailed unstructured interviews. Water intensive commercial utility tariffs (Rs 75/kL) for water-intensive consumers are set much higher than the price of tanker water (Rs 45/kL) and more that ten times the price of pumping from private wells (Rs 5/kL). Not surprisingly, these consumers prefer alternative sources of supply over piped supply at least for all their non-potable needs.

#### *5.6.3.2 Physical Limitations*

Even if the cost of water was not an issue (for instance it constituted a negligible fraction of establishments' overall costs), commercial consumers would be restricted in terms of supply from the utility. This is due to the intermittency problem described in section 5.3.2. Even if commercial establishments did not care about the quality of water, the pumping limitation associated with the aquifer capacity described in section 5.2.3 prevents commercial establishments from getting all of the water they need from their own wells. We note that the physical limitations are only applicable to very large commercial facilities, for which the aquifer properties and distribution system are restrictive. The larger the facility, the more likely it is tanker dependent. Thus, in the case of commercial consumers, purchases from private tankers are the only option given the physical limitations of the distribution and aquifer systems.

In summary, consumers respond to the variability in supply by making coping investments depending on their ability to invest. Coping investments benefit residential consumers but not commercial consumers who remain heavily tanker dependent.

## 5.7 Chapter Summary

In this chapter we presented our understanding of the dynamics of the water supply system in Chennai, based on the results of the historical model. We identified the main constraints on consumer well-being as

1) Limited reservoir capacity
2) Limited production capacity of the aquifer and groundwater fluctuations
3) Intermittency in utility supply
4) Short-term and long-term (investments) responses by consumers.

In the next chapter, we extend the model to 2025 under the “Baseline Scenario”: reasonable assumptions of growth in population, income, land use change, and utility investments in supply, etc.

# 6 Chapter Six: Chennai 2025 Baseline Scenario

In this chapter, we present the "Baseline" scenario for the intermediate-term (up to 2025) water supply situation in Chennai. This is the "status-quo" projection of Chennai's water supply. To project water demand and supply in future years, we used reasonable projections of population, land use, utility investments (in a new desalination plant) and consumer investments (in sumps, borewells and connections). As future rainfall cannot be predicted, the model was run for various alternate rainfall scenarios. In this chapter, we only present one scenario where the historical rainfall record from 1989-2006 is repeated from 2008-2025.

The rainfall scenario chosen generates a multi-year drought starting in 2019. The model results show that Chennai would suffer another water crisis similar to that of the 2003-2004 during the future multi-year drought in this scenario. In the simulated future drought, the Telugu Ganga Project does not deliver water, and the reservoir system dries up. The reservoir system remains dry for a prolonged period of almost four years. The piped supply system has to be shut down for several months during the four-year dry spell. As consumers become increasingly dependent on self-supply, the aquifer dries up, and many consumers have to resort to buying tanker water.

While it may seem obvious that "history will repeat itself" when a historical rainfall sequence recurs in the future, it was not what we expected. Our expectation was that the displacement of irrigated agriculture by urbanization would free up enough groundwater, which together with the new desalination plant expected to come online in 2009, would generate enough water to sustain Chennai's population over a future drought. Instead, the model simulations predict that consumers will be worse off during a future multi-year drought. Thus, the Baseline scenario yielded two interesting results. Firstly, the water freed-up from the displacement of peri-urban irrigated agriculture will completely be utilized for urban uses. Basin-scale extraction will remain steady as rising populations, income, commercial and industrial growth takes up most of the water previously used by irrigated agriculture. Secondly, the 100 Million Liters/Day desalination plant (expected to go online in 2009) will be insufficient for Metrowater keep pace with the increase in demand within Chennai.

The chapter is organized as follows: We describe how we extended the integrated model to make projections to 2025. Then we analyze the model projections for the Baseline Scenario.

## 6.1 Extending the model to 2025

In this section, we describe how the model was extended to 2025. The process of extending the model to 2025, involved projecting the following exogenous parameters of the model as described in the model development in Chapters 3 and 4 as shown in Table 6.1.

**Table 6.1: Exogenous Input Parameter Changes in Baseline Scenario**

| **Module** | **Exogenous Inputs** | **Basis of Forecast** |
|---|---|---|
| Surface Water Module | Rainfall | Two rainfall scenarios tested. Each is a repeat of a portion of the historical record |
| | Reservoir evaporation | Same as history |
| | Reservoir capacity | Same as history |
| | Telugu Ganga water transfers | Assumed to be a function of rainfall in Chennai |
| Water Utility Module | Water abstracted from other sources | Veeranam, Well Fields and Local Sources assumed at historical values – constant in every period.<br>New 100 MLD desalination plant comes on in 2009 |
| Groundwater Module | Land use map | Used SLEUTH, a software based on the Clark Urban Growth Model to forecast land use |
| | Electricity price | No change in real costs<br>(i.e., assumed to rise at inflation) |
| | Pump and well specifications | Same as history |
| Tanker Market Module | Cost of transportation<br>Labor and capital costs | No change in real costs<br>(i.e., assumed to rise at inflation) |
| Consumer Module | Population | Population assumed to increase at 2% per year, as defined in Master Plan |
| | Income | Real income assumed to increase at 4% per year, uniform across all households |
| **Module** | **Exogenous Inputs** | **Basis of Forecast** |
| Consumer Module | Fraction of households in each category | The income brackets (In 2005 rupees) for each of the bottom three categories is assumed to be constant.<br>It is assumed that consumers "move" to the next category, when their income exceeds a particular threshold |
| | Consumer demand function | Same as history, for each consumer category |

Each of the following major model input changes is described in detail in the following sections: rainfall, land use, population, income and fraction of household in each consumer category.

### *6.1.1 Rainfall Scenarios*

Future rainfall is obviously unknown and uncertain. For the future period, we assumed that the rainfall patterns observed in the past would be maintained. For rainfall projections to 2025, monthly rainfall rates were taken from the historical record. No allowance was made for possible changes in rainfall occurring due to climate change. Analysis of historical rainfall indicates that rainfall was less variable in the first half of the available rainfall record (1965-1989) than the latter half (1989-2007). The difference in variance was statistically significant[80], but the difference in mean assuming unequal variances was not found to be statistically significant. While this merits investigation, the rainfall record was too short to draw any broader conclusions on the possible effects of climate change. To capture the different variances, we used rainfall scenarios consisting of the first and second halves of the available historical rainfall record and a third rainfall scenario from the middle. Each rainfall scenario assumed that a past sequence of rainfall would repeat itself in the future: Rainfall Scenario 1 assumed that the historical record from 1989-2006 was repeated in the period 2008-2025. Rainfall Scenario 2 assumed the historical record from 1972-1989 was repeated in the period 2008-2025. Rainfall Scenario 3 assumed the historical record from 1980-1996 was repeated in the period 2008-2025. Each of the three rainfall scenarios generated a multi-year drought but at different times and with different degrees of severity. Once the rainfall record was fixed for the future period other input variables which were a function of rainfall, such as recharge, reservoir inflows and Telugu Ganga deliveries could be estimated.

Only model results for Rainfall Scenario 1 are presented in this chapter. However, sensitivity analysis of the final policy conclusions, to the other two rainfall scenarios is discussed in Chapter 7. Figures 6.1 A, B and C show the annual rainfall in mm/year, for the three rainfall scenarios.

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[80] Null hypothesis: Standard deviation in both rainfall sets was the same. The hypothesis was rejected as the F-Test on variance was significant at the 1% level, indicating that rainfall was more variant in the second half of the rainfall record.

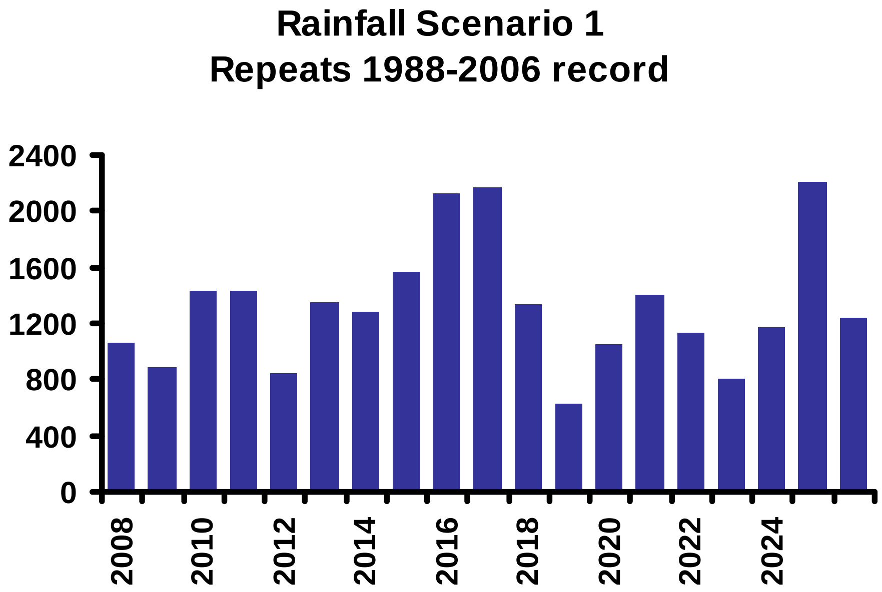

Figure 6.1 A: Rainfall Scenario 1: Annual Rainfall in forecast period

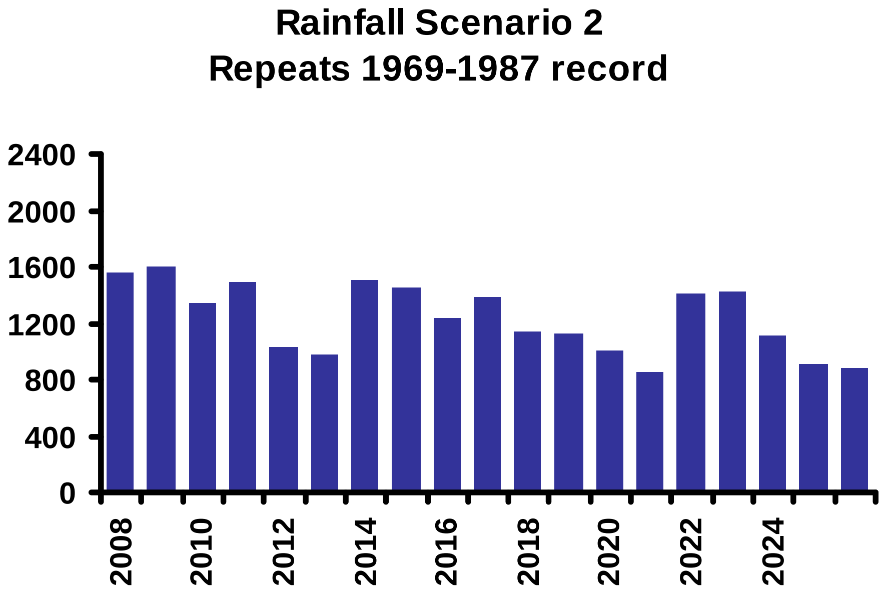

Figure 6.1B: Rainfall Scenario 2: Annual Rainfall in forecast period

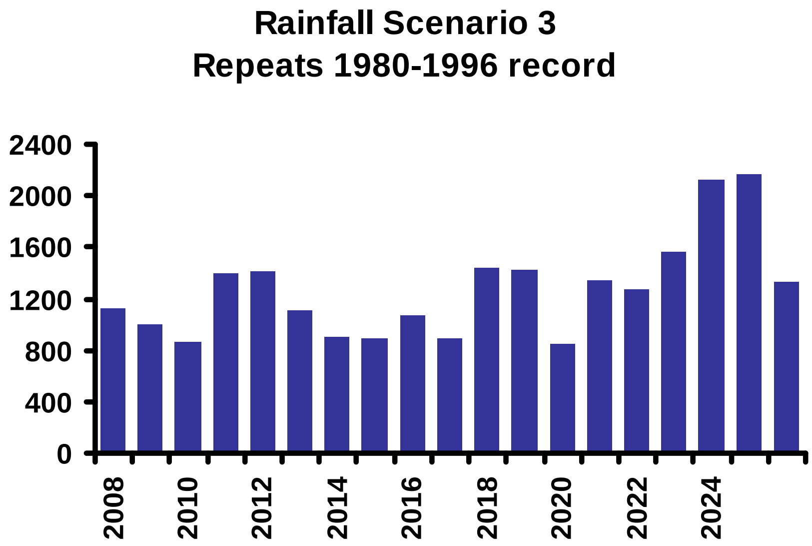

**Figure 6.1C: Rainfall Scenario 3: Annual Rainfall in forecast period**

### *6.1.2 Telugu Ganga project deliveries*

The Telugu Ganga Project deliveries constitute a significant component of Chennai's water supply. In fact the quantity of water delivered by the Telugu Ganga Project is equivalent to between one to three times the median flow from the local watershed. Therefore, assumptions regarding the future of the Telugu Ganga project are critical to the analysis. In Chapter 5 we showed that if Telugu Ganga deliveries occur regularly at current levels of 3500 Million cubic feet (Mcft) for all future years, then Chennai will not suffer a water crisis. However, failure to receive water for even one or two years will once again precipitate a water crisis similar to that of 2003-2004. In Appendix L, we argue that the politics of inter-state water transfers make it likely that Telugu Ganga project will fail to deliver water again during future drought periods.

In the Baseline scenario, the political process of water transfers was implemented by "shutting-off" Telugu Ganga deliveries when rainfall is less than the 75% of the median rainfall. In other years, the quantity received via the Telugu Ganga project between the months of September and January, is assumed to be proportional to annual rainfall in the previous 12 months. The proportionality factor used was the ratio of annual rainfall to the median annual rainfall. So in a median rainfall year Chennai will receive 3500 Mcft. Over the forecast period, Telugu Ganga inflows vary between 1500 and 5500 Mcft for Rainfall Scenario 1.

### *6.1.3 Water available from other sources*

Besides the reservoir system, (which stores water from local runoff and the Telugu Ganga Project), Chennai also gets water from several other sources: the Veeranam Project, well-fields to the north and a small quantity from local surface water bodies. For the historical period, these were treated as exogenous known inputs to the model. For future periods assumptions regarding how much water would be available from these sources need to be made. The assumption is that water from the Veeranam project will always be available at 180 MLD, and the well-fields and local sources will yield a total of 90 MLD. Furthermore, we assume that water from the planned 100 MLD desalination plant will be available after 2009. The desalination plant would run at 100% capacity utilization during droughts but the capacity utilization could be lower in wet periods when water from other sources is plentiful. In effect, a minimum of 370 MLD from these other sources is guaranteed in all periods. Thus, after meeting commitments to industry and neighboring towns, and accounting for delivery losses leakage to groundwater, about 200 MLD would be left for delivery within Chennai at all times[81]. Finally, it is assumed that 50 MLD can be procured via purchases from farmers in an emergency. An emergency is defined as a period when the piped supply system has to be shut down.

### *6.1.4 Land use Map Projections*

In Chapter 3, we described how the recharge and extraction was applied to the groundwater model based on land-use. Therefore, to run the integrated model in future years we needed updated land use maps. Land use was forecasted using software called SLEUTH, based on the

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[81] The assumption regarding the Veeranam project is probably an over-estimate. The water delivered to Chennai may be even lower than 200 MLD if the Veeranam Project fails. Even though the Veeranam project failed to deliver any water for several months in the last few years, we justify this assumption by the following argument: All elements of the Veeranam project are within the control of Metrowater. Although the Veeranam project is a downstream project of the contentious inter-state Cauvery River, unlike the Telugu Ganga case, Tamil Nadu has a constitutional riparian right to the river. The Cauvery Water Tribunal ruling has a legal basis, even if enforcement of the tribunal ruling is complex, and deliveries from this project are likely to be much more reliable. Moreover, all stakeholders of the project are within the state. In the absence of inter-state political bargaining it will be easier to achieve consensus. Importantly, the Veeranam water is delivered under pressure by pipeline (not an unlined open canal) to Chennai, so chances of enroute theft are minimal.

Clarke Urban Growth Model[82]. A brief description of the land use forecast process is provided below.

Four LANDSAT-5 TM satellite images were obtained: for years 1988, 1991, 2000 and 2007. The LANDSAT images were classified into four land use classes: water, agriculture/forest, urban, and ocean. Past, current and future roads were input as maps into SLEUTH because urban growth usually occurs along major roads. The SLEUTH model was used in calibration and forecast mode. The SLEUTH model was first run in "calibration mode". Here the four classified images from 1988 to 2007 were used to obtain the growth parameters in SLEUTH. Using the images from the 1987-2007 a consistent pattern of urban growth was established. Land was converted from agricultural to suburban use as farmers sold land to developers and speculators, over time suburban areas became urban as new suburbs became established. The growth was fastest along major highways, with areas adjacent to major roads developing much faster than interior locations. Water bodies and marshy areas were slow to develop.
The growth parameters in SLEUTH that were relevant for Chennai consisted of a "spread coefficient" (which determines the extent of growth along roads, and a "diffusion coefficient" (which determines how quickly areas adjacent to existing urban areas urbanize). A complete description of the land-use forecast is presented in Appendix M. SLEUTH produced land use forecasts for every year to 2025. The projections presented herein are "maximum likelihood" given historical growth patterns. The land-use maps for three selected years are shown in Figure 6.2.

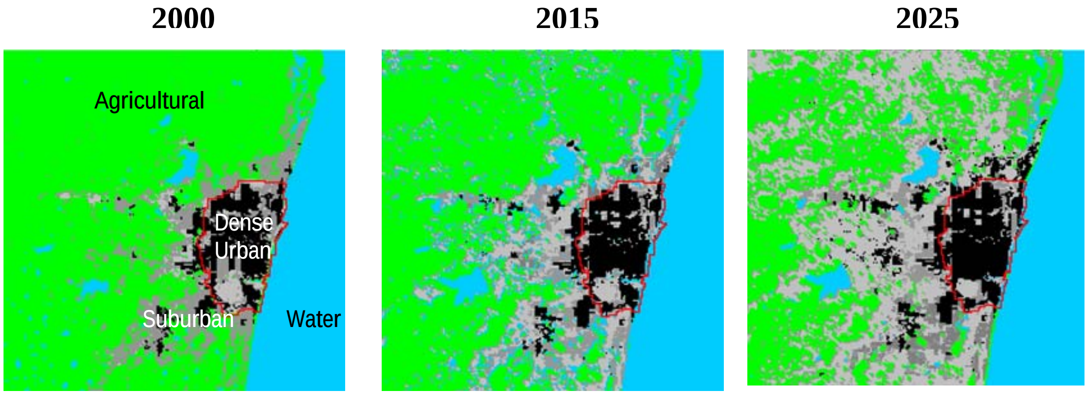

**Figure 6.2: Land use forecasts using SLEUTH**

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[82] Clarke (undated)

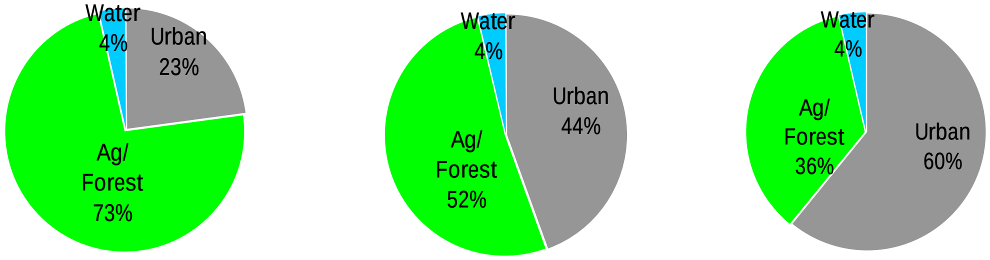

**Figure 6.3: Land use percentages using SLEUTH**

### *6.1.5 Population and Population-density Projections*

Population growth rates, both within the city and in peri-urban areas, were based on projections in the Chennai Metropolitan Master Plan (CMDA, 2006). The population growth rate assumed in the different areas was based on the Master Plan is shown in Table 6.2.

**Table 6.2: Annual population growth rates**

| | **Projected Population Growth** |
|---|---|
| **Within city limits** | **1.18%** |
| **Peri-urban areas** | **2.25%** |

**Source: CMDA, 2006**

However, for future years, population density projections, not aggregate population projections in each census unit are needed. Outside the city, residential and commercial water use is dominantly groundwater based. In order to estimate groundwater extractions accurately, we need to know the population density in each grid cell for every period in the future.

To convert population projections into population density projections, we use the SLEUTH land use maps as well as a manually classified 2007 Google-Earth Image. The Google Earth image allowed us to split the broad urban category generated by the SLEUTH classification into urban and suburban categories. The classification of the Google Earth Image was done manually. The Google Earth Image was overlaid with a grid of the same resolution as the model. Then each grid cell was assigned as urban or suburban visually depending on the density of housing. Grid cells with single family homes interspersed with vacant land and trees were classified as suburban. Grid cells with dense urban settlements were classified as urban.

We calibrated the population density for each grid cell for 2001 for each land-use category so that the aggregate population in each census unit i.e., the total population in each census unit matched 2001 census data. The 2001 population densities for each land use category were:

Urban ~13,000 people /Sq km or 750 people/grid cell

Suburban ~ 4,500 people /Sq km or 250 people /grid cell

Agricultural ~ 1450 people /Sq km or 70 people/grid cell

For future periods the population density was assumed to increase at a rate such that overall populations are consistent with population growth in each period[83]. Figure 6.4 shows the population density map projected over time with the city boundary is shown in red.

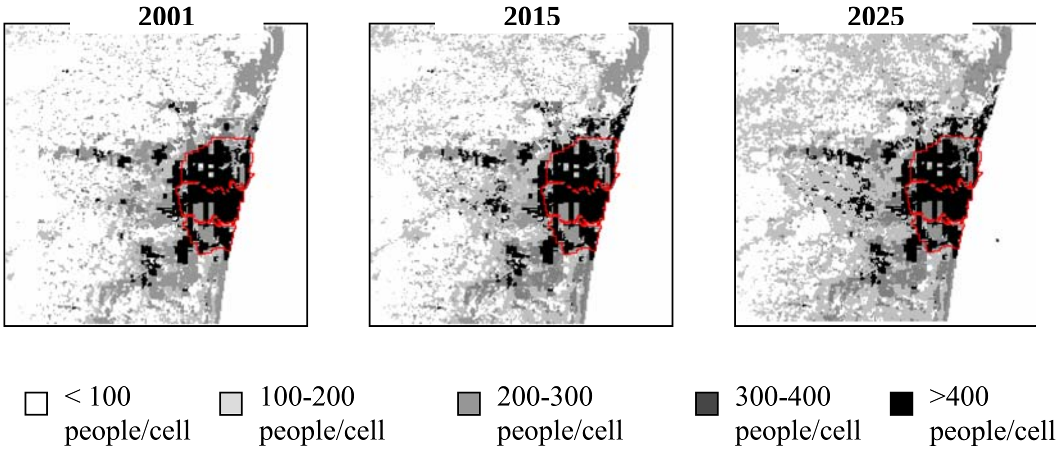

**Figure 6.4: Population density projection maps**

### *6.1.6 Consumer investments in connectivity, storage and wells*

In the Baseline scenario, we assume that as incomes rise, consumers will invest in connectivity, sumps, and borewells. To forecast the fraction of households in each consumer category, we examined the distribution of households by consumer category and income. The median income in each consumer category determined from the Jan 2006 household survey is shown in Table 6.3.

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[83] Given changes in land use predicted by SLEUTH from agricultural to suburban and from suburban to urban, a 2% population density growth rate was the value necessary to produce a total population increase in each census unit of 2.25% per year. Because the rate of urbanization was higher than population growth, the population density growth was lower.

**Table 6.3: Fraction of households by consumer category in 2006**

| Category | Median Income | Percent of HH |
|---|---|---|
| Unconnected consumers | Rs 1,500/Month* | 16% |
| Manual consumers | Rs 3,500/Month * | 20% |
| Manual with borewell consumers | Rs 7,500/Month | 35% |
| Sump consumers | Rs 10,000/Month | 29% |

* Because the lowest income category, in the household survey, was "Less than Rs 5000/Month" included almost all the unconnected and manual consumers, we had to make an assumption. Unconnected consumers were assumed to be poorer and earning less than Rs 0-Rs 2500/Month, while manual consumers were assumed to earn Rs 2500- Rs 5000/Month.

Next, assuming that real[84] household incomes rise uniformly at 4% per year[85], we projected household incomes for all deciles of the population in 2025. (We used real incomes and real costs expressed in 2005 rupees). Then, we recalculated the fraction of households in each consumer category in 2025. We assumed that the income brackets map to each consumer category in exactly the same way[86]. The procedure used was as follows: We used the distribution of consumers into income brackets in 2006 from the household survey shown in Table 6.3. We assume household incomes are more or less uniformly distributed within each category. For instance, if 20% of the consumers reported incomes between Rs 5,000/month and Rs 10,000/month, then we assume that 4% earn between 5,000 and 6,000 and so on. By assuming real incomes rise at 4% per annum, we were able to produce an income distribution in 2025. By assuming that the cut-offs for connections, borewells and sumps remain the same, we were able to translate the distribution of incomes into a distribution between consumer categories. Once the fraction of consumers in each category was set for 2025, we interpolated the fraction of households in each consumer category between 2005 and 2025, to obtain the fraction of households in each consumer category for every intermediate year. Figure 6.5 shows the projected fraction of consumers by category in 2006 versus 2025.

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[84] Real income means household income in 2005 rupees.

[85] Narayanswamy and Zainulbhai, 2007

[86] This is equivalent to assuming that costs of all goods rise at the inflation rate. i.e., no dramatic technological or other shifts occur that make the cost of drilling borewells or installing sumps different relative to the costs of other goods and services.

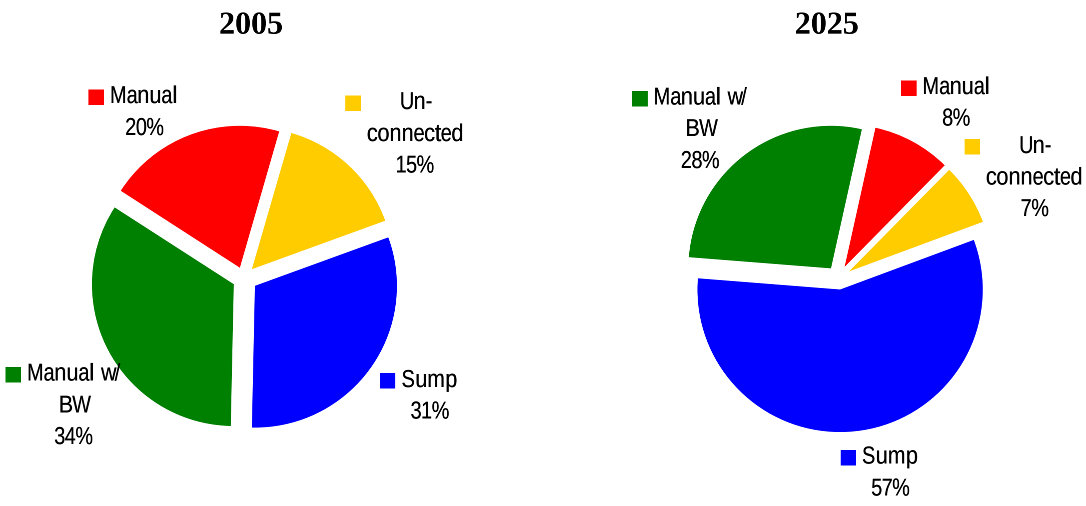

**Figure 6.5: Projected percentage of households by consumer category**

### *6.1.7 Utility investments in new supply*

The only new supply source incorporated in the Baseline Scenario is the new 100 MLD desalination plant. This plant has already been commissioned and is expected to come online in 2009 and is assumed only to be used at capacity in periods when the reservoir system is dry.

## 6.2 2025 Baseline Results

The integrated model was run to 2025 using each of the rainfall scenarios described in the previous section. The three rainfall scenarios each generate a multi-year drought. The model results indicate that for each rainfall scenario, the Telugu Ganga project will not deliver water for one or more years. When the Telugu Ganga water is not delivered, the reservoir system dries up and the piped supply system within Chennai will shut down. In periods when utility supply is either severely restricted consumers will become dependent on self-supply via private wells. As the drought progresses, the water table will drop, and a greater and greater fraction of wells will go dry. Consumers will become increasingly dependent on private supply, and suffered welfare losses. Only the results of Rainfall Scenario 1 (derived from the 1988-2006 rainfall record) are presented in this chapter. The results for the other two scenarios are similar to Rainfall Scenario 1 and no particular insight can be derived from them, so they are not presented in detail. However, sensitivity to different rainfall scenarios will be presented for the policy analysis.

### 6.2.1 *Inputs for Rainfall Scenario 1*

In this scenario, rainfall is 75% of the median or less in 2009, 2019, 2021 and 2022. Based on our assumption about the correlation between Chennai's rainfall and the Telugu Ganga project, the modeled Telugu Ganga water delivery fails in four years when rainfall is 75% of the historic median (scenario years 2009, 2019, 2021 and 2022), as shown in Figure 6.6. For Rainfall Scenario 1, rainfall is less than 75% of the median rainfall, in years 2008, 2011, 2018 and 2022. In each of these years, the Telugu Ganga Project water fails. Furthermore, while Chennai enjoys a prolonged wet spell between 2014 and 2016, there is an extended dry period between 2018 and 2023, in which there are no big storms.

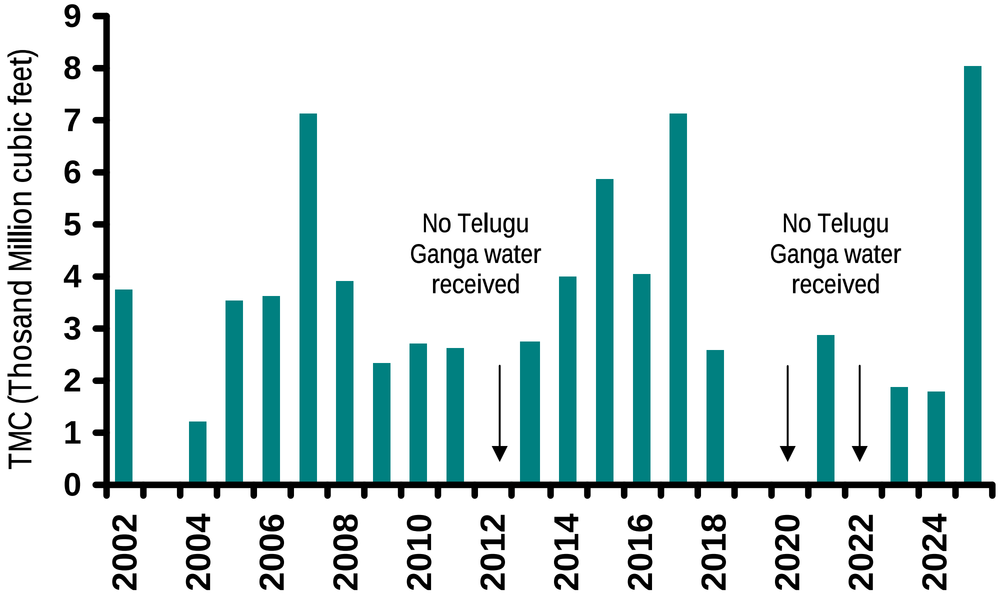

**Figure 6.6: Telugu Ganga deliveries to Chennai: Baseline case (Rainfall Scenario 1)**

### 6.2.2 *Surface Water Module Outputs*

Under this Rainfall Scenario, the reservoirs dry up completely on several instances following the failure of the Telugu Ganga Project in years 2009, 2013. Between 2019 and 2024, the reservoirs remain almost dry for a prolonged period of almost 5 years because in this rainfall scenario, no major storms replenish the reservoirs between 2018 and 2023. Telugu Ganga water is received only in limited quantities. Coumputed reservoir storage up to 2025 is shown in Figure 6.7.

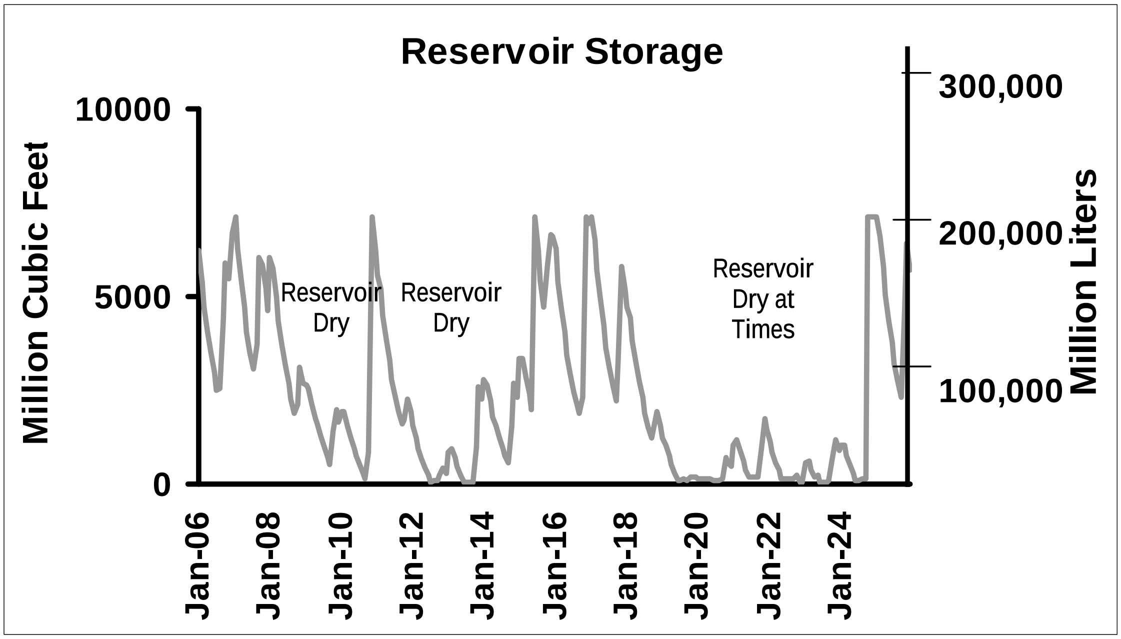

**Figure 6.7: Reservoir Storage in Baseline scenario (Rainfall Scenario 1)**

This figure shows that for this Rainfall Scenario, the reservoir is dry or very low, in 2009, 2012-2014 and between 2018 and 2024.

### *6.2.3 Water Utility Module Outputs*

Utility supply to Chennai is reduced considerably when the reservoirs dry up, even if water availability from other sources is held steady. The reservoir management rules require the fraction of water diverted from the reservoir system is a simple fraction of available storage plus a constant quantum required to meet industrial supply. In periods when water available to the utility is low, the quantity of piped supply available to consumers is proportionally lower. The model triggers a shut-down of the piped system, when available supply (after pipeline losses) falls to a one-quarter of demand or less. The entire city is supplied via mobile supply under these crisis circumstances. Figure 6.7 below depicts the total utility supply available to Chennai over time broken down by source. It can be seen that during the drought, the desalination plant is an major fraction of total supply.

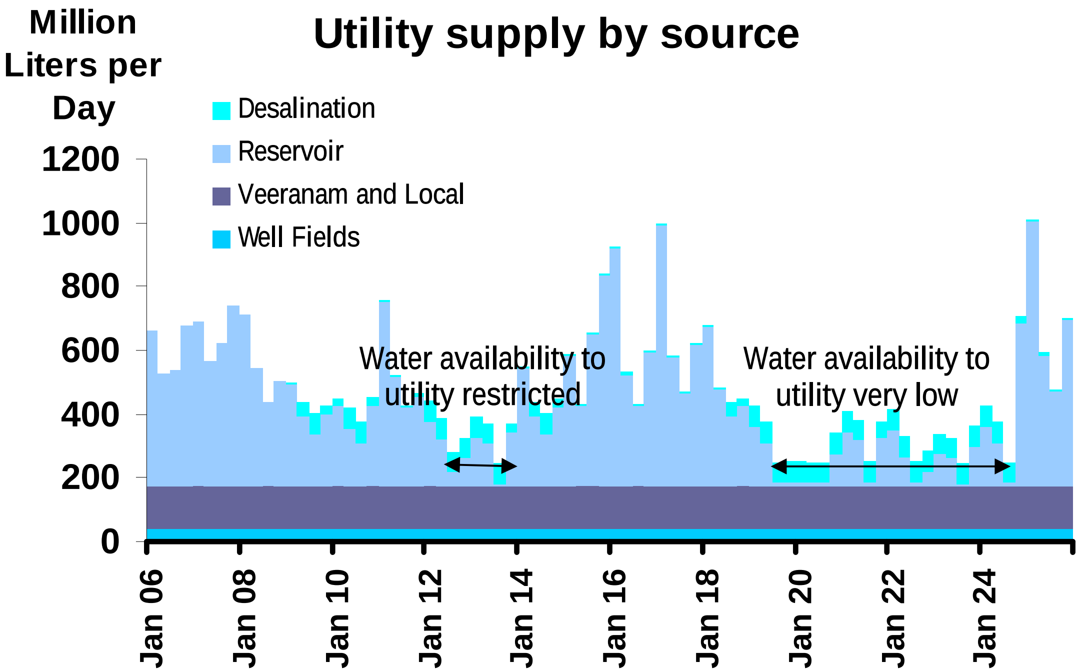

**Figure 6.8: Utility Supply to Chennai: Baseline case (Rainfall Scenario 1)**

Figure 6.8 indicates that over the 20 year future period, for this Rainfall Scenario, the utility supply system is heavily restricted for over a year two times: once in 2011 and again between July 2021 and 2023. Each of these restrictions occurs in response to the reservoirs drying up.

### *6.2.4 Groundwater Module Outputs*

Figure 6.9 shows the fraction of wells within Chennai that become dry over time. In earlier chapters, we presented the "fraction of wells dry" variable as an indicator of the average groundwater level within Chennai, an output of the groundwater module.

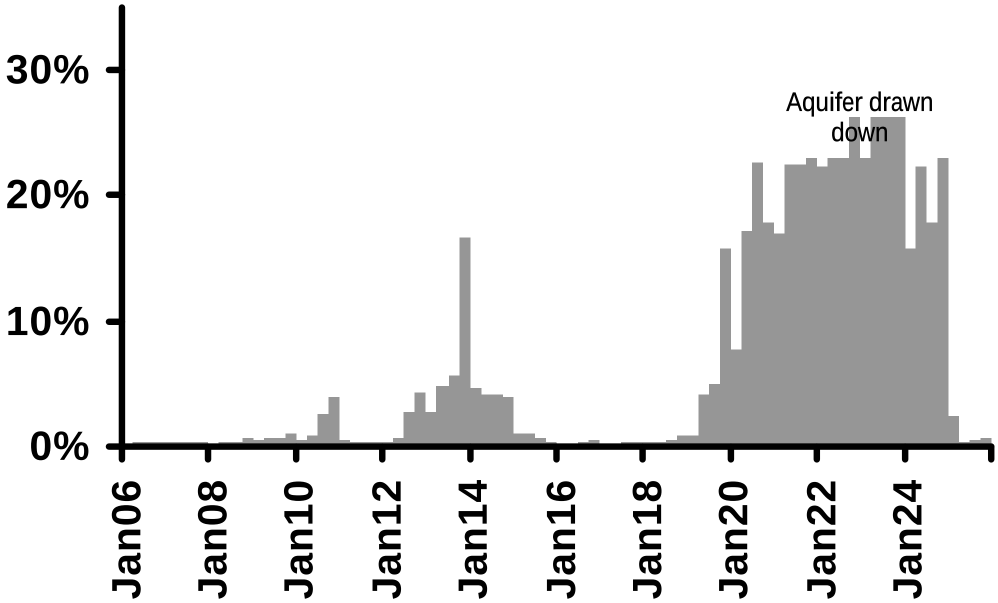

**Figure 6.9: Percent of wells dry in Baseline case (Rainfall Scenario 1)**

When the piped supply system is heavily restricted, groundwater levels within Chennai are drawn down. As the quantity supplied to consumers via the piped supply system is restricted starting in July 2021, consumers become increasingly reliant on self-supply from their wells and the groundwater in the aquifer is gradually depleted. In the Baseline scenario, each “reservoir dry” episode is accompanied by falling groundwater levels in Chennai.

It is noteworthy that the fraction of wells dry peaks at 26% versus a peak of 22.5% during the historical simulation. In other words, the same rainfall sequence causes the aquifer to dry up to a greater extent. The model indicates that this is a real phenomenon attributable to population increase within the city. Significantly, the construction of a 100 MLD desalination plant in 2009 does not satisfy projected demand increases.

### *6.2.5 Tanker Markets Module Outputs*

As a greater and greater fraction of consumers’ private wells dry up, a tanker market emerges. The estimated size of the tanker market is seen in Figure 6.10. The tanker market reaches its peak in the summer of 2023, when almost a 26% of Chennai’s wells go dry.

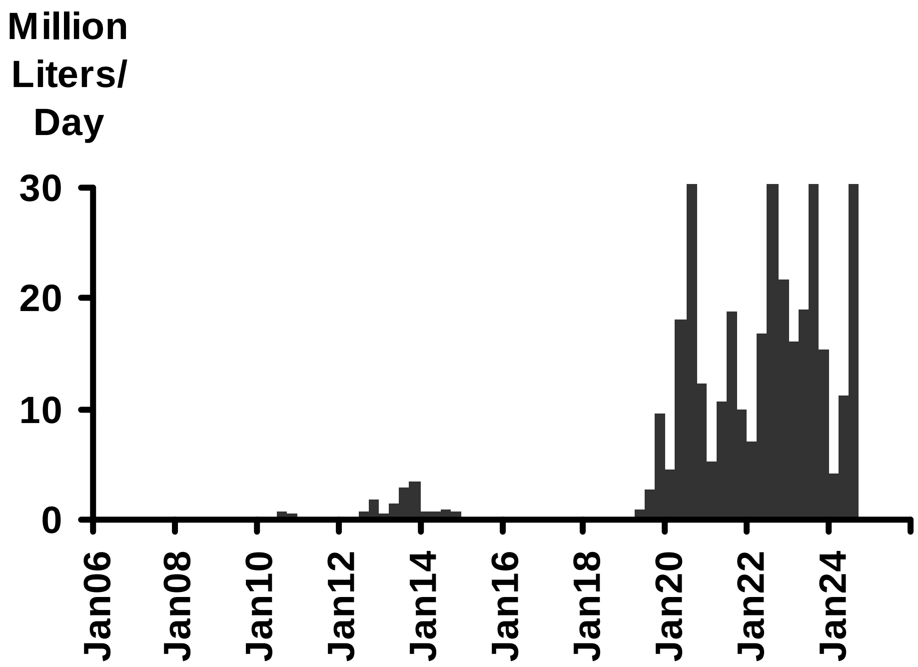

Figure 6.10: Residential tanker market in Baseline Scenario (Rainfall Scenario 1)

### *6.2.6 Consumer Module Outputs*

The average quantity of water consumed by households by source is shown in Figure 6.11.

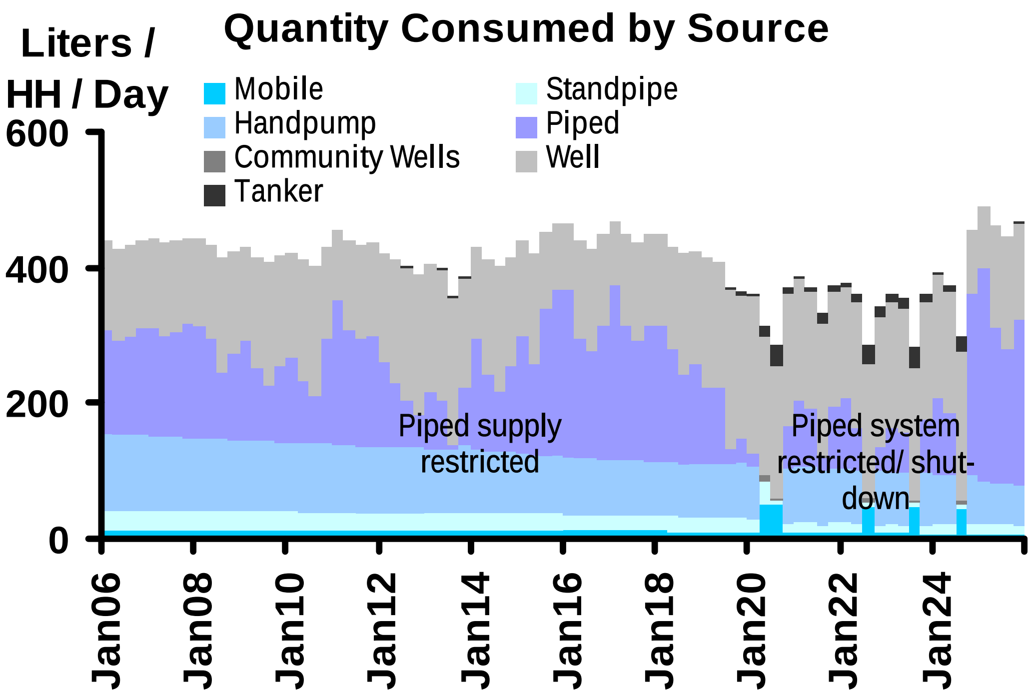

Figure 6.11: Quantity consumed by source in Baseline case (Rainfall Scenario 1)

Consumers compensate for reductions in piped supply by augmenting the water supply using their own wells. If the piped supply system is shut down for a prolonged period, consumers become increasingly tanker dependent. Total consumption is decreased by 25-33 percent.

Figure 6.12 shows the consumer surplus over time for the Baseline scenario. From the figure about it can be seen that consumers suffer a welfare loss of over Rs 100 million per month (that represents an average loss to households of Rs. 2.50/day) during a multi-year drought compared to a normal year.

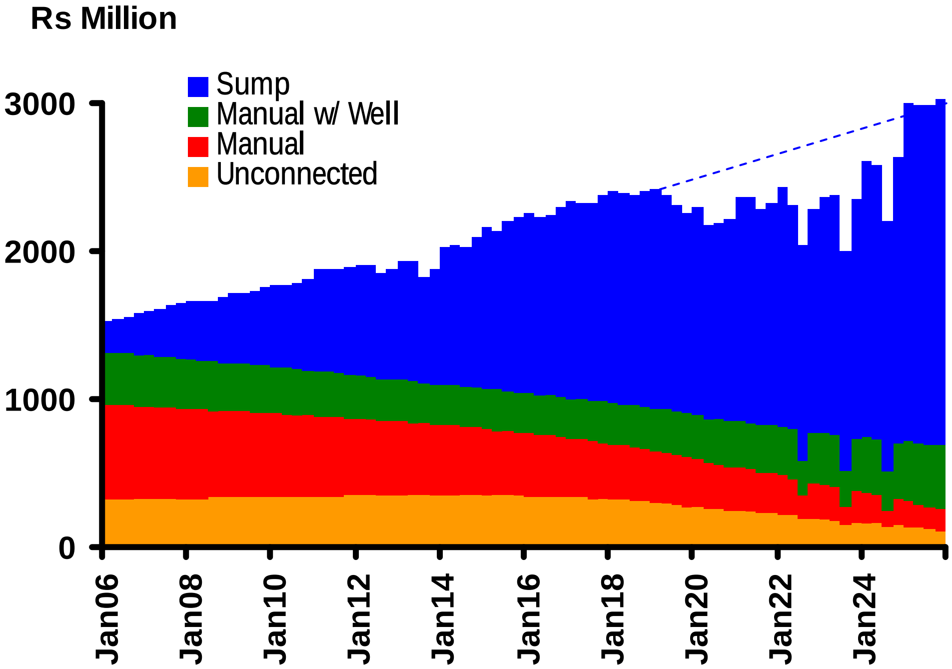

**Figure 6.12: Total consumer surplus in Baseline case (Rainfall Scenario 1)**

### 6.3 Insights from Baseline Run

In the previous sub-sections, we have presented the results of the Baseline Scenario. For the most part, the results are consistent with the historical simulation. However, there was one unexpected result from the Baseline Scenario. We expected that land use changes might produce a significant decrease in groundwater extraction, as groundwater-intensive rice agriculture was replaced by less water-intensive urban land use. However, that did not happen. In fact the model detected only a very small decrease of about 3% in total basin groundwater extractions over time, even while groundwater extraction within the city increased steadily.  Figure 6.13 depicts the total basin groundwater extraction projected by the model over time (for Rainfall Scenario 1).

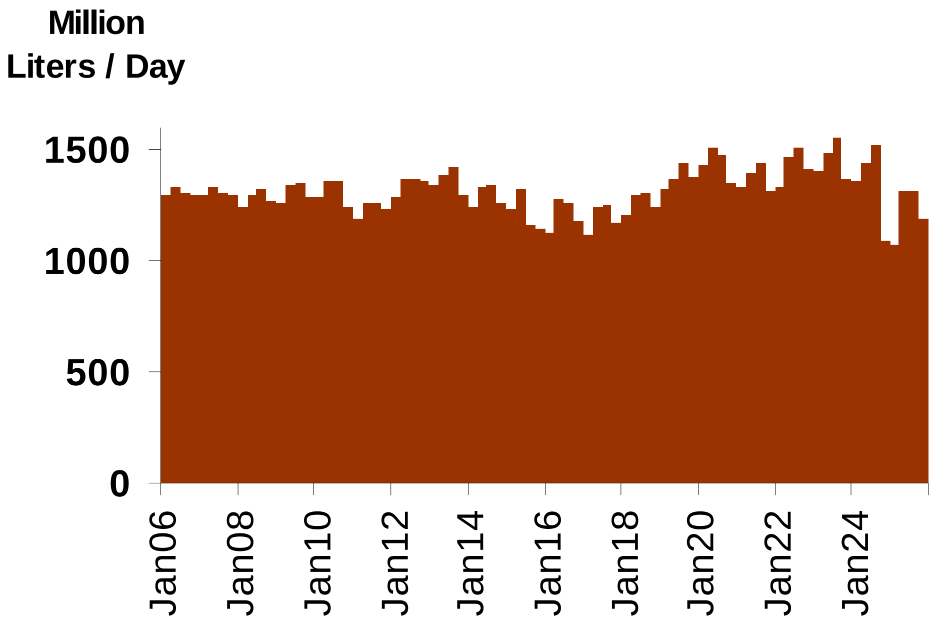

**Figure 6.13: Basin groundwater extraction in Baseline case (Rainfall Scenario 1)**

It turns out that two competing factors balance out to keep overall extraction more or less constant.  On the one hand, water-intensive agriculture is displaced by urban uses. On the other as population densities, incomes and industrial/commercial needs rise over time, demand for water increases.   From 2010 to 2025 the proportion of urban and agricultural land switched from 35% urban and 61% agricultural to 60% urban and 36% agricultural. Figure 6.14 shows snapshots of the total extraction in Chennai basin in two periods: Jan-Apr 2008 and Jan-Apr 2024. These two years had about the same rainfall, so the differences in groundwater extraction are not attributable to differences in water availability.

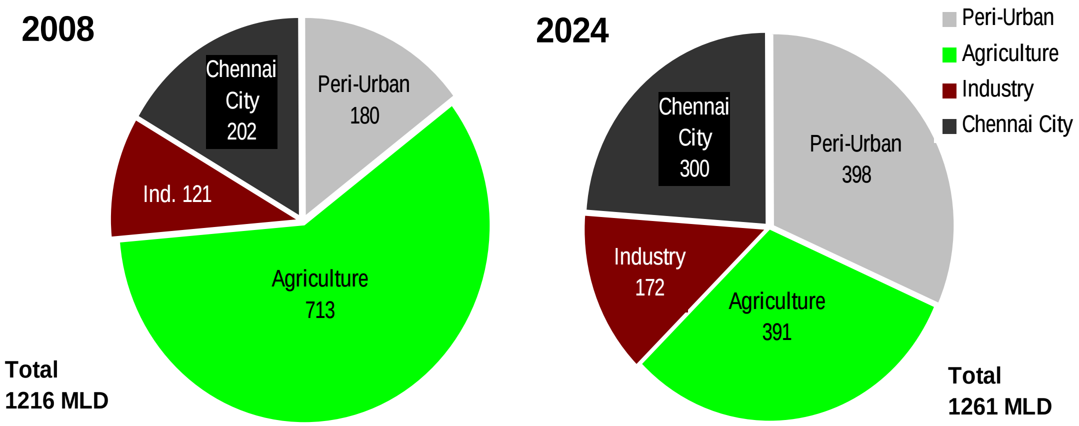

**Figure 6.14: Break-down of basin groundwater extraction over time in Baseline case**

From Figure 6.14, we see that while agricultural extractions do indeed drop significantly, this decrease is compensated by increases in urban groundwater extraction. Several factors contributed to the rise in urban groundwater use. Firstly, the projected industrial/commercial growth rate of 2.25%/year in the peri-urban area contributes higher groundwater extractions. Secondly, domestic peri-urban extractions also increase. While population increases at 2.25% per year, the fraction of households with indoor plumbing also increases significantly because of rising incomes. So not only do the number of peri-urban households increase by about 45 percent between 2010 and 2025, the quantity extracted per household further increases by 50 percent. Similarly, population growth and rising incomes within the city of Chennai also contribute to higher extraction. The rise in extraction from urban uses, is essentially compensated for by retirement of agricultural land.

This finding is significant. In Chapter 1, we argued that the distributed nature of water consumed by irrigated agriculture in Tamil Nadu, implies that reallocation of water from agricultural to urban uses occurs via natural processes of urbanization. Cities grow and develop new suburbs. If centralized utility supply (obtaining water from large surface water sources) is not expanded, the main source of water to peri-urban suburbs arises from the replacement of a distributed network of agriculture wells by a distributed network of peri-urban wells. The Baseline scenario results suggest that at the densities of population prevalent in the peri-urban areas in Chennai, water freed up by replacement of irrigated agriculture by urban land uses yields just enough water to provide for peri-urban water needs.

## 6.4 Chapter Summary

In this chapter, we showed that despite investment in a desalination plant, consumers will suffer if the aquifer dries up following a shut down of the piped supply system during a future drought. The loss of groundwater and piped utility supply, two relatively low-cost sources forces consumers to purchase high-cost private tanker water resulting in welfare losses.

In the next chapter, we examine policy options aimed at mitigating or removing these welfare losses. We investigate policies that allow a uniform quantity of water to be supplied by the water utility each month. We will also examine policies that involve actively managing the aquifer to ensure that consumers can depend on private wells during a drought.

# 7 Chapter Seven: Chennai 2025 Policy Simulations

In this chapter we address the third research goal presented in Chapter 1, identifying the policy that would best improve consumer surplus, reliability, and sustainability of the Chennai water system. The chapter is organized as follows. We begin by describing the criteria and metrics that were used to compare the different policies. Then we briefly introduce the policies and present the summary of our findings for the three policies. Each policy is then presented in detail. For each policy, we document the parameter changes made to the model and discuss the outputs of individual modules. All results are presented for a single rainfall scenario that repeats the historical rainfall sequence from 1989 to 2006, for the period 2008 to 2025.

The policies are ranked by evaluating how the policies perform by each criterion. The model results suggest that none of the three approaches discussed in Chapters 1 and 2, Supply Augmentation, Efficiency Improvement and Rainwater Harvesting, is best by all criteria. A combination of Rainwater Harvesting and Efficiency Improvement seems best. However, these results are contingent on the level of the tariff set under the Efficiency Improvement policy. If tariffs are raised significantly, the model results suggest that households would use two sources of water, high-quality, high-cost utility supply for potable needs along with a low-quality, low-cost, self-supply via private wells for their non-potable needs. We refer to this special case Rainwater Harvesting and Efficiency Improvement policy as a “Dual-Quality” policy. The model results suggest that a Dual-Quality policy might best address Chennai’s water supply challenges.

Finally, we also explore the robustness of the results by offering a sensitivity analysis to key parameters: policy costs and implementation efficacy. Because all of the policies mainly yield benefits during drought periods, the results are somewhat dependent on the length and severity of drought; so sensitivity to alternate rainfall scenarios is presented for each policy.

## 7.1 Five Criteria

### *7.1.1 Economic Efficiency or Welfare Maximization*

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.

**Estimation of Benefits:** 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. Aggregate policy benefits are therefore the sum of the consumer surplus and utility revenues.

**Consumer surplus gains:** Benefits to consumers are estimated as the total difference (versus the Baseline) in consumer surplus over the 18-year period from 2008 to 2025.

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

**Equation 7.1**

where

$CS^{Policy}$ is the aggregate consumer surplus for all Chennai consumers under the policy

$L^{Policy}{}_{i,j,t}$ 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.

$NP$ is the number of periods in the model

Consumer surplus under the Baseline Scenario $CS^{Baseline}$ is similarly estimated. The difference in consumer surplus, $\Delta CS$ from a particular policy is defined as

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

NOTE: The model does not discount costs and benefits. This decision was made for two reasons. Firstly, 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. Discounting would only be fair if we ran Monte-Carlo simulations that included many rainfall scenarios with droughts occurring at different intervals. Secondly, the costs of the policies (except Rainwater Harvesting) are often ongoing O&M costs, not upfront capital costs. 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. If costs and benefits incurred in each time period discounting will only have the effect of weighting earlier years more but will not change the overall benefit-cost analysis result.

**Revenue accrued to 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

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

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/HH/day

*NP* = Number of periods in the model

**Equation 7.2**

**Estimation of Costs:** Costs of implementing the policy were estimated as follows. The capital costs (if any) for each policy were assumed to last 25 years and so prorated over the 18-year forecast horizon 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.

### *7.1.2 Welfare Threshold*

The Welfare Threshold criterion evaluates the level of distress suffered by the poorest households in the driest year. The rationale for developing this criterion is as follows: The benefit-cost analysis as defined earlier does not afford any special consideration to extreme fluctuations in consumer well-being. The benefit-cost analysis uses the net *average* costs and benefits over time. Thus, as long as the welfare losses in dry years are compensated by welfare gains in wet years, variations in welfare from year to year are perfectly acceptable.

However, the benefit-cost analysis could result in underestimating consumer suffering in dry years. In the model, consumer surplus is estimated by integrating the willingness-to-pay function, which is in turn bounded by household income; i.e., consumers can at most give up everything they have to avoid dying of thirst. Consequently, the benefit-cost analysis cannot properly account for the "suffering" caused by drastic reductions in water availability, particularly to poor households. In fact during the 2003-2004 Chennai drought, poor consumers in some slums rioted[87] when they did not receive sufficient mobile supply because they could not afford to purchase water from private sources. Such acute distress to consumers cannot be captured by consumer surplus estimated from a willingness-to-pay function. To account for this limitation, we compare the various policies based on the fraction of "distressed" households, where distressed households are defined as households enjoying less than the "life-line" level in the driest period, a metric we refer to as the welfare threshold metric ($WT_{DRY}$). Thus, the welfare threshold ($WT_{DRY}$) was defined as the fraction of households enjoying less than the "life-line" consumer surplus level. The equation below shows how the welfare threshold metric was estimated.

$$WT_{DRY} = \frac{\sum_{j=1}^{12} \sum_{i=1}^{6} Lu^{Policy}{}_{i,j,DRY} * HH_{i,j,DRY}}{\sum_{j=1}^{12} \sum_{i=1}^{6} HH_{i,j,DRY}}$$

$$\begin{aligned} Lu^{Policy}{}_{i,j,DRY} &= 1 \text{ if } L^{Policy}{}_{i,j,DRY} < L_{Threshold} \\ &= 0 \text{ if } L^{Policy}{}_{i,j,DRY} >= L_{Threshold} \end{aligned}$$

**Equation 7.3**

The threshold consumer surplus level $L_{Threshold}$ was defined to be the consumer surplus enjoyed by the poorest category of Unconnected consumers in a normal year

### *7.1.3 Reliability of utility supply*

The Reliability criterion tests the reliability of piped utility supply, specifically the extent to which policies can prevent the shut down of the piped supply system. There are several reasons one may wish to have *some* piped utility supply available in all periods, regardless of whether water from alternate source is available. Firstly, utility supply is the only source of cheap potable water. So there may be health effects of having no access to piped supply, as

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[87] Personal interviews with residents in Odai Kuppam

consumers are fully dependent on untreated, potentially contaminated groundwater. Secondly, the shut-down 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

$$ShutDown(Months) = 3\text{ (Months/Period)} * \sum_{t=1}^{NP} u_t$$

$$\begin{aligned} &where \\ &u_t = 1 \text{ if piped supply is completely shut down} \\ &u_t = 0 \text{ if piped supply is available} \\ &\text{NP} = \text{Number of periods in the model} \end{aligned}$$

**Equation 7.4**

### *7.1.4 Equity*

The purpose of the Equity criterion is to assess the equity effects of each policy across consumer categories. Since the consumer categories map to income levels, the equity criterion can be used to judge the equity implications of policies. The metric used was the net benefit per month (averaged over time and space) from the policy as a fraction of consumers' monthly income.

$$\Delta CSI^{Policy}{}_i = \frac{\overline{\Delta CS^{Policy}{}_i}}{I_i} = \frac{\sum_{t=1}^{NP} \sum_{j=1}^{12} (L^{Policy}{}_{i,j,t} - L^{Baseline}{}_{i,j,t})}{(Months / Period) * NP * J * I_i}$$

$$\begin{aligned} &where \\ &\Delta CSI^{Policy}{}_i = \text{the average incremental consumer surplus to each consumer category} \\ &\text{as a fraction of monthly income} \\ &\Delta CS^{Policy}{}_i = \text{the average incremental consumer surplus to each consumer category} \\ &\qquad\qquad \text{(averaged across zones and over time)} \\ &L^{Policy}{}_{i,j,t} = \text{Consumer Surplus for consumer category} \\ &NP = \text{Number of periods in model} \\ &I_i = \text{Average monthly income in consumer category i} \\ &J = \text{No of zones within Chennai} = 12 \end{aligned}$$

**Equation 7.5**

### 7.1.5 Utility profit maximization

Given that the utility is the water planner and decision maker, it is unlikely that the utility would rely on a policy that maximized social welfare but not profits. For each policy we assess if there are any associated revenue streams (or reduced costs to the utility) that could offer an incentive for the utility to enforce, implement or promote the policy and maximize utility profits. This criterion measures revenue streams (or cost savings) to the utility. Revenue is the same as defined earlier in the benefit-cost analysis case.

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

**Equation 7.6**

## 7.2 Summary comparison of three policies

In Chapter 1, we presented three policies, Supply Augmentation, Efficiency Improvement and Rainwater Harvesting. In this section, we present our summary analysis of the three policies. Supply Augmentation involves building a new desalination plant. The Efficiency Improvement Policy involves raising tariffs and using the revenue to fix pipeline leaks and the Rainwater Harvesting policy involves having consumers direct rooftop and yard rainfall runoff to recharge the Chennai aquifer. In this section, we describe qualitatively, the biophysical and welfare effects of the three policies under Rainfall Scenario 1. In the next section, we evaluate and rank the policies by applying the criteria set out earlier.

The three policies differ significantly in terms of their impacts on the biophysical system and consumers. The Supply Augmentation policy increases availability in the utility supply system because of the water produced by the second desalination plant. This allows the piped supply system to remain operational (albeit at curtailed levels) even in the driest periods. So all consumers get 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. The Efficiency Improvement policy also results in greater, more reliable utility supply because of lower pipeline leakage. However, because tariffs for sump consumers are raised significantly, these consumers suffer net losses in consumer surplus. On the other hand, manual consumers benefit greatly because piped supply system remains operational (albeit at curtailed levels) even in the driest periods. The Rainwater Harvesting policy cannot prevent a shut down of the utility system, as the policy introduces no chances to the reservoir or utility operations. However, improved recharge allows groundwater available to consumers even in the driest period, greatly reducing dependence on private tankers.

Table 7.1 presents a summary of the bio-physical effects of each policy relative to the Baseline Scenario.

**Table 7.1: Summary results of the three policies**

| **Module** | **Supply Augmentation** | **Efficiency Improvement** | **Rainwater Harvesting** |
|---|---|---|---|
| Reservoir Module | Same as Baseline | Same as Baseline | Same as Baseline |
| Utility Module | New desalination plant in 2015, keeps piped supply operational in future multi-year drought | Reduction in pipeline leakage keeps piped supply operational in future multi-year drought | Same as Baseline: Piped supply system shuts down for 9 months at the peak of the drought. |
| Groundwater Module | 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 Module | 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 Module | Consumers benefit from improved utility supply from second desalination plant | Consumers benefit from improved utility supply due to lower pipeline leakage | Consumers benefit from improved groundwater availability |

In the next section we discuss how the policies fared when evaluated against the five criteria defined earlier.

### *Benefit-Cost Analysis*

Analysis of the costs and benefits of the policies indicates that Supply Augmentation is not cost-effective. The cost of operating the second desalination plant far exceeds the increase in consumer surplus enjoyed by consumers. In contrast, the Efficiency Improvement and Rainwater Harvesting policies each yield positive net-benefits and are cost-effective.

Efficiency Improvement is cost-effective because losses suffered by consumers due to the increase in tariff are offset by the improvements in piped supply. The improved reliability of piped supply, particularly during drought periods, allows consumers to depend less on private sources of supply. The net benefits from Rainwater Harvesting are highest. The benefits from Rainwater Harvesting arise entirely from the increased availability of groundwater during drought periods.

### ***Equity Analysis***

The Rainwater Harvesting policy yields the maximum benefits to the poorest consumers, because it prevents shallow community wells to stay wet during the drought period. The Efficiency Improvement and Supply Augmentation solution do not improve the condition of the poorest consumers much; these consumers lack private utility connections, and so have little to gain from the improved availability utility supply generated under these policies.

### ***Reliability Analysis***

The Supply Augmentation and Efficiency Improvement policies are able to prevent a complete shut down of the piped supply system because of water produced by the second desalination plant and reductions in pipeline leakage, respectively. Not surprisingly, under Rainwater Harvesting there is no change to the quantity and reliability of piped supply relative to the Baseline. Like the Baseline Scenario the piped supply system shuts down for 9 months during a future multi-year drought.

### ***Welfare Threshold Analysis***

The Rainwater Harvesting policy (although an improvement over the Baseline) performs the worst of the three policies, in terms of the Welfare Threshold criterion. The Rainwater Harvesting policy results in a larger number of “distressed consumers” for the following reason: For reasons explained earlier, the Rainwater Harvesting policy cannot prevent a shut-down of the piped supply system during a future drought. With Rainwater Harvesting, at the peak of the drought, Manual consumers, who are dependent on piped supply for all their water needs, are no better off than Unconnected consumers. In fact, both consumer groups are forced to depend on mobile-supply, community wells and water vendors. In contrast, the improved reliability of the utility system under Supply Augmentation and Efficiency Improvement ensures that Manual consumers with private utility connections get at least some water even in the driest periods. This greatly minimizes the fraction of Chennai's households that are distressed.

***Utility Profit Maximization***

The Efficiency Improvement policy yields the highest revenues to the utility. This is expected; it is the only policy that involves raising tariffs on consumers. In contrast, the revenues generated by the Supply Augmentation and Rainwater Harvesting policies (relative to the baseline) were relatively small[88]. Table 7.2 shows how the policies stack up against the five criteria.

**Table 7.2: Summary results of the three policies evaluated by criteria**

| **Module** | **Supply Augmentation** | **Efficiency Improvement** | **Rainwater Harvesting** |
|---|---|---|---|
| Net Benefits | Rs (6150) Million | Rs 750 Million | Rs 1910 Million |
| Percentage increase in monthly income (Poorest consumers) | 0.35% | 0.15% | 0.40% |
| Welfare Threshold | 10% | 10% | 24% |
| Reliability | No shut-down | No shut-down | 9 Months shut-down |
| Utility Revenues | 107 | 2660 | 35 |

### *7.2.1 Policy rankings*

Based on the summary above, in this section we rank the policies based on the criteria set out earlier . We see that on a purely efficiency and equity basis Rainwater Harvesting is the best policy. However, it does not generate much revenue for the water utility, is not optimal by the welfare threshold criterion, and cannot prevent a shut-down of the piped supply system. While Rainwater Harvesting is the welfare maximizing policy, it is not a profit maximizing one. Given that the utility is the water planner and decision maker, it is unlikely that the utility would rely solely on Rainwater Harvesting. Table 7.3 shows the policy rankings by the five criteria. If two policies had the same value they are given the same ranking.

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[88] Rainwater Harvesting, surprisingly, also resulted in a small revenue gain for the utility. This occurred because consumers in the "Manual w/ borewell" category of consumers became less dependent on the handpumps as their wells yielded sufficient water because of improved aquifer conditions. Consequently, more water was available in the piped distribution system for use by metered sump consumers. This resulted in a small revenue boost for the utility.

**Table 7.3 : Policy rankings**

| Criterion | Metric | Supply Augmentation | Efficiency Improvement | Rainwater Harvesting |
|---|---|---|---|---|
| **Benefit-Cost Analysis (Welfare Maximizing)** | Highest net benefits | **3 (Not cost-effective)** | **2** | **1** |
| **Equity** | Most gain by poorest consumers | **2** | **3** | **1** |
| **Welfare Threshold** | Fraction of distressed households | **1** | **1** | **3** |
| **Utility Revenue (Profit Maximizing)** | Highest revenue to utility | **2** | **1** | **3** |
| **Piped Supply Reliability** | Least months of shut-down of piped supply | **1** | **1** | **3** |

In this section we presented the summary of the three policies and ranked them according to different criteria. Thus, none of the three policies perfectly satisfies all criteria. In the next section, we examine and discuss the detailed module-level outputs for each policy. In later sections we will explore the possibility of implementing combinations of policies.

## 7.3 Detailed policy outputs

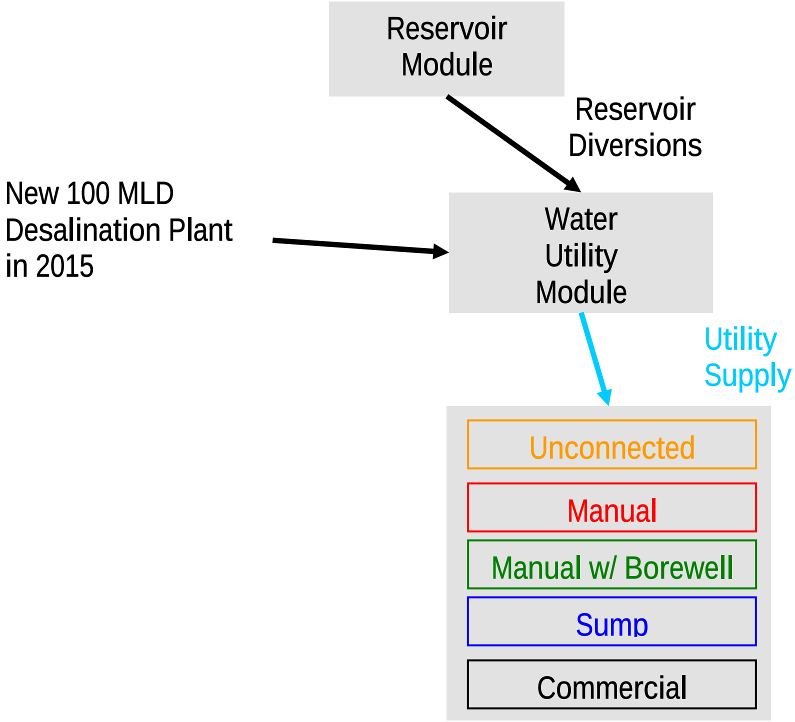
In this section, we present the outputs of the integrated model as well as the module-level outputs for each of the three policies: Supply Augmentation, Efficiency Improvement and Rainwater Harvesting. All results presented are for Rainfall Scenario 1. In each case the outputs are compared to the Baseline scenario. To avoid any misinterpretation that the model is actually predicting a future drought, the year labels have been dropped. Instead model results are presented merely for 3-month periods 1 to 76. Thus, Period 1 = Jan-Apr 2006 and Period 76 = Oct-Dec 2025. All policies are assumed to be effective from Period 13 or January 2009. The new desalination plant comes online in Jan-Apr 2015 corresponding to Period 37.

## 7.4 Supply Augmentation

The Supply Augmentation policy involved the following changes to the baseline model. A second 100 MLD desalination plant would be commissioned in 2015. The desalination plants were assumed to run only to the extent required. It was assumed that the plants would run at a minimum 25% and maximum 100% capacity utilization.

### *7.4.1 Module-level Parameter Change*

The parameter changes were made to exogenous inputs in each sub-module are shown in Figure 7.1.



| **Module in which parameter is changed** | **Parameter Changed** | **Baseline Assumption** | **Supply Augmentation Assumption** |
|---|---|---|---|
| **Utility Module** | Water abstracted from other sources | One 100 MLD desalination plant in 2009 | A second 100 MLD desalination plant added in 2015 |

**Figure 7.1: Model Parameter Changes for Supply Augmentation Policy**

### 7.4.2 *Reservoir Module*

There were no changes to the reservoir module, so the outputs of the reservoir module were identical to the Baseline Scenario.

### 7.4.3 *Utility Module*

Under the Supply Augmentation policy total quantity of water available increased during the dry periods, because of the addition of the second desalination plant. Figure 7.2 shows the total water available to the utility, broken-down by source under the Supply Augmentation and Baseline scenarios.

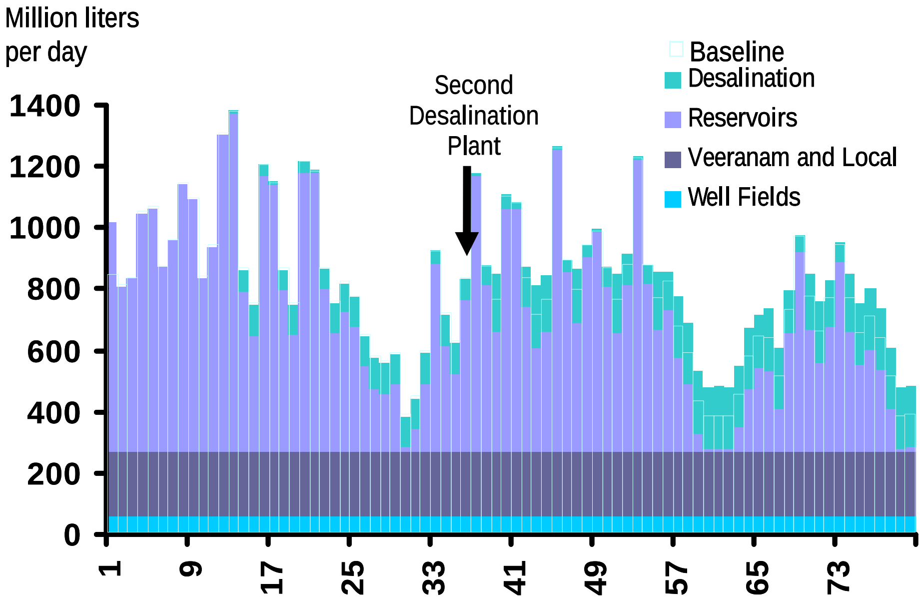


**Figure 7.2: Total Utility Supply under the "Supply Augmentation" scenario**

Under the Supply Augmentation scenario, utility supply during the multi-year drought is higher that the Baseline scenario. The increase in water available to the utility is entirely due to the second desalination plant. Figure 7.3 shows the quantity consumed from different under Supply Augmentation

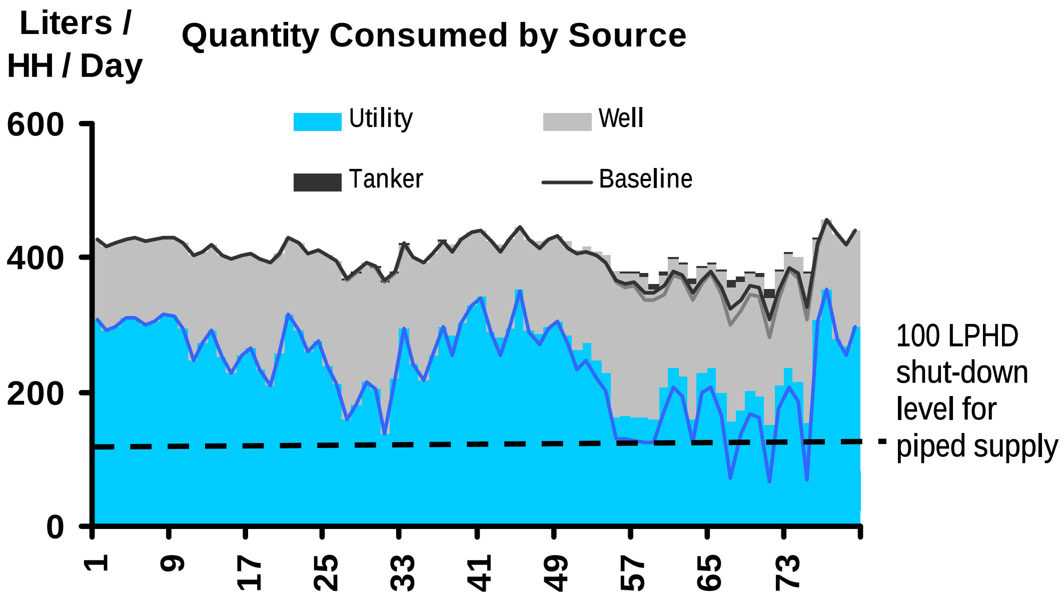


**Figure 7.3: Quantity consumed by source under Supply Augmentation**

A major difference between the Supply Augmentation scenario and the Baseline scenario is that under Supply Augmentation, the piped supply system does not shut down in any period. i.e., the reliability of the piped system improves to 100%. The second desalination plant allows water availability to stay above the shut-down threshold where it can still be supplied by the piped distribution system. However, because the total quantity of water available is much lower during the drought, piped supply is curtailed.

### *7.4.4 Groundwater Module*

As piped supply is curtailed during the drought, consumers become increasingly dependent on private wells, and the aquifer is drawn down. Figure 7.4 shows the fraction of wells becoming dry in Chennai under the Supply Augmentation scenario.

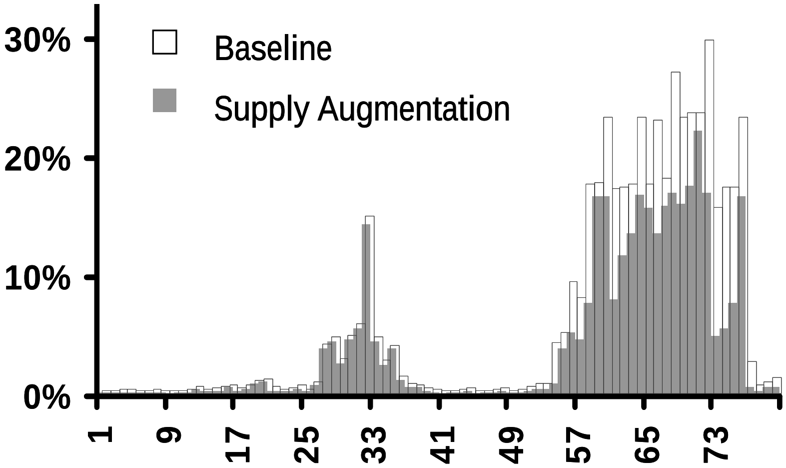


**Figure 7.4: Percent of wells dry under the Supply Augmentation scenario**

If the Supply Augmentation policy is implemented, groundwater levels drop during the drought, though not as much as the Baseline scenario. As more water is available through the utility supply system, consumers extract less groundwater.

### *7.4.5 Tanker Market Module*

During drought periods, as groundwater levels drop and private wells go dry, consumers become increasingly tanker dependent. Under the Supply Augmentation scenario fewer wells dry up as compared to the Baseline case. Consequently the tanker market is smaller than the Baseline case as shown in Figure 7.5.

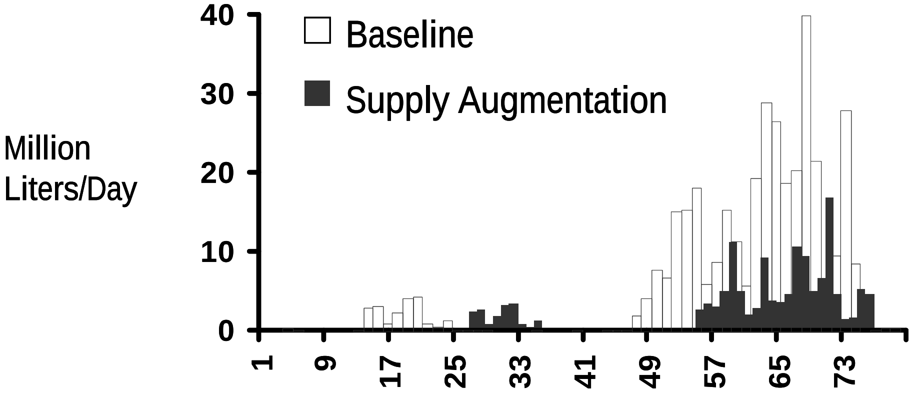


**Figure 7.5: Residential tanker market under the Supply Augmentation scenario**

### *7.4.6 Consumer Module*

The difference in consumer surplus between the Supply Augmentation scenario and the Baseline scenario is significant during drought periods, when the second desalination plant prevents a complete shut-down of the piped supply system. The availability of some utility supply allows consumers to depend less on groundwater and tanker water.

The consumer surplus under the Supply Augmentation scenario relative to the Baseline is shown in Figure 7.6. The difference in consumer surplus is shown in Figure 7.7.

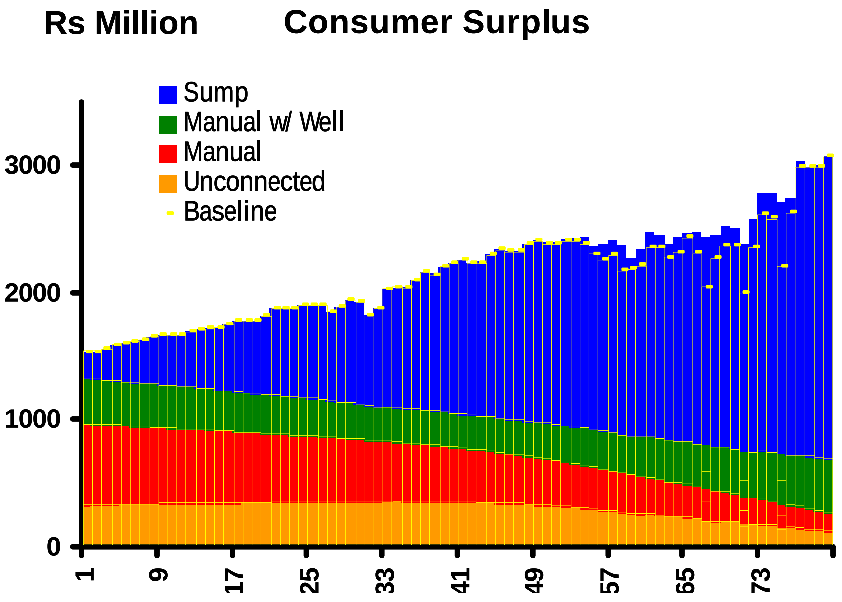


**Figure 7.6: Consumer Surplus under Supply Augmentation (relative to Baseline)**

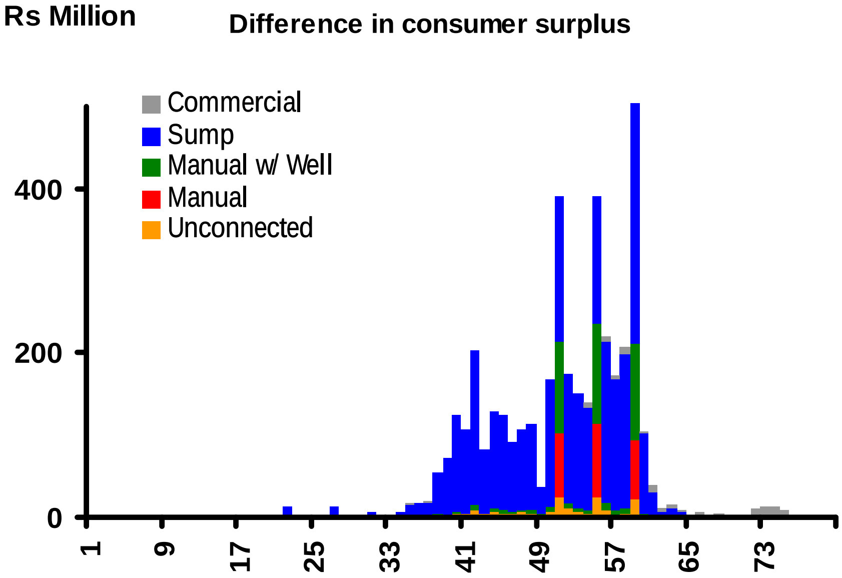


**Figure 7.7: Difference in Consumer Surplus under Supply Augmentation**

All consumer categories benefit from Supply Augmentation, but the benefits are mostly during drought periods. In these periods the second desalination plant allows the piped supply system to remain operational, reducing dependence on private wells and tankers. However, analysis of the consumer surplus differences across consumer categories indicates that while sump consumers benefit much more than other categories in absolute terms. This is a direct result of using willingness-to-pay as a measure of consumer surplus. In other words, wealthy people have a higher willingness to pay and therefore benefit more from increased availability of lower cost water. However, when average net benefits are computed as a fraction of income, the poorest categories of consumers benefit the most.

### *7.4.7 Production costs of desalination*

The production cost of desalinated water was assumed to be Rs 40/kL[89] and the desalination plant costs were assume to be scale linearly with quantity produced. For instance, for a 100 MLD desalination plant running at 100% capacity utilization, the cost of production for each 90-day period is Rs 100 * 90 * (40/1000) ~ Rs 320 million. Figure 7.8 shows the quantity of water produced by the desalination plant under the Supply Augmentation scenario.

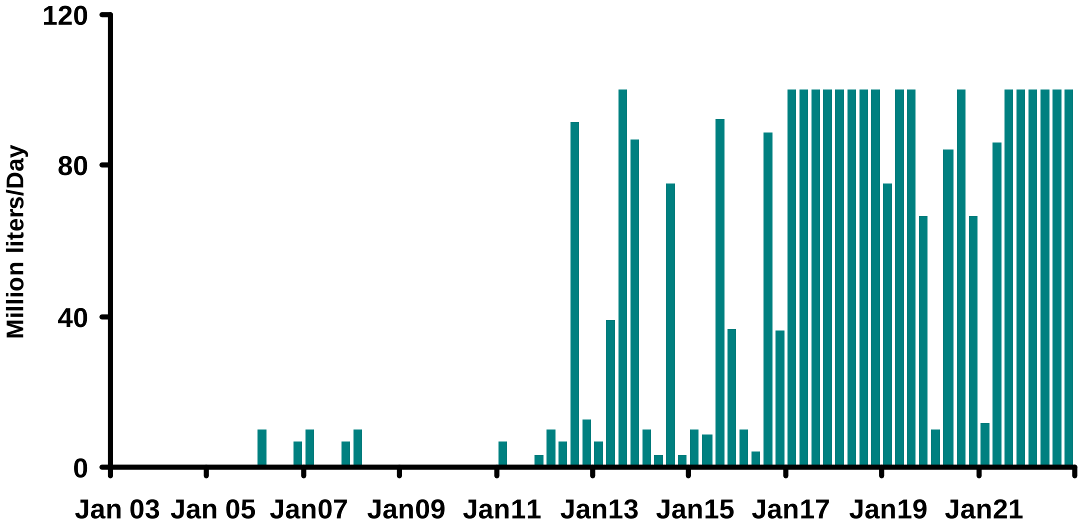


**Figure 7.8: Production from second desalination plant**

Over the forecast period, the additional cost incurred from running the second desalination plant works out to Rs 10,500 million. Figure 7.9 compares the total costs and total benefits of the policy over the forecast horizon from 2008 to 2025.

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[89] Metrowater, 2006

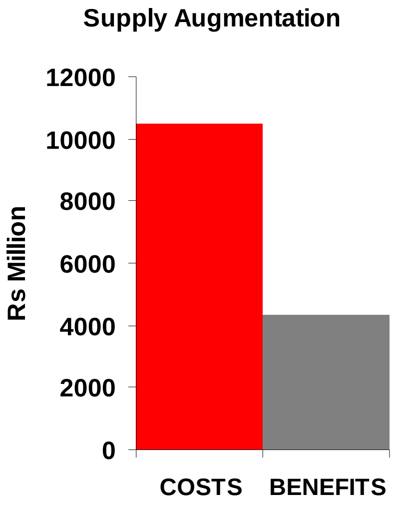


**Figure 7.9: Benefit Cost Analysis from Supply Augmentation**

Figure 7.10 shows the incremental benefits by consumer category as a fraction of monthly income.

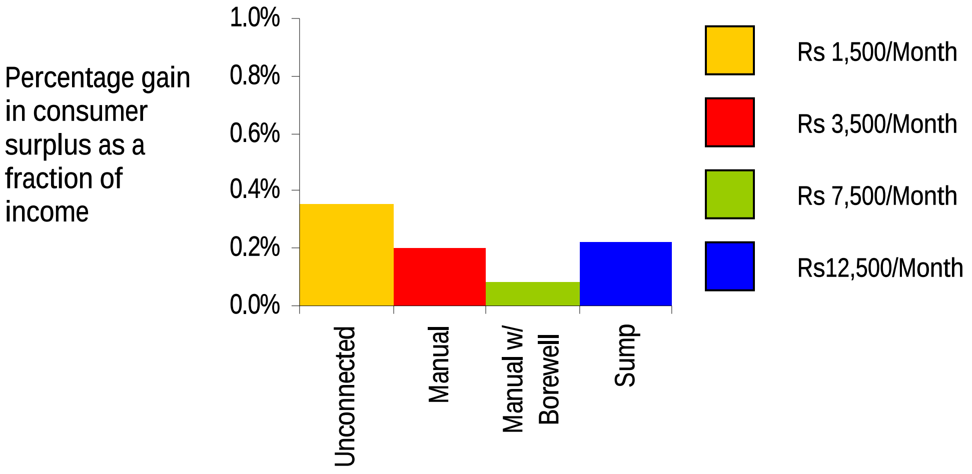


**Figure 7.10: Equity Analysis of Supply Augmentation**

### *7.4.8 Sensitivity Analysis*

The uncertain parameters in this policy simulation are the true costs of desalination and to different rainfall scenarios. Figure 7.11 shows how the benefit-cost analyses changes for desalination costs varying from a minimum of Rs 15/kL to a maximum of Rs 60/kL based on the range of worldwide desalination costs.

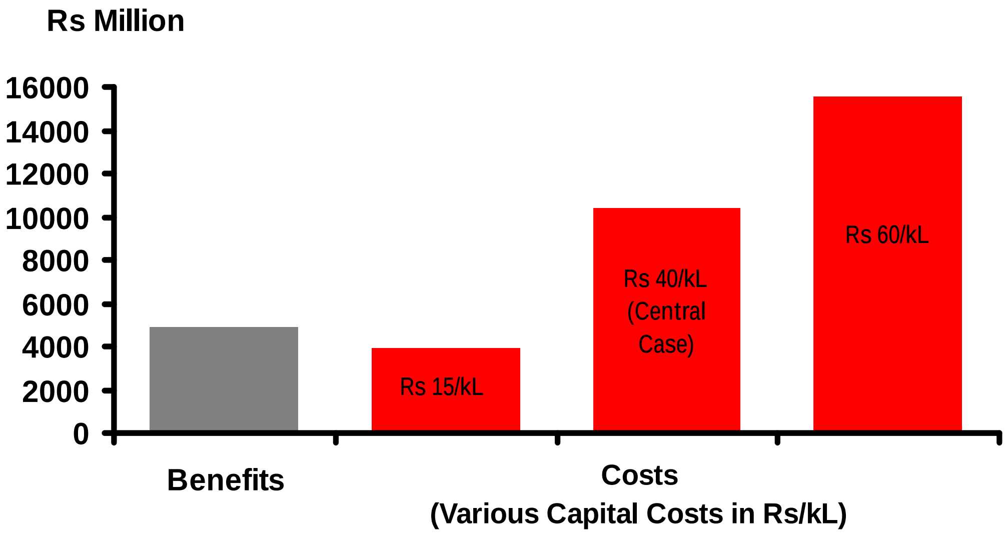


**Figure 7.11: Sensitivity to Desalination Costs: Supply Augmentation**

A comparison of the costs of production versus net benefits suggests that desalination would be cost-effective at about Rs 17/kL. While this analysis was applied to costs of desalination, the argument could be extended to any new production source: at current income levels no project with production costs much higher than this should be considered.

Figure 7.12 shows how the benefit-cost analyses changes for alternate rainfall scenarios, Rainfall Scenarios 2 and 3, presented in Chapter 6.

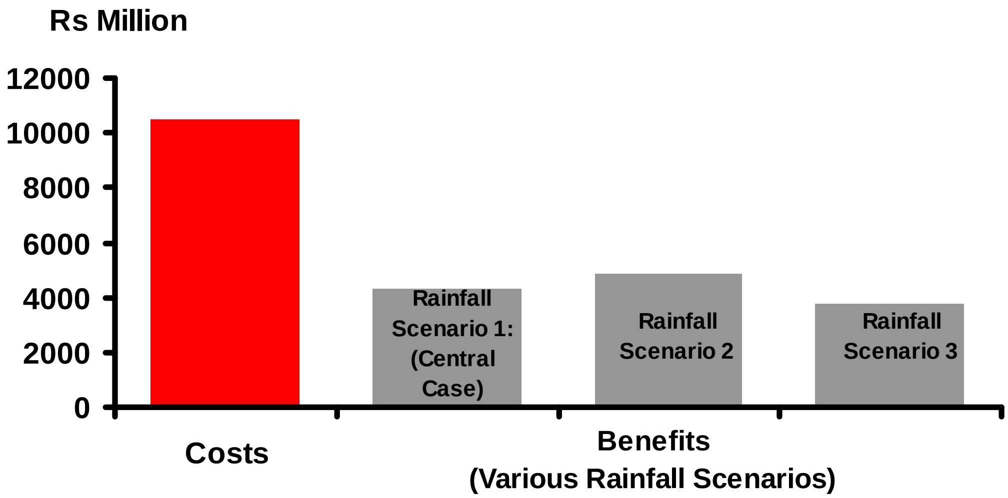


**Figure 7.12: Sensitivity to rainfall scenarios: Supply Augmentation**

The net-benefits of desalination would not be positive for any of the three rainfall scenarios tested.

## 7.5 Efficiency Improvement

The second policy tested was the Efficiency Improvement policy, whereby the water utility raises tariffs and uses the revenue generated to fix leaky pipes. To implement this scenario, two changes were implemented. Firstly, the cost of piped supply was increased to 5.45 Rs/kL for all sump consumers. This price was chosen so that the cost of piped supply would remain just below the cost of groundwater extraction from private wells. Thus, under Efficiency Improvement, utility supply remains the cheapest and best quality source available to consumers. Secondly, pipeline leakage was decreased over time. Specifically, pipeline losses were assumed to decrease at 3% per year. This rate was chosen so that pipeline losses would halve to about 14% by 2025.

As a reference, the world’s best water utilities have losses as low as 5%. In the United States water utilities suffer typically losses in the range of about 15-25%. However, the situation is not entirely comparable in Chennai. In western utilities the utilities mains are pressurized at all times, a situation often referred to as “24*7 supply”. In contrast, in intermittent supply systems the pipeline pressures are much lower or not pressurized at all. So a  system with 14% pipeline loss when managed intermittently Chennai would be suffer much higher losses if the pipes were suddenly maintained pressurized at all times. Figure 7.13 shows the pipeline losses assumed in the model.

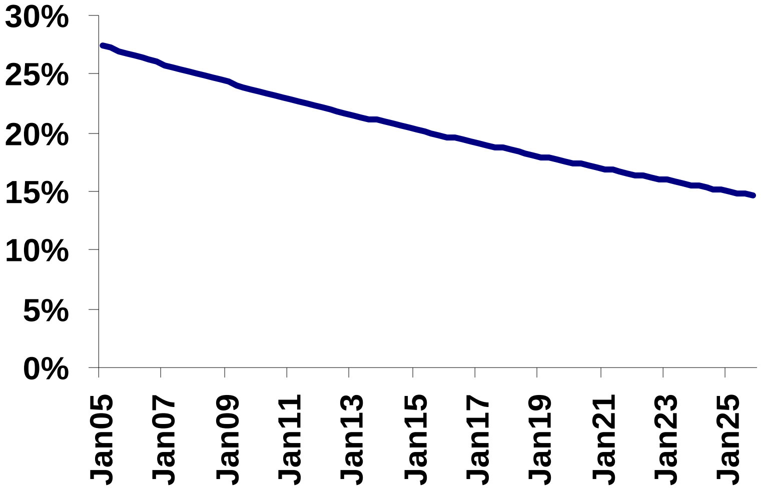
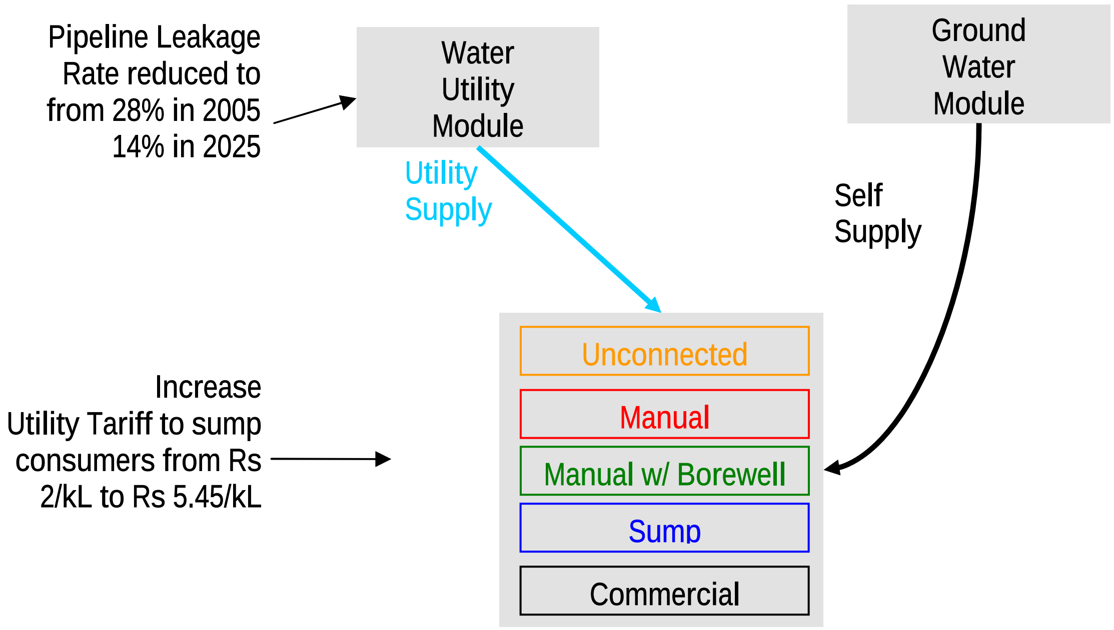


**Figure 7.13: Pipeline leakage under Efficiency Improvement**

Figure 7.14 shows the parameter changes that were made to the model.



| Module in which parameter is changed | Parameter Changed | Baseline | Supply Augmentation |
|---|---|---|---|
| **Utility Module** | Pipeline Losses | 25% in 2005 | 15% in 2025 |
| **Consumer Module** | Price of utility supply | Rs 2.0/kL | Rs 5.45/kL |

**Figure 7.14: Parameter changes under Efficiency Improvement**

The reservoir storage and total available utility supply are the same as those in the Baseline scenario. So these module outputs are not presented.

### *7.5.1 Utility Module*

Under the Efficiency Improvement scenario, more water is available to consumers because of the lower leakage. However, at the same time consumers demand less water on account of higher tariffs. Figure 7.15 shows the quantity of water consumed under the efficiency improvement scenario (versus the Baseline Scenario).

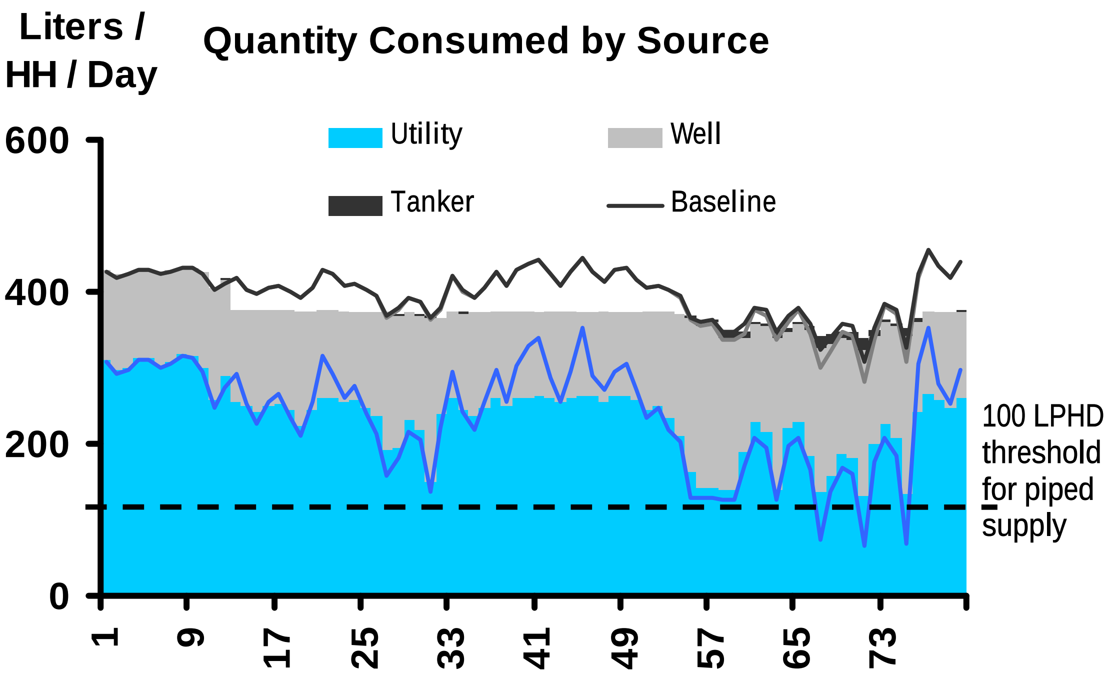


**Figure 7.15: Quantity consumed in the Efficiency Improvement Scenario**

Thus, the effect of this policy on consumption varies. Specifically, the effect depends on when consumers were supply limited or demand limited in a given period under the Baseline scenario. In dry periods when utility supply is restricted or shut down under the Baseline scenario, total consumption increases relative to the Baseline case. This is because more utility supply is available to consumers as distribution pipeline losses are reduced. In contrast, in wet periods, when utility supply is plentiful and demand is the limiting factor in the Baseline case (i.e., consumers are able to saturate their demand with utility supply), consumption decreases. In this case with Efficiency Improvement higher tariffs induce conserving behavior and decrease demand. Significantly, Efficiency Improvement allows the piped supply system to stay above the shut-down threshold in all periods. Thus the number of months of no piped supply drops from 9 months in the Baseline Scenario to zero under Efficiency Improvement.

### *7.5.2 Groundwater Module*

Although the piped supply system remains operational in all periods, supply may be restricted in drought periods. As piped supply is curtailed, consumers become increasingly dependent on private wells, and the aquifer is drawn down. Figure 7.16 shows the fraction of wells going dry in Chennai under the Efficiency Improvement scenario.

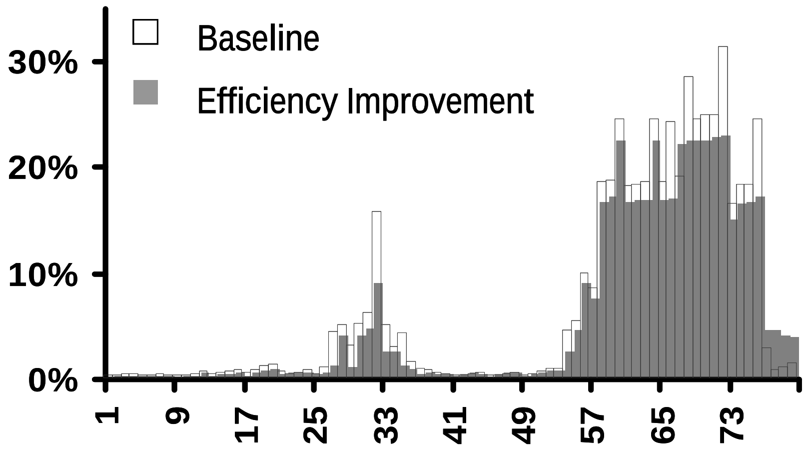


**Figure 7.16: Percent of wells dry in the Efficiency Improvement Scenario**

Under the Efficiency Improvement policy, groundwater levels do drop during the drought and to almost the same extent as the Baseline scenario. This occurs because the reduction in pipeline losses has the effect of reducing groundwater recharge.  Figure 7.17 compares the groundwater extraction and recharge under the Efficiency Improvement scenario to that in the Baseline scenario.

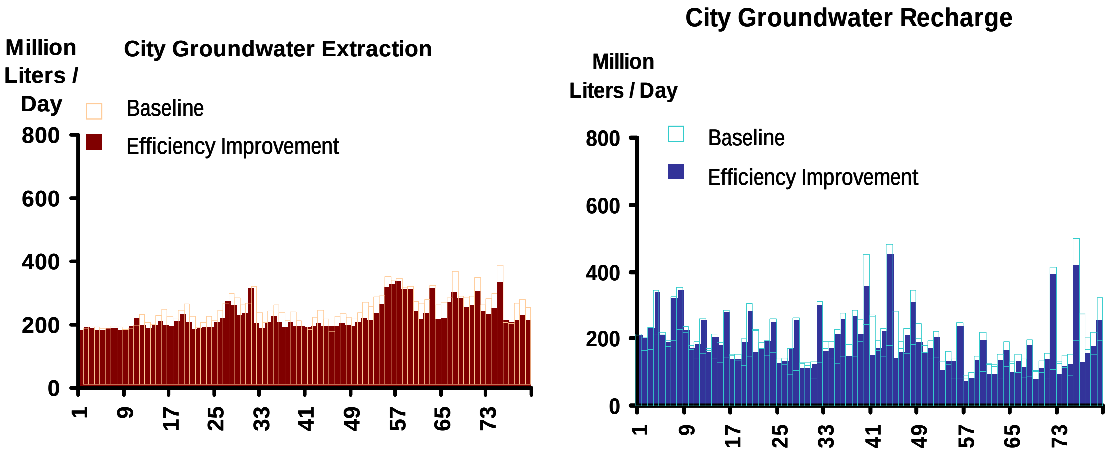


**Figure 7.17: Extraction and Recharge under Efficiency Improvement**

Both groundwater extractions and recharge in Chennai are simultaneously reduced under the Efficiency Improvement scenario. On one hand, extractions from private wells decrease as more utility supply is available; on the other hand, less pipeline leakage results in less groundwater recharge. The two factors balance out so that groundwater levels are almost the same as the Baseline scenario.

### *7.5.3 Tanker Market Module*

As groundwater levels drop during droughts, consumers' wells dry up and consumers become increasingly tanker dependent. Figure 7.18 shows the total size of the residential tanker market in Chennai under the Efficiency Improvement scenario.

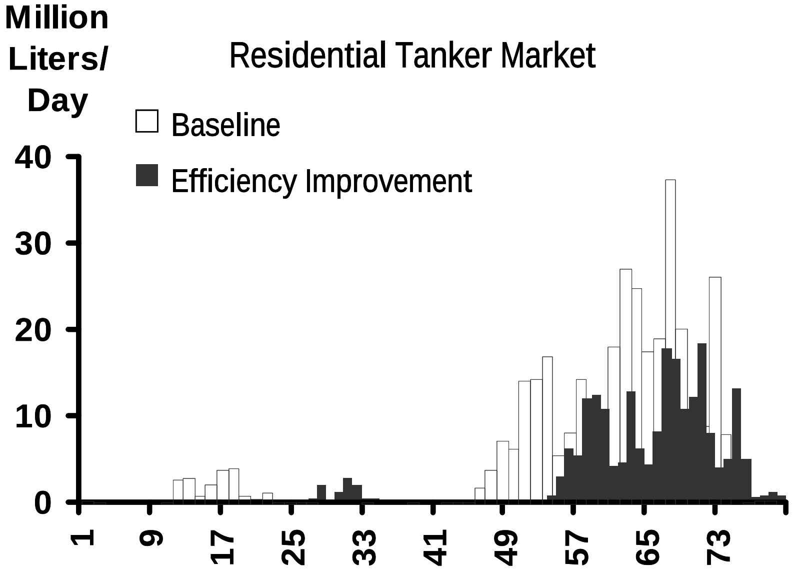


**Figure 7.18: Residential tanker market under Efficiency Improvement**

The Efficiency Improvement policy has the effect of reducing the size of the tanker market. Although the aquifer dries up to the same extent, the availability of utility supply allows consumers to reduce their dependence on private tankers.

### *7.5.4 Consumer Module*

The consumer surplus under the Efficiency Improvement scenario relative to the Baseline scenario is shown in Figure 7.19. The difference in consumer surplus between the Efficiency Improvement and Baseline Scenarios is shown in Figure 7.20.

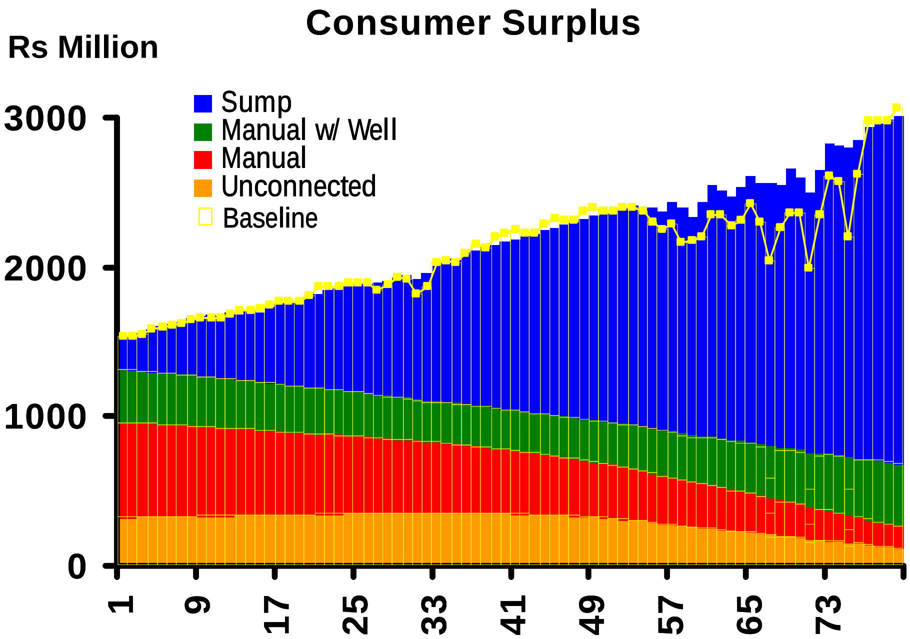


Figure 7.19: Consumer Surplus under Efficiency Improvement (relative to Baseline)

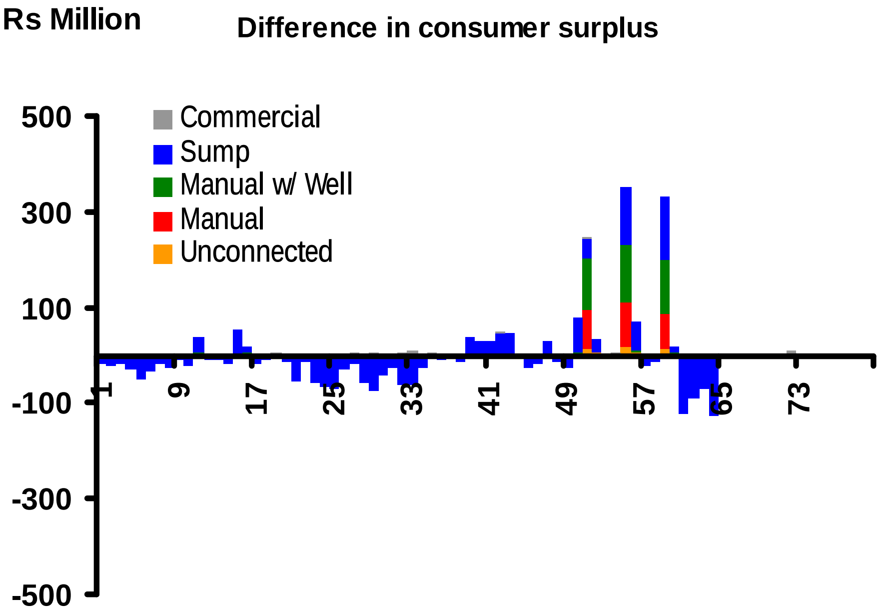


Figure 7.20: Difference in consumer surplus under Efficiency Improvement

Consumer surplus does not change much under the Efficiency Improvement scenario compared to the Baseline case because although more water was available via the utility system because of lower pipeline leakage, the tariff was also increased. Thus, consumer surplus gains from increase in utility water availability during drought periods offset the decrease in consumer surplus due to higher tariffs. However, the consumer surplus losses were limited to sump consumers who face higher tariffs. The lowest income groups benefit from Efficiency Improvement because they do not pay higher tariffs, but benefit from the increased availability of piped supply.

The main benefit of the Efficiency Improvement policy is from additional revenues to the utility. The implicit assumption is that utility revenues will be directed to improving supply, benefiting all consumers. So the higher tariffs (though resulting in a direct loss of consumer surplus) translate to higher revenues for the water utility, which indirectly benefit consumers. Total utility revenue is estimated by aggregating over time the product of the quantity consumed by sump consumers by the rate charged per kL. The net revenue generated from the policy is simply the difference in total utility revenue (Figure 7.21) under the Baseline scenario versus the Efficiency Improvement scenario. Most of the gain is from the tariff increase (from Rs 2/kL to Rs 5.45/kL) rather than from the incremental water delivered due to reduction in pipeline losses.

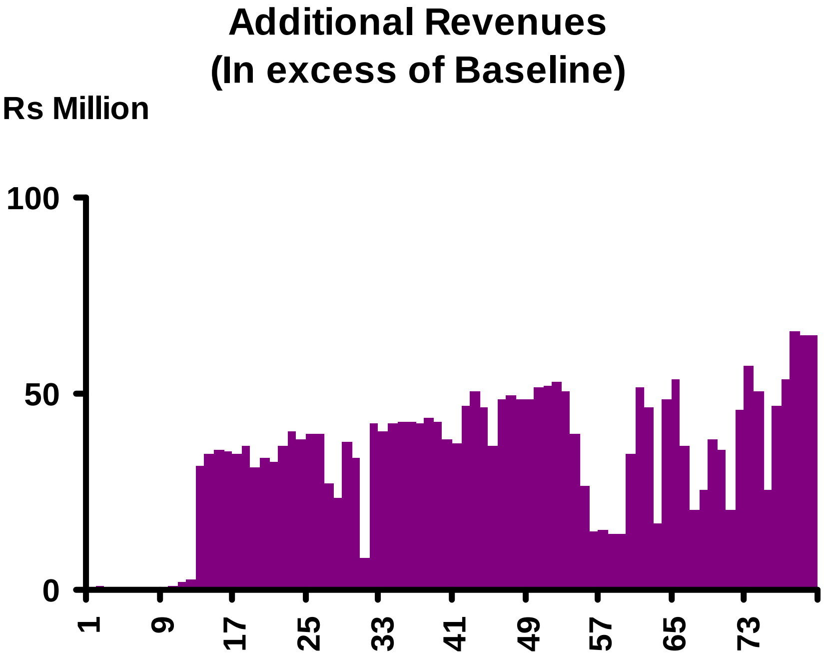


**Figure 7.21: Revenues generated for utility under Efficiency Improvement**

### 7.5.5 *Production costs of conserved water*

Estimating the policy costs of the Efficiency Improvement scenario was challenging because costs of fixing leaky pipelines were hard to obtain. Typically, these costs are specific to the individual distribution systems and leak-detection programs reinstated. Here we assume "normalized" conservation costs in terms of Rs/connection. These costs were based on expert opinion[90]. The total costs of fixing pipeline leaks were cited to be Rs 5000-Rs 7000/ connection. Accordingly, the total costs of the program, prorated to the 18-year forecast period, were estimated at Rs 1,800 million. Figure 7.22 compares the total costs and benefits under the Efficiency Improvement scenario

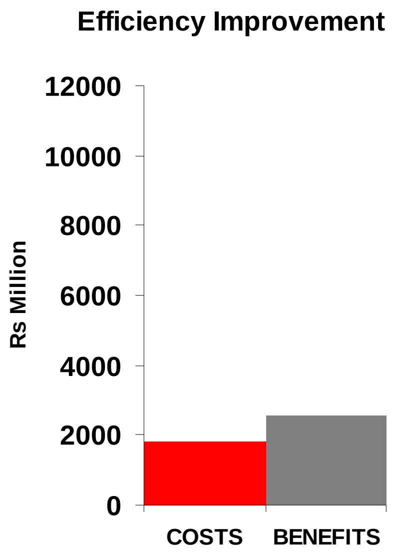


**Figure 7.22: Benefit-Cost analysis under Efficiency Improvement**

The Efficiency Improvement scenario results in net benefits of Rs 746 million. In contrast with the other policies, however, the benefits accrue in the form of increase in revenues to the utility rather than consumer surplus (which was very small and negative).

Figure 7.23 shows the benefits under the Efficiency Improvement scenario by consumer category as a fraction of monthly household income. Under Efficiency Improvement Sump consumers suffer a small net loss in consumer surplus because of the higher tariffs. However, all consumer categories benefit from improved utility supply.

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[90] Chary, 2008.

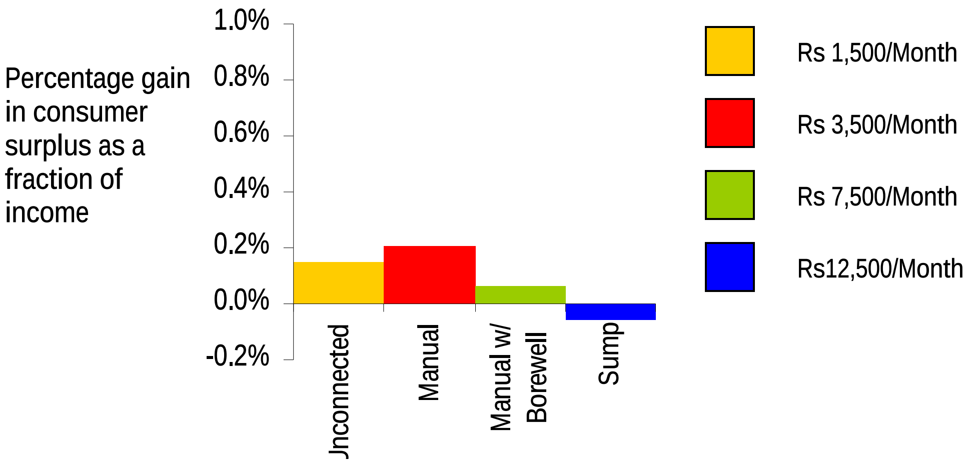


**Figure 7.23: Equity Analysis of Efficiency Improvement policy**

### *7.5.6 Parameter Sensitivity Analysis*

The uncertain parameters in the Efficiency Improvement scenario include the cost of fixing leaky pipes and rainfall. In the absence of comprehensive comparative studies, it is difficult to establish to what extent leakage will decrease at different levels of investment. Figure 7.24 shows the sensitivity of the model to costs of the policy. Figure 7.25 shows the sensitivity of the benefit-cost analysis to the different rainfall scenarios.

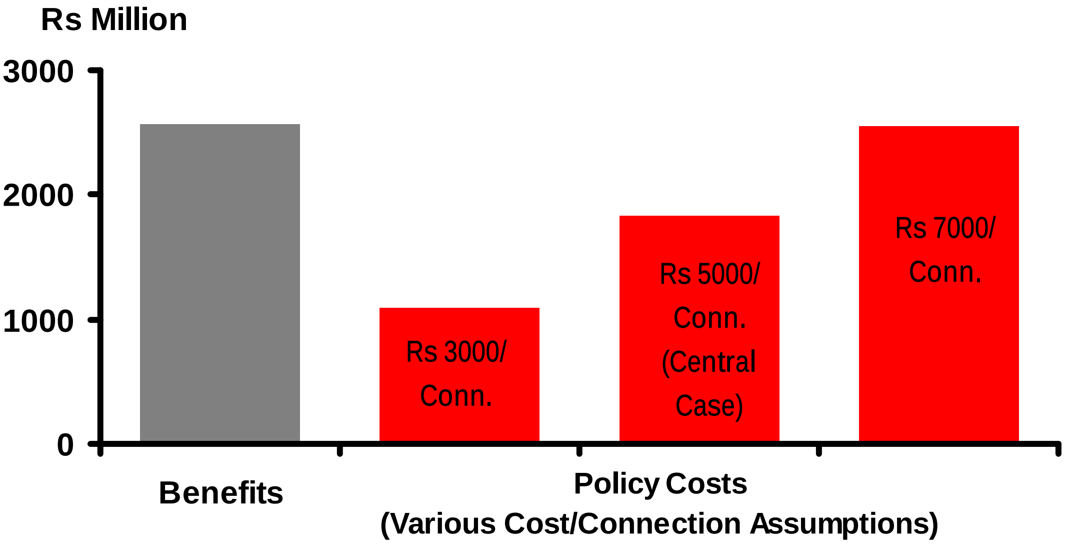


**Figure 7.24: Sensitivity of Benefit-Cost Analysis to Costs**

Thus, programs resulting in reduction of pipeline losses are cost-effective up to a cost of about Rs 7000/connection.

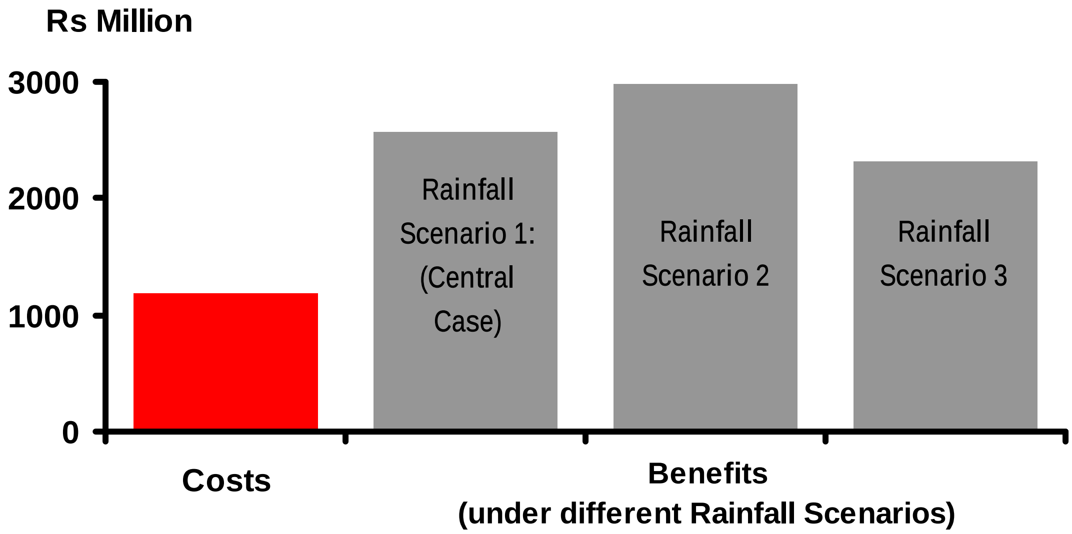
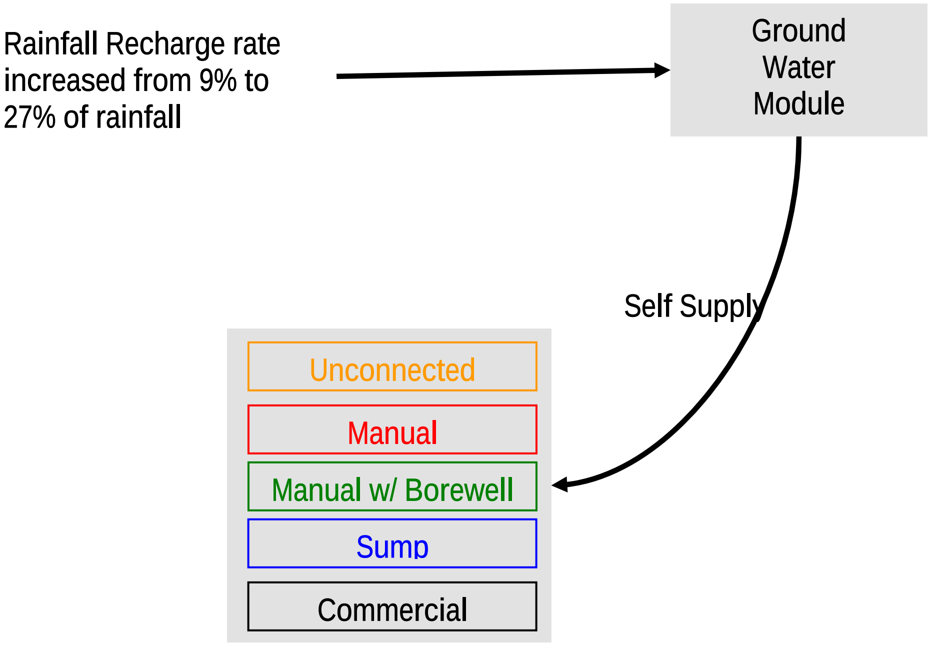


**Figure 7.25: Sensitivity to Rainfall Scenarios: Efficiency Improvement**

The net benefits varied only slightly under different rainfall scenarios indicating that the results are fairly robust to uncertainty in future rainfall (here the cost of fixing leaks was assumed to be Rs 5000/connection)

## 7.6 Rainwater Harvesting

The third policy tested was one where the consumers, enterprises, communities and the utility pursue rainwater harvesting aggressively to manage recharge into the Chennai aquifer. Under this policy, households and enterprises capture rooftop and yard rainwater and direct it into an infiltration pit or abandoned well in their property. It was assumed that with these management efforts recharge rates would increase from 9 percent to 27 percent of rainfall. Figure 7.26 shows the parameter changes that were made to the model



| Module in which parameter is changed | Parameter Changed | Baseline | Supply Augmentation |
|---|---|---|---|
| **Groundwater Module** | Recharge within city | 9% of rainfall | 27% of rainfall |

**Figure 7.26: Model Parameter Changes under Rainwater Harvesting Scenario**

The reservoir storage and total available utility supply under Rainwater Harvesting are the same as the Baseline scenario. Therefore, they are not presented.

### *7.6.1 Utility Module*

Figure 7.27 shows the quantity of water consumed under the Rainwater Harvesting scenario versus the Baseline scenario.

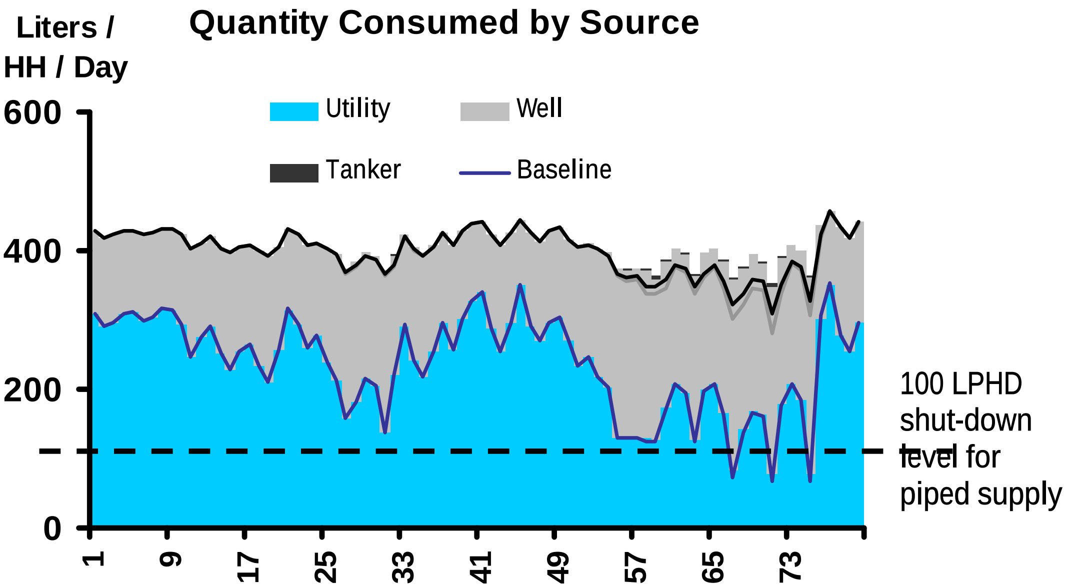


**Figure 7.27: Quantity consumed in the Rainwater Harvesting scenario**

In this scenario, the quantity of water is available via utility supply is the same as the Baseline scenario. Not surprisingly, the Rainwater Harvesting policy cannot prevent a shut-down of the piped supply system. The major gains occur in the quantity consumed via self-supply.

### *7.6.2 Groundwater Module*

Figure 7.28 shows the fraction of dry wells in Chennai with Rainwater Harvesting.

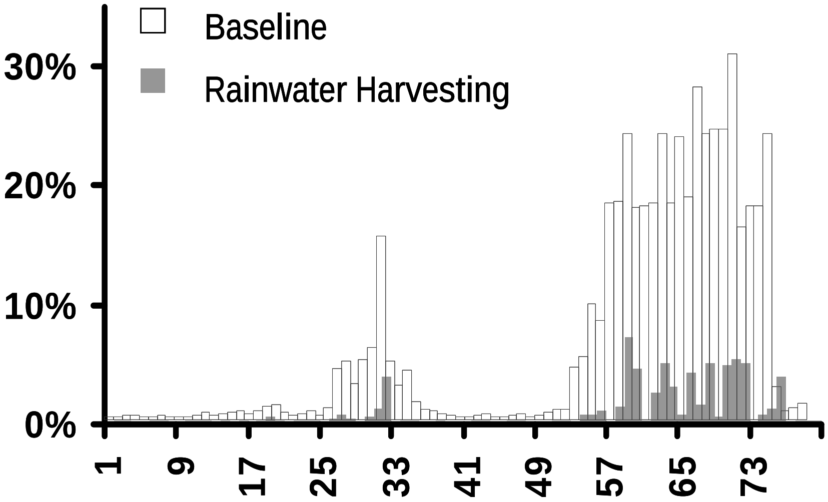


**Figure 7.28: Percent of wells dry in the Rainwater Harvesting scenario**

As would be expected, groundwater levels are shallower under the Rainwater Harvesting scenario due to improved recharge. At the peak of the drought, fewer than 10 percent of the wells go dry versus 30 percent in the Baseline scenario.

### *7.6.3 Tanker Market Module*

Figure 7.29 shows the size of the residential tanker market generated in Chennai.

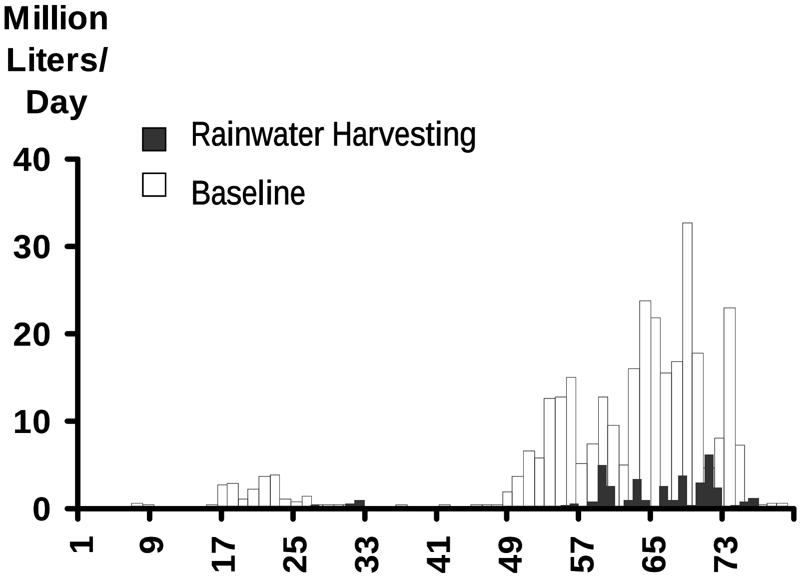


**Figure 7.29: Residential tanker market in the Rainwater Harvesting scenario**

As groundwater levels drop and wells dry up, consumers become tanker dependent during the drought just as in the Baseline scenario. However, because far fewer wells go dry in the Rainwater Harvesting case, the total tanker market is also much smaller.

### *7.6.4 Consumer Module*

The consumer surplus under the Rainwater Harvesting scenario relative to the Baseline is shown in Figure 7.30.

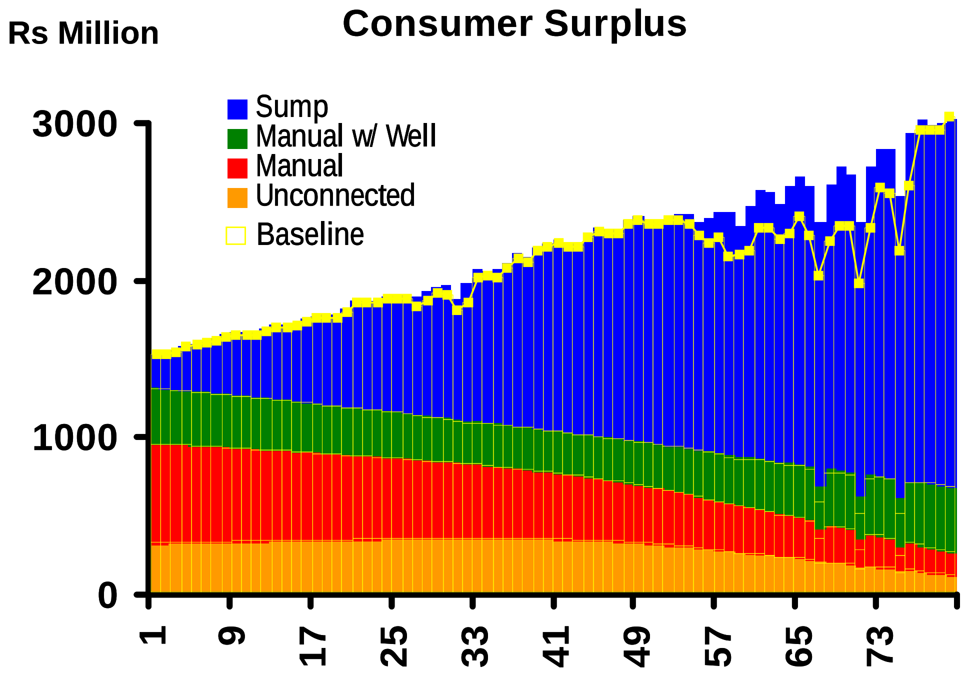


**Figure 7.30:** **Consumer Surplus under Rainwater Harvesting scenario**

The difference in consumer surplus with the Rainwater Harvesting policy is shown in Figure 7.31.

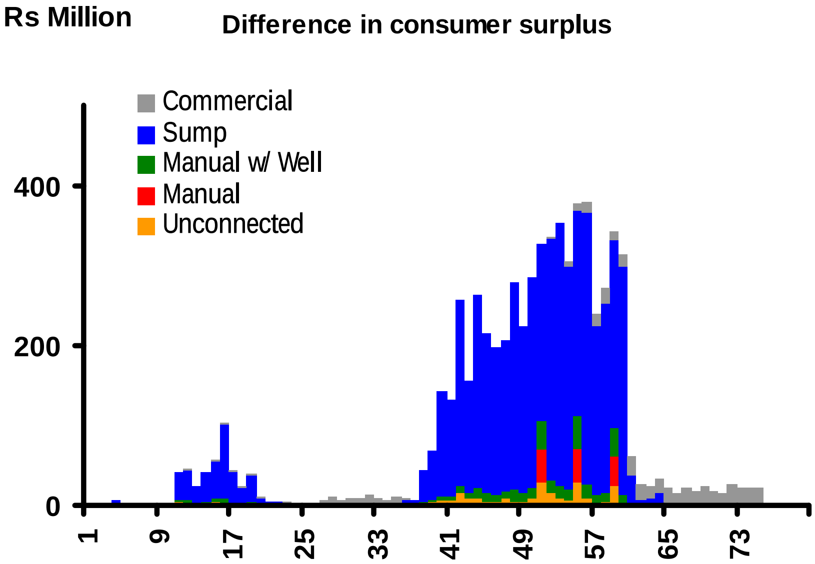


**Figure 7.31: Difference in Consumer Surplus under Rainwater Harvesting**

The benefits of Rainwater Harvesting are manifested during droughts when improved recharge prevents the aquifer from being drawn down. Availability of groundwater allows consumers to purchase less water from tankers. The consumer surplus benefits of Rainwater Harvesting accrue from avoided purchase of tanker water. The Gross benefits from Rainwater Harvesting are almost 5,300 million[91].

### *7.6.5 Cost of the Rainwater Harvesting Policy*

Rainwater Harvesting fixtures are assumed to have a life-span of 25 years. The cost of rainwater harvesting was assumed to be Rs 5,000 per household and medium commercial establishment in Chennai[92]. Each water-intensive commercial establishment was additionally assumed to invest Rs 100,000. These costs were prorated to the 18-year forecast period. The total cost of rainwater harvesting cost works out to Rs 3,480 million. The total costs and benefits from Rainwater Harvesting are shown in Figure 7.32.

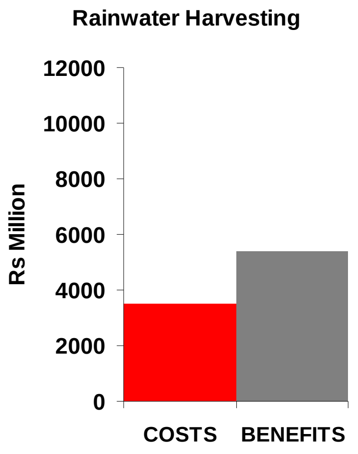


**Figure 7.32: Benefits and costs with Rainwater Harvesting**

At a 27% recharge rate, Rainwater Harvesting generates net benefits of Rs 1910 million over the 18-year forecast period.

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[91] These gains can be verified by a simple back-of-the-envelope calculation as follows. If households enjoy a modest gain in consumer surplus of Rs 2.75/day (using 500 liters of well water instead of 250 liters of tanker water) during drought periods by avoiding tanker purchases; when multiplied by about 1.25 million households this generates a consumer surplus gain of 1125 million/year for each of 4 drought years over the forecast time-frame or about Rs 5,000 million. Benefits to commercial consumers are over and above this.

[92] http://www.rainwaterharvesting.org/Urban/Costs.htm

Figure 7.33 shows the benefits under the Rainwater Harvesting scenario by consumer category as a fraction of monthly household income.

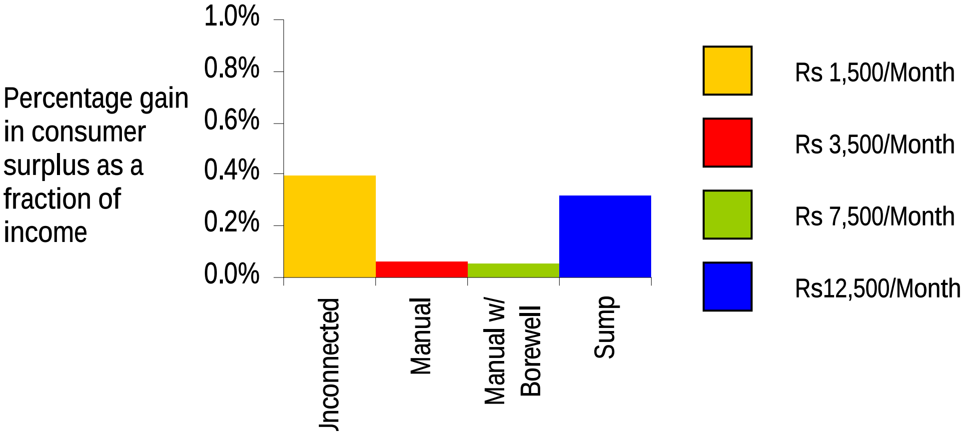

**Figure 7.33: Equity Analysis of Rainwater Harvesting policy**

### *7.6.6 Sensitivity Analysis*

The main parameters in this policy simulation, besides rainfall, is the magnitude of recharge that can be generated from rainwater harvesting. We have arbitrarily assumed that the recharge rate can be boosted from 9% to 27% if simple rooftop rainwater harvesting efforts are properly implemented. This is a completely arbitrary assumption which can ultimately only be tested by long-term studies of recharge in the Chennai urban area. Figure 7.34 shows the sensitivity of the benefit-costs analysis to this model parameter.

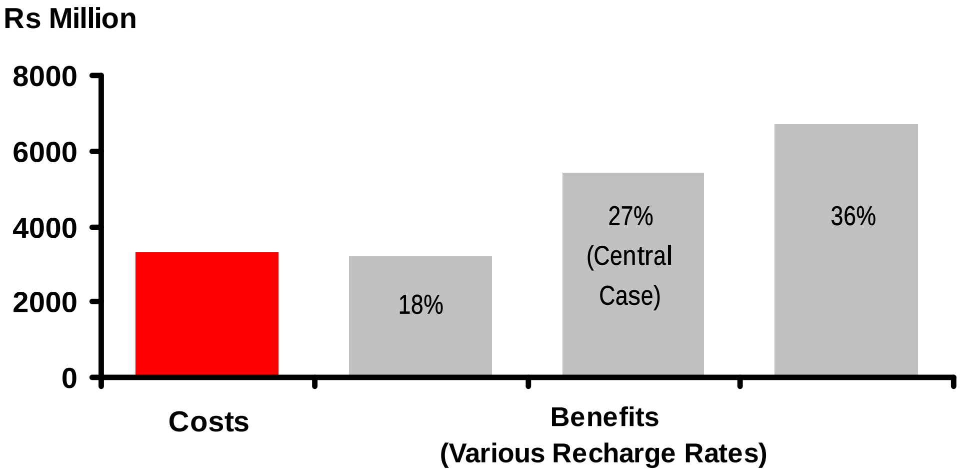

**Figure 7.34: Sensitivity to Recharge Rate: Rainwater Harvesting**

Thus, the benefits of rainwater harvesting are fairly sensitive to recharge rate increases from the policy. If total recharge rate is doubled, the Rainwater Harvesting policy just breaks even. However, if the recharge rate achieved is closer the one quarter of rainfall estimated suggested by some NGOs, then the benefits would be significant.

Figure 7.35 shows the sensitivity of the benefit-costs analysis to cost of rainwater harvesting. The cost is estimated as an average per household cost to generate 25% recharge rate. The policy cost does not need to be distributed equally amongst households. For instance, low income households may invest nothing at all, while neighborhood or communities may invest in improved storm water drainage collectively. The costs here are merely average per household costs.

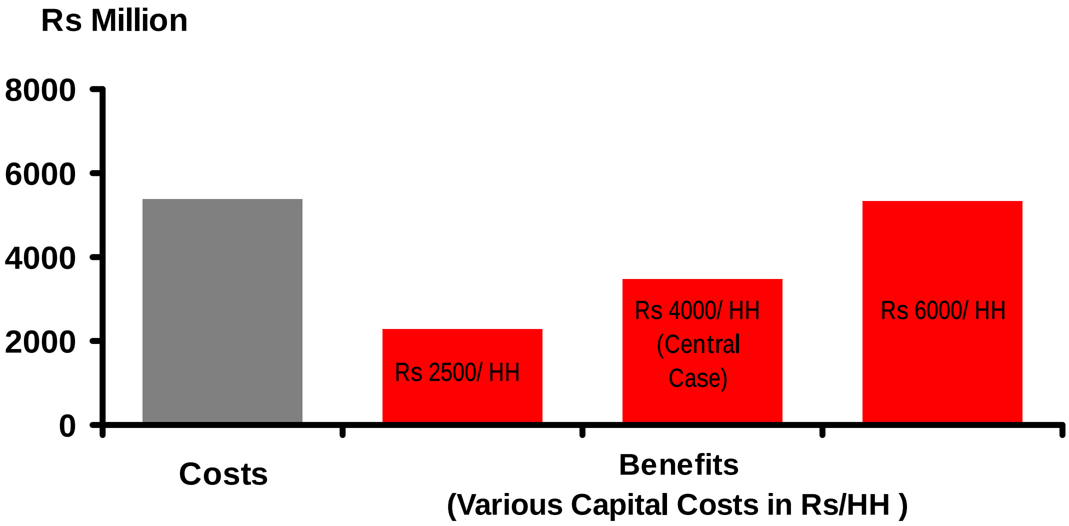

**Figure 7.35: Sensitivity to Policy Costs: Rainwater Harvesting**

From the figure above we see that Rainwater Harvesting would not be cost-effective above an average investment cost of Rs 6000/household.

Figure 7.36 shows how the benefit-cost analyses changes for the three rainfall scenarios, presented in Chapter 6, assuming a 27% recharge rate in each case.

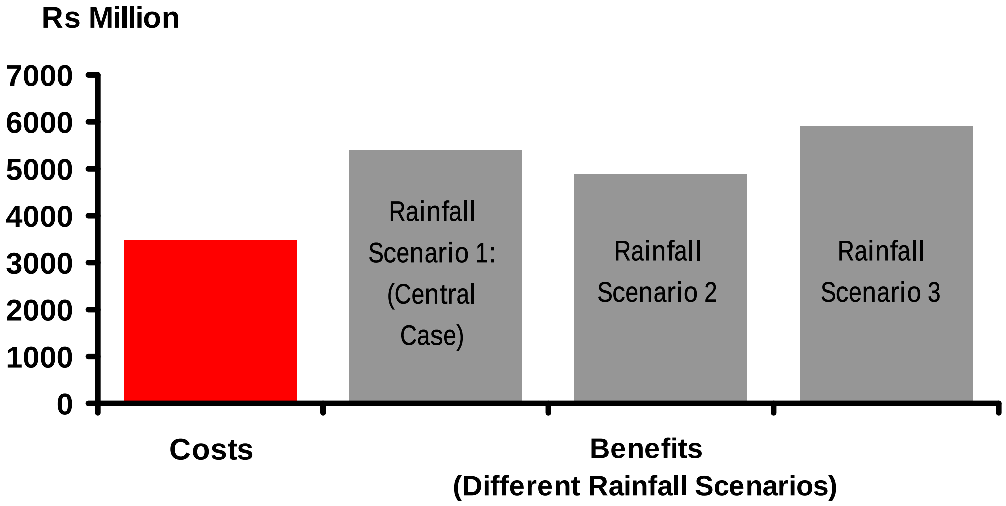

**Figure 7.36: Sensitivity of Rainfall Scenarios: Rainwater Harvesting**

Figure 7.36 indicates that Rainwater Harvesting would yield significant net benefits for all three rainfall scenarios presented in Chapter 6.

## 7.7 Combination of Rainwater Harvesting and Efficiency Improvement

Earlier in the Chapter, we argued that none of the three policies evaluated perfectly satisfies all the criteria. Rainwater Harvesting and Efficiency Improvement are each cost-effective. However, while Rainwater Harvesting maximizes social welfare it does not improve utility profits. In this section we present the results of a combination Rainwater Harvesting and Efficiency Improvement. The model parameter changes were simply a combination of the individual policies shown in Figure 7.37.

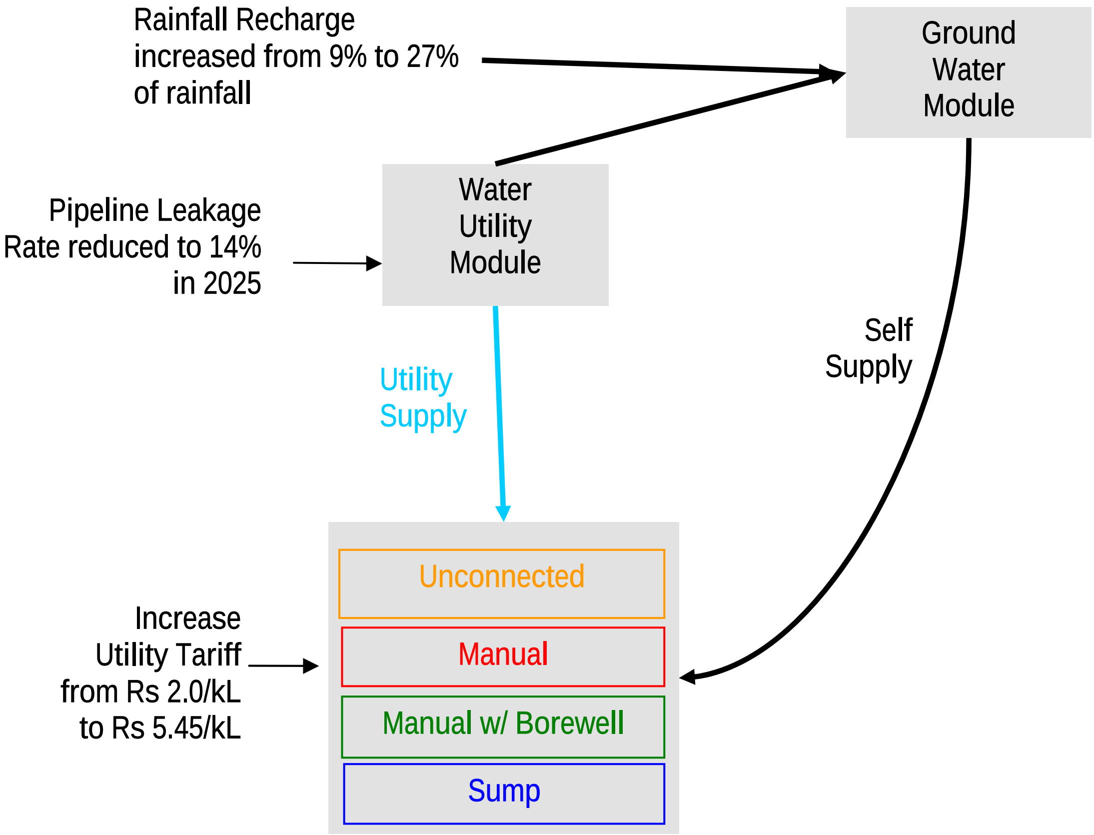

**Figure 7.37: Model parameter changes: Rainwater Harvesting +Efficiency policy**

| **Module in which parameter is changed** | **Parameter Changed** | **Baseline** | **(Combined: Rainwater Harvesting + Efficiency Improvement)** |
|---|---|---|---|
| **Utility Module** | Pipeline Losses | 28% in 2005 | 14% in 2025 |
| **Consumer Module** | Price of utility supply | Rs 2.0/kL | Rs 5.45/kL |
| **Groundwater Module** | Recharge within city | 9% of rainfall | 27% of rainfall |

The reservoir storage and total available utility supply are the same as the Baseline scenario. So these module outputs are not presented.

### *7.7.1 Utility Module*

Under the Rainwater Harvesting + Efficiency Improvement scenario, more water is available to consumers via utility piped supply because of the lower leakage. However, at the same time consumers demand less water on account of higher tariffs. More water is also available via consumers well resulting from rainwater harvesting. Figure 7.38 shows the quantity of water consumed under the Rainwater Harvesting + Efficiency Improvement Policy scenario. The policy allows the piped supply system to remain operational in all periods.

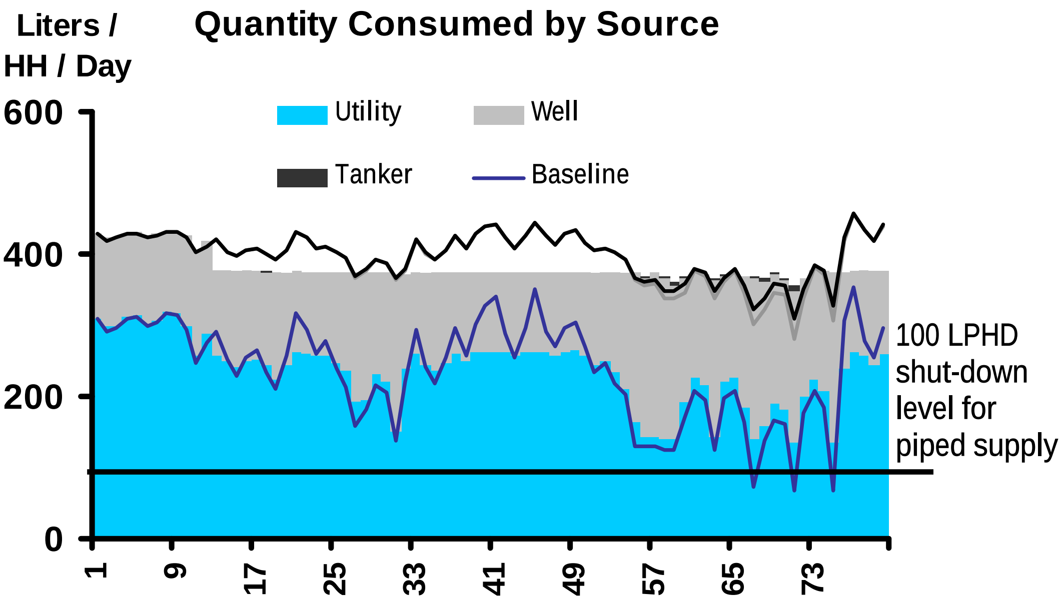

Figure 7.38: Quantity consumed in the Combination Scenario

### *7.7.2 Groundwater Module*

Figure 7.39 shows the fraction of dry wells in Chennai under the Rainwater Harvesting + Efficiency Improvement scenario.

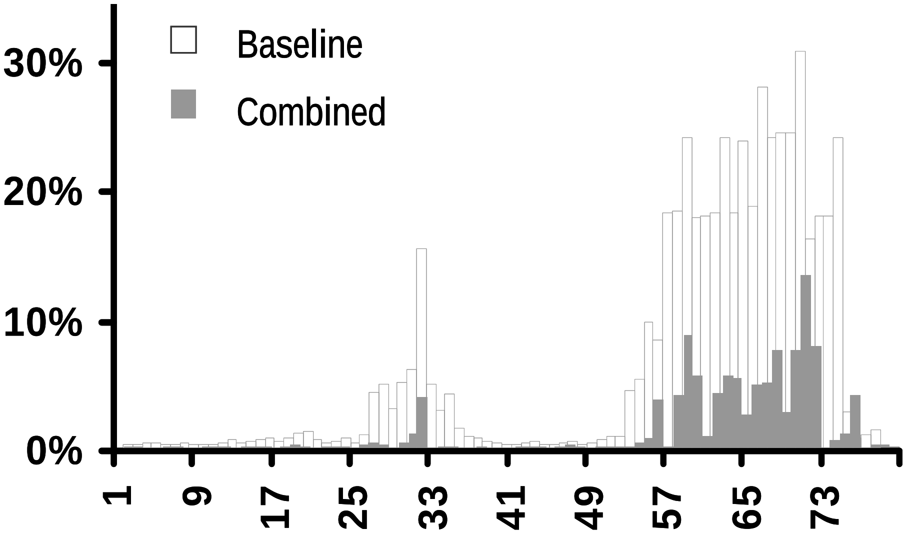

Figure 7.39: Percent of wells dry in the Combination Scenario

About 10-15 percent of the wells go dry with the Combined Policy scenario versus 30 percent in the Baseline scenario. This aquifer gets drawn down more than the pure Rainwater Harvesting case because of the lower recharge.

### *7.7.3 Tanker Market Module*

Figure 7.40 shows the size of the residential tanker market generated in Chennai.

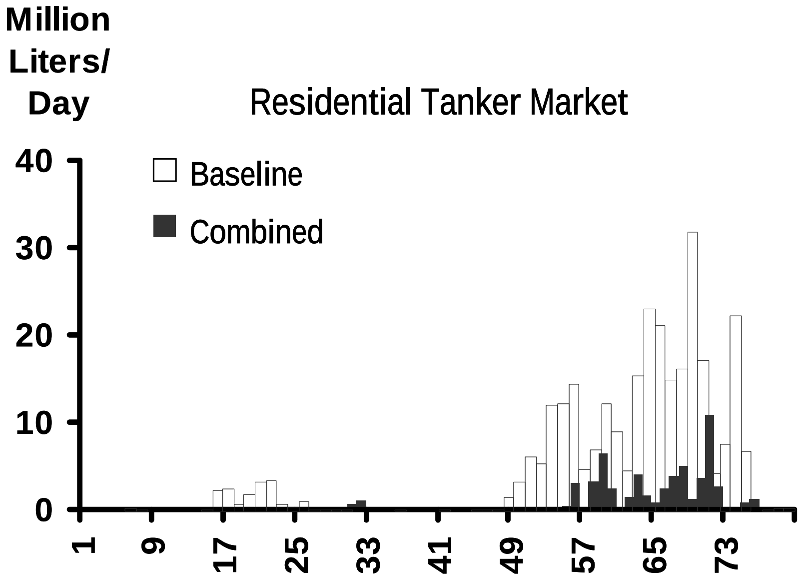

**Figure 7.40: Residential tanker market in the Combination Scenario**

### *7.7.4 Consumer Module*

The difference in consumer surplus with both Rainwater Harvesting and Efficiency Improvement is shown in Figure 7.41. Under the combination of Rainwater Harvesting and Efficiency Improvement, consumers gain from both improved aquifer conditions as well as lower pipeline losses during drought periods. However Sump consumers face small losses in consumer surplus in other periods because of the higher tariffs.

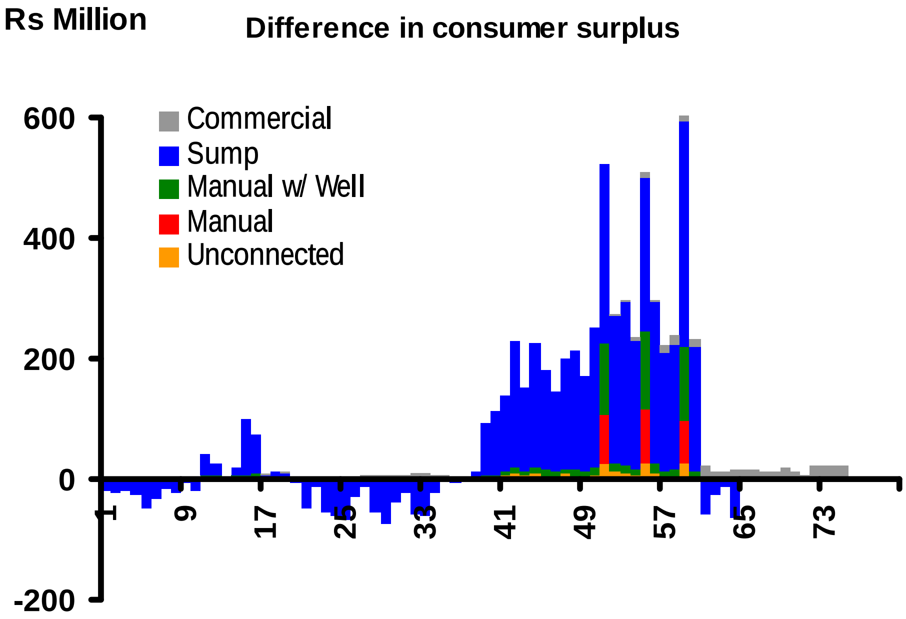

Figure 7.41: Difference in Consumer Surplus under the Combination Scenario

Additionally, the Combination of Efficiency Improvement and Rainwater Harvesting has the added benefit of yielding significant utility revenues from the tariff increase (from Rs 2/kL to Rs 5.45/kL). The incremental revenue stream generated is shown in Figure 7.42.

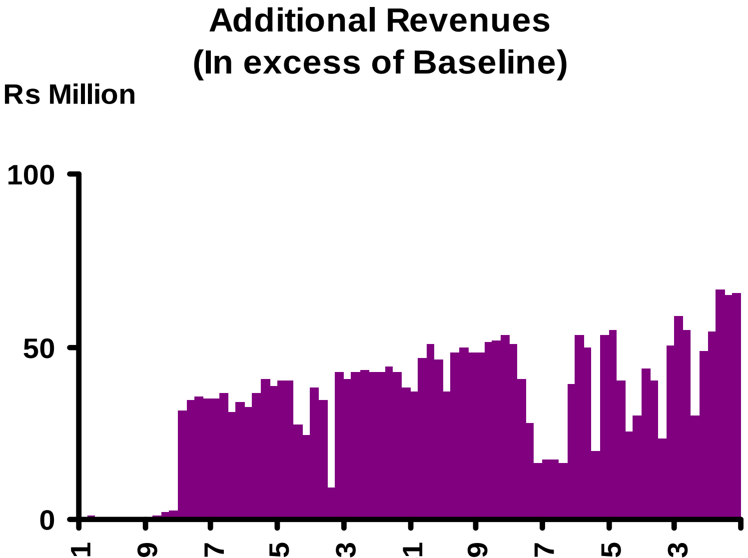

Figure 7.42: Revenues generated by Combination policy

### *7.7.5 Policy Costs*

Policy costs were assumed to be simply the sum of the costs of each. When the policies were combined we found that some of the gains in consumer surplus from rainwater harvesting disappeared as pipeline recharge was lower. However, utility revenue increased significantly, so that net benefits improved. Figure 7.43 shows the benefits and costs under the combination of the Rainwater Harvesting and Efficiency Improvement policies.

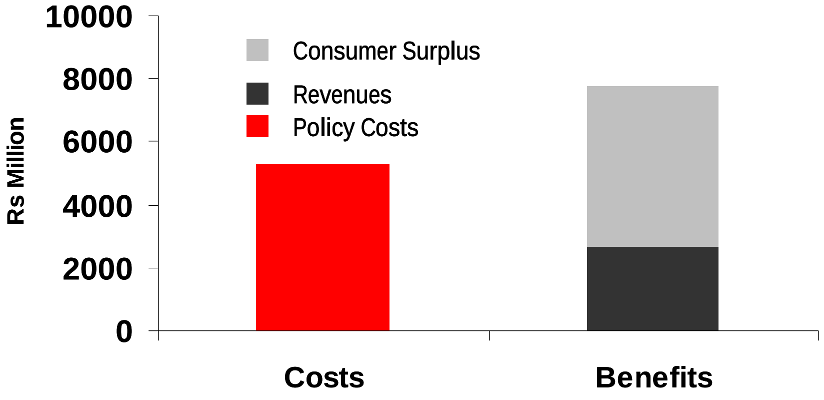

**Figure 7.43: Benefit Cost Analysis of Combination Policy**

The combined policy satisfies all criteria. It generates the highest net benefits of all policies at Rs 2,500 million. The net benefits are only slightly lower than the sum of the two policies separately, but higher than each policy implemented independently. The piped supply system does not shut down so the reliability is 100%. Moreover the policy generates a significant revenue stream of close to Rs 2,700 million for the water utility. The policy reduces consumer surplus in wet years and increases consumer surplus in dry years; so the welfare variance (ratio of consumer surplus per household in driest and wettest years) of the policy is 97 percent, much higher than the each of the three policies implemented separately. Finally, the benefits to the poorest consumer category are also the highest compared to the other policies.

The combination of Rainwater Harvesting and Efficiency Improvement Policy does extremely well by all criteria. However, this still does not guarantee that the policy is socially optimal. One of the problems with the framework is that the tariff policy was assumed to be set exogenously. Specifically, the maximum tariff the utility was allowed to charge was limited to Rs 5.45/kL. This was done to ensure that utility supply would remain cheaper than self-supply (the short-run marginal cost of extraction from private wells), so the tiered supply curve did not “flip”.

In setting the tariff exogenously, we did not consider the utility’s cost of supply. Ideally, the tariff should be set at a rate *at least* equal to the average cost of supply. While the average cost of supply to Metrowater is not known with certainty, it has been estimated to be about Rs 10-15/kL[93]. Thus, even under the Efficiency Improvement policy discussed above, the tariff rate of Rs 5.45/kL entails a massive subsidy to the consumer. It does not allow the utility to fully recover the cost of supply. This results in two types of problems. Firstly, the tariff does not even meet the average cost of supply, let alone the long-run marginal cost. This results in efficiency losses (economists refer to them as deadweight losses). Secondly, as the utility offers water at a highly subsidized rate demand will always outstrip supply. In fact, in part of the low tariffs the utility has been unable to expand supply to the rapidly growing peri-urban suburbs.

In the next section, we explore a new innovative policy approach that combines Efficiency Improvement with a significant tariff increase and Rainwater Harvesting.

### 7.8 Dual Quality

In this section, we examine the situation where the utility raises tariffs significantly.
Such a policy would involve a fundamental change to consumer behavior. Centralized utility supply would no longer be the least-cost source of supply. This policy implementation and outcomes are as follows.

1. The utility meters and charges consumers with sumps a significantly higher tariffs of Rs 10/kL. Consumers with handpumps continue to be charged on a fixed rate basis.
2. Utility supply is no longer the cheapest source of supply. The tiered supply curve “flips” so that self-supply is cheaper. A large fraction of consumers switch to private wells for their non-potable needs.
3. Because demand for piped supply, within Chennai is reduced significantly, the utility now has water to supply suburbs along the IT corridor. This excess water is assumed to be sold at an average of Rs 10/kL.

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[93] Mathur and Thakur, 2003

4. By significantly reducing demand and enhancing supply uniformity, the system can begin a transition to a 24-hour continuous supply in all served areas.
5. The utility aggressively pursues rainwater harvesting policies to manage urban groundwater so enough water is available in wells.

Although this policy is simply a combination of Efficiency Improvement and Rainwater Harvesting, using higher tariffs, because of the dramatically different outcomes, we will refer to this policy as the "Dual-Quality" policy. The policy is referred to as "Dual Quality" because it involves combining low-cost, low quality decentralized supply with a high-cost, high-quality, full-pressure "24*7 supply". A prototype for a typical apartment complex in Chennai is shown in Figure 7.44.

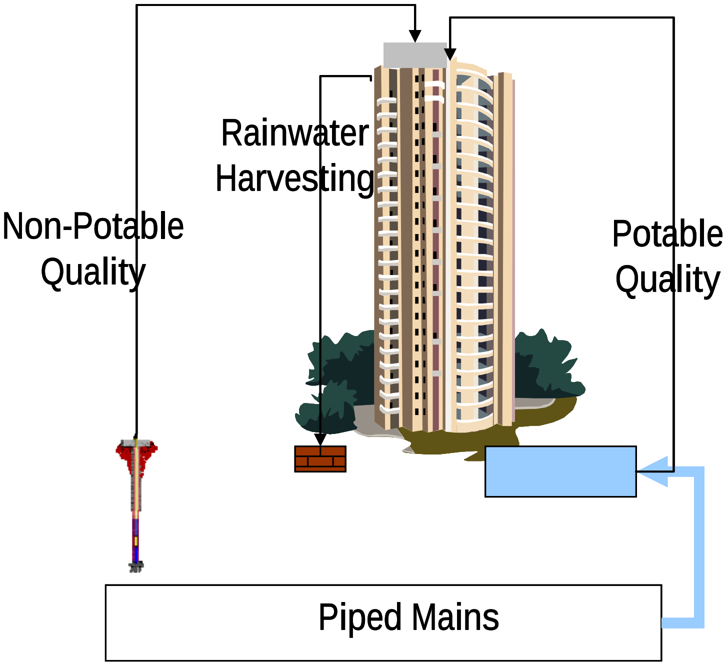
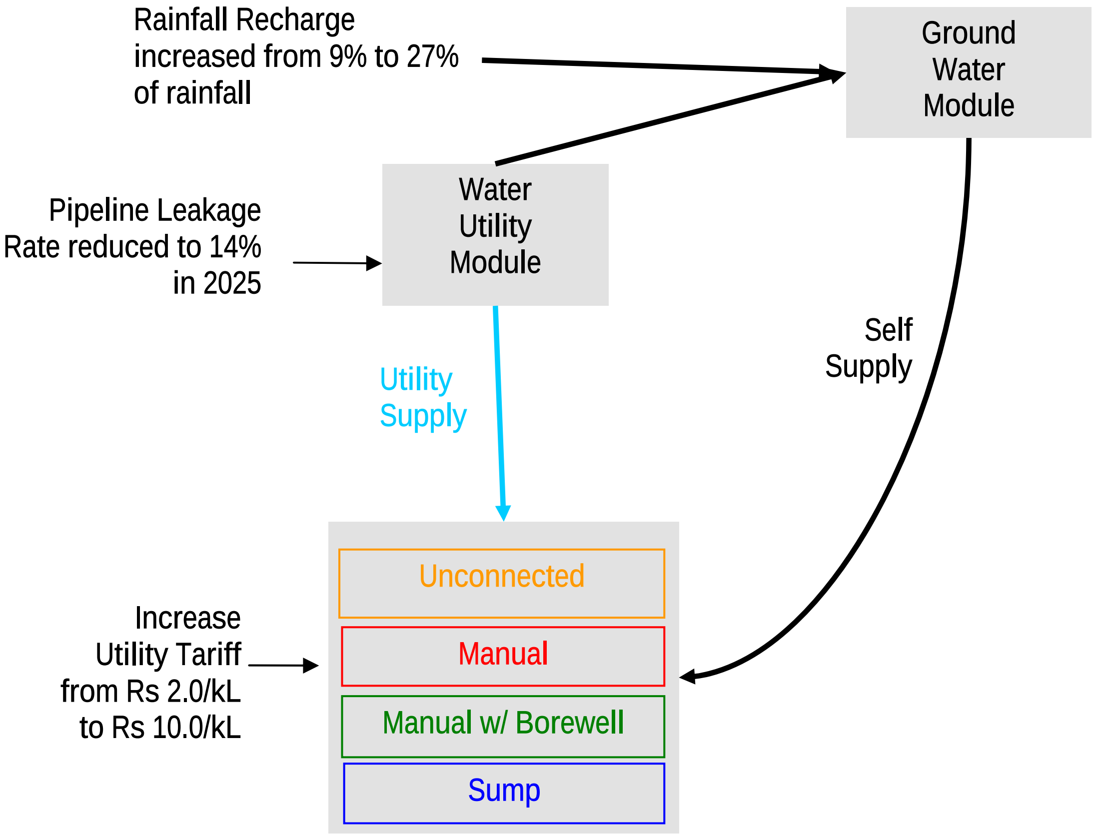


**Figure 7.44: Model building with dual-quality**

The following parameter changes were made to the model to test the effects of pursuing a Dual-Quality policy. The costs of the policy are assumed to be the sum of the costs of Rainwater Harvesting and Efficiency Improvement plus costs of plumbing retrofits, if any. The parameter changes made to the model are shown in Figure 7.45.



| **Module in which parameter is changed** | **Parameter Changed** | **Baseline** | **Dual-Quality** |
|---|---|---|---|
| **Utility Module** | Pipeline Losses | 28% in 2005 | 14% in 2025 |
| **Consumer Module** | Price of utility supply | Rs 2.00/kL | Rs 10.00/kL |
| **Groundwater Module** | Recharge within city | 9% of rainfall | 27% of rainfall |

**Figure 7.45: Model parameter changes with Dual-Quality solution**

The reservoir storage and total available utility supply are exactly the same as the Baseline Scenario. Therefore, they are not presented.

### *7.8.1 Utility Module*

Under the "Dual-Quality" scenario the primary change occurs in the consumer module. We assume that significantly increasing the utility tariff will "flips" the tiered supply curve. The supply curve to sump consumers changes as shown in Figure 7.46.

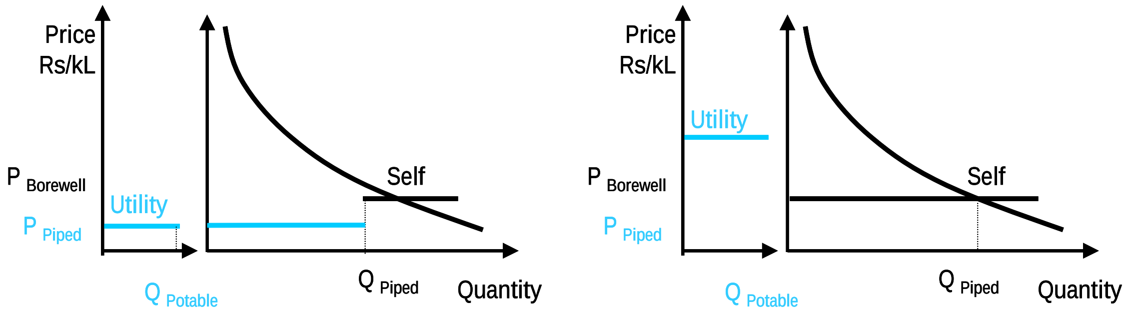


**Figure 7.46: Tiered supply curve under the Dual-Quality scenario**

From the figure above we see utility supply is no longer the cheapest source of water. Instead, consumers switch to self-supply for non-potable needs. The total quantity consumed is shown in the Figure 7.47.

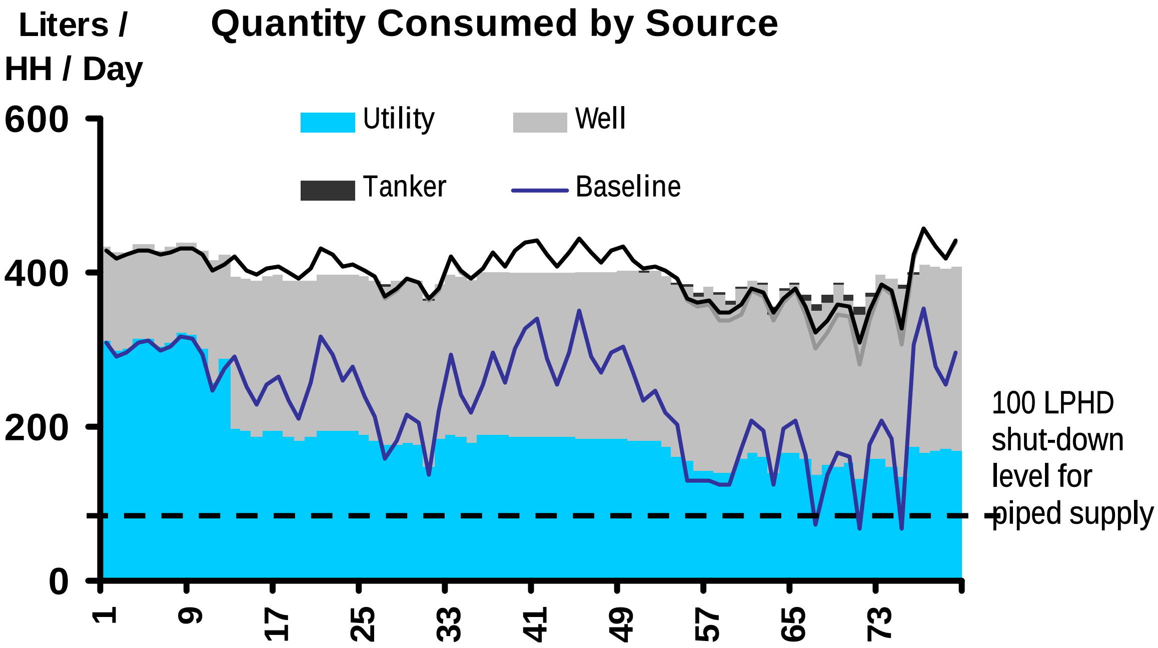


**Figure 7.47: Quantity consumed by under the Dual-Quality scenario**

Under the Dual-Quality policy, the consumption of piped supply is considerably reduced. The consumption of groundwater based self-supply is increased. An important feature of the Dual-Quality solution is that the quantity of water delivered via the piped supply system is much more uniform across periods.

### *7.8.2 Groundwater Module*

Figure 7.48 shows the fraction of dry wells under the Dual-Quality scenario.

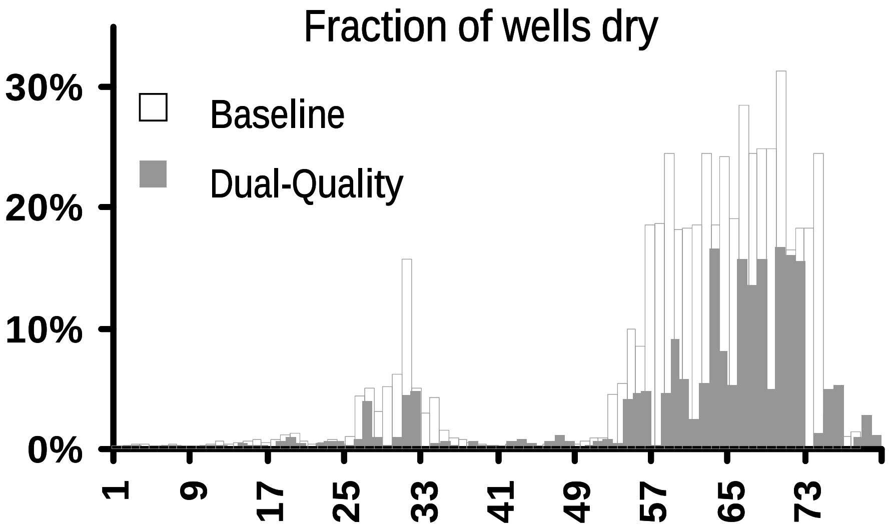


**Figure 7.48: Fraction of wells dry under the Dual-Quality scenario**

Groundwater levels are shallower under the Dual-Quality scenario compared to the Baseline Scenario but worse than the Rainwater Harvesting or Combined Policy scenarios. This effect is entirely due to the increased extraction, since in this scenario self-supply via consumers' wells is the least-cost source available to consumers.

### *7.8.3 Tanker Market Module*

Figure 7.49 shows the size of the residential tanker market generated in Chennai under the Dual_Quality scenario.

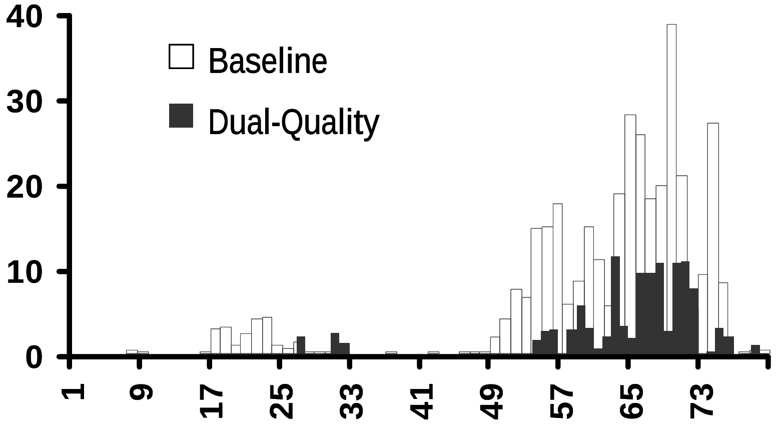


**Figure 7.49: Residential tanker market under the Dual-Quality scenario**

As groundwater levels drop, and wells dry up consumers become tanker dependent during the drought. However, because far fewer wells go dry (because of the aggressive recharge management), the total tanker market is also much smaller.

### *7.8.4 Consumer Module*

The consumer surplus relative to the Baseline is shown in Figure 7.50.

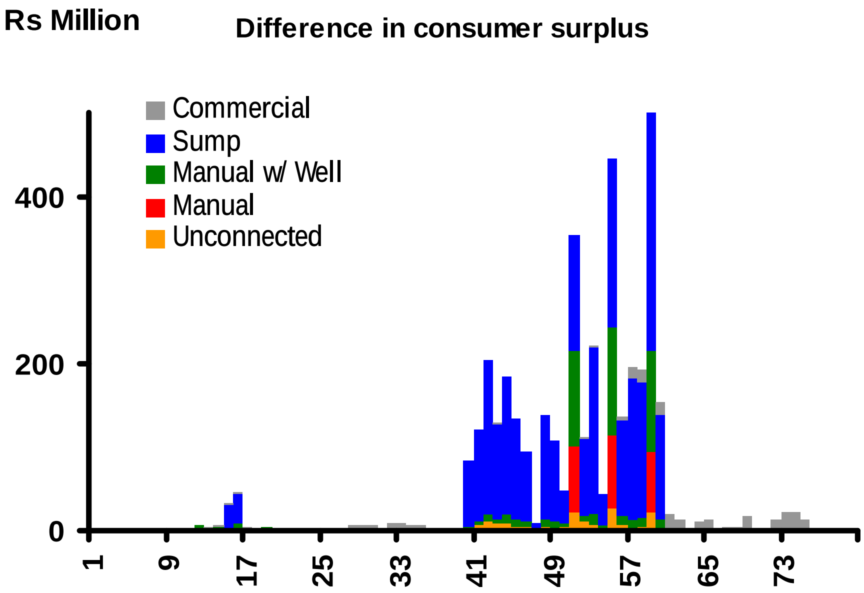


**Figure 7.50: Difference in consumer surplus under the Dual-Quality scenario**

The total costs and benefits from the dual-quality scenario are shown in Figure 7.51.

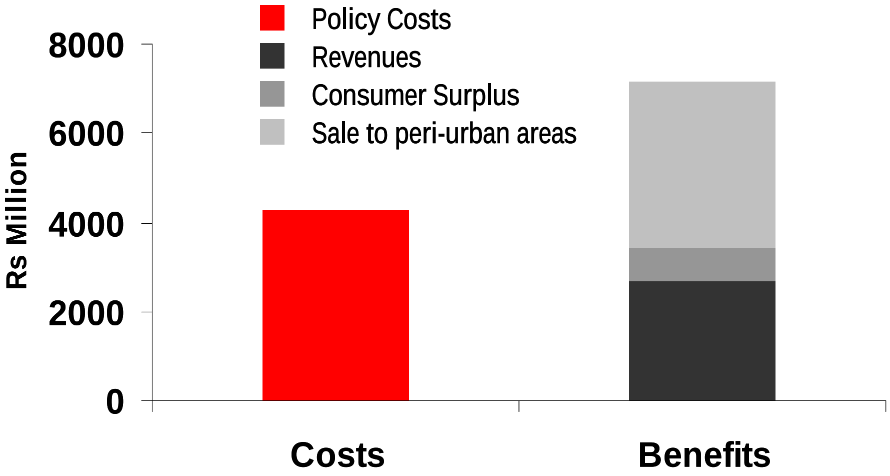


**Figure 7.51: Benefit-cost analysis of the Dual-Quality policy**

The Dual-Quality solution has net benefits of almost Rs 2,820 million over the forecast period. However, in this case, the benefits derive from three sources: consumer surplus gains to consumers and revenues to the water utility. In addition we assume that because the quantity of water delivered within Chennai city is significantly reduced, water is now available for sale in peri-urban areas and commercial establishments at an average of Rs 10/kL.

Figure 7.52 shows the improvement in consumer surplus under the Dual-Quality policy across the different consumer categories, as a fraction of monthly household income.

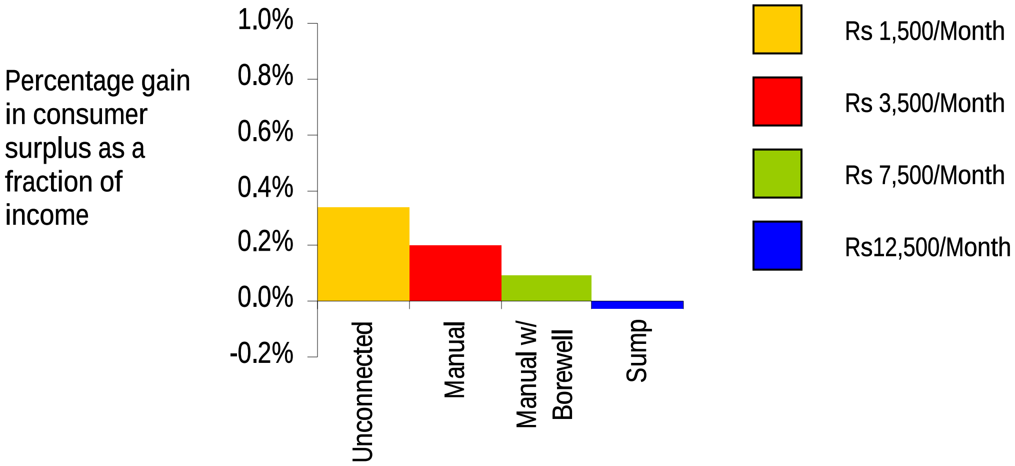


**Figure 7.52: Equity under Dual Quality Policy**

The Dual-Quality is the most progressive of the policies suggested so far, providing maximum benefits to the two poorest consumer categories. Thus, the Dual-Quality solution fares well in terms of all criteria set out earlier

- It has large positive net-benefits and a benefit-cost ratio greater than 1.
- It yields benefits to all consumer classes
- It prevents a shut-down of the piped supply system
- It generates a revenue stream for the utility

Finally, it is the only policy that makes it possible to expand water supply to peri-urban areas.

### *7.8.5 Discussion*

By allowing the tiered-supply curve to "flip", the Dual-Quality solution effectively changed the premise that centralized piped water supply was the cheapest source of supply. In Figure 7.53, we show once again the cost of water to the consumer from different sources.

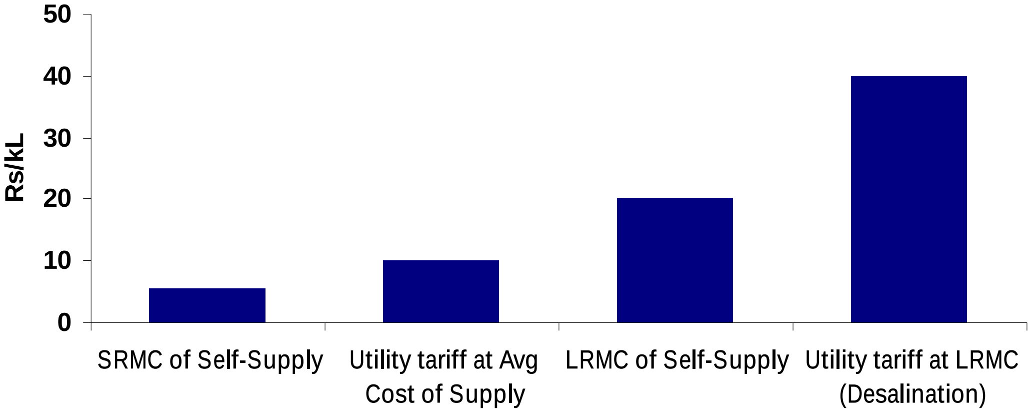


**Figure 7.53: Cost of supply to consumers**

From Figure 7.53 we may conclude the tariff the utility must charge to achieve full cost recovery is greater than the short-run marginal cost of self-supply from wells but less than the long-run marginal cost of self-supply from wells. In simple words, if consumers already have wells, raising tariffs to achieve full-cost recovery would result in a Dual-Quality situation. However, if consumers do not already have wells, they will not invest in them. In Chennai several factors make the Dual-Quality solution optimal.

1) Over 70 percent of the consumers already had access to private wells and therefore the short-run marginal cost and not the long-run marginal cost of extracting water from wells was relevant for most consumers.
2) Consumers already have the ability and infrastructure to manage multiple qualities of water as indicated by the household survey data presented in Appendix F.
3) The long-run marginal cost of utility supply is desalination. Desalination costs many times more expensive that the even the long-run cost of extraction from private wells. This will make it difficult for the utility to charge consumers a rate equal to the long-run marginal cost of supply to the consumer. Even if consumers lack private wells, they will invest in them if tariffs are raised beyond Rs 20/kL.

## 7.9 Problems with analytic method and interpreting the results

The model results are contingent on the certain structural choices made in the model. In this final section, we illuminate some limitations of the modeling process that might influence the model results.

### *7.9.1 Policy benefits to consumers are underestimated*

The model underestimates the benefits from all policies for both wealthy and poor consumers. For wealthier consumers, the model cannot account for household income increases and associated increases in willingness-to-pay beyond Rs 10,000/month. This occurs because of the way the demand function is defined. Specifically, income is a discrete and not a continuous variable in the demand function. Only two income categories, low income (I=0 for Monthly Income < Rs 10,000/month) and high-income (I=1 for Monthly Income >= Rs 10,000/month) were specified in estimating the demand function. Because of this artifact in the demand function, we cannot account for consumers' increased willingness to pay for water as incomes of wealthier households rise much beyond Rs 10,000. Thus, consumers' willingness and ability to buy tanker water and consumer surplus gains from avoided purchase of tanker water is underestimated. To overcome this limitation would require a demand function which used a continuous income/wealth variable and not a discrete income category variable. This would allow us to capture shifts in the demand function (i.e., willingness-to-pay function) as incomes rise over time. Unfortunately, this would further require us to have collected discrete income data in the household survey data set, something we were unable to achieve in our surveys. In fact households showed considerable reluctance in choosing an income category, let alone actual providing actual income data.

Benefits to poorer consumers are underestimated because consumer surplus is estimated by integrating the willingness-to-pay function, which in turn is bounded by household income i.e., consumers can at most give up everything they have to avoid dying of thirst. Consequently, benefit-cost analyses tend to underestimate the "suffering" caused by reductions in water availability to poor households.

### *7.9.2 Willingness –to-pay for quality not considered*

The model made some fairly simplistic assumptions about consumers' preferences regarding water quality. Only two qualities were allowed for, and it was assumed that consumers would not be willing to pay for higher quality water for non-potable needs. Moreover, all groundwater was assumed to be "good enough" for bathing and clothes washing. This may not always be the case, particularly if groundwater is salty or smells bad, as is the case of some coastal suburbs. On a similar note, the groundwater model also did not model salinity or salt-water intrusion. There may be several ways to overcome this limitation. One option might be to incorporate salinity modeling in the groundwater model, as well as include a quality variable in the consumer demand function.

### *7.9.3 Possibility of charging for groundwater ignored*

The model implicitly assumes that groundwater cannot be independently metered and taxed. In this research, we did not consider monitoring and metering groundwater extraction as a viable option, assuming it would be difficult to implement institutionally as well as legally under the current open-access groundwater law. Accordingly, the cost of groundwater was limited to extraction costs. However, if it were possible to charge for groundwater, the analysis would have to be reviewed.

## 7.10 Chapter Summary

In this chapter we examined each of three policy solutions to solve Chennai’s water problem identified in Chapters 1 and 2 of this dissertation. Each policy solution was found to be lacking in one or more of the criteria set out. After examining the pros and cons of each solution we concluded that an alternative solution, a Dual-Quality policy would be more appropriate.

# 8 Chapter Eight – Summary and Conclusions

In this concluding chapter, we summarize the findings and comment on the broader implications of this work. We begin by providing a summary of the contributions in the dissertation. Then the results are presented in the broader context of South Asia. Finally, we offer some future directions that could inform related research work.

## 8.1 Summary of Contributions

### *8.1.1 Theoretical Framework: The integrated water paradigm*

In Chapter 1, we argued that no prior framework could to compare a wide range of policy options including desalination, tariff hikes and rainwater harvesting. We also identified a series of gaps in the literature that make it impossible to compare the policies under current centralized, utility-centric paradigms. The integrated water paradigm framework developed in Chapter 2 of this dissertation addresses many of the gaps in literature laid out in Chapter 1. It makes it possible to integrate multiple agents, qualities, temporal variability and modes of supply into one framework. It offers a means to compare a wide range of policies.

### *8.1.2 Analytic Method: Integrated dynamic model*

In Chapters 3 and 4 we showed how the integrated water paradigm could be implemented as a multi-scale, dynamic, simulation model of the Chennai water supply system. The model allowed us to “replicate” history and develop insights into the nature of the recent drought in Chennai. The model also provided some useful insights into the future prospects for Chennai’s water supply.

The results of the historical run presented in Chapter 5 suggest that the Chennai water supply system was governed by the interactions of availability of water resources and responses of the utility and consumers. The model shows that the Chennai reservoir system is capacity constrained given inflows and current diversions. This results in utility supply being highly intermittent. In periods when utility supply is curtailed, consumers depend on private and community wells. As groundwater extractions increase aquifer water levels fall and consumers’ wells go dry, making it necessary for consumers to purchase tanker water. This results in significant, quantifiable welfare losses. Following the record rains in 2005, the aquifer and reservoir system was completely replenished restoring supply to Chennai.

The historical run offers some additional insights on the tanker market and consumer behavior. The model results show that the combination of intermittency, high utility tariffs, and a shallow aquifer causes large commercial consumers to remain tanker dependent in all periods contributing to a residual tanker market. The model results also indicate that it is rational for consumers to invest in coping mechanisms such as borewells and sumps. Moreover, while borewells provide benefits mainly during droughts, sumps provide benefits primarily in wet years when supply is plentiful.

In Chapter 6, we presented some insights into the future of Chennai's water supply. The surprising result was that the displacement of irrigated agriculture will free up just enough water to meet peri-urban needs as Chennai expands. Basin-scale groundwater extraction remains steady as rising populations, incomes, and commercial/industrial growth take up almost all the water previously used by irrigated agriculture, assuming centralized piped supply is not expanded to peri-urban areas.

### *8.1.3 Policy Solution*

In Chapter 7, we found that none of the three policies recommended in Chapter 1 perfectly satisfies all of the evaluation criteria set out. Supply Augmentation via desalination is not cost-effective. The model results suggest that a combination of Rainwater Harvesting and Efficiency Improvement will best address Chennai's water problems. However, if piped-supply tariffs are raised significantly above the marginal cost of extraction via consumers' wells, then consumers are likely to switch to self-supply from their wells to meet their non-potable needs. Therefore, we recommend a policy that explicitly allows for consumers to rely on high-quality, high-cost, centralized piped supply to satisfy their potable needs and a decentralized low-cost low-quality source (such as private or community wells) combined with aggressive groundwater recharge management to satisfy non-potable needs. We refer to this as the "Dual-Quality" policy.

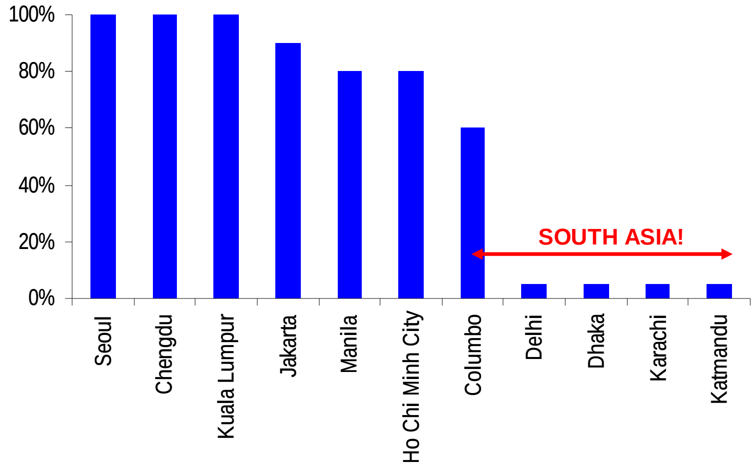
The model results suggest that the Dual-Quality solution has the highest net benefits of all the policies. It is the most progressive in equity terms, sustainable and reliable compared to the other policies. It is the only policy that allows expansion of supply to peri-urban areas given existing limited reservoir infrastructure. Finally, the Dual-Quality solution has the minimum seasonal and inter-annual variability in utility consumption allowing for the possibility that under this policy Chennai may be able to slowly transition to a 24*7 water supply system.

## 8.2 General applicability of results

The analysis presented in this dissertation is specific to Chennai. Even in the Indian context, Chennai is a singularly water-scarce city. It has the lowest per-capita water availability of any large city in India; water availability is also variable across seasons and years. Chennai also has a shallow but productive alluvial aquifer and a very high density of private wells. Furthermore it is a coastal city, so any runoff that is not captured will flow to the sea. Finally, Chennai has not been able to expand reservoir capacity significantly or develop large water resource projects to meet the growing demands of its population. The combination of these makes the Rainwater Harvesting for recharge attractive. Therefore, the question remains as to what extent our results can be extended to other parts of the world. In this section we make the case that South Asia generally faces challenges similar to Chennai that may be addressed using the tools and policies developed in this dissertation.

### *8.2.1 Intermittency in water supply*

South Asian cities have dramatically higher rates of intermittency in utility supply than comparable Asian cities. Figure 8.1 shows the fraction of households with 24*7 water supply in various Asian cities.



**Source: Data from McIntosh, 2003**

**Figure 8.1: Rates of intermittency in Asian countries**

The prevalent intermittency has been attributed to poor management and low tariffs. Efforts to reduce pipeline leakage and reduce demand via tariff increases are important; but as urban areas grow both in income and population at unprecedented rates, developing new sources of water will be unavoidable. Many South Asian cities have also been unable to expand their water supply infrastructure to keep pace with rising demand.  In Chapter 1, we three challenges to expanding utility-based supply in Chennai: infrastructure costs of reallocation from agriculture, distributed nature of irrigation water abstractions, and high cost of alternatives such as desalination.  These challenges may be more common in South Asia than is acknowledged in the literature.

### *8.2.2 Reallocation from agriculture involves infrastructure costs*

Reallocation of water from agriculture to urban areas often entails building expensive new storage reservoirs and often involves resettling displaced populations, settling stakeholder claims, and mitigating environmental damages. South Asian countries (indicated in in red arrows in Figure 8.2) have among the highest densities of population in the world (excluding small island states like Taiwan and Singapore) as can be seen in the Figure 8.2.

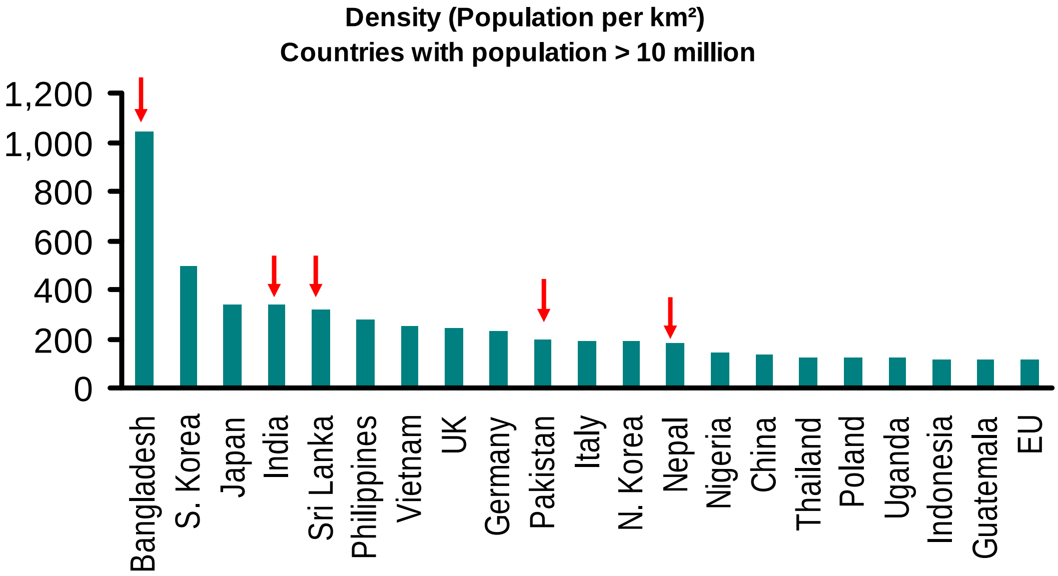
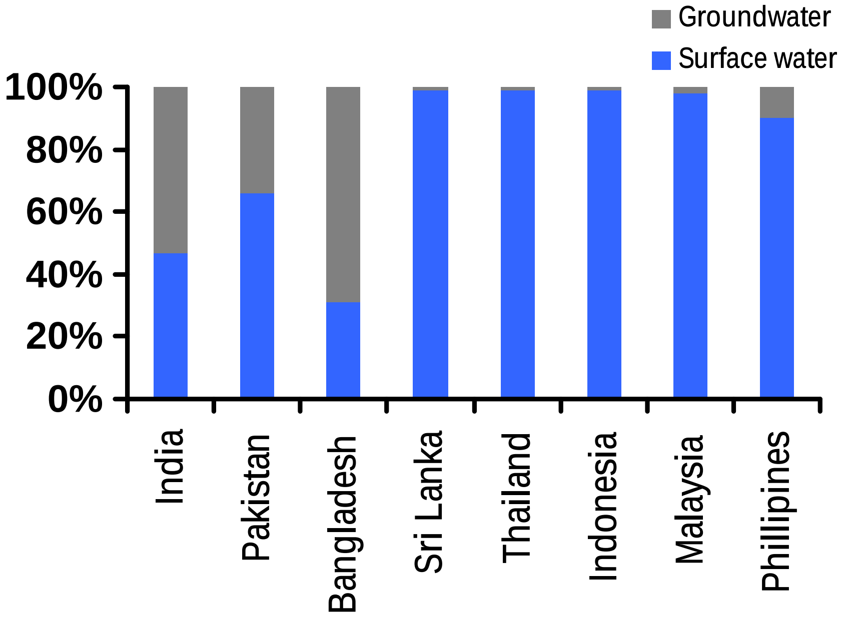


**Figure 8.2: Density of population across countries**

Moreover, within India at least, water reallocation across state boundaries is further complicated by democratic institutions.  As discussed with respect to the Telugu Ganga Project , the presence of regional or state-specific political parties in India make water transfers across state boundaries complex to administer and enforce. These issues have been documented in other inter-state river disputes in India.

### *8.2.3 Agricultural water use is "distributed" and not amenable to reallocation*

In Chapter 1 we argued that although a large fraction of water use in the developing world continues to be for irrigated agriculture, the water is not necessarily amenable to transfer to urban uses. Unlike large rivers or surface water reservoirs, which can be reallocated from agricultural to urban uses relatively easily, groundwater is institutionally, economically and physically challenging to reallocate. Groundwater extraction by agriculture in much of the developing world consists of millions of tubewells extracting small amounts of water. In the case of Chennai, the lack of a large perennial river made it difficult to expand centralized water supply to peri-urban areas. Consequently, the main process by which water becomes reallocated from agricultural to urban uses is via the substitution of peri-urban irrigation wells by peri-urban domestic wells. In India, Pakistan and Bangladesh, the three South Asian countries with the worst intermittency problems, a significant fraction of the irrigation water needs is sourced from groundwater (Figure 8.3).



**Source: FAO Aquastat Database, accessed June 4th, 2008**

**Figure 8.3: Source of irrigation water across countries**

The statistics for South Asian countries indicate that rapid reallocation of irrigation water use to large metropolitan utilities may be challenging in cities other than Chennai.

### *8.2.4 Centralized water supply is not the cheapest source*

In Chapter 7, we identified several reasons why the long-held assumption that centralized piped water supply is the cheapest source of supply broke down in Chennai: the high density of private and community wells, the high marginal cost of supply, high cost of new utility supply, and consumers' ability to distinguish between multiple qualities of water. These basic characteristics can be found in many cities in South Asia as indicated by recent household surveys by Shaban and Sharma (2007). The Dual-Quality solution may therefore find wider applicability beyond Chennai.

## 8.3 Suggestions for future research

Based on the findings in this dissertation, we lay out directions for future research. Two research agendas that emerged during the course of this dissertation research

1. Policy-relevant science
2. Multi-scale feedbacks

### *8.3.1 Policy relevant science and engineering*

#### *1. Empirical information on policy costs and efficacy*

One of the weakest links in this dissertation was the link between policy costs and their physical outcomes. For instance, in the case of the Rainwater Harvesting policy, there was no empirical evidence regarding to what extent a particular level of investment (e.g., Rooftop and yard collection systems) would increase recharge at the basin-scale. Currently, Rainwater Harvesting advocates make simplistic assumptions based on rooftop and yard area and fraction that can be captured; but this is not based on empirical evidence. The few studies on existing rainwater collection systems have documented the quality of installations but not the efficacy of properly installed systems. Similarly, there was surprisingly little empirical information quantifying the cost of leak-detection and conservation programs in the developing world. In Chapter 7, we conducted sensitivity analysis to this parameter. However, ultimately the recommendations made are contingent on scientific confirmation of the assumptions made.

### *2. Health Impacts of using lower quality water for "non-potable needs"*

The Dual-Quality policy relies on the implicit claim that using lower quality groundwater for bathing, flushing and clothes washing will have no negative health effects. This needs to be established empirically.

### *2. Monitoring groundwater extraction by metering sewage*

The Dual-Quality approach implicitly assumes that groundwater cannot be independently metered and taxed. In this research, we did not consider monitoring and metering groundwater extraction in the Chennai basin as a viable option, because it would be difficult to implement institutionally as well as legally under the current open-access groundwater law. However, monitoring groundwater might be possible by metering sewage flows instead of water. More households in Chennai have sewage connections that water connections and more than half the current water use is derived from self-supply. Moreover, charging for sewage would provide incentives for decentralized household grey-water recycling. It would also provide incentives for the utility to aggressively invest in rainwater harvesting to protect groundwater availability during droughts. However, to the best of our knowledge, sewage metering for households has not been attempted in a developing world city. The techno-economic feasibility of such an option merits further research.

### *3. Aquifer Storage and Recovery*

In this work we did not address options for Supply Augmentation other than desalination. However, since our results showed that Chennai is highly reservoir-capacity constrained, a logical option would be to augment capacity via Aquifer-Storage and Recovery. Specifically, by storing surplus Telugu Ganga water or treated wastewater in the Araniyar-Koratailaiyar aquifer (A-K aquifer) where the Metrowater well fields are located. However, since the A-K basin supports a large agriculture economy and groundwater is a common-property resource, it would be a challenge to ensure that the stored water is available to Metrowater and not diverted to farmers. Metrowater recently hired consultants Scott-Wilson Piesold to address precisely these challenges. However, the analyses would benefit from integration with this research, particularly the option to purchase water only during drought years when Chennai needs in most.

### *8.3.2 Multi-scale Feedbacks*

The second category is "multi-scale feedbacks", understanding how changes at one scale influence behavior at other scales in ways that have not been quantified or studied. We suggest two connections or links that merit study.

***1. Intermittency, path-dependency and the transition to 24*7 supply***

Intermittency in water supply is prevalent all over South Asia. The question that faces developing world utilities is why intermittency persists, whether to adapt to intermittency at least in the medium-term, or transition to 24*7 supply as soon as possible and if so, how to achieve this. However, the literature in this area is too fragmented to address these questions effectively.

Intermittent water supply systems are understood to be inefficient; they impose higher costs on users, result in inequitable distribution, and entail high risks of contamination. Unfortunately, commonly offered explanations of poor management, economic scarcity and "culture of acceptance" (McIntosh, 2003) are woefully inadequate. These explanations overlook the issue of incentives, sunk-costs, and system path-dependence.

Earlier in this dissertation we showed that in Chennai, utility supply varies significantly across periods due to a combination of physical (limited reservoir capacity, variations in inter-annual runoff) and management (low tariffs, high leakage) factors. Faced with intermittent and unreliable supply, it is rational for consumers to invest in private coping mechanisms. Once coping investments have been made, they alter the nature and incentives consumers have. This suggests that water supply systems may display a certain level of path-dependence.

We offer the following hypotheses that could be tested by comparative studies of water utilities to explore the feedbacks between utility and consumer behavior.

***Hypothesis 1:*** Once consumers have borewells it will be difficult to raise tariffs far beyond the cost (short-run marginal cost) of extracting water from private wells. Specifically, the widespread prevalence of borewells reduces consumers' willingness-to-pay for utility supply to the short-run marginal cost instead of the long-run marginal cost of self-supply.

***Hypothesis 2:*** Wealthier consumers having made private investments in sumps and borewells, thus converting an intermittent and seasonally variable supply to an effective 24*7 reliable supply, will not support large tariff increases to make the system better for other consumers.

***Hypothesis 3:*** The prevalence of sumps fundamentally alters the nature of the distribution system; once a certain fraction of consumers have sumps, overall system demand becomes "lumpy" so less water is available to everyone else. This in turn increases the likelihood that other consumers will invest in sumps, a positive feedback that causes intermittency to persist.

Once the reasons of intermittency are established, the question of whether to make the transition to 24*7 water supply, can be addressed. The analysis would need to acknowledge that existing coping mechanisms are "sunk costs". Specifically, the cost of prior coping investments should not be factored when deciding whether to transition out of intermittent supply. Finally, a realistic plan to transition to 24*7 supply would consider changes necessary at the basin-scale (seasonally uniform availability of supply), utility-scale (pipe retrofits, management changes), as well as consumer scale (in-home plumbing retrofits).

### *2. Effects of urbanization on runoff*

The second multi-scale feedback we recommended studying, is the effect of urbanization on water resources. Much of the urbanization in the developing world, particularly in peri-urban areas is haphazard and unplanned. There is an almost complete absence of storm water drainage in peri-urban areas. The unintended effect of this urbanization is that rainwater may no longer be reaching reservoirs as the runoff is rerouted. This is particularly relevant in rapidly urbanizing flat regions which rely on small peri-urban "tanks" (ponds) and lakes for water supply and irrigation.

Traditional engineering wisdom dictates that urbanization is accompanied by increased runoff and decreased recharge as unpaved soils are replaced by concrete surfaces. However, during conversations with local academics, some raised concerns that reservoirs and lakes close to Chennai were receiving reduced inflows during the rains as their watersheds urbanized. In effect, large lakes were now being replaced by a million dispersed puddles. Environmental NGOs have suggested that peri-urban lakes played a key role in groundwater recharge. In workshops conducted during the course of this dissertation, the focus was preventing encroachment in peri-urban lakes via fencing. However, it is unclear if preserving the lake area is as important as developing suitable storm water drainage to preserve the integrity of their watershed. The key question of whether cities in expanding are destroying their source of sustenance in the process needs to be addressed.

## 8.4 Conclusions

In Chapter 1 we argued that as cities grow and incomes rise, a new challenge arises: that of supplying water reliably to rapidly growing, increasingly wealthy populations and enterprises, while ensuring that the poor are not left out. Because much of the infrastructure is still being built, there is the opportunity to leapfrog to a more efficient, equitable, sustainable system. The question we asked at the beginning of this dissertation was what might such an efficient sustainable and equitable water supply system look like?

Using a case study of Chennai, India we were able to develop an integrated approach to water supply systems in the developing world. This research makes the case that expanding centralized supply may not always be the least-cost option. Instead, cities might want to consider a combination of high-cost high-quality continuous piped supply and low-cost, low-quality decentralized self or community supply.

# Appendices

# Appendix A. The consumer's discrete choice problem

***A.1: The consumers' discrete choice problem with supply constraints***

In this Appendix, we solve the consumers' choice problem for a consumer facing supply constraints. Consider a consumer who has access to T possible sources of water, where the price of the $k^{th}$ source is $p_k$ such that $p_1 \le p_2 \le ..... \le p_T$

If $q_k$ is the quantity consumed per day from the $k^{th}$ source, and M sources (out of T possible sources) are consumed, then the amount paid by the consumer in each day is

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

Now let us assume there are quantity constraints on the quantity of water available from different sources. Let the maximum quantity available from the $k^{th}$ source be $\overline{q_k}$

Let $Q_M$ is the total quantity of water consumed from M sources (out of T available sources). The total quantity consumed is bounded by the consumers' demand, which in turn is a function *f* of marginal price, income, household size.

$$Q_M = \sum_{k=1}^{M} q_k \le f\left(P_M, ..., N, I\right)$$

Where $p_M$ is the marginal price, $N$ is the total number of members in the household, and $I$ is the monthly household income.

If water quality is disregarded, then the consumers' cost minimization problem reduces to

$$\textit{Minimize}$$

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

$$s.t$$

$$q_k \le \overline{q_k} \text{(quantity consumed from kth source is less than or equal to available supply)}$$

$$p_1 \le p_2 \le \ldots.. \le p_M \text{ (prices are sorted from cheapest to most expensive)}$$

$$Q_M = \sum_{k=1}^{M} q_k \le f(p_M, \ldots, N, I) \text{ (Quantity consumed is less than the demand)}$$

The solution to the consumers' cost-minimization problem is simply

$$q_1 = \overline{q_1}$$

$$q_2 = \overline{q_2}$$

For all infra-marginal sources i.e., $q_k$ s.t. k<M

The Mth source is the marginal source if

$$f(p_{M+1}, \ldots., N, I) < f(p_M, \ldots., N, I)$$

(i.e., the source at which the demand and supply curves intersect)

The quantity of the M<sup>th</sup> source consumed is the minimum of demand and supply.

$$q_M = MIN(f(p_M, D_M, N, I) - \sum_{k=1}^{M-1} q_k, \overline{q_M})$$

### *A.2: The consumers' discrete choice problem with supply constraints*

Now if water quality is added to the mix, the consumer must consumed based on both price and quality. To account for quality, in Chapter 2, we assumed that

5. Consumers can only identify potable and non-potable quality water and potable and non-potable uses
6. Consumers will use only potable quality water for potable uses (drinking, cooking, and rinsing dishes).
7. Demand for potable water is inelastic and hence fixed.
8. Consumers may use potable-quality water for non-potables uses (flushing, bathing, gardening and washing) if available and cheaper to do so. Otherwise, they will use non-potable quality water.
9. Consumers derive a higher marginal benefit from the potable end-uses (drinking, cooking, rinsing) and these will be the last uses to be eliminated during shortages. Moreover, potable quality water will be allocated first to these high marginal value uses.

These rules were implemented as follows:

We assume that the total quantity of potable demand (based on drinking and cooking needs) is fixed at $\overline{Q^P}$ and is perfectly inelastic.

Non-potable demand for water is assumed to be elastic and defined as earlier

$$Q^{NP}{}_M = f(p_M, D_M, N, I)$$

Thus

$$Q_M = \sum_{k=1}^{M} q_k = Q^{NP} + \overline{Q^P}$$

$$Q_M = \sum_{k=1}^{M} q_k = f(p_M, D_M, N, I) + \overline{Q^P}$$

To allocate water between potable and non-potable needs, each source is now tagged with a quality attribute $u_k$, where $u_k$ =1 is the source is potable and $u_k$ =0 if the source is non-potable. We first solve the consumers' optimization problem for potable quality water, for which we get

$$
\begin{aligned}
&Minimize\\
&C^P(P,Q) = \sum_{k=1}^{T} p_k q^P{}_k\\
&s.t\\
&q^P{}_k \le \overline{q_k}\\
&p_1 \le p_2 \le \ldots.. \le p_T\\
&\sum_{k=1}^{M} q^P{}_k = \overline{Q^P}\\
&q^P{}_k = 0 \ \forall u_k = 0
\end{aligned}
$$

The solution to this optimization problem is

$q^P{}_k = u_k \overline{q_k}$ for $k$ s.t. $\sum_{k=1}^{M'} q^P{}_k = \overline{Q^P}$

$q^P{}_k = 0$ for Y> k> M'

In other words, the consumer uses the first M' cheapest potable sources of water.

This has the effect of reducing the quantity of water available from these sources for potable uses. The new constraints on quantity available for non-potable uses are given by

$$\overline{q^N{}_k} = \overline{q_k} - q^P{}_k$$

Now the consumers' optimization problem reduces to the original single quality case, only with new constraints.

$$
\begin{aligned}
&Minimize\\
&C^N(P,Q) = \sum_{k=1}^{T} p_k q_k\\
&s.t\\
&q_k \le \overline{q^N{}_k}\\
&p_1 \le p_2 \le \ldots.. \le p_T\\
&Q^N{}_M = \sum_{k=1}^{M} q_k \le f(p_M, D_M, N, I)\\
&where\\
&D_M = p_M q^N{}_M - \sum_{k=1}^{M} p_k q^N{}_k
\end{aligned}
$$

The solution to the cost minimization problem is

$$q_1 = \overline{q^{N}{}_{1}}$$

$$q_2 = \overline{q^{N}{}_{2}}$$

The quantity of the marginal source consumed is

$$\mathrm{q}_{\mathrm{M}} = Min(f(P_M, D_M, N, I) - \sum_{k=1}^{M-1} q_k, \overline{q_M})$$

# Appendix B. Welfare Estimation Formula Derivation

### B.1 Estimation of consumer surplus

Consumer utility maximization theory dictates that the consumer will consume a total quantum of water so that cost of the marginal unit equals the marginal willingness-to-pay. The functional form used in estimating the willingness-to-pay function was

$$Q = C\ P^{\alpha} N^{\beta} D^{\gamma} I^{\delta}$$

**Equation 0.1**

where C is a constant, Q is the quantity demanded, P is the cost to the consumer, N is the household size, I is the monthly income, and D is the difference variable. The difference variable represents the "income effect" as the difference between the marginal price and the cost of water to the consumer. When the supply curve is tiered as in our model, the difference variable is different for each tier. It is constant within each tier.

As defined earlier if the consumer who has access to T possible sources of water, where the price of the $k^{th}$ source is $p_k$ such that $p_1 \leq p_2 \leq \ldots\ldots \leq p_T$

If $q_k$ is the quantity consumed from the $k^{th}$ source in each time period, and M are sources are used, then the amount paid by the consumer in each time period is

In order to estimate consumer surplus we need to the willingness to pay function i.e., that represents Q as a function of P.

Transposing (Equation 1) we obtain the willingness-to-pay function as

$$W(Q) = \frac{Q^{\frac{1}{\alpha}}}{C^{\frac{1}{\alpha}} N^{\frac{\beta}{\alpha}} D^{\frac{\gamma}{\alpha}} I^{\frac{\delta}{\alpha}}}$$

**Equation 0.2**

Now, In Equation B.2, the difference variable is defined for each tier as

$$D_j = \sum_{k=1}^{j-1} (p_j - p_k) q_k$$

$$D_1 = 0$$

Graphically, the difference variable for tiers 2 and 3 is shown for a hypothetical consumer Figure B.1 and Figure B.2.

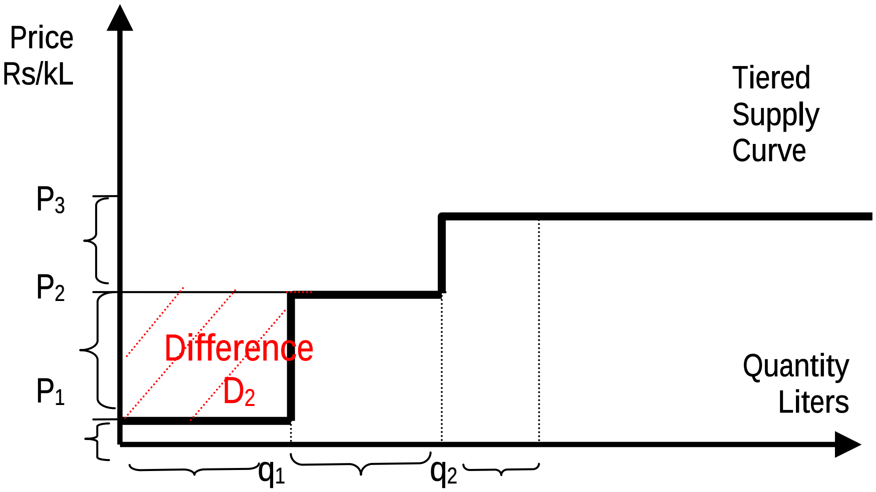


**Figure 0.1: Difference variable for tier 2**

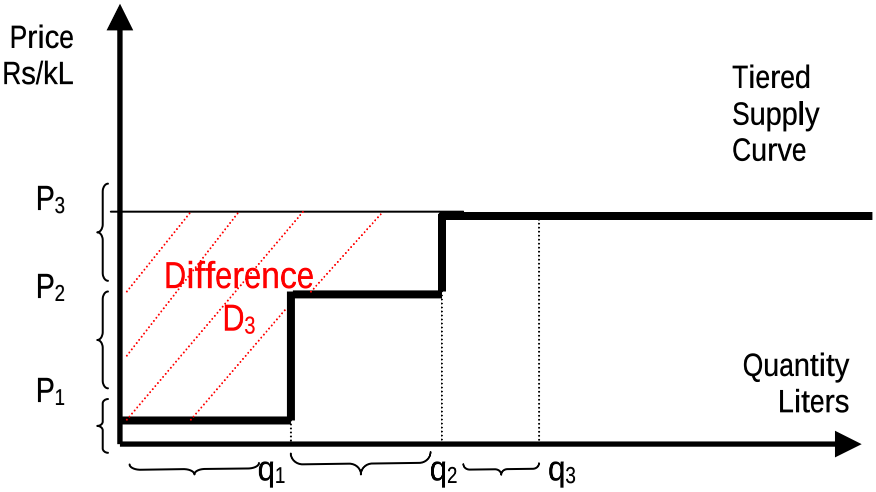


**Figure 0.2: Difference variable for tier 3**

By definition, the difference variable is a function of the price and quantities of the *infra-marginal tiers* only. Because the difference variable changes after each tier, the willingness-to-pay function is piecewise continuous with discontinuities at each tier; i.e. $\sum_i^k \overline{q_i}$ being the points of discontinuity.

However, although the difference variable value changes at each tier but is constant within the tier. This is useful to note when integrating the willingness-to-pay function.

Economists define the incremental consumer surplus accruing to consumers as follows

$$Z(Q) = W(Q) - C(Q)$$

**Equation 0.3**

The marginal benefit or incremental consumer surplus is shown in the figure below.

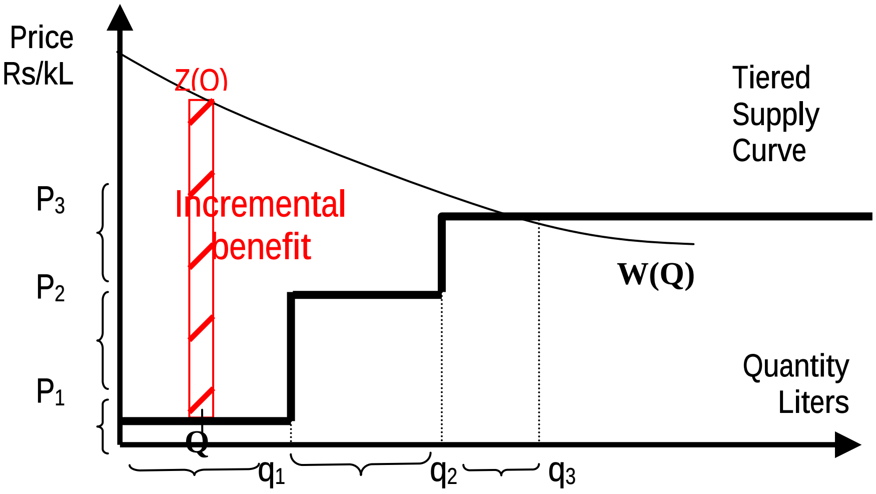


**Figure 0.3: Incremental benefit at consumption Q**

To estimate the total consumer surplus we need to integrate the function Z(Q)

$$CS = \int_0^{Q_M} Z(Q)dQ$$

**Equation 0.4**

From Equations 3 and 4,

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

**Equation 0.5**

We integrate each component of the equation above separately.

$$\int_0^{Q_M} W(Q)dQ = \int_0^{Q_M} \frac{Q^{\frac{1}{\alpha}}dQ}{C^{\frac{1}{\alpha}} N^{\frac{\beta}{\alpha}} D^{\frac{\gamma}{\alpha}} I^{\frac{\delta}{\alpha}}}$$

**Equation 0.6**

Coefficients α, β, γ, C, and, N are independent of Q, we can treat them as constant. However, D is not independent of Q and must be included.

$$\int_0^{Q_M} W(Q)dQ = \frac{1}{C^{\frac{1}{\alpha}} N^{\frac{\beta}{\alpha}} I^{\frac{\delta}{\alpha}}} \int_0^{Q_M} \frac{Q^{\frac{1}{\alpha}} dQ}{D^{\frac{\gamma}{\alpha}}}$$

**Equation 0.7**

The expression can be simplified by splitting the expression at the points of discontinuity. We noted earlier that the difference variable is independent of each tier, so it can be treated as a constant within each component.

$$\int_0^{Q_M} W(Q).dQ = \frac{1}{C^{\frac{1}{\alpha}} N^{\frac{\beta}{\alpha}} I^{\frac{\delta}{\alpha}}} \{ \int_0^{Q_1} \frac{Q^{\frac{1}{\alpha}} dQ}{D_1^{\frac{\gamma}{\alpha}}} + .... + \int_{Q_{M-1}}^{Q_m} \frac{Q^{\frac{1}{\alpha}} dQ}{D_{M-1}^{\frac{\gamma}{\alpha}}}$$

**Equation 0.8**

Solving the integrals for each tier

$$\int_0^{Q_M} W(Q).dQ = \frac{1}{C^{\frac{1}{\alpha}} N^{\frac{\beta}{\alpha}} I^{\frac{\delta}{\alpha}}} \sum_1^M \frac{(1+\alpha)}{D_i^{\frac{\gamma}{\alpha}}} \{ Q_i^{\frac{1+\alpha}{\alpha}} - Q_{i-1}^{\frac{1+\alpha}{\alpha}} \}$$

**Equation 0.9**

Where i=1 is the first tier and i =M is the marginal tier.

For a tiered supply curve, the total cost to the consumer is simply the sum of the amounts paid for water consumed in each tier

$$\int_0^{Q_M} C(Q).dQ = \sum_1^M C_i q_i$$

**Equation 0.10**

Where i =M is the marginal tier

Subtracting Equation B.10 from Equation B.9

Thus, the total consumer surplus is

$$CS(Q) = \frac{1+\alpha}{C^{\frac{1}{\alpha}} N^{\frac{\beta}{\alpha}} I^{\frac{\delta}{\alpha}}} \sum_1^M \frac{1}{D_i^{\frac{\gamma}{\alpha}}} \{ Q_i^{\frac{1+\alpha}{\alpha}} - Q_{i-1}^{\frac{1+\alpha}{\alpha}} ) - \sum_1^M C_i q_i )$$

**Equation 0.11**

# Appendix C. Categorizing consumers from census data

In this Appendix we explain how we categorized Chennai's population into the different categories based on 2001 Housing Census data[94]. Housing Census data were purchased from the Census of India office at New Delhi.

Census data were purchased at the "ward" level. The ward is the smallest census unit within the municipal corporation of Chennai. There are 155 wards, which could be aggregated into 10 corporation zones. The data were based on "Table 8" of the 2001 Housing Census, which asked from which source consumers obtained drinking water and where the source was located. Source options included: tap, handpump, tube-well, open well, lake/river/spring and other. Location options included: within premises, near premises and away from premises. Because the housing census data only asked for the principal source households accessing multiple sources could not be determined. Moreover, the terms "in-house" and "near-house" are somewhat ambiguously defined in the Housing Census questionnaire. Therefore, two assumptions had to be made to map the census categories to the model consumer categories.

1. We assumed "near house or in-house handpump" referred to a private yard tap or handpump.
2. We assumed that half of all consumers using handpumps for drinking water also had borewells (and indoor plumbing) that they were using for non-potable needs. This assumption was based on the fact that half of the households in the 2004 and 2006 household surveys (described in Appendix G that reported having private borewells and indoor plumbing in addition to private wells.

Table C.1 shows how the model categories were derived from 2001 Housing Census data.

---

[94] Government of India 2001.

**Table 0.1: Map of consumer category to 2001 housing census category**

| Model Consumer category | Census Category: Source of drinking water |
|---|---|
| **Unconnected** | All household reporting drinking water source away from house (street tap or public standpipe) |
| **Manual** | 50% of households with in-house or near-house handpumps or taps |
| **Manual w/ Borewell** | 50% of households with in-house or near-house handpumps or taps<br>All households with in-house borewells. |
| **Sump** | In-house tap |

The second change made to census data was in defining the spatial units within Chennai. Although the "ward" is the smallest unit for which census data was available, there was not enough variance between the wards to justify solving the consumers' choice problem for each ward in Chennai. This led to too much redundancy in the model. Instead the spatial unit chosen was the corporation zone.

Zone 10 is the largest in Chennai and included almost all of South Chennai. The decision was made to split corporation zone 10 into three areas:

1. 10A, the Mylapore-Nandanam area, covers wards 142-150.
2. 10B, the Adayar-Besant Nagar area, covers wards 151,152 and 155
3. 10C, the Velachery area, covers wards 153 and 154

Zone 10 was split into three different spatial units because these sub-zones have distinct demographic and geologic characteristics:

1) ***Demographics:*** The Velachary area (zone 10C) of South Chennai is poorer, has lower prevalence of sumps and private utility connections than Besant Nagar and Adayar (zone 10 B), which have relatively wealthy upscale neighborhoods. Zone 10A which includes the Mylapore, Nandanam areas, located north of the Adyar river, is much more commercial and densely populated than the other two.
2) ***Geology:*** The Velachary (zone 10C) area overlays the portion of the aquifer where the hard-rock outcrops. The aquifer is very thin here, so the groundwater access is very different from the coastal zone of Besant Nagar and Thiruvanmyur, which have a sandy aquifer. In these areas, salt-water intrusion may be a problem.

Based on these assumptions the fraction of households by model zone and category is shown in Table C.2.

**Table 0.2: Fraction of households by consumer category in 2001**

| Zone | Unconnected | Manual Only | Manual w/ Borewell | Sump | No of HH |
|---|---|---|---|---|---|
| 1 | 25% | 26% | 33% | 16% | 91629 |
| 2 | 6% | 16% | 42% | 35% | 74805 |
| 3 | 12% | 30% | 41% | 17% | 77335 |
| 4 | 12% | 21% | 33% | 34% | 130544 |
| 5 | 12% | 18% | 32% | 38% | 124848 |
| 6 | 11% | 20% | 40% | 29% | 66666 |
| 7 | 10% | 20% | 40% | 30% | 72575 |
| 8 | 10% | 24% | 33% | 33% | 109771 |
| 9 | 17% | 21% | 33% | 29% | 97574 |
| 10A | 22% | 16% | 34% | 28% | 49538 |
| 10B | 14% | 12% | 37% | 36% | 32495 |
| 10C | 51% | 25% | 17% | 7% | 34433 |
| **Total** | **15%** | **21%** | **35%** | **29%** | **962,213** |

The number of commercial consumers was obtained from Metrowater data[95]. Commercial firms distributed among zones 10A, 10B and 10C in proportion to the number of service connections. The data are presented in Table C.3.

**Table 0.3: Number of commercial consumers in 2005**

| Zone | Medium Firms | Large Firms |
|---|---|---|
| 1 | 1706 | 61 |
| 2 | 7447 | 137 |
| 3 | 4326 | 116 |
| 4 | 1342 | 47 |
| 5 | 5345 | 144 |
| 6 | 4411 | 137 |
| 7 | 8508 | 195 |
| 8 | 7069 | 146 |
| 9 | 1926 | 62 |
| 10A | 921 | 32 |
| 10B | 1207 | 42 |
| 10C | 244 | 9 |
| **City Total** | **44,451** | **1,129** |

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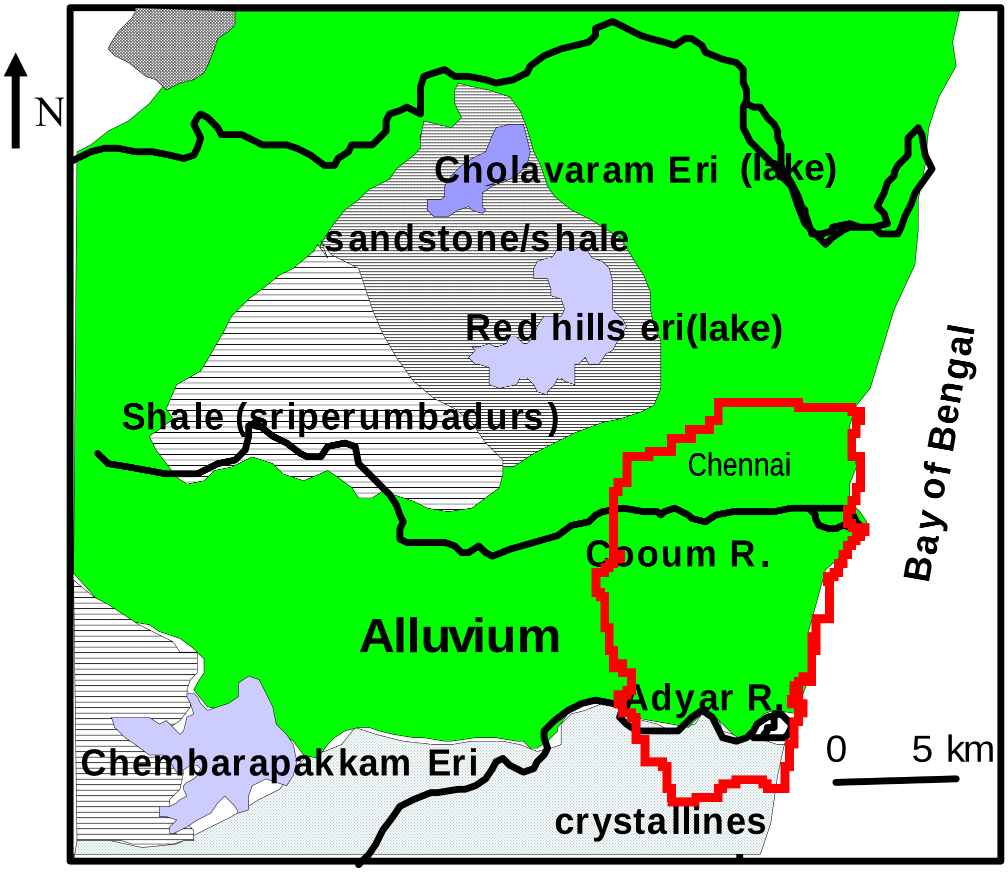
[95] Metrowater 2006 (a)

# Appendix D. Groundwater MODFLOW model

In this Appendix, we describe the conceptualization, development and calibration of the groundwater model. We begin by describing the geology of the Chennai area. Then we describe how borewell logs were used to develop a conceptual model of a 3-layer aquifer system and imported as grid layers into the MODFLOW-2000. Then we describe how the model extent, grid resolution and boundary conditions were chosen. Finally, the calibration of the model is described in detail.

## *D.1 Geology of the Chennai area*

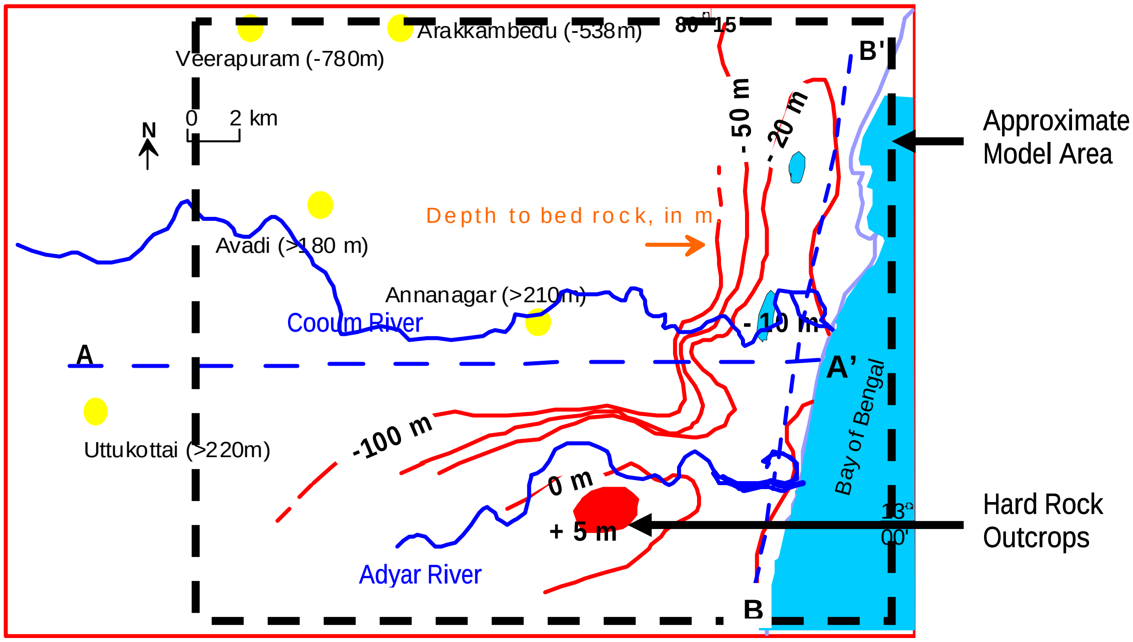
Development of a groundwater model necessitates an understanding of the local geology. In this section we describe the geology of the Chennai region. The geologic environment of Chennai is alluvial. To the south of the Adyar River, the Charnokite bedrock outcrops. North of Chennai near the city reservoirs, shale and sandstone can be found at shallow depths as shown in Figure D.1.



Source: Balukraya 2006

**Figure 0.1: Geology of the Chennai area**

The first task in the groundwater model was to develop an understanding of Chennai's geology. The Chennai area has an alluvial aquifer underlain by weathered charnokite rock to the west and shale (Gondwana formations) to the east. The Chennai area is bounded by the Bay of Bengal to the east and is intersected by two rivers the Adayar and the Cooum. The thickness of the alluvium increases to the north and the west of the basin. It is least to the south west of the model, where the weathered bedrock outcrops (near St. Thomas Mount in Chennai). Figure D.2 shows main features of the Chennai bedrock topography.

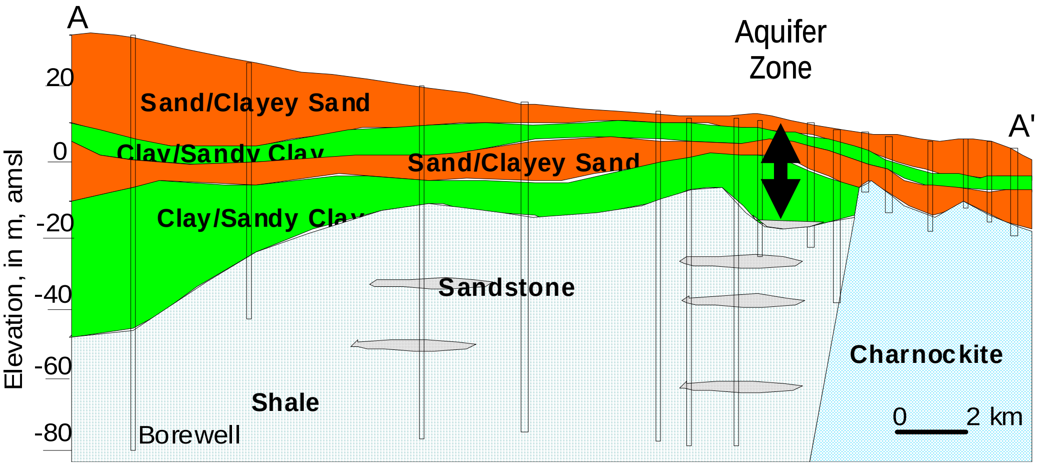


* Yellow dots are named villages with know depth-to-bedrock values

Source: Balukraya 2006

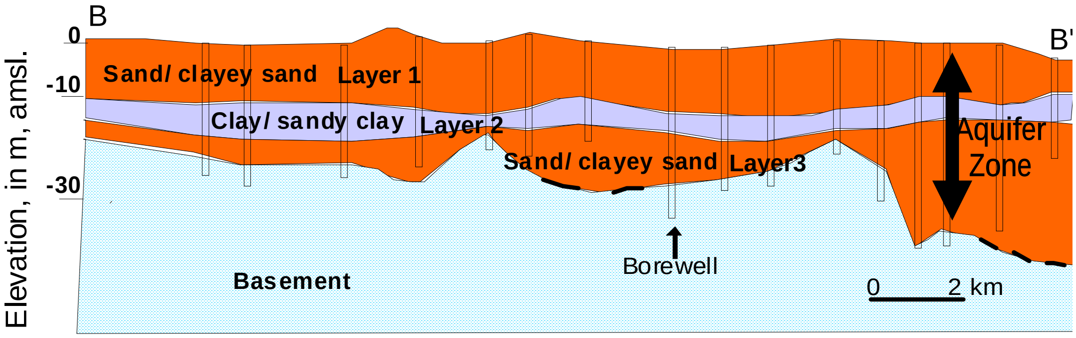
**Figure 0.2: Bedrock topography**

The bedrock outcrop area is shown in red in Figure D.2, with the depth to bedrock labeled as 0 to 5 m. The area of the integrated model is delineated by the dotted black line. Two cross-sections (shown as blue dotted lines in Figure D.2) produced by Prof Balukraya from the University of Madras, Dept of Applied Geology are shown in Figures D.3 and D.4.



Source: Balukraya 2006

**Figure 0.3: Cross-section AA'**



Source: Balukraya 2006

**Figure 0.4: Cross-section BB'**

To develop the layer thickness of the various layers, we used lithologic (logs of geologic layers identified by borehole drillers) data collected from various sources. We started with a database of over 400 lithologs. We collected additional reliable lithologs from Hydrosoil Engineers, a local borewell drilling company with very reliable data. We also collected the 1967 UNDP geologic map of the Chennai basin. Unfortunately, much of the data was unreliable or used inconsistent classification systems. Ultimately, we reduced the sample to 64 lithologs that were internally consistent, had reliable co-ordinates, and were consistent with the UN geologic map.

From the lithologs and earlier model of the Chennai aquifer (Ravi, 1997) we decided that the Chennai aquifer system could be best simulated as a three-layer system; an unconfined sand layer, a clay aquitard and a lower confined clayey sand layer. The aquifer is underlain by weathered charnokite rock to the west and shale to the east. Since the charnokite is weathered for the top 3-15 m, the weathered portion of the charnokite was merged into the lower sand/sandy-clay layer. The underlying shale and un-fractured charnokite rock are assumed to be impermeable.

### *D.2: Developing the MODFLOW model layers*

The thicknesses of the three layers were contoured using the 64 lithologs. Each layer was contoured. The thickness of the weathering was contoured separately and added to the lower confined layer. Well elevations from various state (Public Works Department) and federal agencies (Central Ground Water Board) and our own monitoring wells were contoured to produce an elevation map. In all we had 250 elevation points in the basin. Figures D.5, D.6, D.7 and D.8 show the contours of the thicknesses of the upper sand, middle layer and confined lower sand.

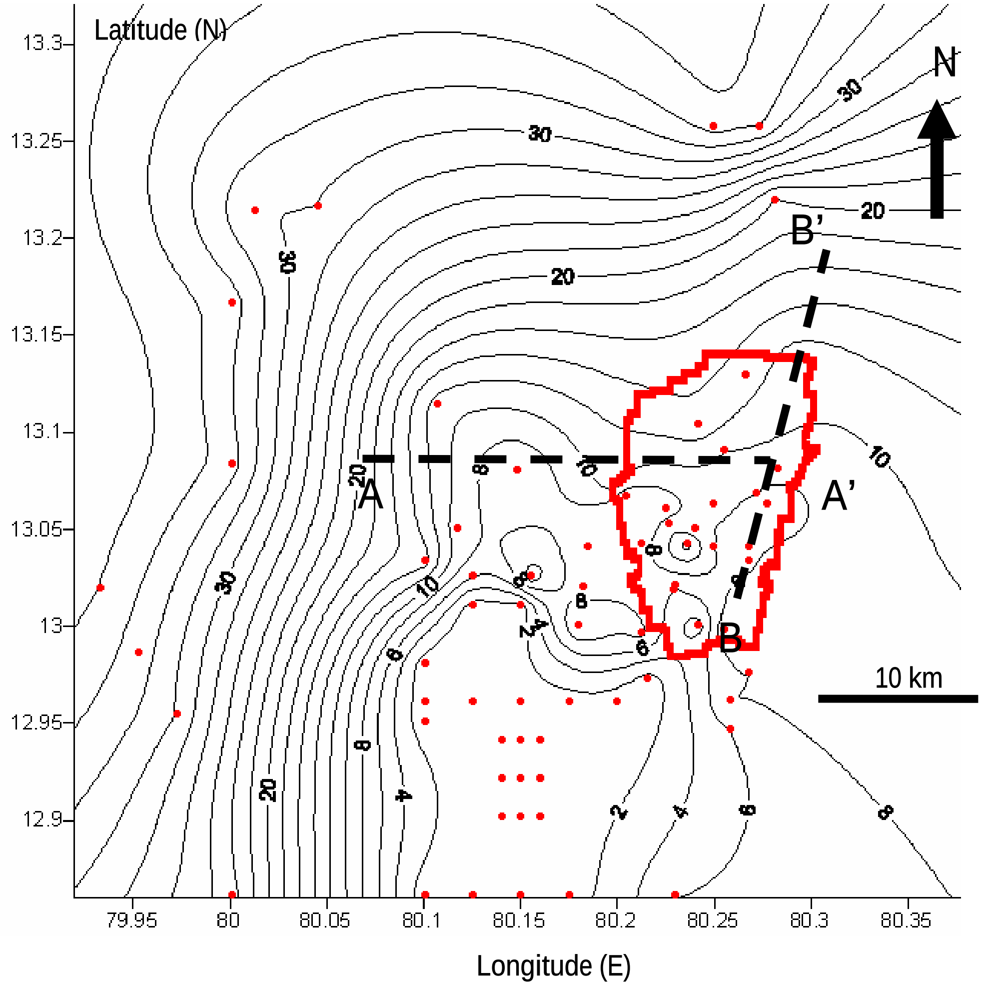


**Figure 0.5: Contours of thickness (in meters) of upper unconfined sand layer**

From the figure above it can be seen that the thickness of the upper sand layer increases to the north and west of the model area. In the Chennai city area, it is about 4 to 10 m thick.

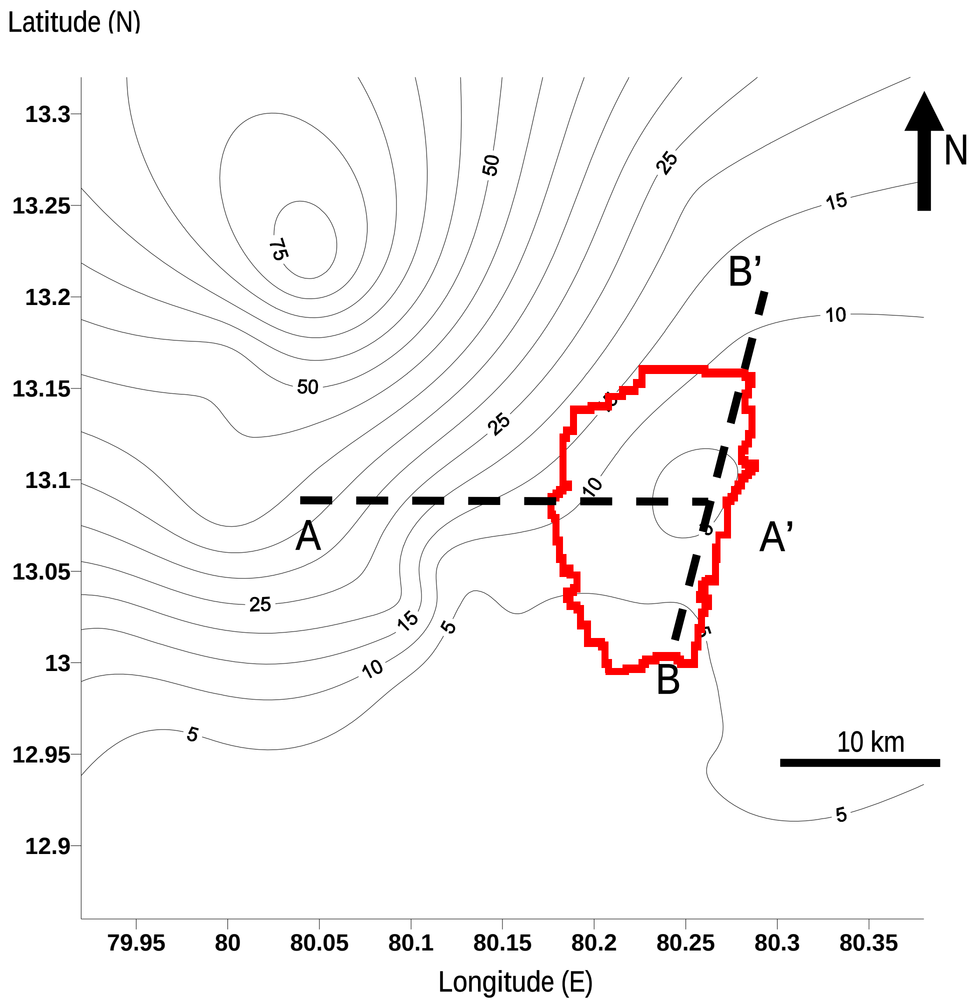


**Figure 0.6: Contours of Thickness (in meters) of Aquitard**

From the figure above it may be seen the aquitard is about 5 m thick in the city, increasing towards the north and west

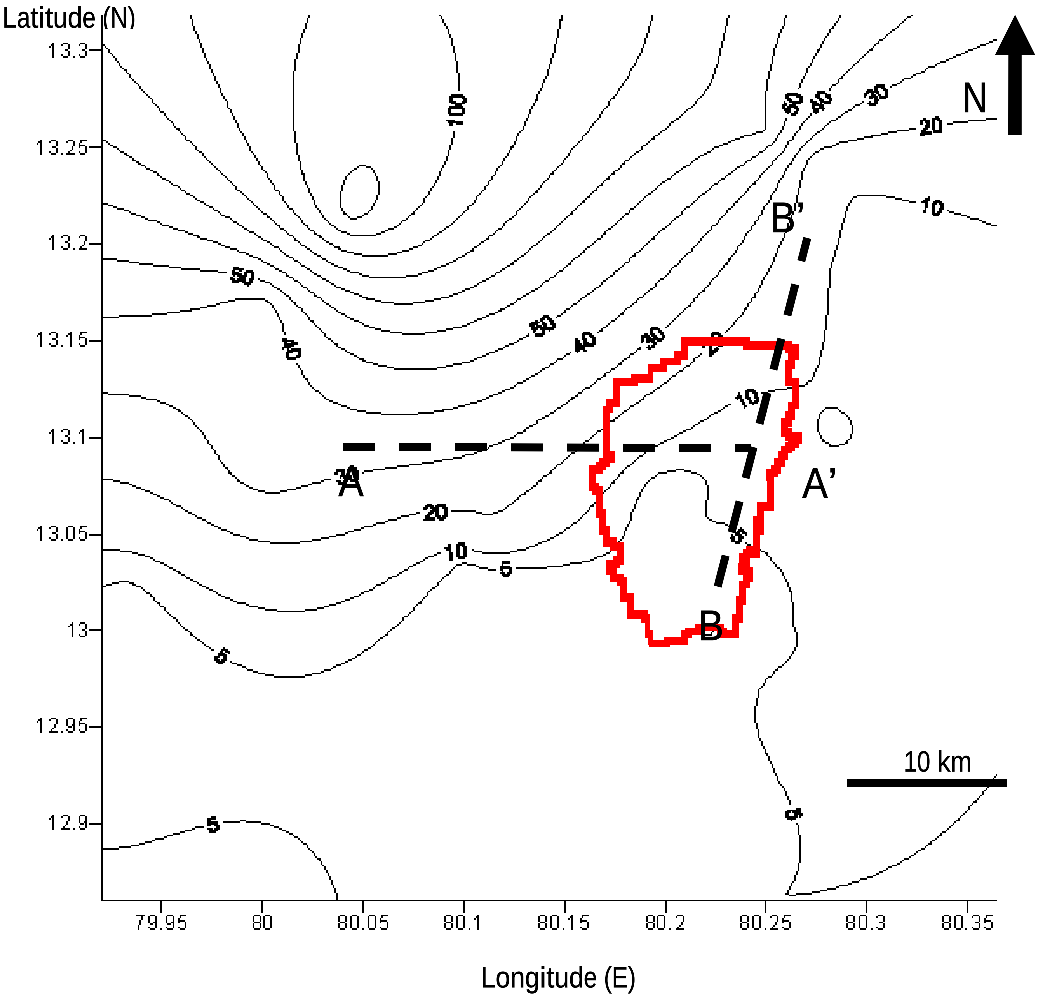


**Figure 0.7: Contours of Thickness (in meters) of Lower Confined Sand Layer**

The thickness of the lower sand layer is about 5-10 m within Chennai. It increases significantly to the north-west portion of the model area. In the area where the bedrock outcrops, the aquitard is very thin even non-existent. Since MODFLOW does not allow layer thicknesses to become zero, wheever the layer disappears, the thickness of the aquitard layer was arbitratily set to 10 cm but using a higher conductivity.

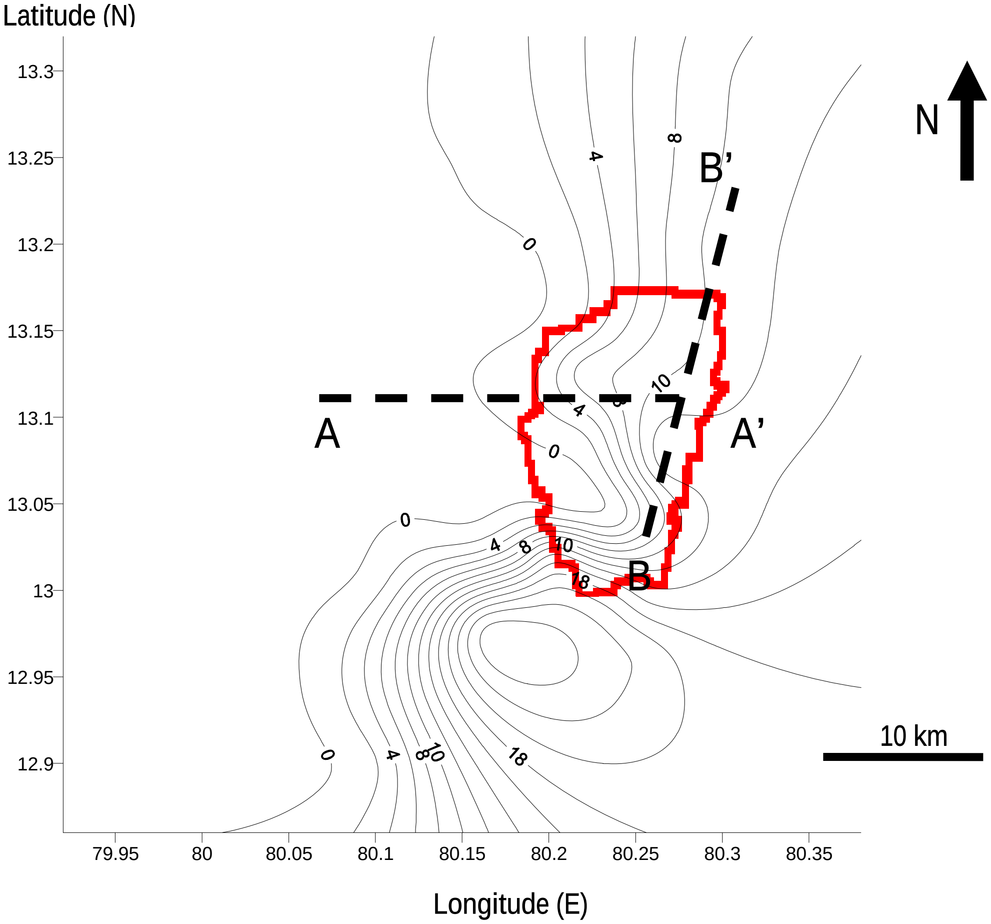


**Figure 0.8: Contours of Thickness (in meters) of Bedrock Weathering**

From the figure above it may be seen the thickness of the weathered rock is about 8-12 m in Chennai. To the South, where the charnokite bedrock outcrops the depth of the weathering can be as high as 20 m in the portion. The weathered portion is assumed to be negligible in the shale formations to the west. Once the thickness of different layers had been contoured, these could directly be imported as three 231*231 grid layers into the MODFLOW software[96]. These were used to develop the aquifer simulation model of the Chennai aquifer system.

### *D.3 Choice of layer types*

One of the challenges faced in the modeling effort was dealing with the periodic drying and wetting of the upper unconfined aquifer. Treating the layers as confined was the only way we

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[96] USGS, undated.

could avoid serious computational issues arising from cells drying up and rewetting between the dry and wet years. Our groundwater model treated all the model layers as confined. The thickness of the upper saturated layer was set to the average saturated thickness of the unconfined layer.

### *D.4 Boundary Conditions*

The boundary conditions used were as follows. The eastern boundary is the Bay of Bengal. It is a constant head boundary[97]. The underlying shale and un-fractured charnokite are treated as the bedrock and serve as the lower no-flow boundary in the model. The western boundary is a transient head boundary. Though the head here varies seasonally, it does not change much across years. The northern and southern boundaries are "no flow" boundaries. Figure D.9 shows the whole model area with contours of observed heads (above MSL) in April 2002.

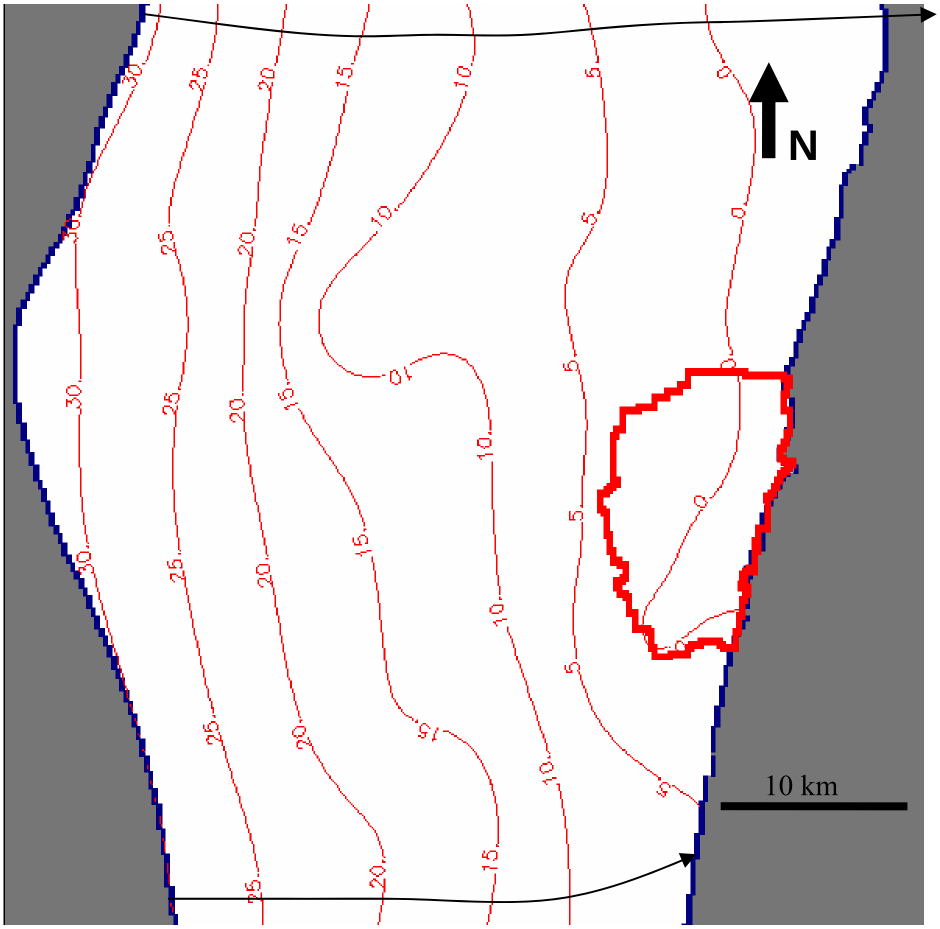

**Figure 0.9: Boundary Conditions**

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[97] Although sea level does of course change with tides, for the time-step of the model which is three months, these diurnal changes are not relevant.

From the figure it can be seen that the heads are roughly perpendicular to the northern and southern edges of the model area. If we draw the flow lines at the northern and southern edge of the model area, so that very little water flows across these “imaginary flow lines”, they turn out to be almost straight lines, parallel to the model edges.

### *D.5 Estimation of groundwater recharge*

We estimated groundwater recharge to be a function of land use.  A land use map overlaid on the MODFLOW model grid is shown below. The land use map (Figure D.10) was developed manually by inspecting a Google-Earth Satellite Image.

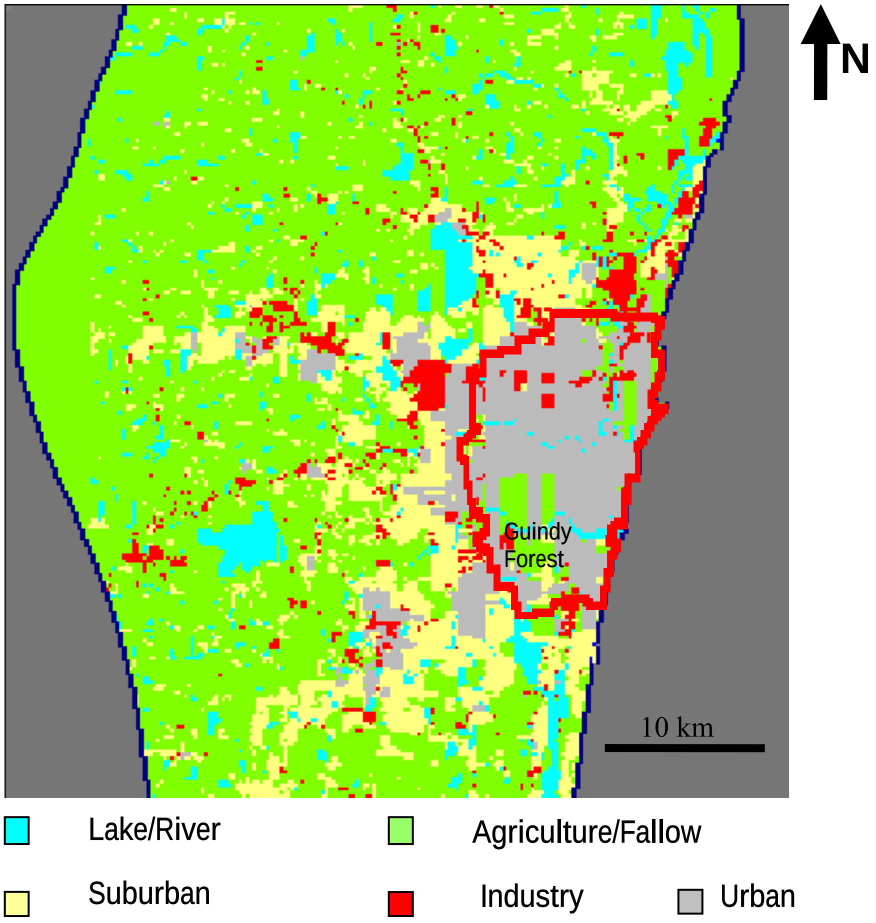

**Figure 0.10 Land use map**

Recharge is a function of rainfall, and land use. Our groundwater model assumes a fixed fraction of rainfall will recharge the aquifer. The fraction, based on measurements by Ravi (1997), was assumed to be between 15 and 20 percent.  The fraction recharging in highly urbanized areas is assumed to be reduced by 50%.  Urbanized areas contribute lesser recharge because a greater fraction of the land surface is paved. In addition to rainfall, within the city, leakage from water and sewer mains was found to be a significant source of recharge. The recharge from pipelines was assumed to be equal to the pipeline losses estimated in the utility module, uniformly distributed over all urban cells within Chennai city (i.e., excepting forested areas and rivers where there are obviously no mains). Sewage flows were assumed to be about 70 percent of water flows (30 percent of water into the household is assumed to be consumptive) for a each household. In estimating sewage flows, water supply from non-utility sources such as wells and tankers were also considered. Thus, Chennai could have significant sewage flows even in years when the piped system was not operational because of water supplied via private wells and tankers.

In lakes and along stream beds, the infiltration is a function of the standing water head, the number of days of standing water, and stream/lake bed conductivity. Fortunately, the lakes around Chennai are underlain by a thick layer of clay and contribute very little to recharge. On the other hand, river beds are sandy and permeable. However, the Adayar and Cooum rivers are dry over most of their course for most of the year; they only recharge groundwater during the few rainy days each year when they carry storm-water. Within the city of Chennai, the rivers do transport sewage discharged by the city's sewage treatment plant but the interaction with groundwater is restricted by the sludge deposited along the river bed.

### *D.6 Estimation of groundwater extraction*

Groundwater extraction was estimated based on land use type and census block. For purposes of determining extraction the following categories were created (Table D.1).

**Table 0.1: Extraction Categories**

| Land use | Census Area | Groundwater extraction estimation basis |
|---|---|---|
| Urban | Chennai city | From Consumer Module |
| Sub-urban | Chennai city | From Consumer Module |
| Water/Forest/Barren | Chennai city | No extraction |
| Urban | Outside Chennai | Based on density of population and fraction of households with indoor plumbing |
| Sub-urban | Outside Chennai | Based on density of population and fraction of households with indoor plumbing |
| Water/Forest/Barren | Outside Chennai | No extraction |
| Industry | Outside Chennai | Ind_Extraction = 50 kL/grid cell/day (Calibrated Parameter) |
| Agricultural | Outside Chennai | Ag_Extraction = 40 kL/grid cell/day (Calibrated Parameter) |
| Tanker source areas | Outside Chennai | Based on size of tanker market |

One of the advantages of using this method is that it significantly reduced the total number of calibrated parameters, excluding geologic parameters, in the groundwater model to just four. Agricultural extraction, industrial extraction, recharge rate in rural areas, and recharge rate in urban areas. All other parameters were endogenous to the model. This significantly reduced over-parameterization of the groundwater model.

***Extraction within the city of Chennai***

Within the city of Chennai, the extraction is derived from the Consumer module. The Consumer module generates the quantity actually extracted by individual households or establishments. The total extraction per grid cell is obtained by aggregating the groundwater extraction over all households and commercial establishments in that grid cell. Extraction is only assumed to occur in cells classified as "urban or sub-urban" within Chennai. Water bodies and forest areas like the Guindy national forest area (green area in land use map within Chennai south of Adyar river) are excluded.

***Urban/suburban extraction in peri-urban areas***

Outside the city, we assumed that all urban water needs are met through groundwater extraction, either via a village scheme or through private wells. This method was applied to cells classified as urban as well as suburban. The actual extractions were estimated as follows: First, we estimated the density of households per grid-cell, using 2001 census data for each census block. Next we used housing census data for each census block to estimate the fraction of households with indoor plumbing (ranges from 35% in blocks close to Chennai to 16% in blocks far away). Based on the demand function for households, we estimate that household with indoor plumbing use ("tap" households") about 470 L/HH/day (about 105 LPCD) as opposed to 235 L/HH/day (about 52 LPCD) for non-plumbed households ("non-tap" households). Finally, we estimate the fraction of wells which are dry in any period from the groundwater model. Thus we could estimate well extraction as follows.

$$\text{Extraction}(x,y,t) = (1-\text{Frac\_Dry}(x,y,t)) * (\text{Tap\_HH}(t)*470 + \text{NonTap\_HH}(t)*235)$$

**Equation 0.1**

***Agricultural extraction in basin***

In agricultural areas, we made reasonable assumptions about crops sown, irrigated acreage, type of irrigation. The main crops sown in the Chennai Metropolitan region were found to be rice, groundnut, sugarcane and pulses. Reference crop evaporation values for these crops are presented in Table D.2. The acreage sown under the principal crops in presented in Table D.3.

**Table 0.2: Crop water needs per season**

| Crop | Mm/season |
|---|---|
| Rice | 750 |
| Groundnut and pulses | 300 |
| Sugarcane | 2000 |

**Table 0.3: Acreage sown in Chennai basin area**

| DISTRICT | Kancheepuram | | | Thiruvallur | | |
|---|---|---|---|---|---|---|
| CROPS (Ha sown) | Kuruvai | Samba | Navarai | Kuruvai | Samba | Navarai |
| Rice | 5,740 | 29,269 | 16,899 | 14,564 | 32,037 | 9,100 |
| Other Food Grain | 256 | 859 | 859 | 2,331 | 2,892 | 2,892 |
| Sugarcane | 343 | 1,151 | 1,151 | 1,038 | 1,656 | 1,656 |
| Fruits and Vegetables | 254 | 852 | 852 | 1,181 | 1,465 | 1,465 |
| Groundnut | 2,655 | 3,775 | 3,775 | 3,291 | 5,465 | 5,465 |
| Other Non-Food Crops | 480 | 1,611 | 1,611 | 365 | 452 | 452 |

Source: Government of Tamil Nadu, 2006

It was assumed that on average only about 40% of a cell area classified as agricultural was actual sown area. This assumption was necessary to make the total sown acreage estimated from the land use map match the net sown area reported in Table D.3. Furthermore, 65 percent of crop water needs were assumed to be met from groundwater extraction based on average figures for Kancheepuram and Tiruvallur districts.

Ag_Extraction = Frac_GW * Crop_Water_Needs

**Equation 0.2**

Although detailed village-level data on cropping patterns were available, we found that too many assumptions had to be made and using spatially disaggregated cropping data did not yield results in the groundwater model. In the interests of parsimony, using a single extraction value for all agricultural cells, 37 kL/grid cell/day, was implemented. The value was adjusted to be 20% higher in summer and 20% lower during the SW-monsoon, when tank irrigation is widespread. This simplistic assumption produced the best and fairly consistent results.

### *Tanker extractions*

We assume zero extraction from lake beds, river beds and reservoirs.

Tanker market extractions are assumed to be located in fallow-land, close to roads, in peri-urban Chennai where the water table is relatively shallow. The quantity of tanker extraction assigned to "eligible tanker source area grid cells is the total tanker market divided by the number of grid cells. This process has been explained in detail in Chapter 3 of the dissertation.

### *Industrial extractions*

In the industrial areas of Manali and Avadi-Ambattur, we assume that any shortfalls in supply to industries via Metrowater are met via tanker markets because demand for industrial water is relatively inelastic.

### *D.7 Estimating Transmissivity and Storage Coefficients*

While the ranges of these parameters are derived from lithologs, and pump tests, these parameters fine-tuned by the calibration process. Data obtained from various pump tests are presented in Table D.4.

**Table 0.4 : Pump Test data**

| **Parameter** | **Location of test** | **Value** | **Data Source** |
|---|---|---|---|
| Hydraulic Conductivity | Kilpauk, Chennai | 50 m/day | Central Ground Water Board, 2004 |
| | Well Fields | 100-200 m/day | Scott Wilson Piesold, 2005 |
| | Red Hills (Clay) | 2 m/day | United Nations,1987 |
| | Chepauk, Chennai | 15 m/day | United Nations,1987 |
| | Red Hills Tirulavallur Rd | 106 m/day | United Nations,1987 |
| | Tambaram (Hard Rock) | 3 m/day | United Nations,1987 |
| | Koyambedu | 82 m/day | United Nations,1987 |
| Storativity | Uttukotai | 0.009 | Central Ground Water Board, 2004 |

These pump test values were use to guess the hydraulic conductivity in various zones in the model area. The actual values were fine tuned by the calibration process described below.

### D.8 Calibration

To estimate the values of the hydraulic conductivity we used a two-pronged approach. We used a steady-state model to calibrate the "steady-state parameters", then applied the steady-state parameters to a transient model to estimate the transient parameters.

The transient groundwater equation is presented below.

$$\frac{\partial}{\partial x}(K_x \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(K_y \frac{\partial h}{\partial y}) + \frac{\partial}{\partial z}(K_z \frac{\partial h}{\partial z}) = S_s \frac{\partial h}{\partial t} + G$$

where

G = Sources/ Sinks

K = Hydraulic Conductvity

S = Specific Storage

h = Hydraulic Head

**Equation 0.3**

If the system is in steady-state $S_s \frac{\partial h}{\partial t} = 0$, the groundwater equation reduces to

$$\frac{\partial}{\partial x}(K_x \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(K_y \frac{\partial h}{\partial y}) + \frac{\partial}{\partial z}(K_z \frac{\partial h}{\partial z}) = G$$

where

G = Sources/ Sinks

K = Hydraulic Conductvity

**Equation 0.4**

Now clearly, the groundwater flow system is not in steady-state. However, the groundwater observation data, we were able to find two periods (January 2002 to January 2003 and July 2004 to July 2005) in which the groundwater patterns did not change significantly over a 12-month period. So we could simulated the system as being in steady-state using aggregate recharge and discharge over each of the two 12-month periods.

The heads in the two steady-state periods are shown in Figures D.11 and D.12 respectively.

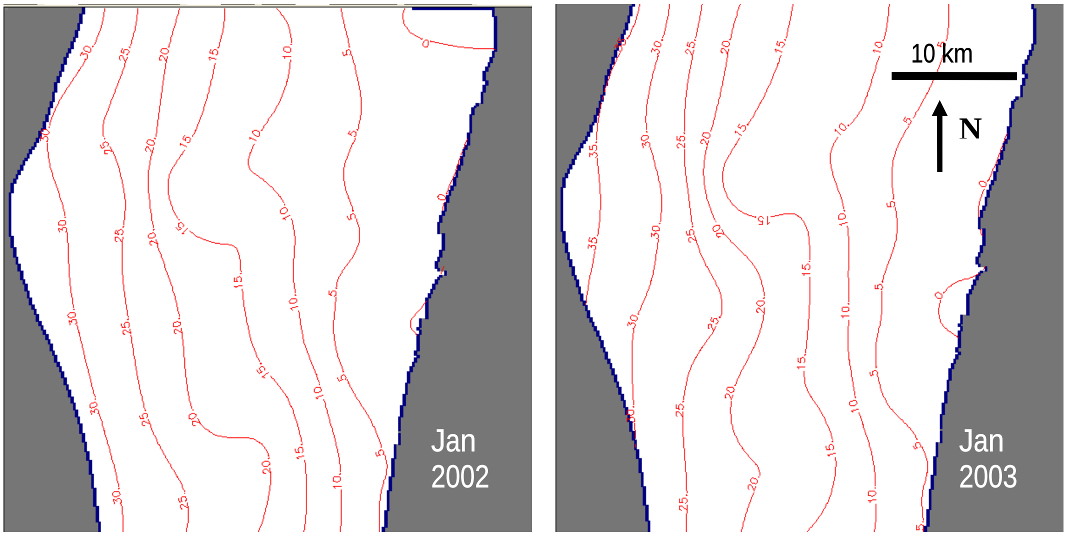

Figure 0.11: Hydraulic Heads (m above MSL): January-2002 to January 2003

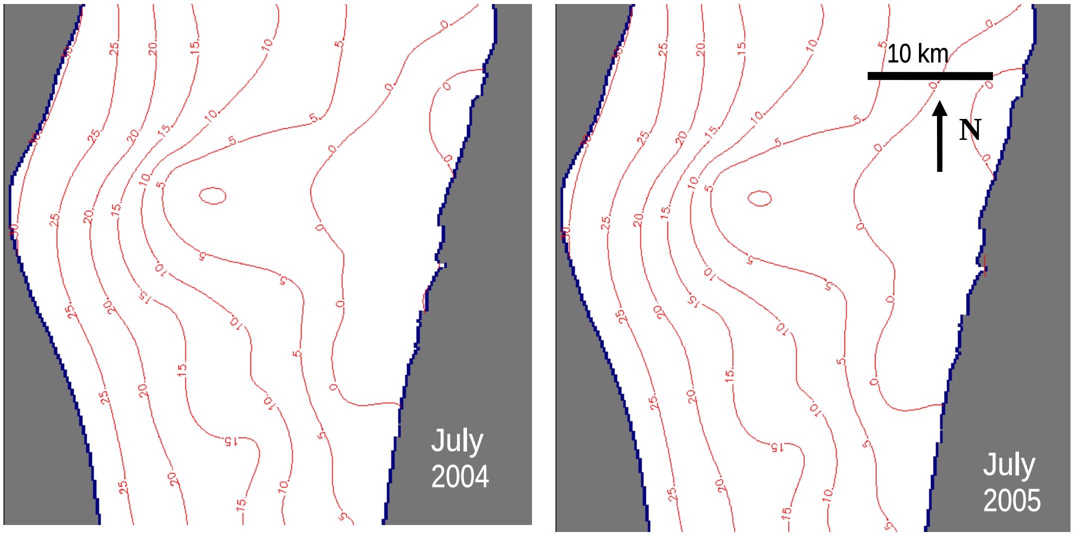

Figure 0.12: Hydraulic Heads (m above MSL): July 2004 to July 2005

To configure the initial hydraulic conductivities for the upper unconfined aquifer, we identified four types of areas: Alluvium, River Channels, Weathered rock outcrop and Alluvium with surficial clay. The entire model area was divided into seven zones (Figure D.13) each zone corresponding to one. The zone map was based on the geologic map of Chennai developed by the UNDP (United Nations, 1987) as well as earlier research by local scholars (Ravi, 1997).

The initial hydraulic conductivites input into the model were based on the pump-test data in Table D.4, we assumed highest conductivity in the river channels (between the Adayar and

Cooum rivers) outside Chennai, and along the Koratalaiyar river to the north. We assumed a slightly lower conductivity for the rest of the alluvium. The weathered rock area was assumed to have a much lower conductivity. Finally, in small areas where surficial clay was significant (in the Anna Nagar and Mandavalli areas of Chennai for instance), we assumed the conductivity was locally much lower, closer to the conductivity of clay. Vertical conductivity was assumed to be a tenth of the hydraulic conductivity because of the clay layers. In the weathered rock area, the vertical conductivity is assumed to be the same as the horizontal conductivity. Average recharge and extraction for the year were used.

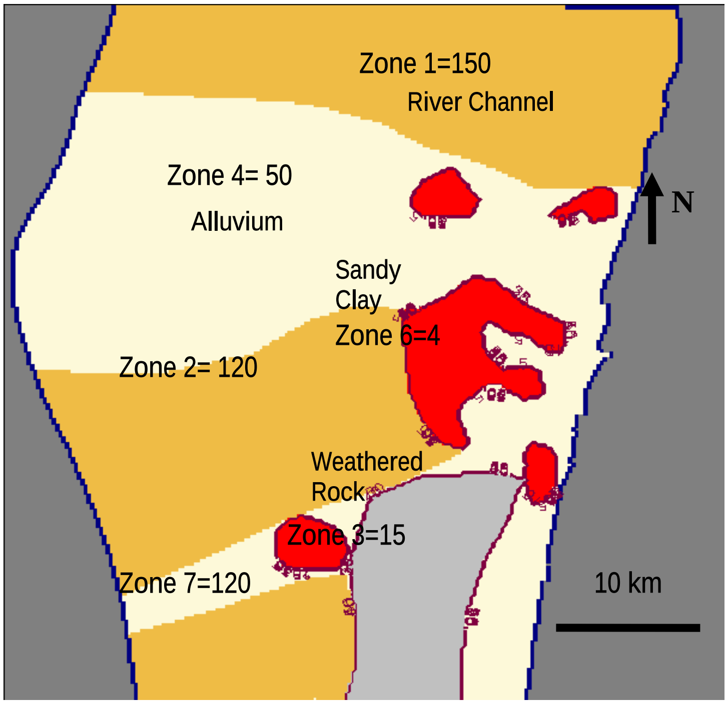

**Figure 0.13: Calibrated Hydraulic Conductivities (in meters/day)**

The calibrated versus observed heads for the steady-state model are shown in Figure D.14 and D.15.

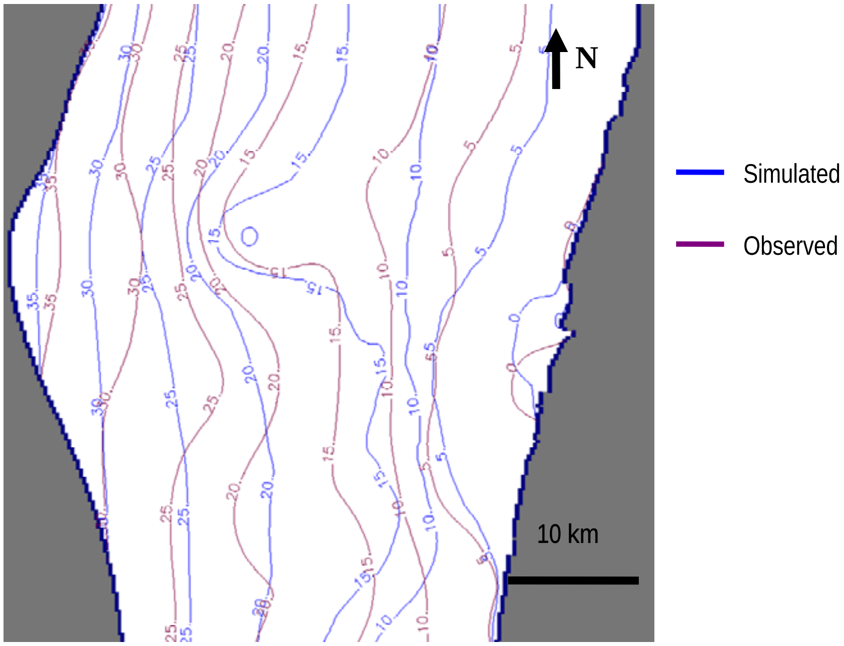

**Figure 0.14: Steady-state model, calibrated versus observed heads: Jan 2002 to Jan 2003**

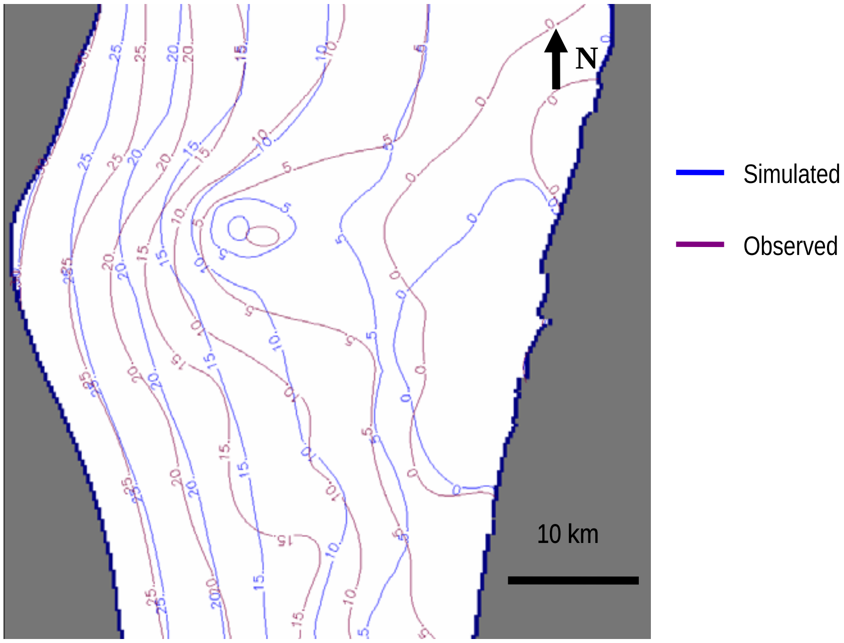

**Figure 0.15: Steady-state model, calibrated versus observed heads: Jul 2004 to Jul 2005**

For both steady-state models we were able to get the simulated heads within 1 m of observed heads. During the calibration process we found that the extent and location of the weathered rock zone to the south was quite important in replicating heads in that area. While the general extent and shape of bedrock outcrop was obtained from the contoured lithologs and the 1987, UN map, minor modifications were made to make the heads match. Thus, from the steady-state runs, we were able to separately calibrate the hydraulic conductivity. We were also able to get upper and lower bounds for recharge and discharge.

The steady-state calibration yielded two important insights. Firstly, it set the bounds for total extractions (including domestic and commercial) within Chennai between 200 to 250 MLD (about 40-50 LPCD). Beyond this range it would be very difficult to replicate the heads observed, using reasonable values of conductivity and recharge.  Secondly, in agricultural areas, groundwater extraction had to range between 35 and 45 kL/day/ grid cell. Beyond this range it would be difficult to match the heads in areas outside Chennai.  Finally, the calibrations of urban and agricultural extractions were quite independent. Because the agricultural and urban areas are segregated, each could be calibrated independently. i.e., it was not possible to compensate for higher agricultural extraction by assuming lower urban extractions and vice versa.

An iterative approach to calibration was adopted. We began by guessing initial K values, recharge and extractions. We then ran the steady-state model to obtain reasonable matches between observed and modeled heads, given for these initial values of hydraulic conductivity. Once these were fixed, we could use the transient run to calibrate transient parameters, like storativity.  Finally, we entered our best estimates of parameters in the integrated model. Then actual extractions from the Consumer module were linked to the groundwater model. Once the whole model was linked, we needed to fine tune all parameters again. A flow-chart containing the iterative approach is presented in FigureD.16.

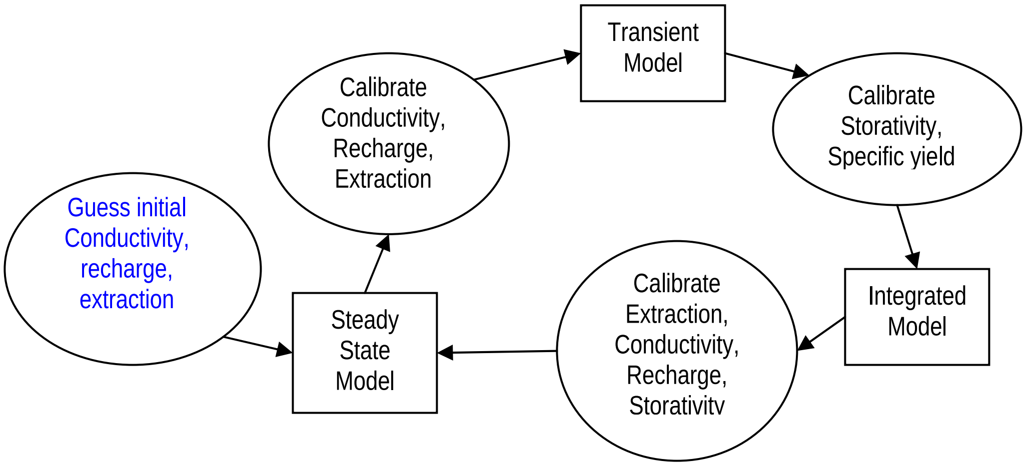

**Figure 0.16: Iterative calibration process**

For the transient model, we had to assume specific yield values between 1 and 5% for the upper layer. However, because the model layers were modeled as confined layers, these had to be divided by the layer thickness and entered as storativity values. The final parameters used in the different zones are shown in Table D.5.

**Table 0.5: Final Parameter Values**

| | **Layer1** | | | **Layer2** | | | **Layer3** | | |
|---|---|---|---|---|---|---|---|---|---|
| | **HK** | **VK** | **SS** | **HK** | **VK** | **SS** | **HK** | **VK** | **SS** |
| Zone 1 | 150 | 15 | 5% | 4 | 0.4 | 0.0005 | 100 | 10 | 0.0025 |
| Zone 2 | 120 | 12 | 5% | 4 | 0.4 | 0.0005 | 100 | 10 | 0.0025 |
| Zone 3 | 50 | 5 | 1% | 15 | 15 | 0.0010 | 15 | 15 | 0.0010 |
| Zone 4 | 50 | 5 | 3% | 4 | 0.4 | 0.0005 | 25 | 2.5 | 0.0010 |
| Zone 5 | 50 | 5 | 3% | 4 | 0.4 | 0.0005 | 25 | 2.5 | 0.0010 |
| Zone 6 | 10 | 1 | 1% | 4 | 0.4 | 0.0005 | 25 | 2.5 | 0.0010 |
| Zone 7 | 50 | 5 | 3% | 4 | 0.4 | 0.0005 | 25 | 2.5 | 0.0010 |
| Zone 8 | 10 | 1 | 1% | 4 | 0.4 | 0.0005 | 25 | 2.5 | 0.0010 |

* HK= Horizontal conductivity in m/d
VK= Vertical conductivity in m/d
SS = Storativity or specific yield

The hydrographs of the transient run from the final calibration, after iterating back and forth between the steady-state and integrated models are shown in figures D.17 to D.27. Note that these wells only are for the specific hydrographs shown for which we had continuous data. For the spatial maps, we used data from multiple data sets[98], about 140 wells. Hydrographs for selected wells from different parts of the model area were prepared. The locations of the selected wells are presented in Table D.6.

**Table 0.6: Location of wells in model area**

| **Agency-Well #** | **Location** | **Latitude (N)** | **Longitude (E)** | **Row** | **Col** |
|---|---|---|---|---|---|
| PWD-13227 | Perungudi | 12.9583 | 80.2381 | 183 | 160 |
| CGWB-1008 | Attipatu | 13.2625 | 80.2903 | 31 | 186 |
| PWD-13235 | Pallavaram | 12.9725 | 80.1536 | 176 | 118 |
| CGWB-512 | T-Nagar | 13.0778 | 80.2292 | 123 | 156 |
| PWD-13024 | Pakkam | 13.1528 | 80.0306 | 86 | 56 |
| CGWB-561 | Vepery | 13.0833 | 80.2708 | 120 | 176 |
| CGWB-1022 | Tirumazhisai | 13.0625 | 80.2792 | 131 | 72 |
| CGWB 816 | Tirumangalam | 12.9833 | 80.2272 | 120 | 141 |
| CGWB 490 | Alwarpet | 13.0833 | 80.2000 | 149 | 170 |
| PWD-13021 | Chettipedu | 13.0250 | 80.2583 | 145 | 44 |
| PWD-13144 | Tiruvottiyur | 13.0333 | 80.0056 | 95 | 159 |
| PWD-13156 | Nungambakkam | 13.1333 | 80.2361 | 145 | 166 |

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[98] CGWB 2007, Metrowater 2007, WRO 2007

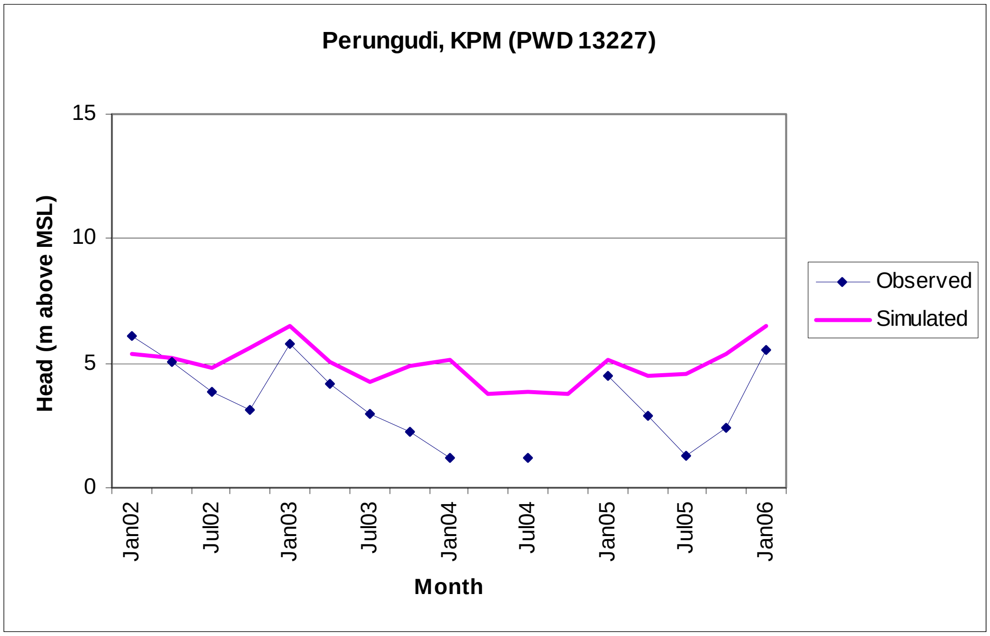

Figure 0.17: Observed versus Calibrated Hydrograph –PWD 13227

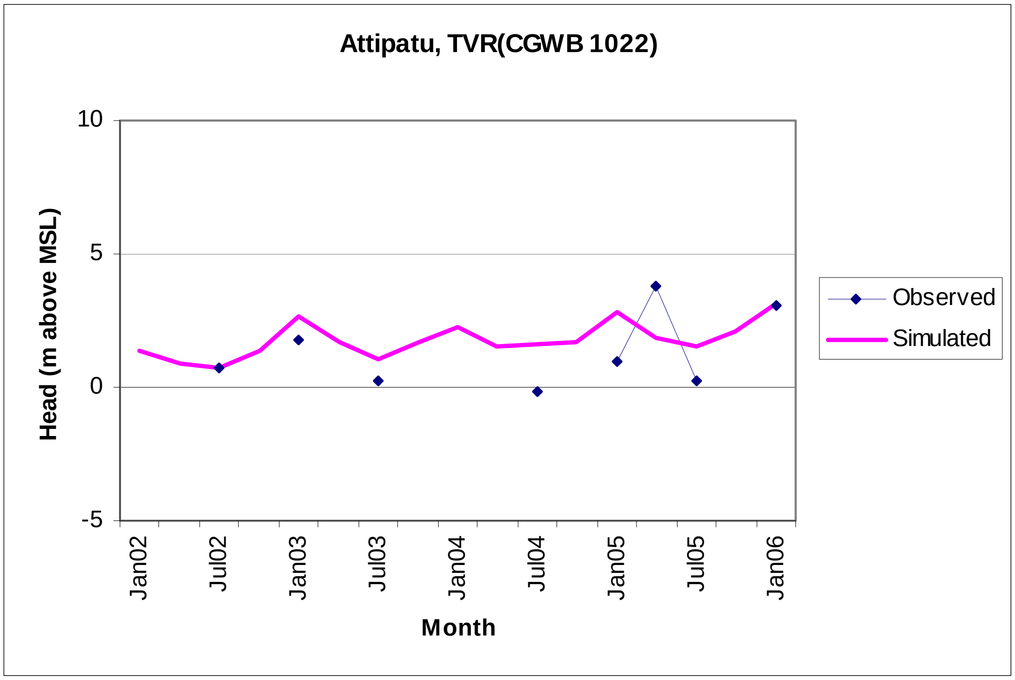

Figure 0.18: Observed versus Calibrated Hydrograph – CGWB 1022

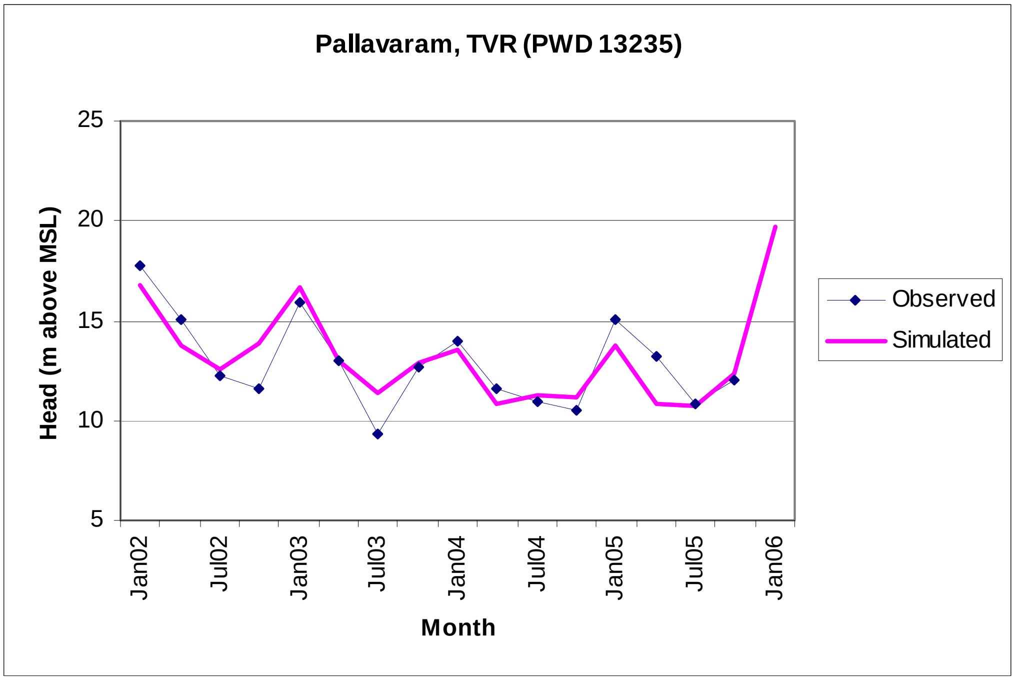

Figure 0.19: Observed versus Calibrated Hydrograph –PWD-13235

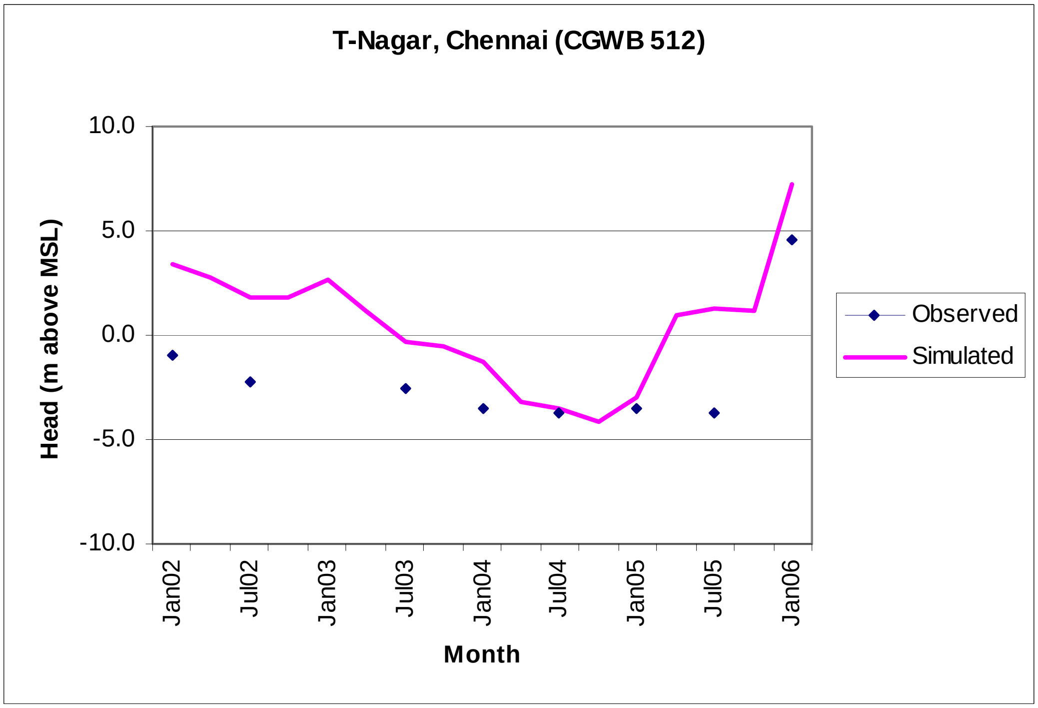

Figure 0.20: Observed versus Calibrated Hydrograph –CGWB-512

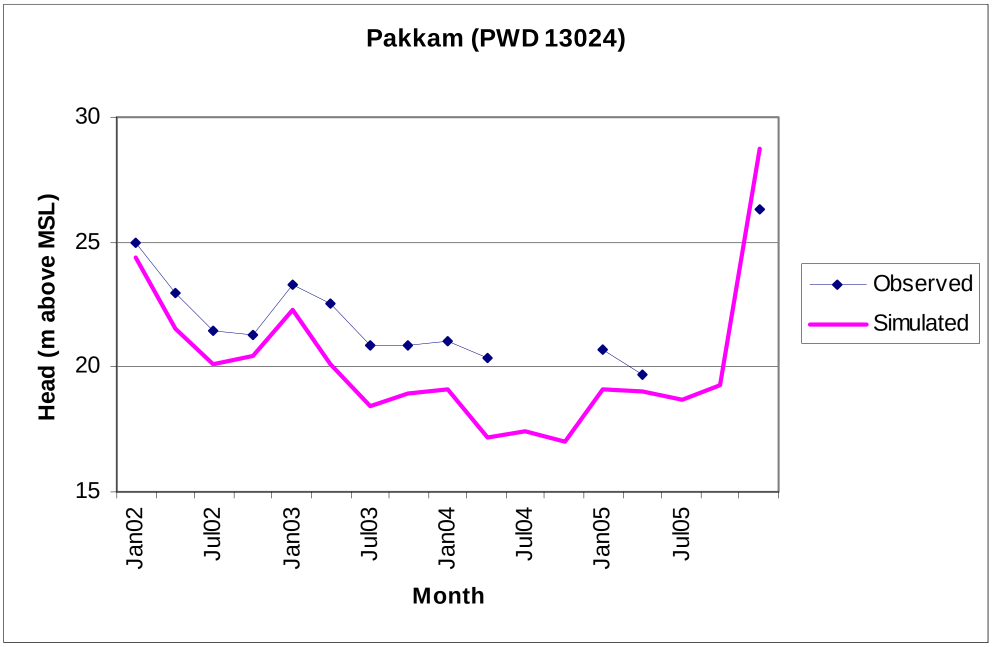

Figure 0.21: Observed versus Calibrated Hydrograph –PWD 13024

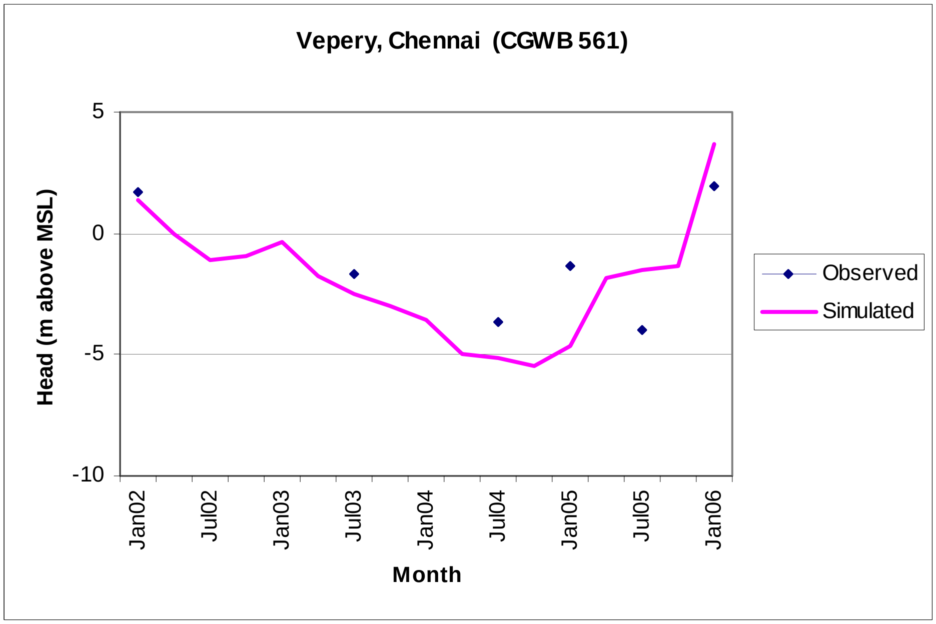

Figure 0.22: Observed versus Calibrated Hydrograph –CGWB-561

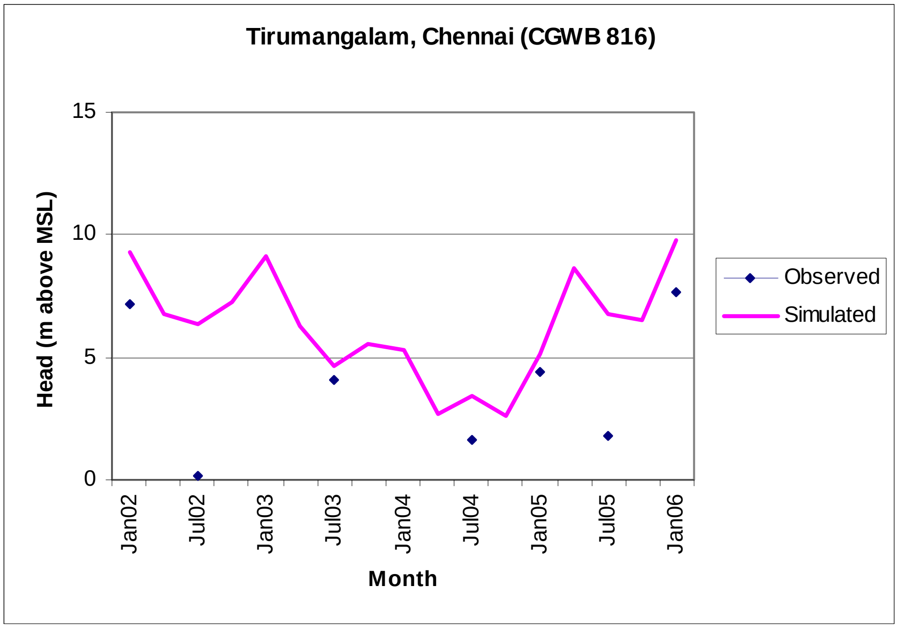

Figure 0.23: Observed versus Calibrated Hydrograph –CGWB-816

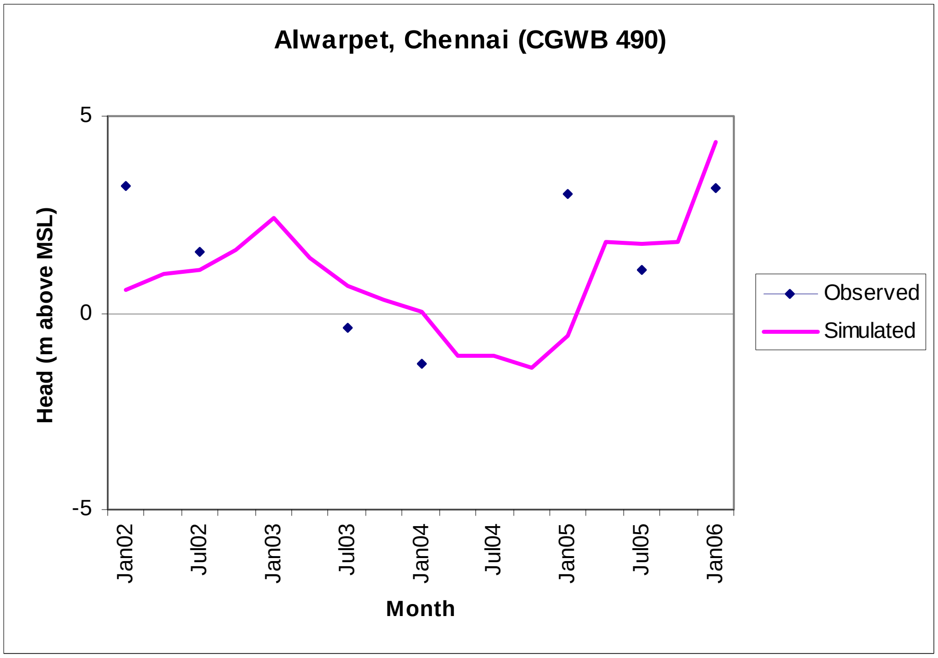

Figure 0.24: Observed versus Calibrated Hydrograph –CGWB 490

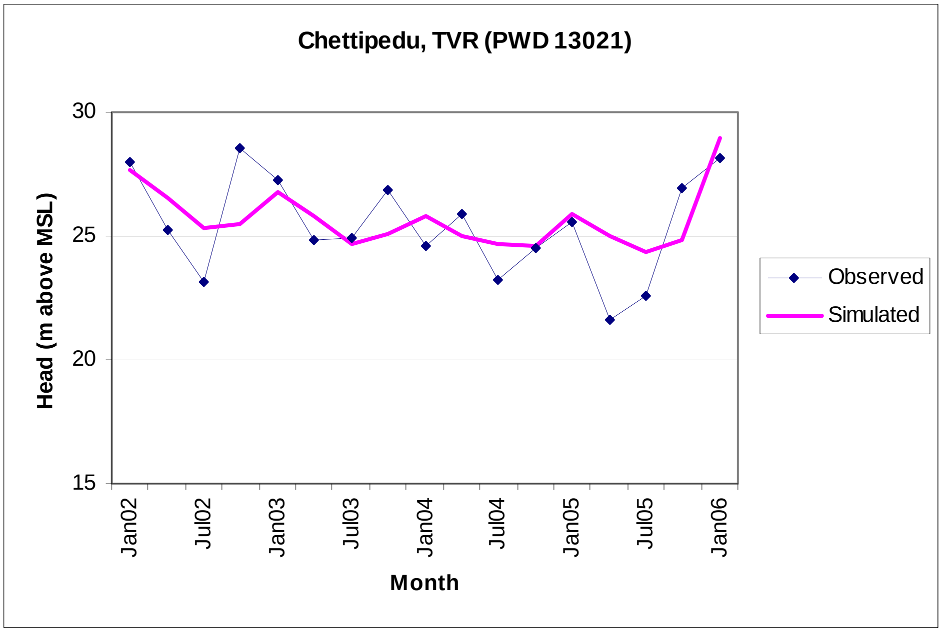

Figure 0.25: Observed versus Calibrated Hydrograph –PWD 13021

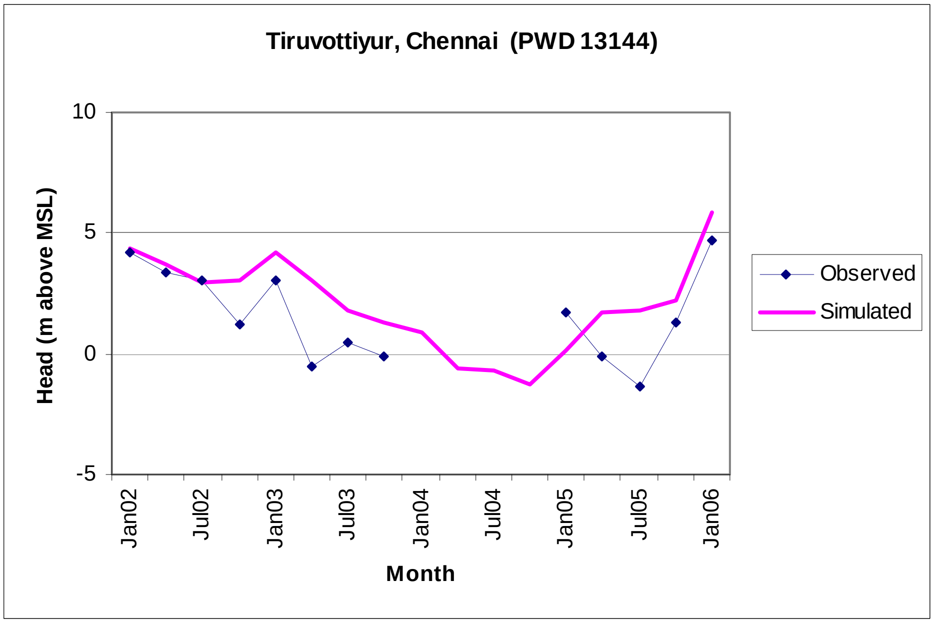

Figure 0.26: Observed versus Calibrated Hydrograph –PWD 13144

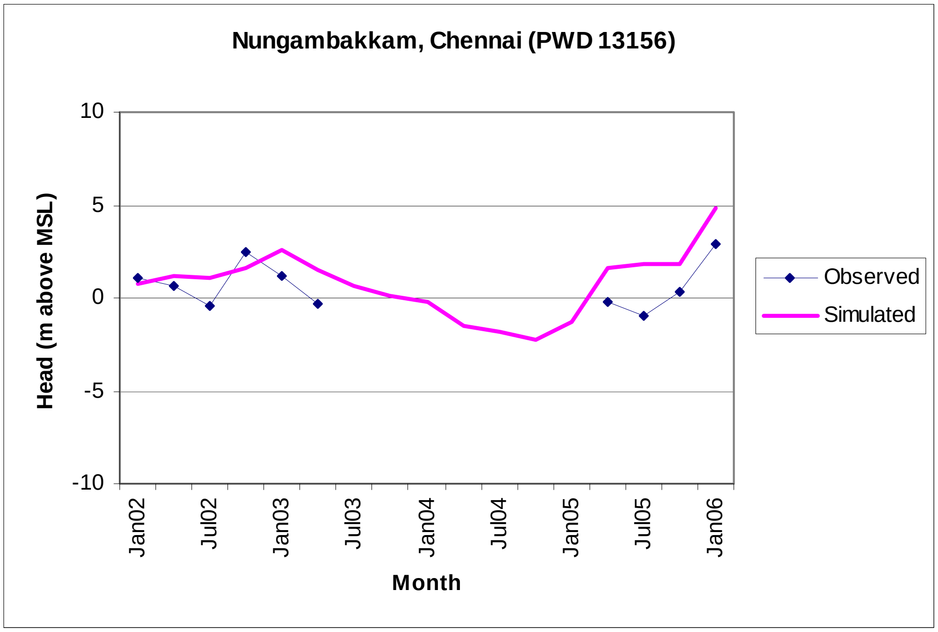

Figure 0.27: Observed versus Calibrated Hydrograph –PWD 13156

# Appendix E. Fraction of water allocated to Chennai

In this Appendix, we discuss how we deduced the allocation of water between Chennai city and the Manali-Avadi industrial area and adjacent municipalities. As described in Chapter 4, this needed to be done because the total water supplied from all sources to Metrowater far exceeds the quantity supplied within Chennai. A significant component of the water is supplied to heavy industries outside the city and peri-urban townships.

To determine the allocation, we assumed that water is allocated proportional to demand between Chennai and adjacent industrial/peri-urban areas. Based on this proportional allocation assumption we obtained the fraction of total supply in any period that would be distributed within Chennai. Next the fraction was further fine-tuned so that the simulated total utility supply matched the data reported by Metrowater.

***Estimation based on proportionality rule***

We assume that Metrowater allocates water between Chennai and surrounding areas in proportion to the demand of each. Metrowater's estimate of the demand from heavy industry in the Manali-Avadi industrial area outside Chennai and adjacent municipalities is as shown in Table E.1.

**Table 0.1: Water demand: Chennai versus adjacent areas**

| Area | **2006 Water Demand (Million Liters/ Day)** |
|---|---|
| Utility supply (domestic, commercial and industrial) within Chennai City | 861* |
| Industries north of Chennai | 100 |
| Utility supply (domestic and commercial) to peri-urban towns | 362 |
| **Total demand in basin** | **1326** |

Source: Metrowater 2006(a)

In Table E.1, the ratio of estimated water demand within Chennai to the total basin demand (including neighboring industrial zones and municipalities) is 861/1326 = 64 percent. This implies that in a given period, if Metrowater allocates water in proportion to demand, Chennai should receive about two-thirds of the available supply.

***Calibration with reported data***

The quantity of water from the reservoirs, well-fields, Telugu Ganga, Veeranam Project and local sources was known for the historical period as shown in Figure E.1.

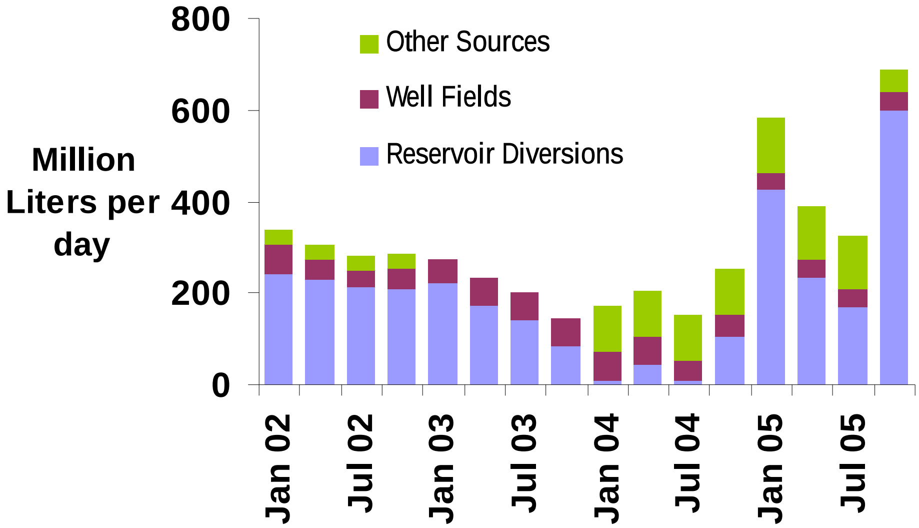

**Figure 0.1: Total water supply from different sources**

For modeling purposes we assumed that Chennai's share of available water is maintained at 65 percent, approximately the five year average. Using this fraction, the simulated city supply was close to the actual city supply in all years as can be seen in Figure E.2. From Figure E.2, we may observe that the calibrated model utility supply numbers match reported figures by Metrowater reasonably well. Figure E.2 shows utility supply by year and not for each three-month model period because utility supply was only available as annual data.

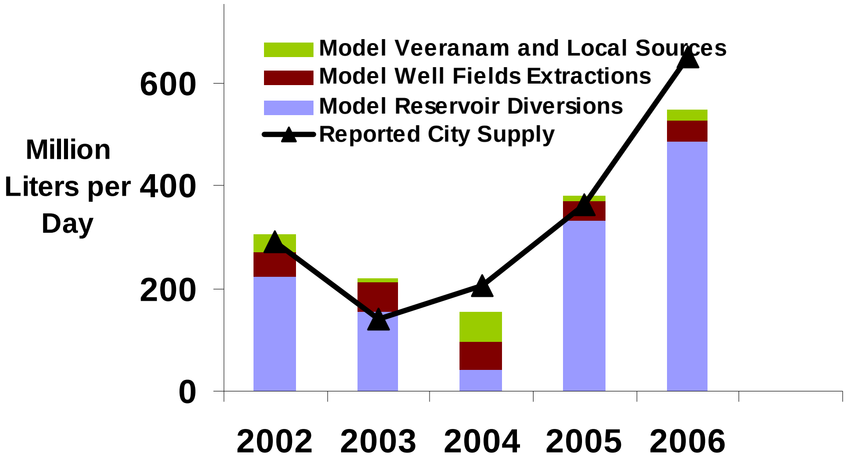

**Figure 0.2: Calibrated versus reported total utility supply**

# Appendix F. Household Surveys

In this Appendix, we present water-use data from two household surveys, each of about 1500 households, conducted in 2004 and 2006.

### *F.1: 2004 Survey Description*

The 2006 survey was a repeat survey of an earlier one commissioned by the Centre for Science and Environment (CSE), New Delhi in December 2004-January 2004, at the peak of a multi-year drought[99]. The Centre for Science and Environment generously shared both the raw data and the hard copies of the surveys with us. The original CSE survey used a stratified sampling procedure to select a total of 1510 households. The sampling process was as follows. The 155 census wards (neighborhoods) in Chennai were allocated into 9 strata. 31 wards were selected randomly from each of the 9 strata. The nine strata included combinations of three income levels (high income, medium income and low income) and three supply levels (high number of streets receiving no supply, medium number of streets receiving no supply, and low number of streets having no supply). The total numbers of households selected from nine strata were in proportion to the number of households in each stratum as per the 1991 census.

### *F.2: Survey Design*

The January 2006 survey, designed by us, followed the wettest monsoon in Chennai's recorded history. The 2006 survey resurveyed the same households interviewed in 2004 as far as possible[100]. However, the questionnaire was redesigned to better meet our data requirements.  The changes made it possible to have a consistent nomenclature and a mutually exclusive, collectively exhaustive set of supply sources. A total of 1488 households were surveyed in 2006.  Thus the two surveys represented two extremes in the Chennai water supply situation, a drought and a very wet year.

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[99] Vaidyanathan and Saravanan, 2004

[100] Although every effort was made to contact the same households, this turned out to be a very difficult task as street numbers were changed in most parts of the city between 2004 and 2006. Moreover, if the residents were away or unavailable, another house was selected randomly from the same street. As a result, while the 2006 survey sampled the same streets and has distribution of households as the earlier survey, the actual households were not identical. The 2006 survey schedule was altered to clarify some ambiguous questions in the 2004 survey questionnaire.

In both years, the surveys were conducted by the postgraduate students in the Department of Social Work at Madras Christian College. In both cases, the fieldwork was closely supervised by faculty member Mr. Prince Annadurai.

A pre-test of 50 households from 5 wards was conducted to test the altered survey schedule. Several in-depth training sessions were held to train the students and clarify definitions using pictures, hypothetical scenarios and demonstrations. "Manuals" with definitions were provided to the surveyors to clarify definitions. The survey schedules used in the 2004 and 2006 surveys are presented in at the end of this Appendix.

### *F.2.1 Socio-economic characteristics of sample households*

In 2006, a total of 1488 households from 31 wards (the smallest census unit within the city, averaging a little over 1 sq km in area) were surveyed. The sample included a total of 7318 household members, about a quarter of whom were children. More than 80 percent of the heads of households reported having secondary or higher level education. 45 percent of the heads of households had full-time regular jobs. About a third of the heads of households were self-employed. The rest were pensioners or casual wage laborers. The 2004 sample had a similar demographic profile.

38 percent of the sampled households were "low-income", with a monthly household income of less than Rs. 5000 per month. 8 percent were high income with household incomes of Rs. 20,000 or more per month[101]. 7 percent of the households lived in apartment complexes.
65 percent of the households were owner-occupied. The rest were rented. House ownership was strongly correlated with income. Most households (almost 90 percent) in high-income households owned their houses versus a little over half of the low-income households.

It is known that households using water from taps use a lot more water than households that have to manually collect the water from a source. To account for this, households were also post-classified as "tap" and "non-tap" households[102], based on how they actually accessed water. Tap households were defined as households having indoor plumbing (defined by

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[101] We observed that there was some tendency to under-report income. Some households who were clearly high-income based on house-type, and appliances in the household, claimed to be low or medium income. However, there was no way to cross-check this at the time of the survey.

[102] Strand and Walker, 2005

presence of an overhead tank[103]). Tap households typically obtained water from the Metrowater pipe mains, electrified wells, and occasionally private tankers. Non-tap households collected water manually in pots, from in-house handpumps, public standpipes, wells, Metrowater tankers[104], water vendors[105], or community wells/ water bodies. The water is stored in pots or barrels in the house and accessed using a mug or an outlet at the base of the container.

In 2006, 66 percent of households surveyed were found to be "tap" consumers, the rest were non-tap consumers. As would be expected, indoor plumbing is strongly correlated with income. Only 42 percent of low-income consumers have indoor plumbing versus all but one of the high-income households as shown in Table F.1.

**Table 0.1: Mapping indoor plumbing to income**

| **Income** | **Tap** | **Non-Tap** |
|---|---|---|
| Low Income (< Rs 5 K/Month) | 42% | 58% |
| Medium Income (5K – 10K/ Month | 64% | 36% |
| Upper Medium Income (>10-20K/Month) | 97% | 3% |
| High Income (>20K/Month) | 99% | <<1% |

### *F.2.3 Supply Sources in 2004 vs. 2006*

Households surveyed were asked detailed questions of the nature and sources of their water supply. Since the 2006 survey questionnaire was different from the 2004 schedule, the two surveys are not perfectly comparable. However, every attempt was made so that the surveys would be comparable at least at an aggregate level. For purposes of comparison, the categories were mapped as follows:

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[103] This robustness of this definition was cross-checked by examining how consumers accessed water. In almost all cases the presence of a OHT indicated a piped connection or an electric borewell. Likewise, households not having OHTs reported gathering water in pots from different sources.

[104] In addition to piped supply and standpipes, Metrowater also supplies water to low-income neighborhoods and neighborhoods where the pressure in the piped mains is too low "deficient neighborhoods" by plying operating tankers. Households line up at the tanker each day and collect anywhere for 3-10 pots of water.

[105] Water vendors are private entrepreneurs. They collect water in pots at free public standpipes and transport them by bicycles or push-carts to low-income neighborhoods. They go door-to-door selling the water for about Re 1 per pot.

**Table 0.2: Matching categories in two surveys**

| 2004 Survey Category | 2006 Survey Category |
|---|---|
| ***Public Sources*** | |
| In-House Supply | Metrowater piped supply<br>Metrowater in-house handpump<br>Direct connection /Yard tap |
| Outside tap/Handpump | Public Standpipe, Street tap |
| Metrowater tanker<br>Fixed Tank[106] | Mobile Supply / Metrowater tanker |
| ***Public Sources*** | |
| Own Well | Own Well |
| Private tanker[107] or water vendor | Private tanker or water vendor |
| Packaged Water | Packaged Water |
| Other well<br>Community well | Other/ Community sources |

The number of sources accessed in both surveys is shown in table F.3. While in both years, the majority of households used, two or more sources of water, more sources were used in 2004, than 2006. The number of sources accessed was much higher in 2004.

**Table 0.3: Number of sources used**

| Number of Sources | 2004 | 2006 |
|---|---|---|
| Single Source | 23% | 35% |
| Two Sources | 34% | 50% |
| Three or more sources | 43% | 15% |
| Non-Reporting | <<1% | <<1% |

The fraction of households using a particular source is shown in Table F.4. The fractions do not add up to 100% because households accessed multiple sources of water in both years.

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[106] As we understand it, fixed tanks refer to the black street-level Sintex tanks installed by Metrowater. In our field surveys, we found that these were filled once or twice a day by Metrowater lorries and households did not distinguish between water collected directly from the lorry and water collected from the tank filled earlier in the day by a lorry.

[107] Private tankers purchase water from farmers in peri-urban areas and transport them to the city charging anywhere between Rs 550 and Rs 800 for a 12 kiloliter tanker. Metrowater also allows consumers to purchase water by paying Rs 650 for a 12 kL lorry. These purchases were treated as private tanker supply. Only a handful of households availed this facility in 2006.

**Table 0.4: Fraction of households accessing a source**

| Overall fraction of HH reporting supply | Jan 2004 | Jan 2006 |
|---|---|---|
| **Public (Utility) Sources** | | |
| Inhouse Metrowater Supply | * | 81% |
| Metrowater Piped Supply | | 31% |
| Metrowater Handpump | | 49% |
| Public Standpipe/Street Tap | 27% | 12% |
| Metrowater Lorry | 12% | 8% |
| **Private (Non-Utility) Sources** | | |
| Own Well | 66% | 48% |
| Private Lorry/ Water Vendor | 7% | 4% |
| Packaged Water | 36% | 21% |
| Other | 4% | <1% |

*Although the 2004 survey reports some in-house piped use, this is small and assumed to be erroneous, because the piped system was largely not operational or highly curtailed during that period.

Not surprisingly, households received more in-house Metrowater supply in 2006 and almost none in 2004, as public supply was greatly curtailed because of the drought. In 2004, Metrowater ran tankers to supply water to most neighborhoods. So the number of household reporting Metrowater tanker supply was higher in 2004. Households generally reported greater dependence on all private sources in 2004, because of the poor utility supply. Surprisingly, despite utility supply being plentiful in 2006, the fraction of households using private wells was still significant at 48 percent.

The sources of supply accessed were strongly correlated with income in both years. Table F.5 and F.6 show the fraction of households in each income category who received supply from a given source. Note that the definition of "High Income" was slightly different in the two surveys.

**Table 0.5: Fraction of households accessing a source by income - 2004**

| Number of HH Reporting access in 2004 | Low Income | High Income > 15K/Month |
|---|---|---|
| Metrowater InHouse Supply | -- | -- |
| Public Standpipe/Street Tap | 78% | 18% |
| Metrowater Tanker | 67% | 10% |
| Own Well | 39% | 83% |
| Private Tanker/ Water Vendor | 10% | 32% |
| Packaged Water | 10% | 81% |
| Other | 20% | 1% |

**Table 0.6: Fraction of households accessing a source by income – 2006**

| Number of HH Reporting access in 2006 | Low Income | High Income > Rs 20K/Month |
|---|---|---|
| Metrowater In-House Supply | 70% | 96% |
| Metrowater Piped Supply | 10% | 79% |
| Metrowater Handpump | 62% | 29% |
| Public Standpipe/Street Tap | 28% | 4% |
| Metrowater Tanker | 11% | 1% |
| Own Well | 39% | 82% |
| Private Tanker/ Water Vendor | 4% | 3% |
| Packaged Water | 17% | 79% |
| Other | 1% | 0% |

### *F.3: Uses of Water*

Households were also asked to report the purposes for which water from different sources were used. Tables F.7 and F.8 show the percentage of households receiving supply from a particular source that reported a particular use.

**Table 0.7: Sources versus Uses 2004**

| Sources vs. Uses in 2004 | Drink | Cook | Wash | Bath | Toilet |
|---|---|---|---|---|---|
| Metrowater Inhouse Supply | 71% | 72% | 54% | 55% | 49% |
| Public Standpipe/Outside Tap | 20% | 20% | 21% | 21% | 21% |
| Metrowater Tanker | 82% | 87% | 33% | 35% | 27% |
| Own Well | 16% | 35% | 86% | 87% | 87% |
| Private Tanker/ Water Vendor | 15% | 26% | 42% | 41% | 39% |
| Packaged water | 100% | 27% | 0% | 0% | 0% |
| Other | 14% | 25% | 90% | 91% | 90% |

**Table 0.8: Sources versus Uses – 2006**

| Source versus uses in 2006 | Drink | Cook | Wash | Bath | Toilet |
|---|---|---|---|---|---|
| Metrowater Piped Supply | 59% | 86% | 72% | 69% | 65% |
| Metrowater In house Handpump | 52% | 92% | 52% | 52% | 46% |
| Public Standpipe/Outside Tap | 83% | 94% | 90% | 85% | 84% |
| Metrowater Tanker | 81% | 71% | 60% | 60% | 57% |
| Own Well | 10% | 24% | 93% | 95% | 98% |
| Private Tanker/ Water Vendor | 32% | 91% | 29% | 21% | 18% |
| Packaged water | 100% | 8% | 0% | 0% | 0% |
| Other | 5% | 18% | 77% | 86% | 100% |

The data indicate that Metrowater water (piped supply, handpump supply, and tanker supply) was more likely to be used for cooking and washing; uses that necessitate higher quality water. Water from Metrowater is chlorinated and therefore known to be better quality. Well water and community sources are untreated sources and were more likely to be used for flushing, bathing and washing. The quality of water from private tankers, vendors and public standpipes varies depending on the source[108] and the uses correspondingly varied.

### *F.4: Estimating quantity of water supplied:*

In the sections above we have confined our analysis to the proportion of households using various sources of water. No quantitative estimates of the amount of water used have been provided so far. In the absence of metering, estimation of the quantity consumed is very difficult. In both surveys the quantity of water used by source was estimated indirectly. It should be noted that the quantity estimates involved making assumptions about pump efficiency and should therefore be interpreted with caution.

After considering several options, a method of estimating the quantity of water supplied based on pump operation times was chosen. Both piped supply and wells are pumped to overheads tanks and allowed to flow by gravity to taps within the house. The quantity of water supplied could be calculated using time for which the pumps were turned on each day, the horsepower of the pump and pump curve[109].

The quantity of water accessed (in liters per capita per day or LPCD) from different sources is shown in Table F.9. The LPCD figures are averages for the whole sample and should be interpreted accordingly.

**Table 0.9: Liters per capita per day by source**

| **Liters per capita per day (LPCD) from different sources** | **2004LPCD** | **2006 LPCD** |
|---|---|---|
| **Public (Utility) Sources** | -- | -- |
| Metrowater Inhouse | 0 | |
| Metrowater Piped Supply | | 30 |
| Metrowater Handpump | | 19 |
| Public Standpipe | 12 | 2 |
| Metrowater Lorry | 6 | 2 |

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[108] While private tanker operators get untreated water from peri-urban tankers, water vendors collect water from public standpipes. Some public standpipes are connected to a borewell and yield untreated even saline groundwater. Others are connected to the piped supply system and supply treated water.

[109] The pump curves were reasonably similar, so that it was reasonable to attempt a quantity estimation even without specific information on the brand used.

| **Liters per capita per day (LPCD) from different sources** | **2004LPCD** | **2006 LPCD** |
|---|---|---|
| **Private (Non -Utility) Sources** | **--** | **--** |
| Own Well | 36 | 46 |
| Private Lorry/ Water Vendor | 4 | 2 |
| Packaged Water | 0.8 | 0.7 |
| Other | | ~0 |
| **Total LPCD** | **59** | **101** |

Not surprisingly, households consumed less water in 2004 than 2006. Much of the water in 2004 came from private, often labor-intensive sources of water. In contrast, in 2006, most of the water came from public or piped sources of water. When the figures are disaggregated by income, the pattern that emerges is more complex. Although in both years, well water accounted for anywhere from 30 to 60 percent of the water supplied to all income groups, low income groups were more reliant on wells than high income groups in the wet year (i.e. received a higher fraction of their supply from wells). High income households received enough public supply and operated their wells less often.

In contrast, during the drought, high income sump households received less public supply (see Chapter 5 for discussion on this), but were also able to compensate to some extent by extracting more groundwater. The lower overall consumption might indicate that groundwater supply may also have been restricted by supply constraints. The water table was much lower in 2004 and many wells went dry. Moreover, the lower water table meant that water was being extracted from the poorer-yielding lower aquifer. Low income households had shallower wells (almost 20 ft. shallower), and thus more likely to have their wells run dry. This view is consistent with our earlier hypothesis that groundwater was a limiting factor in 2004. By comparing the household survey data in 2004 and 2006 we can conclude the following

1. Households can and do use multiple sources of water to meet their needs
2. The sources used depend on availability of water from different sources. i.e. exogenous supply constraints
3. During a drought, households cope by shifting to either (more expensive) private or more labor intensive sources and also use less water overall.
4. The sources of water accessed by households vary between dry and wet years.
5. The sources of water accessed also depend on the infrastructure investment in access (wells), storage (overhead tanks and sumps) and treatment facilities.

In summary, access to water appears to a function of access to public supply, quantity and quality of groundwater and a household's investment in infrastructure and ability to pay for private water.

## *F.5: Commercial Survey Description*

While the 1998 Economic Census data list million of commercial establishments in Chennai, there are only about 44,000 commercial connections, and only 1000 "water intensive" commercial connections (establishments exceeding 300 kL/day).

In surveying commercial establishments, only medium and large water-using establishments were surveyed. This is because only medium and large commercial establishments use significant about of water. Large water-intensive commercial consumers were over-sampled and comprised 15% of the sample even though they constitute less that 5% of Metrowater's commercial consumers. About 217 commercial establishments conducted in December 2006 and January 2006. The total sample size is relatively small and dictated by budgetary and time constraints.

The distribution of establishments in our sample was as follows:

**Table 0.10: Types of establishments surveyed**

| **Establishment Type** | **Fraction** |
|---|---|
| Restaurant | 13% |
| Hotel | 12% |
| Educational | 6% |
| Hospital | 8% |
| Office | 16% |
| Retail | 17% |
| Other | 27% |

Of these about 15% had 30 or more employees and were defined as "large commercial".

Of the establishments surveyed, almost 60 percent of the establishments used multiple sources of water.

**Table 0.11: Fraction of establishments using multiple sources**

| Number of Sources | **No of establishments** | **Percent of establishments** |
|---|---|---|
| Non-Reporting | 4 | 2% |
| 1 | 84 | 39% |
| 2 | 107 | 49% |
| 3 | 19 | 9% |
| 4 | 3 | 1% |

While private wells were the sole source of water for 44% of single-source establishments, as high as 14% of establishments depended entirely on privately purchased water.

**Table 0.12: Source dependence of commercial establishments**

| **Main source** | **Percent of establishments** |
|---|---|
| Metrowater piped supply | 21% |
| Own Well | 44% |
| Private Tanker | 14% |
| Others | 5% |

# Appendix G. Survey Questionnaire

**Investigator:**

**Date:**

**Ward No:** **House Number:** **Name of street:**
**Schedule Number:**

**Dwelling Classification code (Circle appropriate):**
**1 SLUM** **2 FLAT** **3 HOUSE** **4 GOVT. QUARTERS**

## 1. Household Characteristics

**1.1** Brief Description (Briefly Describe the house – e.g. Large Posh mansion, Government quarters for lower level staff, government quarters for officers, well-maintained apartment complex etc.)

**1.2** Number of Members in household defined as family members sharing a kitchen (Fill in all blanks, 0 if none)

**1.2.1** Adult males ______
**1.2.2** Adult females ______
**1.2.3** Children (< 18 years) ______
**1.2.4** Total ______

**1.3** Nature of Family (Circle appropriate)

1. Nuclear
2. Joint Family (Several families with adult males, sharing kitchen)
3. Extended Family (Several related families living together with separate kitchens)
4. Other ____________________

**1.4** Education of household head defined as primary wage earner (Circle appropriate):

1. Illiterate
2. Primary
3. Secondary
4. Diploma
5. Degree
6. Post-Graduate

**1.5** Occupation (job) of household head defined as primary wage earner (Circle appropriate):

1 Self employed [a]
2. Regular Employee in organised sector [b]
3. Regular employee in unorganised sector [c]
4. Casual wage employment [d]
5. Pensioner

[a] Anyone who works on his own account i.e. a small shop owners, rickshaw driver.
[b] Organized Sector includes registered firms including companies, formal retail establishments, government etc.
[c] Unorganized Sector includes small shops, workshops, tea stalls etc.

**1.6** Monthly income of the household (Circle appropriate):

1. < 5k
2. Rs.5k-10k
3. Rs.10k – 20k
4. > Rs.20k

**1.7** Respondent (Must be 18 years or older) (Circle appropriate**):**

1. Male head
2. Other adult male
3. Female head
4. Other female

**1.8** House Ownership (Circle appropriate):

1. owned
2. rented

**1.9** Occupancy (how many families here) (Circle appropriate):

1. Single occupancy (only one family living in house)
2. Multiple occupancy (House with several families with separate kitchens)
3. Block of flats / apartments

**1.10** (An apartment complex is defined as the set of households that share common water facilities, it could be one building, a few buildings or the entire colony)

**1.10.1** What is the total number of households in the complex? _________

**1.10.2** How many residents in all? ________

## 2. Description of water infrastructure

**2.1** Do you have one or more underground sumps? (Circle appropriate):

1. Yes
2. No

**2.1.1** If yes, How many sumps? _________

If Yes, What is the storage capacity of the sump in liters of each

**2.1.2** SUMP 1. __________________ liters OR _____ ft*______ ft*_____ ft

**2.1.3** SUMP 2 __________________ liters OR _____ ft*______ ft*_____ ft

**2.1.4** SUMP 3 __________________ liters OR _____ ft*______ ft*_____ ft

**2.1.5** SUMP 4 __________________ liters OR _____ ft*______ ft*_____ ft

**2.2** Which of the following sources contribute water into the sumps? (Put a tick mark in appropriate box/ boxes)

| | Metrowater | Groundwater | Tanker | Other |
|---|---|---|---|---|
| **2.2.1** SUMP 1 | | | | |
| **2.2.2** SUMP 2 | | | | |
| **2.2.3** SUMP 3 | | | | |
| **2.2.4** SUMP 4 | | | | |

**2.3** Do you have one or more overhead tanks (OHTs)? (Circle appropriate):

1. Yes
2. No

**2.3.1** If yes, How many overhead tanks? _________

If Yes, What is the storage capacity of each overhead tank?

**2.3.2** OHT 1. ___________________ liters OR _____ ft*______ ft*_____ ft
**2.3.3** OHT 2 ___________________ liters OR _____ ft*______ ft*_____ ft
**2.3.4** OHT 3 ___________________ liters OR _____ ft*______ ft*_____ ft
**2.3.5** OHT 4 ___________________ liters OR _____ ft*______ ft*_____ ft

**2.4** Do you have one or more wells/borewells (Circle appropriate):

1. Yes
2. No

**2.4.1** If yes, How many wells? _________

**2.5** Do you have one or more pumps (Circle appropriate):

1. Yes
2. No

**2.5.1** If yes, How many? _________

Please fill in the pump details below

| | Connecting? (e.g SUMP 1 to OHT 1) | Age of Pump (approx. years) | Horsepower of each pump(HP) (Horespower is a unit which shows how powerful a pump is) | How many times per day is it operated? | How many minutes each time |
|---|---|---|---|---|---|
| **2.5.2** PUMP 1 | | | | | |
| **2.5.3** PUMP 2 | | | | | |
| **2.5.4** PUMP 3 | | | | | |
| **2.5.6** PUMP 4 | | | | | |

**Draw Infrastructure Diagram Below**

(Indicate pumps, underground sumps, overhead tanks. Also specify if the water is salty)

## 3. Means by which you get water supply

### 3.0 METROWATER CHARGES

**3.0.1** Do you pay the Metrowater tax assessment? (Circle appropriate):

1. Yes
2. No

**3.0.2.** If yes,
Metrowater tax assessment for your home **Rs/6months**_____________

**3.0.3** If no, why not?

_________________________

**3.0.4** Do you have a metered Metrowater connection?

1. Yes
2. No

**3.0.5** Does the meter work?

1. Yes
2. No

**3.0.6** If it works, how often do you get a bill

a) Monthly
b) Bi-monthly
c) Other ____

**3.0.7** What was the amount for last billing cycle (Excluding arrears) ________

**3.0.8** What was the amount of water consumed according to the bill? ________

**By which of the following methods do you get public <u>water supply?</u> (Check all that apply)**

1) Individual Metrowater piped supply from overhead or community storage tank
2) Outside tap (shared by many households)
3) Metrowater supply via handpump (in house or compound)
4) Metrowater water lorry (free)
5) Public standpipes (Roadside hand pumps)
6) Direct Metrowater tap (directly from pumping station **not via** tank/sump)

### INDIVIDUAL METROWATER PIPED SUPPLY VIA STORAGE

### 3.1 Water from Metrowater piped supply via your storage tank/sump?

**3.1.1** How many <u>hrs/day</u> does the sump receive Metrowater supply? ______

**3.1.2** How many <u>days/wk</u> does the sump receive Metrowater supply? ______

**3.1.3** How many times per day do you run the pump from the sump with Metrowater to the overhead tank? ________

**3.1.4** How many minutes do you run the each time? ________

**3.1.5** Roughly how full is the tank when you turn off the pump
1) Quarter full or less
2) Half Full
3) Three-quarters full
4) Full
5) Overflowing

**3.1.5** Is the overhead tank shared with other households?
1) yes
2) no

**3.1.6** If so, how many households (including your own) share the overhead tank?
_____

**3.1.7** If so, how many people (including your own family) share the overhead tank?
______

**3.1.8** Is the water from Metrowater piped system insufficient for all purposes (as of yesterday) i.e. Do you need to supplement from other sources?
1) Yes
2) No

## OUTDOOR CONNECTION SHARED BY MULTIPLE HOUSEHOLDS

### 3.2 Water from Outside connection

**3.2.1** How many <u>hours per day</u> do you get supply? ______
**3.2.2** How many <u>days per week</u> do you get supply? ______
**3.2.3** How much water do you get each day (on supply days) for your household
____________ small kodams/ large kodams/ small bkts/ large bkts/ liters

**3.2.4** How many households share the outdoor tap connection? __________

## METROWATER SUPPLY VIA HANDPUMP (IN HOUSE OR COMPOUND)

**3.3**
**3.3.1** How many <u>hours per day</u> is water available in the handpump? ______
**3.3.2** How many <u>days per week</u> is water available in the handpump? ______
**3.3.3** How much water do you get each day (on supply days) for your household
____________small kodams/ large kodams/ small bkts/ large bkts/ liters

## METROWATER WATER LORRIRS (FREE)

**3.4** If you get water from Metrowater water lorries**,** how is it collected?
a) Directly fill from tankers
b) Via Sintex tank

**3.4.1** How many pots does your household get per day? ________
**3.4.2.** How much do you pay for tanker water (including tips to driver – "tea selav")?
______ paise for ________ kodams
= __________ / kodams

**ROADSIDE STANDPIPE**

**3.5** Do you or someone in your household personally get water from the local Metro water roadside stand pump?

**3.5.1** How far away is the nearest standpipe? ________
**3.5.2.** How many trips per day do you make? ________
**3.5.3** How many pots do you carry back per trip?_________
**3.5.4** Who makes the trip in the household?

a) Unemployed adult male
b) Employed adult male
c) Unemployed adult female
d) Employed adult female
e) Child

**3.5.5** How much time does it take to complete a round trip including filling water? ____ (min)

**METROWATER DIRECT CORPORATION CONNECTION**

**3.6 How much water do you get from the direct connection?**
**3.6.6** How many hours per day do you get water in the tap? ______
**3.6.2** How many days per week? ______
**3.6.3** Total quantity collected per day

____________ small kodams/ large kodams/ small bkts/ large bkts/ liters

**4. Which of the following other private/community sources do you use?**
**(a few times in the last year - check mark all that apply)**

1) Metrowater Water Lorry on Purchase Basis
2) Private Water Lorry
3) Packaged Water
4) Water vendor
5) Own Well (open or borewell)
6) Other's Well
7) Community pond/lake/well
8) Direct use of seawater/ river water
9) Other (Specify) ________________

**METROWATER WATER LORRY (PURCHASE BASIS)**

**4.1** When did you last buy from a **Metrowater water lorry** on a purchase basis ?

1) within the last week
2) within the last month
3) within the last three months
4) more than 3 months ago

**4.1.1** In the last 3 months, how many times did you get supply from private tanker? __

**4.1.2** Quantity bought-last time (Circle appropriate unit)

_____________ small kodams/ large kodams/ small bkts/ large bkts/ liters
(Note full tanker is usually 12,000 liters)

**4.1.2** Amount paid last time___________ (for quantity purchased)

**4.1.3** How many days did the water lorry supply last you _______________days

## PRIVATE WATER LORRY

**4.2** When did you last buy from **private water lorry ?**

1) within the last week
2) within the last month
3) within the last three months
4) more than 3 months ago

**4.2.1** In the last 3 months how many times did you get supply from private lorry ______

**4.2.2** Quantity bought-last time (Circle appropriate unit)

______________ small kodams/ large kodams/ small bkts/ large bkts/ liters

(Note full tanker is usually 12,000 liters)

**4.2.3** Amount paid last time ____________ (for quantity purchased)

**4.2.3** How many days did the water lorry supply last you ________________days

## 4.3 PACKAGED WATER

**4.3.1** In what forms do you buy packaged water, how often, and how much?

| **Form** | **Volume of one unit** | **How often (times/week)** | **Price (Rs/unit)** |
|---|---|---|---|
| Sachet | 250 ml | | |
| Jerry Can | 12 liters/ 25 liters | | |
| Bottle | 1 liter/ 2liters | | |
| Other | | | |

## 4.4 WATER VENDOR

(Water vendors are the people who go door-to-door selling water in pots)

**4.4.1** When did you last buy from a water vendor**?**

1) within the last week
2) within the last month
3) within the last three months
4) more than 3 months ago

**4.4.2** How often do you buy vended water? _________ times per month

**4.4.3** Number of kodams bought-last time ______________

**4.4.4** Amount paid last time____________

## GROUNDWATER (i.e. WELL WATER)

**4.5 What type of well do you have?**

1) Open well
2) Borewell
3) Both

## OPEN WELL DETAILS

**4.5.1 Period when open well was originally constructed**

1) before 1970
2) 1970-1980
3) 1980-1990
4) After 1990

**4.5.2** What is the current depth of the well? _______

**4.5.3** What was the depth at the time of construction? _______

**4.5.4** Is the open well now in use ? 1) Yes
2) No

**4.5.5** If No, which year was it abandoned _______

**Answer the following questions about the open well only if well is being used**

**4.5.6** How many times has your well/borewell been deepened? __________

**4.5.7** Does the pumped groundwater go into either the overhead tank or sump?

1) Yes
2) No

**4.5.8** If No, explain how the groundwater is used ______________

**4.5.9** What type of pump do you have?

1) Manual
2) Electric jet pump
3) Electric submersible pump
4) Diesel Pump

**4.5.10** How many times/day is the pump typically operated? __________

**4.5.10A** How many minutes each time is the pump typically operated? __________

**4.5.11** Is the wellwater shared by multiple households

1) Yes
2) No

**4.5.12** If yes, how many households? _________

**4.5.13** How many people in all? _______

## BOREWELL DETAILS

**4.5.14 Period when bore well was originally constructed**

1) before 1970
2) 1970-1980
3) 1980-1990
4) After 1990

**4.5.15** What is the current depth of the well? _______

**4.5.16** What was the depth at the time of construction? _______

**4.5.17** Is the bore well now in use ? 1) Yes
2) No

**4.5.18** If No, which year was it abandoned _______

**<u>Answer the following questions about the bore well only if well is being used</u>**

**4.5.19** Does the pumped groundwater go into either the overhead tank or sump?
1) Yes
2) No

**4.5.20** If No, explain how the groundwater is used ______________

**4.5.21** What type of pump do you have?
1) Manual
2) Electric jet pump
3) Electric submersible pump
4) Diesel Pump

**4.5.22** How many times/day is the pump typically operated? __________

**4.5.22A** How many minutes each time is the pump typically operated? __________

**4.5.23** Is the wellwater shared by multiple households
1) Yes
2) No

**4.5.24** If yes, how many households? _________
**4.5.25** How many people in all? _______

## 4.6 OTHER'S WELL

**4.6 When did you last take from another person's well/tap ?**
1) within the last week
2) within the last month
3) within the last three months
4) more than 3 months ago

**4.6.1** How often do you do this? ________ per month

**4.6.2** Quantity taken last time
_____________ small kodams/ large kodams/ small bkts/ large bkts/ liters

**4.6.3** Price paid
___________ per small kodams/ large kodams/ small bkts/ large bkts/ liters

## 4.7 COMMUNITY POND/LAKE/WELL

Do you or someone in your household personally collect water from the local pond/lake/well

**4.7.1** How far away is the nearest community source? (Circle appropriate)

1. Less than 100 meters
2. More than 100 meters but less than 0.5 km
3. 0.5 km to 1 km
4. More than 1 km

**4.7.2.** How many trips per day do you make? ________

**4.7.3** How many pots do you carry back per trip?_________

**4.7.4** Who makes the trip in the household?

1) Unemployed adult
2) Employed adult
3) Child

**4.7.5** How much time does it take to complete a round trip including filling water?
_________ (minutes)

## USE AT SITE - SEAWATER/RIVER

**4.8.1** Do you use river or sea water directly?

1) Yes
2) No

## 4.9 OTHER SOURCES NOT LISTED ABOVE

Describe the source, try to get an estimate for how much they use and how much they pay for it. Explain in as much detail as possible.

## 4. Sources of water for various uses (Tick applicable boxes)

| **Sources** | **Uses** | | | | | |
|---|---|---|---|---|---|---|
| | Drinking | Cooking | Washing | Bathing | Toilet | Other |
| **Public system** | | | | | | |
| In-house piped supply | | | | | | |
| Outside house tap | | | | | | |
| In-house hand pump | | | | | | |
| Metrowater tanker (free) | | | | | | |
| Roadside handpump | | | | | | |
| Direct Metrowater tap | | | | | | |
| **Private sources** | | | | | | |
| Metrowater tanker purchase basis | | | | | | |
| Private tankers | | | | | | |
| Packaged water | | | | | | |
| Water vendor | | | | | | |
| Own well | | | | | | |
| Other's well | | | | | | |
| Community pond/lake | | | | | | |
| River/ Sea Water | | | | | | |

## 5. Estimated volume of water used for different purposes during the previous day

**5.1** Drinking _____________ small kodams/ large kodams/ small bkts/ large bkts/ liters

**5.2** Cooking _____________ small kodams/ large kodams/ small bkts/ large bkts/ liters

**5.3** Dish Washing _______ small kodams/ large kodams/ small bkts/ large bkts/ liters

(Ask questions below ONLY if they do not know answer above Ques 5.3)
How many meals per day do you cook?
**5.3.1** Breakfast : _________ people
**5.3.2** Lunch : ____________ people
**5.3.3** Dinner : ____________ people

**5.4** Clothes Washing _________ small kodams/ large kodams/ small bkts/ large bkts/ liters
(Ask questions below if they do not know answer above Ques 5.4)
**5.4.1** Do you use a washing machine for washing clothes every day?
1) Yes
2) No
**5.4.2** If Yes, How many loads do you run? _________ per week
**5.4.3** If No, how many buckets of soaked clothes do you wash per day? ______
**5.4.4** OR How many pieces of clothing are washed everyday? ________

**5.5** Bathing _____________ small kodams/ large kodams/ small bkts/ large bkts/ liters

(Ask questions below if they do not know answer above Ques 5.5)
What is the primary method used for bathing? (Circle and fill blanks)

Bucket and Mug
**5.5.1** No of buckets used per person __________
**5.5.2** Size of bucket __________ (Large, Medium, Small)

Shower
**5.5.3** No of minutes per bath ________
**5.5.4** No of baths per day ________

c) Bathtub
**5.5.5** No of times bathtub is used per week _______

**5.6** Toilet Flushing ________ small kodams/ large kodams/ small bkts/ large bkts/ liters

(Ask questions below if they do not know answer above Ques 5.6)
**5.6.1.** How many toilets do you have in your home? (Specify number)
1) Indian style ______
2) Western style ______

**5.6.2** What method of flushing do you employ?
1) Buckets
2) Flush
3) Other _____________________________________

**5.6.3** What is the volume of your flushtank (Circle)
1) Old style flush
2) Slimline flush tank

**5.7** Water used for other purposes

**5.7.1** Cleaning the floor _________ small kodams/ large kodams/ small bkts/ large bkts/ liters
**5.7.2** Gardening _________ small kodams/ large kodams/ small bkts/ large bkts/ liters
**5.7.3** Car washing _________ small kodams/ large kodams/ small bkts/ large bkts/ liters

**5.7.4** Other (Specify purpose and amount)
_________ _________ _________ small kodams/ large kodams/ small bkts/ large bkts/ liters
_________ _________ _________ small kodams/ large kodams/ small bkts/ large bkts/ liters
_________ _________ _________ small kodams/ large kodams/ small bkts/ large bkts/ liters

**5.8** Other relevant observations :

## 6. Comments on quality of water

### 6.1 Own open or bore well

taste -
colour -
smell -
lathering -
deposits/froth if left standing -

| | | | |
|---|---|---|---|
| 6.1A | Is the water fit for drinking? | 1. Yes | 2. No |
| 6.1 B | If not, is it fit for cooking? | 1. Yes | 2. No |
| 6.1 C | If Not is it fit for bathing? | 1. Yes | 2. No |
| 6.1 D | Is it fit for gardening? | 1. Yes | 2. No |
| 6.1 E | Is it fit for washing? | 1. Yes | 2. No |
| 6.1 F | Is it at least fit for flushing? | 1. Yes | 2. No |

### 6.2 Metrowater supply

taste -
colour -
smell -
lathering -
deposits/froth if left standing -

## 7. Water Conservation Measures

**7.1.** Do you have a reverse osmosis system to treat salty groundwater/ seawater?
(A reverse osmosis plant uses a membrane to remove salt from water – its is a very expensive system and costs several lakhs)

1) Yes
2) No

**7.1.1.** If yes, Size : __________ liters/hour
Make: ______________________

**7.2.** Do you use recycled water in toilets?
(Recycled water is bathroom and kitchen waste water which is treated and used again)

1) Yes
2) No

**7.3** Do you use recycled water in the garden?

1) Yes
2) No

**7.4** Has your house/building installed rainwater harvesting?

**7.5** If yes, Which year was it installed ____________

**7.6** Who helped design it?

1 metro water
2 ngo
3 other consultant
4 plumber
5 self

**7.7** Who constructed it?

1 ngo
2 authorised contractor
3 plumber
4 other (specify_________)

**7.8** What was the total cost Rs_____________

**7.9** Do you have RWH for collecting

1 rooftop water
2 water from open ground
3 both

**7.10** What purification method do you use to treat water?

1. Boiling
2. UV Filter (Aquaguard)
3. Alum
4. Chemical Treatment
5. Ion Exchanger
6. Other

## 8. Permission for further contact

**May we contact you over phone for follow-up questions or clarifications? Yes/No**

**8.1** If yes telephone no. of the household

8.**2** What is a convenient time to call?

## 9. Would you be interested in participating in a groundwater study?

The study will involve a student visiting your house 3 times over the next year to measure the water level in your well. We are ideally looking for abandoned borewells for drilling which records exist. We are willing to pay a nominal fee for access to your borewell. If so, please give us your contact information

# Appendix H. Demand Estimation

The estimation of residential demand for water has been the subject of many research studies. Research in the area has previously focused on model specification and estimation. However, most of the studies have used datasets from the developed world, or developing world cities where the utility supply is reliable and metering data exists. To implement the integrated model, however, we needed a demand function for Chennai, a place where metering is sparse, consumers depend on multiple sources of water, and consumers change the sources accessed depending on the supply situation. Herein, we describe our demand estimation method for Chennai.

This Appendix is organized as follows: We document some of the general challenges with demand estimation in the developing world. We explain our approach to demand estimation and how it addresses the challenges. Then we briefly describe the data set used and justify the choice of functional form. Finally, the results of the regression analyses and coefficients estimated are presented.

## H.1: Challenges with demand estimation in the developing world

Studies aimed at demand estimation in the developing world have been plagued by four problems.

5) **Quantity Estimation Problem:** The challenge in estimating quantity consumed arises from the fact that metering coverage may be sparse, and water meters often do not work.
6) **Supply Constraint Problem:** Because of the unreliable nature of public supply, even if metered data is widely available, the quantity consumed may reflect supply conditions and not consumer demand. Furthermore, consumers often get water from multiple sources, making dependence on utility supply inappropriate.
7) **Price Estimation Problem:** Often in developing countries, poorer consumers tend to depend on manually collecting water from public standpipes or community sources such as wells, ponds or rivers. Although water from standpipes is free, consumers still pay a significant “price” in terms of time and labor costs of hauling water.
8) “**Income-Effect” Problem:** The challenge in estimating average price occurs because in many developing cities, particularly in South Asia, utility supply is available for only a few hours each day; so many households rely heavily on alternative coping mechanisms such as private wells and tankers or vendors to satisfy their needs. Since the choices

available to households vary, the marginal price is not related to the price paid for infra-marginal units.

### H.2: Review of literature on household-level studies

Demand Estimation studies in the developing world have been relatively sparse. Most studies rely on utility-level data sets. The few household-level studies[110] that exist have often depended on the existence of good supply and data on metering. Obtaining good data sets in developing countries is a challenging task because estimating quantity consumed, marginal price and average price are each difficult for reasons discussed in the preceding section.
A few recent studies have begun to address some of these problems. Strand and Walker (2005) pooled data sets to include coping and non-coping households to incorporate households lacking indoor plumbing. Nauges and Jon Strand (2007) acknowledge the possibility of households depending on multiple sources, but only focus on the dominant source. To our knowledge, there have been no studies so far that have been able to tackle all the complex challenges associated with demand estimation in the developing world.

### H.3: Approach to Demand Estimation:

In this research, we adopted an alternative approach to estimating the household demand function. We applied the tiered-supply curve theoretical framework developed in Chapter 2, modeling the water from multiple sources as a special case of an increasing block rate tariff, using the method suggested by Nieswiadomy and Molina (1988). Since by definition, the tiered supply curve must always be an increasing block-rate tariff we did not concern ourselves with the literature addressing more general tariff structures. A pooled data set of 1488 households in Chennai the January 2006 household survey and 1510 households from the January 2004 survey was used in demand estimation. The questionnaire and the statistics for the household surveys are presented in Appendix F.

The tiered supply curve approach permitted us to address many of challenges in demand estimation identified earlier. In the following section we document how using the tiered supply curve approach addresses some of these challenges.

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[110] Rietveld *et al.* 1997, Strand and Walker 2005, Gunatilake *et al.* 2001

## H.4: Overcoming the problems

We overcome the usual problems with developing country data sets as follows

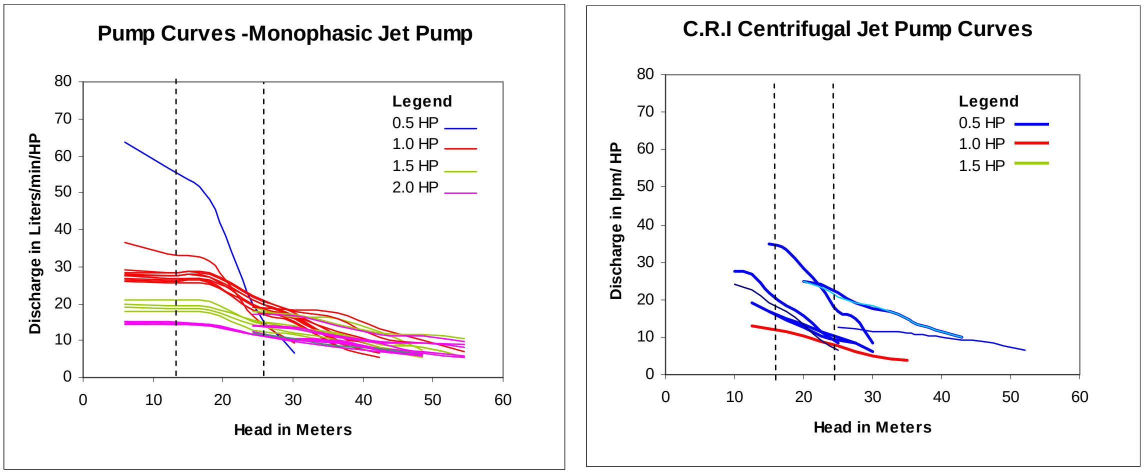
### *Quantity Estimation Problem*

We included all modes of supply, utility supply, self-supply and private supply (tankers and vendors). We used pump times, pump HP and pump rating curves, to determine how much water was pumped from the sump to the overhead tank and the borewell to the overhead tank to estimate quantity of supply as shown in the equation below.

$$\mathbf{Q_{Utility} = Pump\_HP * Rated\ LPM/HP * Minutes\_per\_day}$$

**Equation 0.1**

where Rated_LPM was the flow rate in liters per minute obtained from published pump curves. The pump curves for two popular pump manufacturers, CRI and Suguna pumps, are shown below in Figure H.1.



Source: Data collected from manufacturers

**Figure 0.1 : Rating Curves from two popular pump manufacturers**

For the utility (Metrowater) piped supply from the underground sump to overhead tank, we used a head of 15 m which translated to an average of 25 liters per minute (LPM) for each HP of pump capacity. For the groundwater pumping we factored in the depth to groundwater and in-well drawdown and used an average head of 25 m, which gave us a pump-rate of 15 liters per minute (LPM) for each HP of pump capacity.

Using this method allowed us to be able to use data from a household survey on number of minutes pumped, and pump capacity to determine the quantity of utility supply delivered to the overhead tank each day. We expect that these data are likely to be “noisy”, since residents were unlikely to be timing the minutes for which the pump is turned on and were likely to offer ballpark estimates rounded to the nearest 15 minutes. However, over the 1500 household sample, these errors would even out.

### *Price Estimation Problem*

We use opportunity cost of the time to estimate the cost of water extracted manually. In the household survey, we asked consumers collecting water manually to record the minutes spent in collecting water. By conducting a sensitivity analysis of the final results on opportunity cost of time, we were able to estimate the opportunity cost of time.

In estimating the opportunity cost of time we used the following facts:

6) The opportunity cost of time had to be between 0 and 12 Rs/hr. At Rs 12/hr, the cost of a pot of water would be close to Re 1/pot, the price charged by water vendors.
7) No households purchased vendor water when water supply in standpipes was available, so the average opportunity cost of time had to be much lower than Rs 12/hr.
8) Moreover, the household survey indicated that 75 percent of the water collected was by unemployed women in the household.
9) Households with sumps and borewells must have a higher opportunity cost of time to justify these high capital investments.

In the integrated model, we tested various opportunity costs between 3 and 12 Rs/hr. We assumed that unconnected and manual households had an opportunity cost of Rs 2/hr. The opportunity cost of Manual w/ borewell and sump households averaged Rs 10/hr.

In conducting the sensitivity analysis, consistent values were used to estimate the demand function and in the Consumer module. The sensitivity to opportunity cost of time is presented in the main text of Chapter 4.

### *Supply Constraint Problem*

We were able to work around the supply constraint problem by using the tiered-supply curve; households are NEVER supply constrained. If the utility supply is insufficient, households simply go on to the next most expensive source. Thus, they face a supply curve very similar to an increasing block-rate tariff. In developing our demand estimation methodology, we rely heavily on the increasing-block rate tariff literature.

***Income Effect Problem***

We were also able to overcome was the "income effect" problem. By using the "difference" variable in the regression, we were able to account for the fact that infra-marginal units were cheaper than the marginal price.

### H.5: Functional form of residential demand function

The demand function for water for the representative household is typically specified as Q = f(P,I,D,H). This equation describes the relationship between water consumption on the one hand (Q), the marginal price of water (P), household income (I), difference variable (D) and household size (H).

The functional form used in estimating the demand function was

$$Q = C\ P^{\alpha} N^{\beta} D^{\gamma} I^{\delta}$$

**Or**

$$\mathbf{Log}\ Q = c + \alpha\,\mathbf{Log}\ P + \beta\,\mathbf{Log}\ A + \gamma\,\mathbf{Log}\ D + \delta\ \mathbf{Log}\ I + \mu$$

**Equation 0.2**

where

Q= Quantity demanded is measured in liters/household/week

P= Marginal Price in Rs/kL

N= Number of members in the households

D= Difference Variable

I = High Income variable = 1 if income > Rs10,000/month
= 0 otherwise

Our utilized data set covers water consumption in 727 households from the 2006 data set and 125 households from the 2004 data set. Most of the points that were dropped had incomplete quantification data.

### H.6: Residential Demand Function: Regression Parameters

Demand elasticities were here estimated by OLS on the pooled set of data.

Our results on the pooled data set show that water cost in all cases has the traditional negative effect on water demand.

**Table 0.1: Regression results for residential demand function estimation**

| Dependent Variable | Coefficient | Std. Err. | t | P>\|t |
|---|---|---|---|---|
| Log(Marginal Price) | -.4637122 | .031428 | -18.88 | 0.000 |
| Log(Household Size) | .3610758 | .04402 | 8.20 | 0. |
| Log(Difference) | .2652644 | .0122495 | 21.66 | 0.000 |
| Log(Low_Income) | .1537797 | .0385264 | 3.99 | 0. |
| Log(Apartment) | -.21411 | .0776289 | -2.76 | 0. |
| Constant | 4.459721 | .1831602 | 24.35 | 0. |

Observations: 852
Adjusted $R^2$: 54.3%

### H.7: Functional Form for Commercial Demand Function

The demand function for water for commercial establishment was typically specified as
Q = f(P,WI,D,N).

This equation describes the relationship between water consumption (Q), the marginal price of water (P), water intensiveness of the industry (WI), difference variable (D) and number of full-time employees (N).

The functional form used in estimating the demand function was

$$Q = C\ P^{\alpha} E^{\beta} D^{\gamma} WI^{\delta}$$

Or

$$\text{Log } Q = c + \alpha \text{ Log } P + \beta \text{ Log } E + \gamma \text{ Log } D + \delta \text{ Log W}I + \mu$$

**Equation 0.3**

where

Q= Quantity demanded is measured in liters/establishment/week

P= Marginal Price in Rs/kL

N= Number of full-time employees

D= Difference Variable

I = Water Intensive variable = 1 if industry is water-intensive
= 0 otherwise

Our utilized data set covers water consumption in 217 establishments from the 2006 data set. Only 118 of these had complete and internally consistent data.

### C4.6: Regression Parameters

Demand elasticities were here estimated by OLS on the pooled set of data. The estimated regression parameters are shown in Table H.2.

**Table 0.2: Regression results for commercial demand function estimation**

| **Dependent Variable** | **Coefficient** | **Std. Err.** | **t** | **P>\|t** |
|---|---|---|---|---|
| Log(Marginal Price) | -.2083004 | .1072077 | -1.94 | 0.055 |
| Log(Full Time Employees) | .8592428 | .0630367 | 13.63 | 0.000 |
| Log(Difference) | .0634609 | .023829 | 2.66 | 0.009 |
| Log(Water Intensive) | 1.935975 | .1487632 | 13.01 | 0.000 |
| Constant | 6.171252 | .4419062 | 13.97 | 0.000 |

Observations: 118
Adjusted $R^2$: 75%

# Appendix I. Reservoir Storage Backcast

In this Appendix, we explain how reservoir storage was "backcast" using the rainfall-inflow relationship developed from the actual inflow data collected for the period 2002-2007.

## I.1: Reservoir storage backcast: Method

Reservoir storage was backcast for the period from 1965-2002. The data available[111] for this period included monthly rainfall, and reservoir system storage on the first day of the month. End of month storage was calculated by computing the water balance each month, starting with the storage on January 1st 1965. Monthly inflows were estimated as a function of monthly rainfall using the calibrated rainfall-runoff relationship. Net evaporation was factored in using the average monthly lake evaporation rate. Outflows or diversions were based on the diversion rule used for the calibration run of 2002-2006 i.e. diversion to Chennai was assumed to be a simple fraction of storage.

An important insight from the backcast is the fraction diverted to Chennai utility supply had to be recalibrated to improve the fit for earlier periods. Specifically, the fraction diverted was about 4% of reservoir storage each month in the 1970s, gradually increasing to about 7% by 2000. This adjustment in fact reinforces the reservoir storage constraint in Chennai. As Chennai's population has increased in recent years reservoir capacity has not kept pace. As a result, the utility has to divert more water each month from the existing reservoir system, significantly exacerbating the variability in water available from period to period.

## I.2 Reservoir storage backcast: Results

Figure I.1 shows the reservoir storage "backcast" using a simple water balance.

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[111] Metrowater 2007

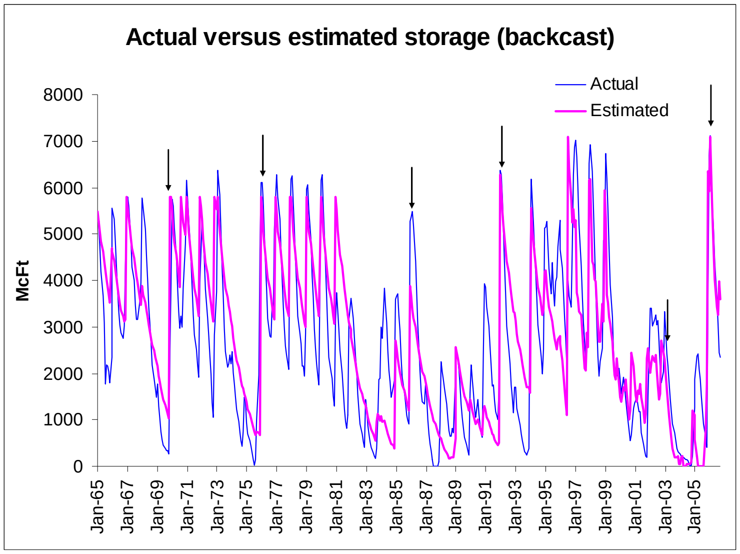


**Figure 0.1: Backcast of reservoir storage**

The $R^2$ is about 65 percent – acceptable but not great. The times the error is the most is when we "miss" a major inflow event that fills up the reservoir.

### I.3: Reasons for discrepancy

This is because we are using monthly rainfall – so there is a problem with data aggregation. This can be explained as follows. As explained in Chapter 3 (Section 3.4), monthly reservoir inflows were specified as an exponential function of monthly rainfall. This implies if there is a major rainfall event at the end of the month and the single rainfall event (say 400 mm of rainfall) gets divided into two months (as 300 mm in Dec and 100 mm in January) we would seriously under-predict inflow, by almost an order of magnitude.

For instance, for the example above, the estimated inflow in the two cases would be

$I_1 = \text{Exp}(0.017*400) = 915$ Mcft/Month

$I_2 = \text{Exp}(0.017*100) + \text{Exp}(0.017*300) = 171$ Mcft/Month

This indicates that using monthly rainfall as a predictor of reservoir inflow is not ideal. Given more time and better data, we would consider altering using a daily rainfall-inflow relationship. Thus, while the reservoir storage backcast is accurate in months when storms occur in the middle of the month, the model under predicts inflows if rainfall events unfortunately occur at the end of a month and carry over into the next month. In fact, over the historical period we seriously under predicted inflow events five times.

# Appendix J. Development of tiered supply curves

In this Appendix, we present the development, inputs and outputs of the consumer choice module for each consumer category for each of the two reference periods Jan-April 2004, and Jan-April 2006. We present the tiered supply curves and demand curves for the two periods. The intersection of the two yields the total quantity consumed by a representative household in each category. The welfare per household is also compared. Once we have presented the data for all consumer categories we compare them and summarize our findings.

## J.1 Unconnected consumers

Table J.1 shows the simulated prices and quantities available from various sources (both potable and non-potable) to unconnected consumers. Potable sources are shown in blue.

**Table 0.1: Prices and quantities available to Unconnected consumers**

| **Unconnected** | | **Liters/ Household /Day** | |
|---|---|---|---|
| | **Cost** | **Jan04** | **Jan06** |
| **Mobile** | **Rs 20/kL** | 90 | 90 |
| **Standpipe** | **Rs 10/kL** | 0 | 226 |
| **Shallow Well** | **Rs 10/kL** | 0 (if Dry), 1000 (if Wet) | 1000 |
| **Water Vendors** | **Rs 60/kL** | ∞ | ∞ |

For Unconnected consumers, the tiered supply curve for non-potable supply is as follows: public standpipes, followed by mobile supply, shallow community wells and water vendors. Metrowater mobile supply is the only potable quality source. In this case, the quantity supplied by mobile supply was equal the household potable need of about 90 liters per HH per day (LPHD), so there is none left over for non-potable uses. Unconnected Consumers depended on public standpipes, shallow community wells and vendors for these.

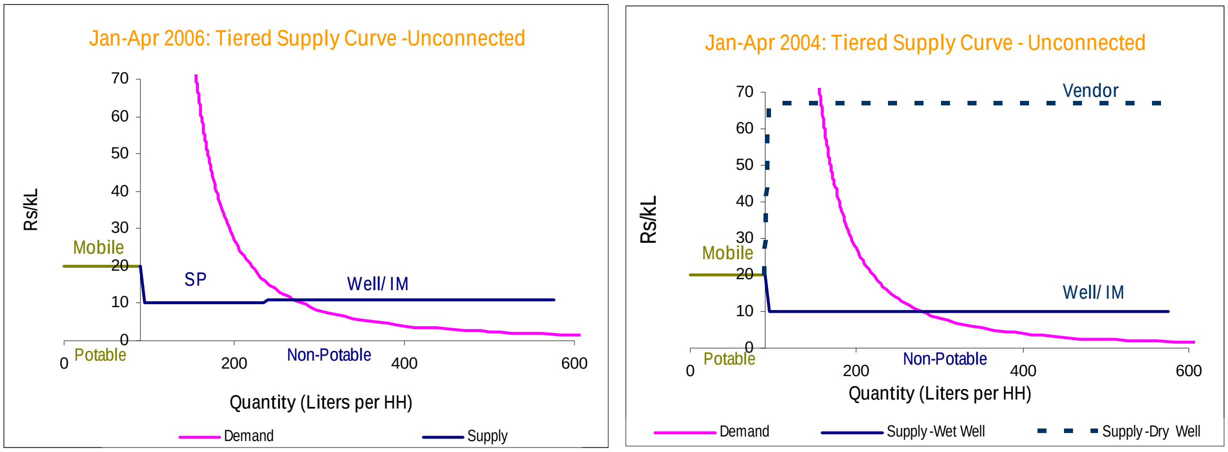


**Figure 0.1: Tiered Supply Curves: Unconnected Consumers**

Based on the demand and supply curves generated by the model, we could estimate the total consumption per household by source as well as the baseline consumer surplus for both reference years (Figure J.2).

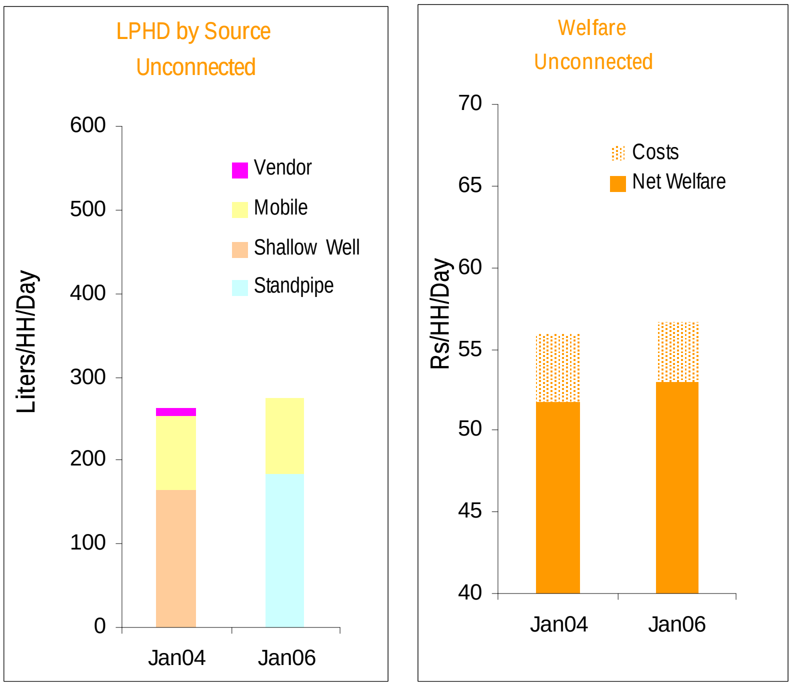


**Figure 0.2: Consumption and consumer surplus – Unconnected consumers**

The modeled total consumption did not change between the dry and wet years for unconnected consumers staying relatively stable at about 250 LPH (or 55 LPCD). These consumers were dependent on mobile supply for their potable needs and we assumed that Metrowater did not curtail mobile supply to unconnected consumers during the drought.

During the 2003-2004 drought periods, unconnected consumers were dependent on shallow wells for their non-potable needs, as no water was available in the public standpipes connected to the piped system. As the shallow aquifer dried up, a small fraction of these consumers were forced to buy water from vendors, and faced higher costs and lower welfare. In 2006, when Metrowater supply was plentiful, consumers used less than the quantity available to them i.e. unconnected consumers were "demand constrained" the time and effort of collection prevented them from using more water even though more water was available. This indicates that once water supply reaches a certain level, these consumers were restricted by demand (cost and effort of collection). Thus, unconnected consumers only enjoy benefit from supply increases when supply is low.

### J.2 Manual consumers

For consumers with private manual connections (HP is yard taps or hand-pumps), the utility connections were clearly the cheapest and best quality source available. During the drought from Oct 2003 to Oct 2004, when the piped supply system shut down, these consumers accessed on mobile supply (which they then used for potable needs) and private or community wells (for non-potable needs). Table J.2 shows the simulated prices and quantities available from various sources (both potable and non-potable) to manual consumers. Potable sources are shown in blue.

**Table 0.2: Prices and quantities available to Manual consumers**

| **Manual** | | **Liters/ Household /Day** | |
|---|---|---|---|
| | **Cost** | **Jan04** | **Jan06** |
| **Mobile** | **Rs 20/kL** | 90 | 90 |
| **Handpump** | **Rs 3.50/kL** | 0 | 1193 |
| **Shallow Well** | **Rs 10/kL** | 0 (if Dry), 1000 (if Wet) | 1000 |
| **Water Vendors** | **Rs 60/kL** | ∞ | ∞ |

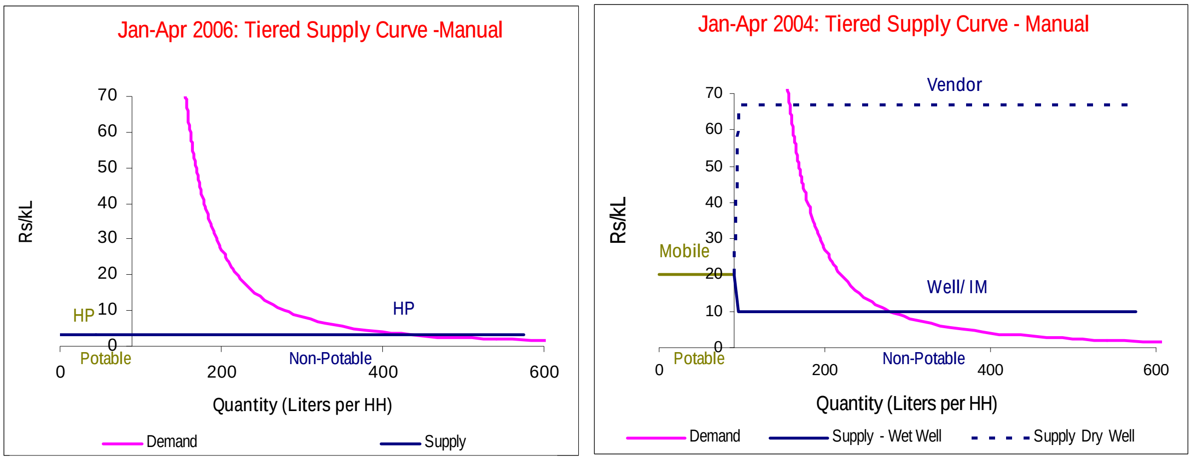


**Figure 0.3: Tiered Supply Curves: Manual Consumers**

Based on the intersection of the demand and supply curves, we estimated the total consumption per household by source as well as the baseline welfare as shown in Figure B5.4.

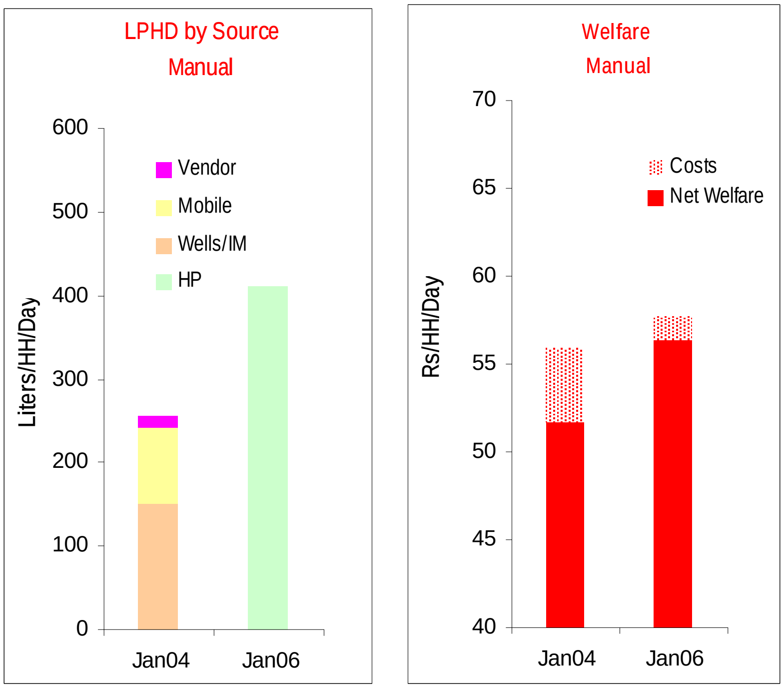


**Figure 0.4: Consumption and consumer surplus – Manual consumers**

During the drought period when the piped system shut down, manual consumers depended heavily on Metrowater mobile supply and community wells to a lesser extent. Manual consumers suffered the greatest losses in welfare during the drought as they were forced to consume less water, from more expensive sources.

### J.3 Manual with Borewell consumers

For consumers with manual utility connections and borewells, the manual connection (yard tap or handpump) is the lowest-cost potable source of supply. However, for non-potable uses, borewell water costs less and is preferred. Table J.3 shows the simulated prices and quantities available from various sources (both potable and non-potable) to Manual with Borewell consumers. Potable sources are shown in blue.

**Table 0.3: Prices and quantities available to Manual w/ Borewell consumers**

| **Manual w/ Borewell** | | **Liters/ Household /Day** | |
|---|---|---|---|
| | **Cost** | **Jan04** | **Jan06** |
| **Mobile** | **Rs 45/kL** | 90 | 0 |
| **Handpump** | **Rs 15/kL** | 0 | 1193 |
| **Private Borewell** | **Rs 5.50/kL** | 0 (if Dry), 6000 (if Wet) | 6000 |
| **Private Tankers** | **Rs 60/kL** | ∞ | ∞ |

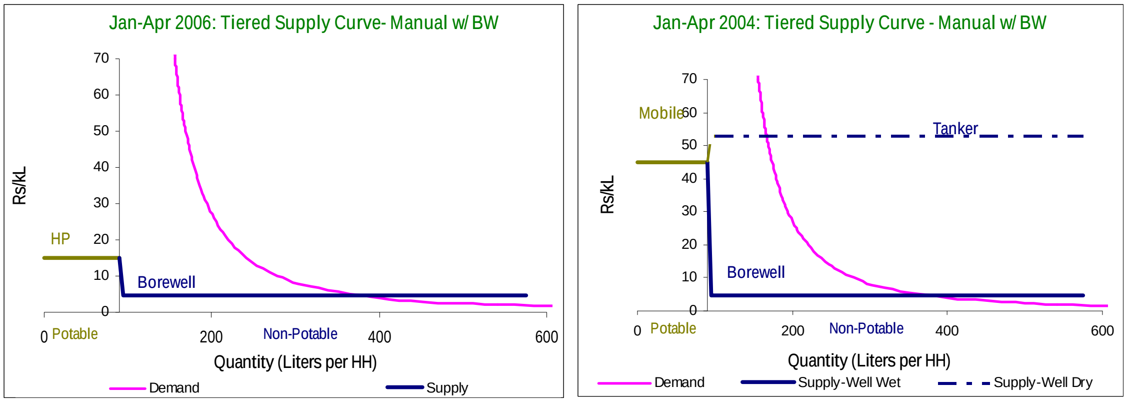


**Figure 0.5: Tiered Supply Curves: Manual with Borewell Consumers**

Based on the intersection of the demand and supply curves, we obtain the total consumption per household by source as well as the welfare as shown in Figure J.6.

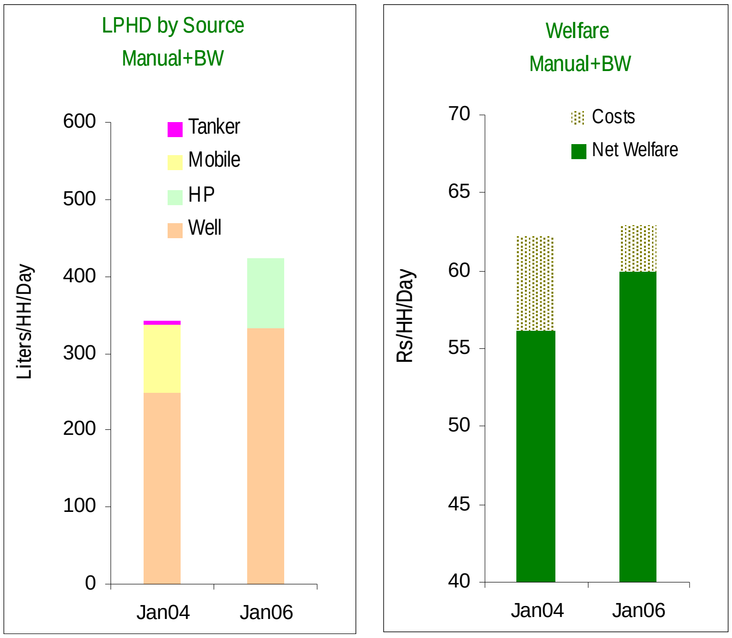


**Figure 0.6: Consumption and consumer surplus – Manual w/ borewell consumers**

These consumers faced higher costs and therefore lower welfare during the drought, on average. During the drought, handpump supply was mostly substituted by mobile supply, a more expensive source.

### J.4 Sump consumers

For consumers with sump connections, piped supply is the cheapest and best quality source of supply and preferred for both potable and non-potable uses. Table J.4 show how the quantity restrictions faced by unconnected consumers.

**Table 0.4: Prices and quantities available to Manual consumers**

| **Sump** | | **Liters/ Household /Day** | |
|---|---|---|---|
| | **Cost** | **Jan04** | **Jan06** |
| **Mobile** | **Rs 45/kL** | 90 | 0 |
| **Piped** | **Rs 1.87/kL** | 0 | 611 |
| **Private Borewell** | **Rs 5.50/kL** | 0 (if Dry), 6000 (if Wet) | 6000 |
| **Private Tankers** | **Rs 55/kL** | ∞ | ∞ |

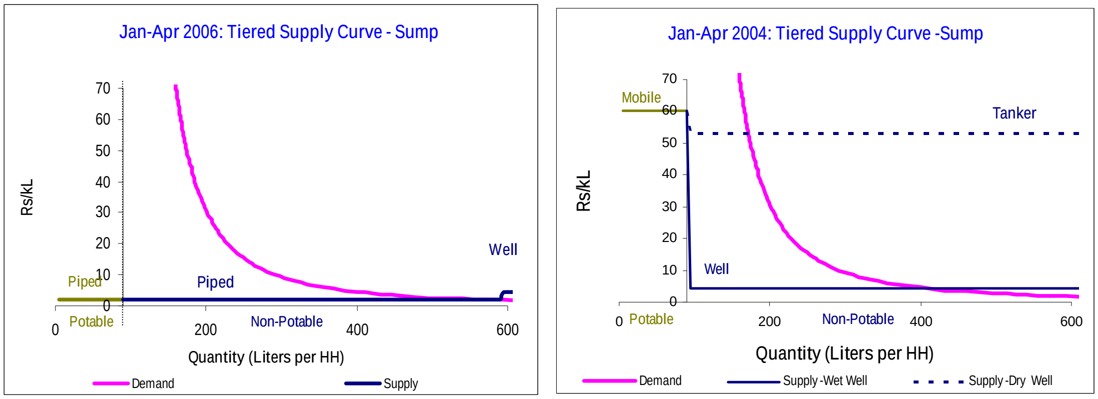


**Figure 0.7: Tiered Supply Curves: Sump Consumers**

Based on the intersection of the demand and supply curves, we obtain the total consumption per household by source as well as the baseline welfare as shown in Figure J.8.

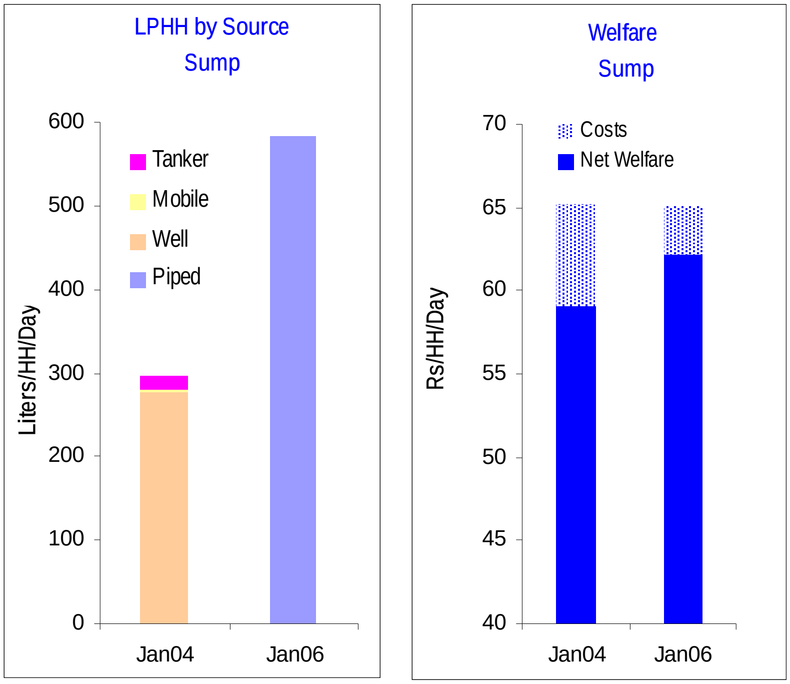


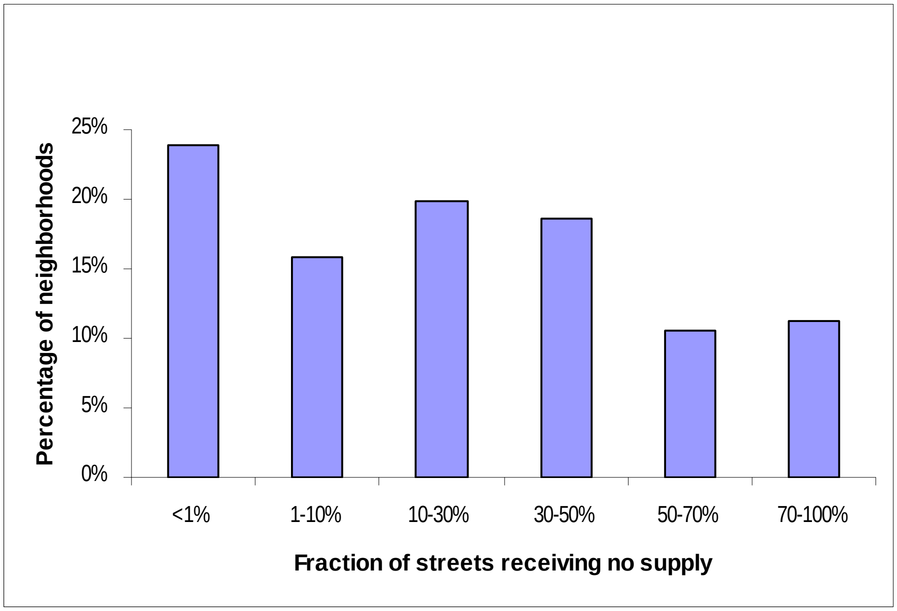
**Figure 0.8: Consumption and consumer surplus – Sump consumers**

# Appendix K. Effects of intermittency

### *K.1 Spatial Variability: Head and tail-end areas*

In water distribution systems, the quantity delivered to consumers varies spatially with the pressure at a particular point in the system. However, in intermittent water distribution systems like Chennai, many zones of the city have zero or negative pressure for much of the day and get little or no water at all. Therefore, areas close to pumping stations (referred to as "head-end" areas) get more water, while areas away from pumping stations (referred to as "tail-end" areas) receive less water.

Metrowater reports the spatial extent of "tail-end" zones in terms of streets that receive little or no piped supply. Figure K.1 shows a histogram of the Metrowater divisions (155 in all) distributed by the fraction of streets receiving no piped supply from the year 2003, before the piped supply system was shut down. About a quarter of the divisions in Chennai, had excellent supply (almost no defective streets), for another quarter had more than half of their streets receiving no supply.



Source: Metrowater 2006 (a)

**Figure 0.1: Fraction of streets receiving no piped supply**

Our model does NOT distinguish between head-end and tail-end areas. To be able to accurately predict head-end and tail-end areas, we would require a formal model of the water distribution system. Because we did not consider differences in utility supply across Chennai, we could make aggregate predictions about city supply, we cannot predictions at the neighborhood scale.

### *K.2 :Frequency of supply*

The difference in the quantity delivered to head-end and tail-end areas depends on the difference in pressure in the head-end and tail-end areas. The utility responded to this situation by altering the frequency of supply to every other day or every third day. For instance, if very little supply is available in a period, Metrowater could only reach tail-end areas by supplying a larger quantity every second day or third day, than a smaller quantity every day. This pattern is well-known to residents in Chennai. Local newspapers regularly report the reservoir situation and the frequency of water supply.

Our model had a time-period of three months. Therefore, frequency of supply cannot be captured. In other words our model would be unable to distinguish between a daily supply of 100 L/HH every single day and a supply of 300L/HH every third day. For most part, this does not affect our conclusions. However, it does explain, the large storage capacities commonly observed in Chennai.

# Appendix L. Telugu Ganga Project

## L.1 Description

The Telugu Ganga Project is an inter-state project which transfers water from the Krishna River located in the northern state of Andhra Pradesh to the city of Chennai located in the state of Tamil Nadu. The Project involves transfer of water 150 km through an open canal to the Poondi reservoir (one of the three reservoirs in the Chennai reservoir system) immediately north of Chennai.

## L.2 Early Conception and Roadblocks

The Telugu Ganga Project was first conceived in the early 1950s when Andhra Pradesh and Tamil Nadu were both part of the same state: the Madras Presidency[112]. So the project was not originally expected to be an inter-state project. When Andhra Pradesh separated from Tamil Nadu and achieved statehood in 1954, Tamil Nadu no longer had rights to the waters of the Krishna River. Early decisions of the Krishna Water Tribunal, which negotiated agreements between the other three riparian states: Maharastra, Karnataka and Andhra Pradesh, rejected Tamil Nadu's requests to be allocated water (Nikku, 2004).

## L.3 Historic Inter-state Agreement

The project was revived in 1976 by Prime Minister Indira Gandhi, who, responding to Tamil Nadu's pleas, convinced the three riparian states to each give up 5 TMC (thousand million cubic feet), or a total of 15 TMC to meet Chennai's acute drinking water needs. Through an inter-state agreement, it was agreed that after accounting for 20% seepage and evaporation losses, Chennai would receive 12 TMC annually and bear the projects' costs.

The quantity sacrificed constituted a small portion (less than 1%) of each state's share. Even so, Indira Gandhi was able to achieve this historic agreement to share water with a non-riparian state mainly because her party, the Congress, was in power in all three riparian states, as well as at the centre at that time (Nikku, 2004).

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[112] As per the Indian constitution water resources are a "state subject". i.e. Water resources completely belong to the state in which they are located. The central (federal) government only has authority to intervene in the management of inter-state rivers and may offer broad policy guidelines and roadmaps.

### L.4 Rise of the regional parties

Unfortunately, before the project could be implemented, the political landscape shifted considerably. The 1980s saw the rise of regional political parties all over India. Regional parties gained prominence in many South Indian states: the AIADMK and DMK in Tamil Nadu and the (TDP) Telugu Desam Party in Andhra Pradesh. Regional political parties do not have fixed affiliations with national parties. Instead, they have tended to form politically expedient alliances with different parties in different general elections. More importantly, regional parties accord priority to meeting the needs of their own state and political base first.

After the Telugu Desam Party came to power in 1983, the charismatic founder and leader (and movie star) NT Rama Rao, demanded that the irrigation needs of the drought-prone Rayalseema district (through which the Telugu Ganga canal passes on its way to Chennai) should be met first. This was an early roadblock in the implementation of the inter-state agreement. Fortunately, around this time another regional party, was in power in Tamil Nadu; this one, the AIADMK, founded by another famous movie star, MG Ramachandran. The two leaders shared a friendship from their previous movie careers, and so were able to reach agreement on the exact location from which water would be drawn, and also agreed in principle to satisfy the irrigation demands of the enroute Rayalseema district.

Meeting enroute irrigation needs was never provided for in the original inter-state agreement. However, each leader was popular and held a clear majority of the seats in his state and each was able to achieve political consensus within his state. After many decades of negotiation, the project was completed in 1996, and Krishna water reached the Tamil Nadu state border for the first time in 1996.

### L.5 Implementation Challenges – Why Chennai has not received the water

Since the Telugu Ganga Project was inaugurated, Chennai has received a maximum of 3.6 TMC of Telugu Ganga water in any given year (barely a fourth of the anticipated 12 TMC). Nikku (2004) lists several implementation problems; insufficient reservoir capacity, demands by local irrigation associations that their needs be met first, drinking water demands of enroute towns, and outright theft from the canal.

Firstly, the reservoirs on the Andhra Pradesh side (Somasaila and Kandaleru) were never built to capacity mainly because of population displacement (resettlement and rehabilitation or

"R&R" as they are referred to in local documents) concerns associated with building reservoirs. Likewise, efforts to build additional storage capacity on the Tamil Nadu side were also frustrated by displacement concerns. Major link canals were never completed either for similar reasons.

Secondly, local irrigators repeatedly protested attempts to send water to Chennai, bypassing their irrigation needs. In 2002, a revered religious figure, Sri Sathya Sai Baba, donated funds to line the canal so that Chennai could receive more Telugu Ganga water. However, local farmers protested the construction. They claimed they were being denied the seepage recharge that was provided for, since the project was intentionally designed to have an open unlined canal. The lining project was subsequently abandoned.

Thirdly, the project never anticipated meeting drinking water needs of enroute towns. In 2004, the local reservoirs serving the needs of the major temple towns of Tirupati[113] and SriKalahasti (located enroute along the Telugu Ganga canal) dried up. Residents protested that their drinking water needs ought to be served before Chennai.

Finally, Nikku (2004) cites multiple instances when the canal was simply breached (and subsequently repaired by local residents) to fill an irrigation tank that had gone dry. In parts where the canal lining was completed, water pumps could be seen pumping water for irrigation throughout the length of the canal.

Figure L.1 shows the actual quantity received from the Telugu Ganga project plotted versus the average rainfall in the Chennai region. The receipts are correlated with rainfall in Chennai (except for the first year when the project was not fully completed).

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[113] For context: Tirupati is the largest pilgrimage centre in the world in terms of visitors. Its revenues, at $130 million annually, are about a third of the Vatican. It is therefore significant in terms of revenue and tax generation.

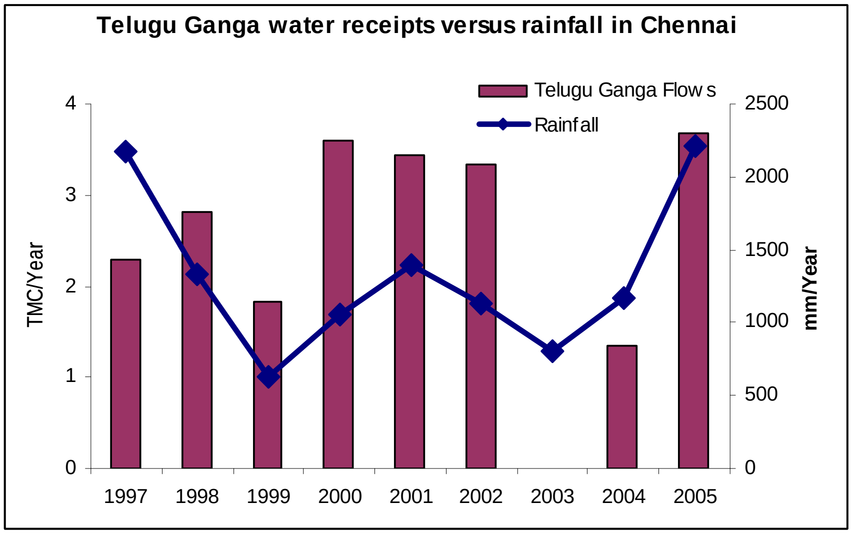

**Figure 0.1: Receipts from the Telugu Ganga Project**

### L.5 Historical Receipts

When the Telugu Ganga Project was originally conceived, it was argued that deliveries from the Telugu Ganga Project should have little correlation with rainfall in the Chennai area, as the head waters of the Krishna River are located in Maharashtra and Karnataka states, areas dependent on the south-west monsoon. In theory, annual rainfall from the south-west monsoon is uncorrelated with that of the north-east monsoon serving Chennai. However, the data nd interviews in Nikku (2004) indicate that the reductions in water arriving at Chennai in 2003-2004, were the result of the demands by irrigators and towns immediately to the north of Chennai, rather than the deficiencies in the distant Krishna basin. These enroute areas receive water from the north-west monsoon that also serves Chennai.

While the historical data set for the Telugu Ganga project is too short to arrive at any conclusive relationship between rainfall in Chennai and water receipts from the Telugu Ganga project, in future years, we will want to consider the likely scenario of Telugu Ganga water being cut off in the same years that Chennai experiences deficient rainfall. Deliveries from the Telugu Ganga project are likely to be exacerbated as new irrigation projects along the Telugu Ganga project achieve completion. The first of several planned projects is expected to come online in August 2008.

### L.7 Summary

The main conclusion from the scholarly research on the Telugu Ganga Project is that the interstate agreement is implemented through political bargaining, rather than a legal or arbitration framework. Specifically, Tamil Nadu cannot take Andhra Pradesh to court if Telugu Ganga water is not received. Instead, the bargaining process is a political one involving the complexities of coalition politics at Delhi. This makes it difficult to model future flows from the Telugu Ganga Project. Based on the short history for which data is available, we forecast that receipts from the Telugu Ganga project are correlated with rainfall in the Chennai region.

# Appendix M. Land Use projections using the SLEUTH

In this Appendix we described the method used to project land use in the Chennai basin. Urban growth around Chennai was projected using a software package called SLEUTH.

### *M.1 Description of Images*

Four LANDSAT 5 images of 30m resolution each were used from different sources. Two images dated August 1991 and October 2000 were geo-referenced images downloaded from the USGS website. Two other images dated February 1988 and May 2007 were ordered from the GISTDA data centre in Thailand. The October 2000 image was used to geo-referenced the two images obtained from GISTDA. The areal extents of the images were as follows:
Latitude Range: 12°5' 0" - 13 ° 21' 0"
Longitude Range = 79 ° 54' 0" - 80 ° 22' 0"

### *M.2 Images Classification*

The images were classified images using ENVI software. First, a K-means unsupervised classification was performed. This separated pixels into 50 distinct spectral classes (groups of pixels having identical spectral reflectance properties). Unsupervised classification techniques do not require the user to specify any information about the features contained in the images. Instead, the ENVI software uses an algorithm to group pixels into a specified number of classes, based on their spectral properties. Often many of the classes derived, are meaningless as they represent a mix of different surface covers. So these 50 unsupervised classes were aggregated into 7 broad land use categories: Urban, Water, Agriculture, Forest, Marsh, Saltpan, and Beach. Later, these 7 broad classes were further condensed to three final classes to improve accuracy: Urban, Water, Barren/vegetation/agriculture

### *M.3 SLEUTH Model*

Land use was projected using a software program called SLEUTH[114]. The SLEUTH model simulates the complex dynamics of any urban growth or land use change system given a set of historical input data. The model simulates urban growth and land use dynamics as a physical

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[114] Clarke undated.

process using cellular automata models[115] and was developed by Keith Clarke, UC Santa Barbara. The term SLEUTH is an acronym of the inputs used:

- **S**lope or land gradient: This provides information about topography. Very steeply sloping land is likely to be less amenable to development.
- **L**and-use classes developed as described earlier.
- **E**xcluded areas: These are areas that are resistant to development because of zoning or regulatory restrictions, e.g., national parks. The excluded areas need not be binary and can allow for probabilistic resistance to urbanization in an attempt to modify the rate of growth, for example to simulate planning
- **U**rban extent over time.
- **T**ransportation: Urban growth occurs preferentially along roads.
- **H**ill-shaded backdrop: Hill shading is only used for visualization purposes and does not play a role in determining model results.

### *M.4 INPUTS:*

The input data were generally derived from remotely sensed imagery or current and historical road maps and processed through a Geographic Information System (GIS) to preserve spatial attributes and topology. The resulting data were converted into GIF format files for use in the cellular automaton model.

The inputs for the Chennai SLEUTH model were derived as follows: Slope, Hill-shade created from downloaded SRTM elevation data (90m resolution). The land-use classification was created from classified ENVI images as described earlier. Water, forest reserves, beaches, salt pans were assumed to be “excluded” areas; i.e., areas that would not be developed easily. Finally, transportation was input as road maps created manually from satellite imagery and current roadmaps. The geo-referenced road map for Chennai was obtained by purchase from Spatial Data Pvt. Ltd., Bangalore, India.

### *M.5 SLEUTH PARAMETERS*

Before forecasting, the model must be calibrated to account for the specific growth pattern observed in Chennai. To do so, SLEUTH employs a calibration routine that examines the

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[115] Clarke and Gaydos 1998

historical data input to derive a set of parameters representing past urbanization trends. The inherent assumption is that past urbanization trends will continue into the future.

The calibration phase of SLEUTH uses a set of five parameters, each of which describes one growth characteristic of an urban area, derived from a transition rule governing urban growth: diffusive growth in new spreading centers, organic growth in infill and edge areas, and road-influenced growth along the transportation network. The parameters are modeled as integer coefficients ranging from 0 to 100. These parameters used in SLEUTH are defined below.

1. Dispersion – controls the overall dispersive nature of the distribution.
2. Breed – determines the likelihood that an urbanized cell will become a growth center (i.e. will spread to neighboring cells).
3. Spread – determines the likelihood that the pixels that comprise a new spreading center will continue to generate new urban pixels.
4. Slope – influences the likelihood that a cell will urbanized along a steep slope. The land around the whole model area was quite flat and this coefficient was irrelevant.
5. Road Gravity – a factor that encourages growth along the road network.

### *M.6 CALIBRATION PROCESS*

Calibration of the model is based on comparing model output and initial model inputs for a range of coefficients. The SLEUTH model parameter coefficients were calibrated using the calibration period from 1988 to 2007. The model was initialized with the earliest available time period, the 1988 image. Then the cellular automaton model "forecasts" urban growth from 1988 to 2007, using a coefficient set. Each coefficient set process produces a set of likely images, one for each year from 1988 to 2007. By varying the coefficient values, many images of urban extent are produced. These images are then compared to the control data available for "goodness of fit". In the case of the Chennai model, three control images from August 1991, October 2000, and May 2007 were available. The degree of similarity between the simulated images and the control images was determined through a set of metrics that were calculated and stored in a log file.

An exhaustive approach to finding the optimal set of parameter coefficients would be to generated runs every possible combination of parameters and choose the set that yields the greatest fit between the simulated and control images. This was too time-consuming. Instead we adopted a method suggested by Clarke and Gazilius (undated) explored the parameter space in successively finer intervals. Simulations at intervals of 25 (values = 1, 25, 50, 75, and, 100) in the first iteration and intervals of 10 in the second iteration were performed.

SLEUTH provides different statistical metrics to assess the fit between the calibrated model and the classified images. These metrics vary based on type of accuracy that is most desired. After experimenting with many metrics, three different metrics were used because of their relevance to goals of the research.

1. ***Fraction Urban***: This metric provided a least squares regression between the percent of available pixels urbanized compared to the urbanized pixels for the control years.
2. ***Fmatch***: This metric is the goodness of fit across all land use classes defined as follows #_modeled_LU_ correct / ( #_modeled_LU_correct + #_modeled_LU_wrong)}
3. ***FMatch by land use***: The above metric was broken down by land use category to test how the calibration performed for each land use category.

After many calibration runs on a range of parameter values, it was observed that the dispersion, and slope coefficients did not make much of a difference. Instead, growth in Chennai was mostly influenced by the spread coefficient and road extents.
Final parameter values used for the SLEUTH model are specified below:
Dispersion = 1, Spread = 60, Breed = 10, Slope = 1, Road Gravity = 70

### *M.7 SLEUTH PROJECTIONS*

To forecast with SLEUTH, the model was initialized with the most recent data (the 2007 image) as the "seed" layer. SLEUTH then executes a finite set of transition rules that influence state changes within the Cellular Automaton model using the parameter set derived via calibration (Dispersion = 1, Spread = 60, Breed = 10, Slope = 1, Road Gravity = 70)
These growth parameters were applied to extrapolate land use to 2025. Based on an urbanization probability derived from the parameter set, a particular cell is either urbanized or not urbanized. Monte Carlo simulation is employed to reduce stochastic bias. SLEUTH generates one image (maximum likelihood) for each future year. Finally, since SLEUTH generates a land use classification with a 30 m resolution (because the LANDSAT images had a 30 m resolution), the SLEUTH image projections had to be aggregate to the cruder 220 m resolution of the integrated model. The aggregation algorithm used the “mode” or the most frequently occurring land use category to determine the land use classification of the 220 m grid cell.

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