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Reimagining the past – use of counterfactual trajectories in socio-hydrological modelling: the case of Chennai, India

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Abstract. The developing world is rapidly urbanizing. One of the challenges associated with this growth will be to supply water to growing cities of the developing world. Traditional planning tools fare poorly over 30–50 year time horizons because these systems are changing so rapidly. Models that hold land use, economic patterns, governance systems or technology static over a long planning horizon could result in inaccurate predictions leading to sub-optimal or paradoxical outcomes. Most models fail to account for adaptive responses by humans that in turn influence water resource availability, resulting in coevolution of the human–water system. Is a particular trajectory inevitable given a city's natural resource endowment, is the trajectory purely driven by policy or are there tipping points in the evolution of a city's growth that shift it from one trajectory onto another?

Socio-hydrology has been defined as a new science of water and people that will explicitly account for such bidirectional feedbacks. However, a particular challenge in incorporating such feedbacks is imagining technological, social and political futures that could fundamentally alter future water demand, allocation and use. This paper offers an alternative approach – the use of counterfactual trajectories – that allows policy insights to be gleaned without having to predict social futures. The approach allows us to "reimagine the past"; to observe how outcomes would differ if different decisions had been made.

The paper presents a "socio-hydrological" model that simulates the feedbacks between the human, engineered and hydrological systems in Chennai, India over a 40-year period. The model offers several interesting insights. First, the study demonstrates that urban household water security goes beyond piped water supply. When piped supply fails, users turn to their own wells. If the wells dry up, consumers purchase expensive tanker water or curtail water use and thus become water insecure. Second, unsurprisingly, different initial conditions result in different trajectories. But initial advantages in piped infrastructure are eroded if the utility is unable to expand the piped system to keep up with growth. Both infrastructure and sound management decisions are necessary to ensure household water security although the impacts of mismanagement may not manifest until much later when the population has grown and a multi-year drought strikes. Third, natural resource endowments can limit the benefits of good policy and infrastructure. Cities can boost recharge through artificial recharge schemes. However, cities underlain by productive aquifers can better rely on groundwater as a buffer against drought, compared to cities with unproductive aquifers.

1 Introduction

The world's population is rapidly urbanizing. One of the challenges associated with this growth will be to supply water to rapidly growing cities of the developing world. With growing population size and density, more water must be sourced from outside the boundaries of the cities and wastewater collected, treated and released safely into the environment (Lundqvist et al., 2003; McDonald et al., 2011). However, many developing cities are not equipped to meet even current demands let alone future growth. Inadequate and unreliable piped supply in developing world cities has measurable impacts on human well-being (Baisa et al., 2010; Srinivasan et al., 2010b). Although many developing world cities have not achieved reliable water supply, this is not an inevitable trajectory, i.e. not all developing urban systems end up becoming unreliable. For instance, some water Asian utilities (McIntosh, 2014) which have experienced high rates of population growth have managed the transition to "24/7" piped supply.

This paper addresses questions on how urban water systems evolve. Given a set of initial conditions, is a particular trajectory inevitable, or are there tipping points in the city's growth that shift it from one trajectory onto another? If so, are these tipping points influenced by government policy? Are there path dependencies such that early decisions constrain possibilities later?

1.1 Review of methodological approaches

Urban water systems are not pristine, natural systems; they are shaped both by societal decisions on infrastructure, governance, pricing and so forth, as well as the natural resource endowments of the region. Reflecting this, there is a long history of interdisciplinary research in urban water resource management. Traditionally, the focus of this type of research has been on policy prescription and/or infrastructure planning (Gober and Kirkwood, 2010; Brown et al., 2012; Ward et al., 2006). Researchers use economic analyses and water resource system models to make the case for new infrastructure projects, demand-side management programmes or alternative pricing policies. Such studies can broadly be categorized under Integrated Water Resources Management (IWRM) or Integrated Assessment (IA). They identify stakeholder priorities, and then integrate multiple scales of system and agent behaviour by drawing on the relevant disciplines within and across the human and natural sciences to explore alternative management options (Jakeman and Letcher, 2003; Gober et al., 2011). The purpose of such modelling efforts is usually to influence management decisions and understand trade-offs over a range of ecological, social and economic considerations. The role of the scientist in this endeavour is to enable decision-makers to decide how to manage the system better (Liu et al., 2008).

However, in the developing world, traditional planning tools fare poorly over 30–50 year time horizons. Here, systems are changing so quickly that holding land use, irrigation, agricultural technology, economic activity or technology static over the model period results in paradoxical outcomes (Sivapalan et al., 2014). As new technologies develop, users adapt to unreliable water supply. Adaptive responses by humans (acting individually and collectively) in turn may alter the watershed hydrology and consequently water availability. These bi-directional feedbacks often result in unexpected emergent behaviour. Many water managers fail to account for these complexities.

To address this challenge, socio-hydrology (Sivapalan et al., 2012) has been proposed as a "new science of humans and water systems". Socio-hydrology involves understanding the dynamics of coupled human–water systems over large spatial and temporal scales. In addition to studying specific sites, a central goal of socio-hydrology is to build a general theory of coupled human–water systems. This necessitates the inclusion of feedbacks between climate, land use, technology and social systems (Thompson et al., 2013) across multiple scales, sectors and agents in order to explain, in the most meaningful but parsimonious way, trajectories exhibited by coupled human–water systems. Such an improved understanding of the interactions between water and society can be used to improve decision making in the medium to long term (Clark and Clarke, 2011).

Recent discussions on socio-hydrologic methods within the scholarly community suggest that a diverse set of ideas exist on what socio-hydrologic modelling entails. Socio-hydrologic modelling includes a wide range of tools from "toy" models that do not aim to simulate a *specific* human–water system (Di Baldassarre et al., 2013) to coupled models that link agent-based and hydrologic models and validate them against detailed empirical observations. Each of these approaches has advantages and disadvantages. Toy models are relatively inexpensive to develop and are by design abstract and generalizable. However, they run the danger of predicting dynamics that are not in fact observed anywhere in the real world. This is particularly true of models of human behaviour, which are difficult to characterize in general terms. In contrast, "real world" models coupling agent behaviour to hydrologic models that are carefully calibrated and tested against empirical observations may yield reliable results for a particular site, but often lack abstraction and comparability beyond that study site. A third category, "stylized models" (Chakravorty and Umetsu, 2003; Kilgour and Dinar, 2001) offers a compromise between detail and generalizability. Such models have been used by economists in both natural resources and other contexts. A stylized model is a simplified representation of the real world that aims to replicate the *essential dynamics* observed in one or more study sites, but does not attempt to calibrate and validate every variable.

Methodologically, this paper illustrates how a stylized, socio-hydrologic model that explores bi-directional feedbacks between the societal, engineered and hydrologic components of water systems might be applied to achieve insights into household water security in developing urban regions. It presents a model of the coupled human–water system in a single case study site, Chennai, India, over a time span of 30–40 years and explores what factors drive the changes over time. The paper begins with an exploration of possible socio-hydrologic modelling approaches. Next it describes the case study and the stylized model of the water system. The model results then explore the actual trajectory as well as some alternative trajectories and the implications for household water security.

1.2 Socio-hydrologic model conceptualization

There are several challenges in attempting a stylized socio-hydrologic model of the type proposed herein. First, deciding which outcomes are worth explaining, i.e. the act of "framing", involves making choices on which problems are worth focusing on and which linkages to include or exclude (Lane, 2014). With coupled human–water systems, the decision of what to study does not emerge from the theoretical frameworks of a single discipline. Instead, it involves making a judgement about *which and whose* problems matter (Lane, 2014) and how to model them. This is critical because if socio-hydrologic models are intended to feed into the policy process, researchers cannot truly remain "external" observers of the system. As Schlueter et al. (2012) point out, human societies are reflexive and respond in unpredictable ways to new information. As a result, the very process of deciding what to model, which variables are static and which ones may be changed in the model, can influence which policy options get communicated and debated – a self-fulfilling prophecy. As a result, the researcher is not an impartial observer, but (albeit unintentionally) a social engineer too (Lane, 2014). Second, once the "system of interest" is extended beyond the biophysical or engineered sub-systems, every aspect of human society: culture, politics, economic trends, technology, social movements and so forth, and every related sub-sector such as energy, food, public health and biodiversity, is a candidate for inclusion. How can the socio-hydrology model avoid spiralling into a general system dynamics model of the whole world? Third, preventing the future from looking mostly like the past is a non-trivial challenge. How can a researcher "imagine" feedbacks and thresholds that go beyond what has occurred in the past and ensure that the model can accommodate the widest possible range of possible trajectories? In summary, the socio-hydrologic modeller must make a choice about how to frame the problem, decide which human well-being/biophysical outcomes are worth studying, and allow the system to evolve beyond trajectories that have occurred in the past.

With regard to the first challenge of framing the research questions, one approach that has been suggested is to embed the research process within a stakeholder dialogue and let the definitions and questions of interest emerge from these consultations (Tidwell and Van Den Brink, 2008; van den Belt et al., 2010). However, it is not always feasible to embed every research project within a stakeholder process. Instead, to ensure that the research is usable (Dilling and Lemos, 2011), in the present study, the variables, feedbacks and outcomes were chosen by referencing contemporary debates over hot to manage water and through one-on-one interviews with stakeholders and experts. Additionally, the original framework was validated in an expert consultation meeting held at Chennai in 2006. Moreover, a key contribution of this work is that it simulates *past counterfactual trajectories*; i.e. asking if the current water situation would be different if different decisions had been made in the past. Since the focus is on past trajectories, the study sidesteps the "researcher as social engineer" problem to some extent. The second challenge involves deciding which feedbacks to include. Lane (2014) argues that predictive socio-hydrological models are challenging because social futures are not well defined. The position taken here is that the feedbacks and sub-systems simulated depend on the time-span of the model, which in turn depend on the scale of system behaviour that needs to be understood (see Fig. 1). For shorter time periods of about a year (e.g. a specific drought event), infrastructure, economic activity, and political structures can be held constant, though water availability and markets may change. Over a decade or two (e.g. the planning horizon for a water resources agency), infrastructure and politics would change and some incremental improvements in technology and market adjustments would occur, but it would be reasonable to assume that the structure of an economy or cultural beliefs are likely to be the same. Over a hundred years (e.g. in making decisions over major infrastructure projects), all these factors along with hydro-climatic patterns are likely to change. In this study, the temporal choice of 30–40 years dictates which feedbacks are appropriate.

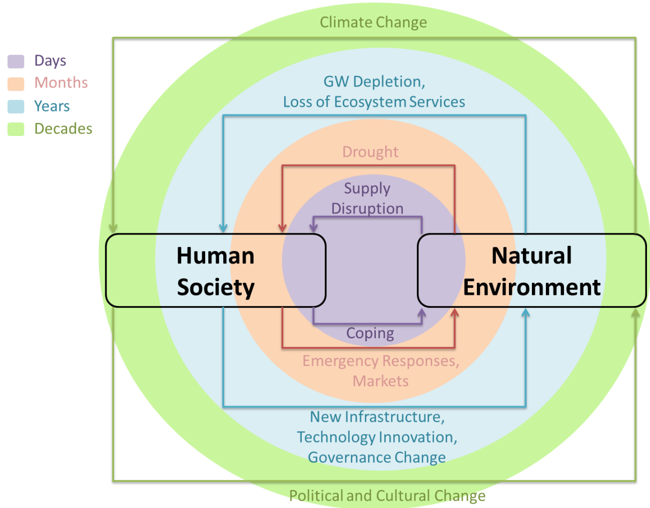

Figure 1. Feedbacks in coupled human–water systems.

The third challenge involves designing models that can accommodate a broader range of feedbacks than have been observed in the past. Focusing on past counterfactual trajectories mitigates this concern somewhat. Counterfactual trajectories use actual rainfall data, political and technology changes that occurred over the period of the model. Only policy variables are allowed to change. In the model presented here, the choice of counterfactual trajectories was based on contemporary debates on how urban water supply should be managed. In recent years, many Indian scholars and practitioners have begun questioning the wisdom that all urban water needs must be met through 24/7, potable piped supply imported from outside the city. They point out that inadequate piped supply does not automatically mean that users do not get enough water to meet their needs. Meeting a portion of urban water needs from local supply or self-supply may be an acceptable or at least realistic alternative (Shah, 2013). Already, many users rely on their own private wells for at least the non-potable component of their needs (Shaban and Sharma, 2007). Taking this into account, the model allows for multiple source dependence.

As the scenarios considered involve a range of water provision options going beyond piped supply, a metric that goes beyond engineering measures of piped supply reliability that could allow comparison over time and alternative trajectories was needed. In recent years "water security" has emerged as a new organizing idea in the water sector, encompassing both human and ecological concerns over multiple spatial and temporal scales. However, in practice, "water security" has been extremely difficult to operationalize (Cook and Bakker, 2012). Based on a broad review of studies on water security, Cook and Bakker (2012) suggest that the concept is best used to guide the selection of narrower, case-specific indices that may be used in policy, modelling or empirical research. In this paper, the term "household water security" is applied at the household scale to refer to the "quantity of water used by the household when all available sources of water are pooled". The evolution of household water security is traced over a 40-year period from 1965 to 2005 using a stylized model of Chennai India

2 Methods

2.1 Case study: Chennai, India

Chennai, formerly Madras, is India's fourth largest city, located in the southern state of Tamil Nadu. As per the 2011 Census, about 8.9 million people resided in the urban agglomeration, which includes peri-urban areas, towns and villages. Chennai lies in the rain-shadow region of the Western Ghats and is dependent on the northeast monsoon – a series of tropical depressions between October and December which deliver large quantities of rain over a few rainy days. Although the city receives almost 1250 mm of rain annually, the rainfall is irregular and episodic.

Unlike other Indian cities, Chennai does not have much of a pre-colonial history. The city of Madras developed around the port and the military establishment of Fort St. George (Gopakumar, 2011). Until about 1870, the population was dependent on privately dug wells or public wells and tanks. Organized water supply to the British colonies was commenced in 1872. As the city grew, three reservoirs were acquired or constructed between 1944 and 1972, to bring the combined storage capacity of Chennai's reservoirs to about 175 million cubic metres (MCM). Following hydrogeological investigations by UNDP between 1966 and 1969, well fields in the Araniar-Kosathalaiyar Basin (A.K. Basin) located north of Chennai were developed for abstracting groundwater. The Chembarambakkam Lake, another small peri-urban reservoir, was acquired for city water supply after its irrigation command area disappeared due to urbanization (Metrowater, 2011) by 2000.

The biggest augmentation to Chennai's water supply occurred via the so-called "Telugu Ganga" project. An agreement was signed jointly by riparian governments of Maharashtra, Karnataka and Andhra Pradesh in 1976 to allocate about 420 MCM annually of Krishna River water to Chennai. Initial works for supplying water under the Telugu Ganga scheme were completed in 1996. Water began to be delivered into Chennai's reservoir system through a 152 km long open canal. This design allowed for significant losses along the way, both through direct lifting and seepage, as the water flows through the drought-prone regions of Andhra Pradesh before reaching the Tamil Nadu border. So only a fraction of the water actually reaches Chennai. Another project, the intra-state Veeranam Water Supply Project, was implemented in 2004 as additional source of water to Chennai. The project supplies 180 million litres per day (MLD) of water to Chennai by drawing water from Veeranam Lake in the Cauvery Basin (Metrowater, 2011) in Tamil Nadu.

The major challenge of Chennai's water supply system and consequently its vulnerability has thus been its inability to store monsoon waters for supply throughout the year. Even today, Chennai's reservoir storage capacity remains very low by Western standards. Even as Chennai's population has almost tripled since 1965, very little new reservoir storage was added. The two most recent projects, Veeranam and Telugu Ganga, did involve "new" reservoir capacity for Chennai, but the reservoirs associated with these projects are controlled by other agencies and Chennai must negotiate with farmers (in the case of Veeranam) and Andhra Pradesh (in the case of Telugu Ganga) to secure releases. This means that the reservoirs are not necessarily managed to optimize Chennai's needs.

Throughout its history, Chennai has been water scarce. Despite this, urban piped water supply has remained unmetred. Rationing rather than pricing has remained the dominant mode of controlling water use. Even today only a fraction of households are metered, but water is supplied for only a few hours each day. Because water supply is unreliable, more than two-thirds of Chennai's households have private wells as a supplementary water source (Srinivasan et al., 2010a). Peri-urban towns and villages are served by several different agencies. Some of these receive bulk supply from Chennai's water utility, while others rely entirely on bore wells. Overall, as the city continues to grow outward rapidly, peri-urban areas are increasingly groundwater dependent. It is expected that peri-urban villages and towns will eventually be supplied with water and sewerage services via the city municipal supply agency, but this is likely to further strain the limited reservoir capacity of the city.

2.2 Model conceptualization and parameterization

The model described here is a "stylized" version of a detailed, spatially explicit coupled human–hydrologic model developed and published previously (Srinivasan et al., 2010a). The previous coupled model was run and calibrated using a variety of hydrologic and socioeconomic data. The model was calibrated for the period from 2002 to 2006, which included both one of the worst droughts and one of the wettest years in historical record. As a result, the model was able to capture both hydrologic and social responses to drought. Longer-term parameters such as reservoir storage, the poor state of the piped supply system and household dependence on private wells were taken as given and constant over the 5-year period.

This present study uses the previous model as a starting point. The parameters for shorter-term processes are imported from the earlier model (Srinivasan et al., 2010a). These include the user demand function, the response of the aquifer system to recharge and pumping, the rainfall-inflow model into the reservoir system, reservoir operations, user behaviour and the functioning of the tanker market. However, the present study explores coevolutionary, temporal dynamics over a much longer period. As the model is run over a longer period, it incorporates additional feedbacks representing slower decadal-scale processes, which were held constant in the previous model. The new feedbacks added include growing income, penetration of indoor plumbing, private wells, the impact of pricing policies on the water utility's finances and thus its ability to expand and maintain infrastructure. The socio-hydrologic model first replicates the actual trajectory of Chennai's water supply system during 1965–2006. Next, "counterfactual" trajectories that might have occurred if different decisions had been taken are explored. The spatial component has been eliminated entirely and the model only focuses on the core urban area of 176 km^2.

The urban water system is conceptualized through a set of equations and feedbacks (see Fig. 2). A key element of this model is the integration of the hydrologic system, the engineered water delivery system and household-level decision making. The reservoir and aquifer system, population and user investments in bore wells were all stock variables. Water supply, pipeline leakages and water extraction and use by users are flow variables. In setting up the model, rainfall, demography, economic growth, prices and user preferences were assumed to be exogenous or external to the model. It was assumed that the presence or absence of water was not a significant determinant in Chennai's growth, which instead was driven by larger macro-economic factors. Investments in infrastructure both by the water utility and private users were, however, determined within the model. The initial conditions – reservoir capacity, reservoir storage, the coverage and efficiency of the piped system in 1965 – were based on actual data. Actual water tariffs fixed by the government were used.

In terms of users, a distinction was made between households with in-house plumbing ("Tap" households) versus those who access water manually from standpipes and public wells ("NonTap" households) for a variety of reasons (Strand and Walker, 2005). This was necessary because both population growth and changing lifestyles are contributing to the city's demand for water. This categorization also allows different demand and supply functions to be used for the two types of users. Poorer households lacking indoor plumbing use water very differently and have a much lower willingness to pay. They also face different resource constraints; they must store water in pots and use it manually rather than from a tap. Consequently they face a higher cost of water (Zérah, 2000; Pattanayak et al., 2005). Wealthier households can invest in underground sumps and pumps and thus face a lower marginal cost of water.

The model incorporates feedbacks between multiple spatial scales (utility versus household) and temporal scales (decadal versus daily). To achieve this, both city-scale long-term decisions (infrastructure investments in reservoirs and piped infrastructure) and short-term decisions (reservoir releases) as well as household-scale long-term investments (private wells) and short-term decisions (cutting back on consumption and procuring water from alternate sources) were considered.

In the long-term, as the city grows, the urban water utility makes decisions about expanding and maintaining the piped infrastructure and reservoirs depending on the financial resources available to it. The model simplistically assumes that improved finances will actually result in better infrastructure (i.e. the money will not all be lost to corruption). In the short term, the water utility makes decisions on how to allocate the resources available to it given the infrastructure available. The state of the infrastructure thus determines how much water is available to households in each period.

Households make independent decisions on how to cope with the available supply. If piped supply infrastructure is insufficient or degraded, households may invest in private wells and underground sump storage. These coping investments allow households to diversify the sources available to them when water shortages occur and enhance their own water security. Moreover, these investments are "sticky" – once made they permanently alter their choice set. In each time period, households optimize their daily water use based on the available quantity and cost of water from different sources. However, the options available to households in the short term are contingent on their long-term coping investments. Households may self-supply from private wells or purchase water from tankers. Thus each feedback —slow or fast — is associated with biophysical changes and socioeconomic changes (Table). These interact to generate emergent behaviour.

The socio-hydrologic model consists of a number of linked sub-models each consisting of one or more equations (Fig. 2). A complete description of the sub-models with the equations is presented in Appendix A.

Table 1. Details of feedbacks between human and natural sub-systems.

Feedback	Sub-models	Description of feedback	Slow/Fast
Nature − > Nature	Climate − > Reservoir	Increase in rainfall => increased inflows into the reservoir system	Fast
	Climate − > Aquifer	Increase in rainfall => increased aquifer recharge	Fast
Nature − > Human	Reservoir − > City Water Supply	Decrease in reservoir storage => cutbacks in piped supply	Fast
	Aquifer − > User Agent	Drop in Groundwater table => more wells going dry	Fast
Human − > Nature	User Agent − > Aquifer	Decrease in piped water availability => more groundwater extraction	Fast
	User Agent − > Aquifer	Increase in private wells => more groundwater extraction	Slow
	Infrastructure − > Aquifer	Improved piped infrastructure => less pipeline leakage into groundwater	Slow
Human − > Human	City Water Supply − > User Agent	Decreased piped supply => switch to private sources like wells and tankers	Fast
	Infrastructure − > City Water Supply	Increase in utility revenues => improved pipeline infrastructure, reservoir capacity	Slow
	Infrastructure − > User Agent	Decreased piped supply => increased drilling of private wells	Slow

– The *Climate Sub-model* specifies the rainfall in Chennai. For the purposes of this study, historical rainfall data were used.

– The *Population Sub-model* specifies the number of Tap and NonTap HH in Chennai. Population growth and rate of increase in Tap HH was based on actual historical data and were assumed to be the same for all trajectories, i.e. it was assumed that water availability does not significantly influence either population growth or the number of households investing in indoor plumbing.

– The *Reservoir Sub-model* estimates storage in the reservoir system at the end of each month. In the historical trajectory, data on reservoir storage, inflows, rainfall and diversions were available and were used to derive the rainfall-inflow and storage-diversion relationships.

– The *City Water Supply Sub-model* distributes the amount of water available in the reservoir system between Tap and NonTap HH. Based on interviews with city water utility engineers, it was assumed that the amount released from the reservoir system is a fixed fraction of reservoir storage at the beginning of the month.

– The *Infrastructure Sub-model* determined the rate of deterioration or improvement in pipelines and thus the pipeline leakage over time as well as the amount of new reservoir storage added based on the how much the tariff exceeds or falls short of the long-run marginal cost of supply.

– The *Aquifer Sub-model* simulates water levels in the aquifer as a bathtub. The depth of the water table in the aquifer is thus a linear function of the total aquifer storage. Given the distribution of well-depths in Chennai, the fraction of wells that go dry is calculated. The amount of groundwater extracted in each period is obtained from the User Agent and Tanker Sub-models.

– The *User Agent Sub-model* was the representation of user (households). It was assumed they make two types of decisions. In the short term, they decide what sources of water to use in a given time period given their income and past investments in wells, sumps etc. In the long term, households must decide whether to get a connection and drill a private well. It was assumed that when piped water supply drops below quantity, a fraction of piped households will drill wells.

– The *Tanker Sub-model* estimates the size of the tanker market by multiplying the number of households purchasing tanker water with the quantity of water each household purchases.

– The *Cost of Water Sub-model* is estimated as the total amount for water divided by the total water use by all households.

3 Model results

The model explored three coevolutionary trajectories that Chennai's water system could have followed. In all three, Chennai's population and economic growth were assumed to be exogenous, i.e. independent of the water situation. The number of households almost tripled from 400 000 to about 1.1 million and fraction of households with indoor plumbing also increased from half of all households in 1965 to al-

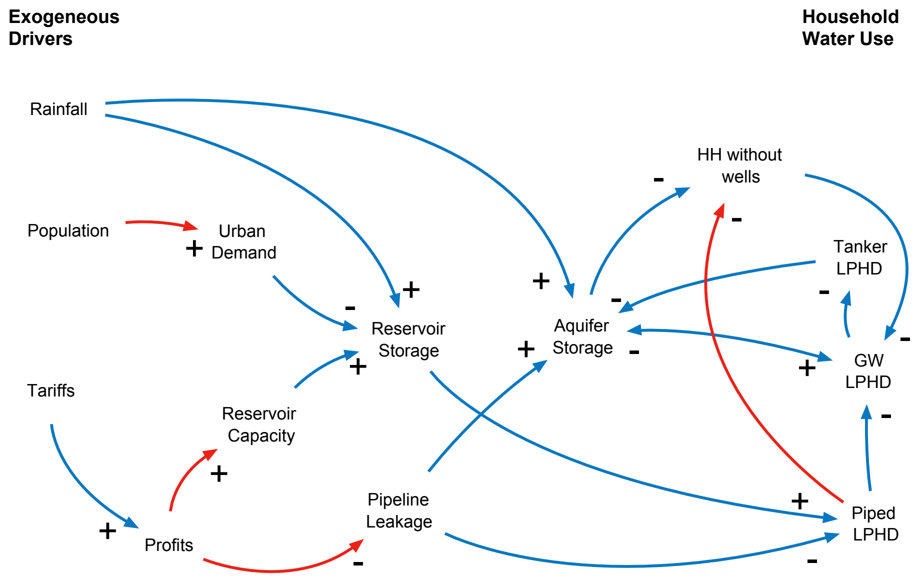

Figure 2. Feedbacks in Chennai's coupled human–water system. The red arrows represent slow feedbacks, while the blue arrows represent fast feedbacks. LPHD is litres per household per day.

most 70 % in 2006. All three scenarios use the same actual historical rainfall scenario. It may be observed that Chennai experienced several prolonged multi-year droughts. The first multi-year drought occurred between 1985 and 1990 and the second one, between 1999 and 2004 (Fig. 3). In all three scenarios, incomes were assumed to grow at about the same rate, so that more and more households were able to afford sumps, bore wells and indoor plumbing and thus the fraction of "Tap" households increased over time. All prices represent real prices in 2005. i.e. inflation is not explicitly modelled.

The first, the current trajectory, is called "Low initial reservoir storage, no metering, flat price". In this trajectory, Chennai starts in 1965 with a relatively low level of surface storage and a flat-rate tariff which does not allow cost recovery. Over time the piped system cannot be maintained; pipeline leakages become worse and less and less of the water reaches users. Very little new storage is added. This scenario essentially replicates historical reservoir storage, tariff and population.

The second, called the "High initial reservoir storage, volumetric tariffs" is a counterfactual trajectory. The initial reservoir capacity in 1965 is about 2.5 times the actual 1965 reservoir capacity. The tariff is high enough to cover both the short- and long-run cost of piped supply and so the infrastructure keeps pace with the population. Reservoir storage gradually increases and pipeline leakage decreases and stabilizes at 5 % over time.

The third, called the "High initial reservoir storage, no metering, flat price" is a another counterfactual trajectory, in which the city starts with 2.5 times the actual 1965 reservoir capacity, but a flat-rate tariff policy does not allow cost

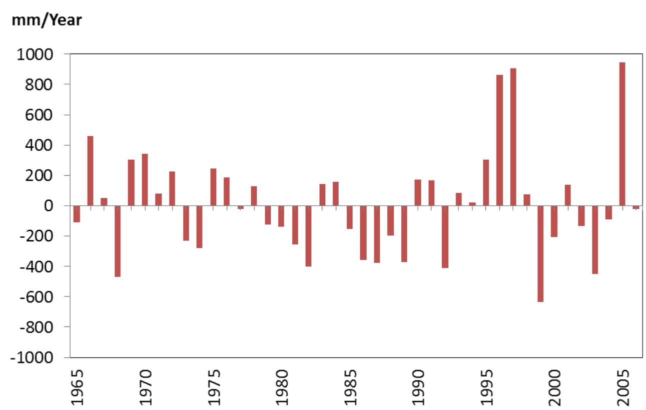

Figure 3. Deviation from average annual rainfall of 1261 mm.

recovery. In this scenario, reservoir capacity stays frozen at 1965 levels and pipeline leakage worsens gradually.

For each trajectory, three types of results are presented: (a) long-term infrastructure changes over time because of investments by the water utility and households; (b) short-term changes in water availability in the reservoir system and aquifer which depend on the infrastructure available as well as rainfall in a given year and (c) short-term changes in water consumed by and costs to households.

3.1 Current trajectory: low initial storage, no metering, flat price

The driving assumptions in this scenario are that the utility starts out with very little reservoir storage but also has no system of metering. The coevolution of the system is presented in a series of graphs (Fig. 4a–i). The flat-rate tariff system does not allow the city to invest in expensive infrastructure projects or maintain the piped network. As a result, reservoir capacity increased by just 20 % even as population almost tripled (Fig. 4a). Pipeline leakage also worsened, increasing from 20 % in 1965 to almost 40 % in 2005 (Fig. 4b). Moreover, in order to serve the growing population with the same level of storage, the utility became more and more aggressive in its management of the reservoir system. The inability to increase reservoir storage along with increased pipeline leakage results in piped supply becoming very unreliable over time (Fig. 4f).

When households do not receive reliable piped supply, it is economically rational for them to invest in private wells. At first, only the wealthiest few households could afford wells, but well ownership gradually increased over time as incomes rose (economic growth was assumed exogenous to the model), (Fig. 4c). Households who had wells were able to use wells whenever piped supply fell short. When only a few households had wells, the aquifer was able to buffer them over a multi-year drought. However, as more and more wells were drilled, the groundwater level dropped faster and faster in drought periods and more households became tanker dependent (Fig. 4g, h). As tanker water is much more expensive than all other sources of water, the cost of water rose sharply during droughts and households became more water insecure (Fig. 4i).

Overall, the historical trajectory is the story of a shift from public investment in reservoirs and piped infrastructure to private investment in wells. However, the common pool groundwater resource which was able to support a few well owning households, got depleted with increases in population.

3.2 Counterfactual trajectory 1: high initial reservoir storage, volumetric tariffs

The second trajectory is based on different initial conditions. The initial reservoir storage is assumed to be 2.5 times Chennai's actual storage in 1965 and comparable to many cities in developed countries. In this case, piped supply is assumed to be fully metered and priced at Rs 13/kL, above the long-run marginal cost of supply. The additional revenue is assumed to be used to maintain the system, expand reservoir storage and inter-basin transfer projects. In this trajectory, the reservoir is assumed to be managed carefully and releases are matched to meet urban demand. However, because water is metered and priced, consumers have incentives to invest in water use efficiency measures. The utility is able to successfully control demand. The reservoir does not dry up as often.

Except for the severe multi-year drought during the 1980s, when piped supply becomes slightly unreliable, Chennai by and large enjoys secure piped supply (Fig. 5). Although the rate of ownership of private wells increases during the drought, well-drilling stops once piped supply is restored; very few new wells are dug. As very few consumers depend on private wells, the aquifer storage does not fluctuate much. No tanker market develops. Consumers are able to satisfy their needs with piped supply in almost all periods. This is the trajectory that most developed world cities have been able to follow. Although consumers incur much higher costs each month over the 40-year period, there is very little variability in the cost of water.

3.3 Counterfactual trajectory 2: high initial reservoir storage, no metering, flat price

The third trajectory for Chennai begins with robust infrastructure, but in this case water is charged at a flat rate and is not metered. As a result, the utility is unable to expand in response to demand or maintain the piped network, which gradually deteriorates. In each consecutive drought, the city is unable to control demand and the reservoir dries up.

For the first 35 years, from about 1965 to 2000, the city does not feel the effects of the weak tariff policy (Fig. 6). When the multi-year drought strikes in the early 2000s, the aquifer no longer has the buffering ability – 70 % of the Tap households have wells by this time. The higher initial reservoir storage helps the city. Only 10 % of the wells go dry and a small tanker market develops – not as severe as the historical trajectory. The cost of water rises because some users must depend on tankers.

3.4 Sensitivity analysis

The model was found to be sensitive to aquifer parameters. Overall, parameters affecting the aquifer were much more sensitive than the reservoir system. Model results were sensitive to "natural" parameters such as the specific yield and "policy-relevant" parameters such as the recharge rate.

In particular, increasing specific yield improves the buffering capacity of the aquifer because groundwater levels do not drop as much for a given level of extraction. Fewer wells go dry during droughts and fewer users are forced to buy expensive tanker water. This suggests that cities which are underlain by less productive aquifers (e.g. the hard rock aquifers found in peninsular India) are likely to be worse off compared to cities underlain by productive aquifers, as private wells are less able to provide a supplementary source of water. Similarly, increasing the proportion of rainfall that recharges the aquifer boosts the buffering capacity of the aquifer. The benefits of improving recharge through artificial recharge and household rainwater harvesting have been discussed elsewhere (Srinivasan et al., 2010b). The sensitivity analysis is consistent with the previous finding that boosting recharge reduces the tanker market size during droughts.

The model is also sensitive to the user demand function. For instance, if the demand function is changed so that households consume 33 % less water, the water table does not reduce as much, and the tanker market virtually disap-

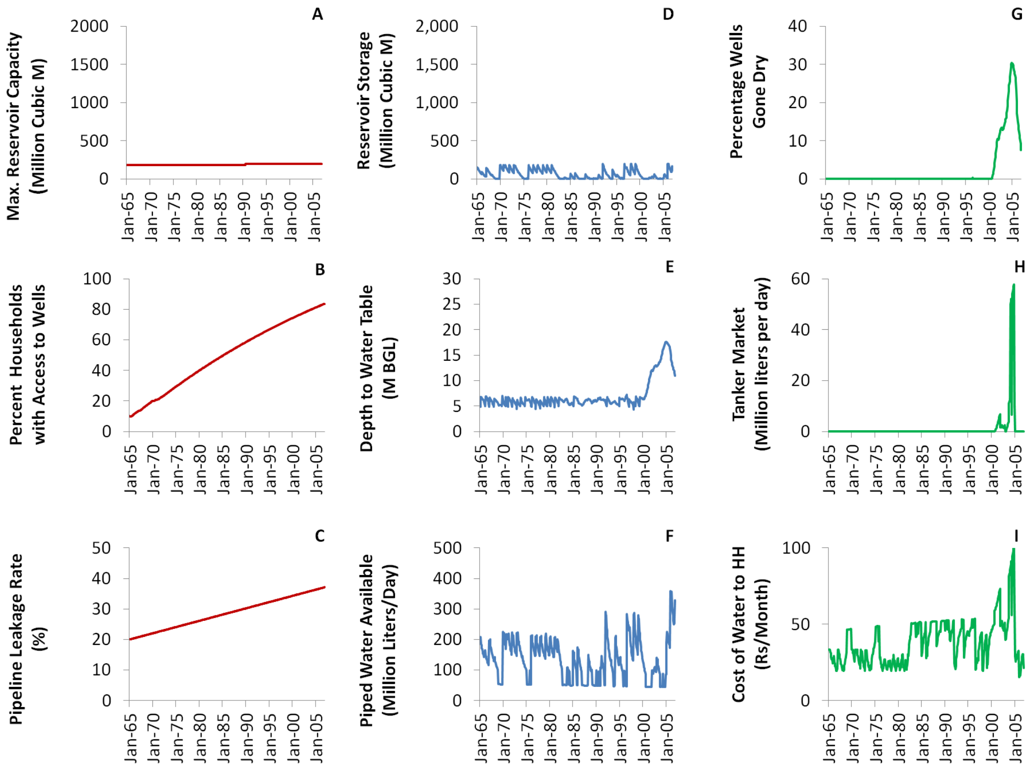

Figure 4. Current trajectory: low initial reservoir storage, no metering, flat price.

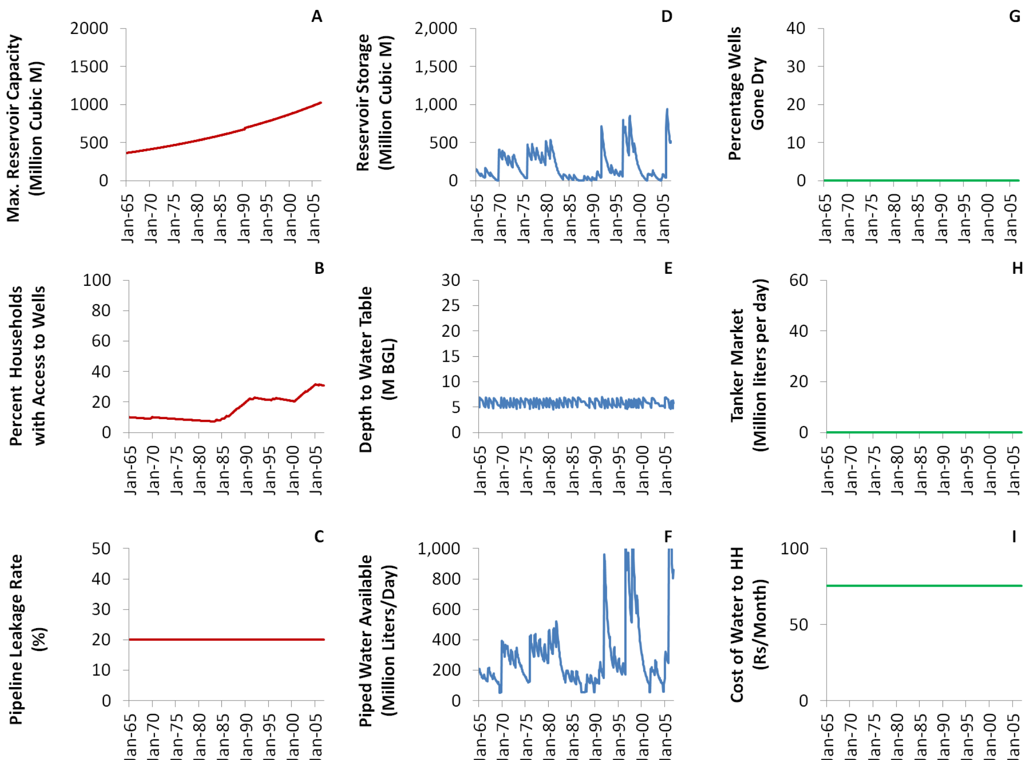

Figure 5. Counterfactual tra jectory 1: high initial reservoir storage, volumetric tariffs.

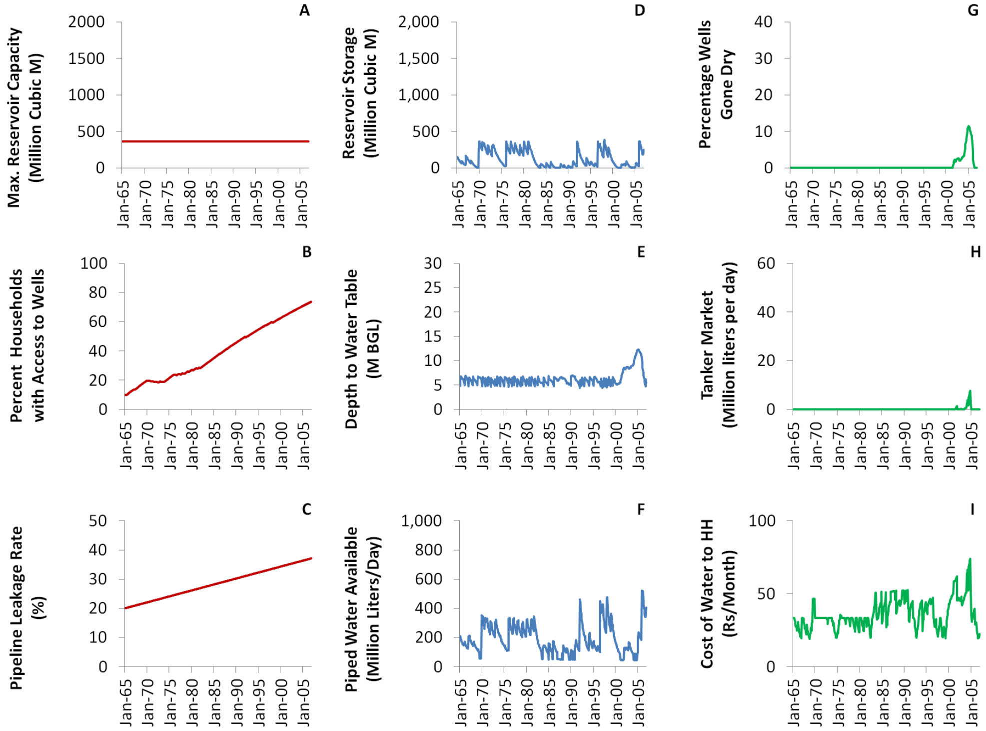

Figure 6. High initial reservoir storage, no metering, flat price.

pears. The demand function used was a simplistic model based on the Chennai household survey (Srinivasan et al., 2010a). However, to our knowledge, no study has successfully modelled water demand under supply constrained conditions, with multiple source dependence in the developing world. This suggests that additional research on user demand is much needed. From a policy perspective, the result shows that any reductions in groundwater extractions such as demand-side management and wastewater recycling would yield significant benefits.

Interestingly, the model is relatively insensitive to increasing reservoir storage. A 50 % increase in initial reservoir storage in 1965 yields only marginal benefits during the prolonged drought of the 1980s. Significant additional reservoir storage is needed to completely prevent piped supply shutdowns during multi-year droughts.

3.5 Model limitations

Any model of a complex real-world system, including the one presented in this paper is likely to suffer from limitations and it is worth reflecting on what effects this may have on the conclusions.

First, the model presented herein is weak on politics. A key assumption is that human responses to water scarcity are primarily techno-economic. While most households in Chennai do indeed respond by making coping investments in sumps and wells or purchasing water from tankers, water users are also citizens who engage in the political process. Indeed, in my own field investigations I encountered several examples of communities, particularly slums, using a range of strategies to lobby the local government to improve water supply. However, it was also clear that there were no universal factors that could predict why some slums were better at securing access to water than others. This suggests that there are inherent limits to quantitative approaches to modelling water security at the household scale.

Second, the narrow definition of household water security (in terms of the average cost of water) overlooks the nuances of reliability, inequity and uncertainty of the amount and timing of supply. Yet, studies show that certain sections of society are disproportionately affected by uncertain timings of supply because of lost wages from waiting for water. Moreover, average costs obscure distributional differences. As socio-hydrology evolves as a field, greater attention to normative lenses and how the choice of outcomes influences the conclusions drawn is needed.

Third, the model presented in this paper makes an assumption that demographic and economic growth are not limited by water scarcity; these were assumed to be exogenous to the model. While there is insufficient evidence on how unreliable water supply might limit long-term economic growth, additional research exploring these feedbacks is warranted. It is difficult to imagine that a city with no water could grow as quickly as one with abundant water supply.

Finally, ideally, socio-hydrologic models should be developed in consultation with stakeholders to frame the research questions, determine which dynamics are essential to replicate, which thresholds are important and which tradeoffs are acceptable. Although the present study is grounded in extensive interactions with domain experts, water managers and users at the study site, the intuition derived from these interactions was not formally codified. It is therefore always possible for the model to be biased by the values and training of the researcher.

4 Conclusions

In the developing world, traditional planning tools fare poorly over a 30–50 year time horizon. In most developing regions, water systems are changing so quickly that holding land use, economic patterns, governance systems or technology static over a 50-year period results in inaccurate predictions leading to sub-optimal paradoxical outcomes. Many water managers fail to account for impacts of the adaptive responses by humans that could result in unexpected outcomes.

Socio-hydrology has been defined as a new science of water and people to precisely address this problem. The goal is to explicitly account for such bi-directional feedbacks and improve predictive insight. While there are several challenges socio-hydrologic modellers face in framing the problem and choosing which outcomes are worth studying, perhaps the biggest challenge is imagining technological, social and political futures. If technology, social preferences, the structure of the economy or governance systems change, these could fundamentally alter future water demand, allocation and use. So while it is necessary to ask decision makers to examine alternative futures and figure out policies that might get us there, it can be an abstract, perilous process.

This paper offers an alternative approach – the use of counterfactual trajectories – that allows policy insights to be gleaned without having to predict the social futures. The approach allows us to instead "reimagine the past"; to observe how outcomes would differ if different decisions had been made in the past. Because the focus is on the recent past, the results could be applicable in other regions facing similar decisions.

A stylized, socio-hydrologic model that explores bi-directional feedbacks between the societal, engineered and hydrologic components of water systems is applied to achieve insights into household water security in developing urban regions, using the case study of Chennai, India. The model includes both "fast" processes such as short-term reservoir management and source switching by consumers; as well as "slow" processes such as long-term investments in infrastructure by the water utility (pipes and reservoirs) as well as users (wells, piped connections). On the one hand, the water utility's investments in pipes and reservoir storage constrains the water available to households in a given period. On the other hand, lack of water availability in a given period prompts a fraction of the users to drill wells. Additionally, the dynamics observed in the model are influenced by the biophysical constraints of the aquifer and watershed hydrology.

This paper presents an example of a socio-hydrologic modelling study, which can model coevolutionary, emergent behaviour. In contrast to traditional water resources management studies, the goal is not to prescribe policy. The model allows the water utility to develop reservoir storage based on the utility's finances. It also allows households to make private coping investments. Household water security evolves based on infrastructure and pricing by the water utility and corresponding coping investments by consumers. Thus, for instance, whereas "optimal" reservoir storage is usually prescribed by a water resources management model, reservoir storage is an emergent property of the system. Instead, the objective is to explore alternative trajectories that a water supply system might have followed.

Two counterfactual trajectories are explored in addition to the actual historical trajectory. The model results offer interesting insights into urban household water security in developing water systems. First, household water consumption in Chennai goes beyond piped water supply; instead, the aquifer acts as a backstop source. When piped supply fails users first turn to their own wells. When their wells dry up, a tanker market develops. When consumers are forced to purchase expensive tanker water, they become water insecure. Second, not unexpectedly, different initial conditions result in different trajectories However, initial advantages in infrastructure are eroded if the utility's management is weak and it is unable to expand or maintain the piped system to keep up with growth. Both infrastructure and management decisions are necessary to ensure household water security. Indeed, if storage capacity has to keep up with demand, Chennai's reservoir storage would need to be ten times the actual storage today and comparable to cities like Boston, MA. This raises the issue of path dependence and the extent to which such increases in reservoir storage are feasible in the current socio-political climate. Even if full metering and a rational tariff policy were followed, emerging social movements in the 1980s over resettlement and environmental concerns of dam-building may have limited Chennai's options as some studies have shown (Feldman, 2009). Third, the effects of weak management and inability to expand reservoir capacity do not manifest right away. Instead, the situation deteriorates over time and the impacts of bad policy may not manifest until much later when the population has grown and a major multi-year drought strikes.

Appendix A

The equations used to specify the model are described below in detail. In describing the model, the subscript t (referring to the model time period of 1 month) is skipped to improve readability. The convention used in describing the variables is as follows: variables prefixed with “Total” refer to city-wide quantities measured in MLD – e.g. “TotalCityDmd” is the total water demand for the city. Variables referring to household level supply, demand and consumption in litres per day are prefixed with “T” or “NT” for Tap and NonTap households respectively and suffixed with “Dmd”, “Sup” and “Use” depending on whether they refer to quantity demanded (if supply were unconstrained), quantity available and quantity actually used. For instance, TPipSup, TPipDmd and TPipUse refer to supply, demand and use from piped supply by Tap households. Reservoir and aquifer models stocks and flows are in m^3 and m^3 per month respectively.

Population Sub-model: population growth in Chennai was based on actual historical projections. The average household size of 4.5 persons per household based on the 2001 Census of India data for Chennai, was assumed to hold good for all households. It was assumed that households gradually converted from NonTapHH to TapHH as they became wealthier; i.e. indoor plumbing gradually increased. The total number of households in Chennai is the sum of the number of Tap and NonTap households:

$$\mathrm{TotalHH} = \mathrm{TapHH} + \mathrm{NonTapHH}. \tag{A1}$$

The fraction of NonTap households (households lacking indoor plumbing) dropped over time from half of all households in 1965 to 33 % in 2005. The increase in indoor plumbing was linked to economic growth rather than water availability and was therefore treated as being exogenous to the model.

Reservoir Sub-model: the reservoirs receive inflows from the local watershed and water from the Telugu Ganga scheme is also delivered into the reservoirs. Local inflows were modelled as an exponential function of monthly rainfall R:

$$\delta S = k e^{\lambda R} + \mathrm{TG} - W - \mathrm{Ev} - O, \tag{A2}$$

where k (1.22) and λ (0.017) are empirically derived constants from the historical rainfall–runoff relationship if rainfall R is in mm month^{-1} and inflows are in Mm^3 month^{-1}. S is the total reservoir storage in cubic metres at the beginning of the period. TG is actual inflow received from the Telugu Ganga project at the state border in m^3 month^{-1}, W is the water supply released from the reservoir for urban supply and Ev is the average lake evaporation calculated from Lake Evaporation data in m^3 month^{-1}. O is the spills from the reservoir downstream; any inflow in excess of maximum reservoir storage ResMax is assumed to be released downstream.

City Water Supply and Distribution Sub-model: the City Water Supply Model distributes the amount of water available in the reservoir system between Tap and NonTap HH. Based on interviews with city water utility engineers, it was assumed that the amount released from the reservoir system (W) is a fixed fraction (p %) of storage S. It is interesting to note that the fraction p did not turn out to be constant over time. In order to match observed storage, p had to be increased over time. Throughout the particularly wet decade of the 1970s, p was approximately 4 %. After 1980, p had gradually increased to 7 % by 2005 suggesting that the reservoir management became more aggressive to meet the increased demand while reservoir storage remained the same:

$$\mathrm{TotalCitySup} = (p.S + \mathrm{TotalImports}) \times \mathrm{Cf}. \tag{A3}$$

The water released from the reservoir system is shared between Chennai and the surrounding towns – only a fraction Cf is supplied within the city. Based on historical data this was averaged to be about 66 % The rest goes to industrial and commercial bulk supply and nearby towns. The amount of water available for piped supply includes diversions from the reservoir system plus imports from an intra-state scheme and well-fields:

$$\mathrm{TotalPipSup} = \mathrm{TotalCitySup} \times (1 - \mathrm{LeakRate}). \tag{A4}$$

A percentage of the water, LeakRate, is lost via pipeline leakage and in turn recharges the shallow aquifer. The rest, TotalPipSup, is distributed via the piped distribution system:

$$\mathrm{TotalCityDmd} = \mathrm{Ind} + \frac{(\mathrm{TapHH} \times \mathrm{TPipDmd} + \mathrm{NonTapHH} \times \mathrm{NTHPDmd}) * 1.2}{10^6}. \tag{A5}$$

The TotalCityDmd is based on how much water would be demanded by households and commercial establishments if supply were unconstrained (i.e. everyone can get as much water as they want. This was estimated based on the demand function explained later (Eq. A21). The factor of 1.2 includes Commercial and Industrial demand, assumed to be 20 % of domestic demand:

$$\mathrm{Shutdown} = \begin{cases} 1, & \text{if TotalPipSup} < \text{TotalCityDmd} \times 0.1 \\ 0, & \text{otherwise.} \end{cases} \tag{A6}$$

It is assumed that if the amount available from all sources drops below 10 % of the city’s demand for water, the piped supply system shuts down and the scarce supply is distributed via tankers without any leakage loss.

The water is delivered to NonTap households via standpipes and Tap households via private piped connections. However, because the two types of consumers access water very differently the water available to them must be modelled separately. Water in standpipes is manually collected during the few hours when the pipes have water in them. In contrast, for private connections, the water is pumped to overhead tanks and flows by gravity to the taps in the house whenever they are turned on. Owing to the lack of storage and effort involved in hauling water around, users who depend on standpipes generally end up accessing much less water.

NonTap households must collect the water manually during the hours of supply (even in the wettest periods, Chennai does not receive 24-hour water supply). During droughts, the city cuts back on hours of supply further. Therefore, in the model, the amount of water accessed by NonTap households depends on how many hours of piped supply is provided, which in turn depends on the availability of water in the piped supply system (TotalPipSup). It is assumed that the rest of the available piped water is equally distributed among Tap households. To simulate this we assumed that the total water supply could be translated to hours of supply based on an empirically derived equation:

$$\text{HrsSup} = \begin{cases} \frac{\text{TotalPipSup}}{\text{TotalCityDmd}} \times 4, & \text{if Shutdown} = 0 \\ 0, & \text{if ShutDown} = 1. \end{cases} \tag{A7}$$

HrsSup represents the number of hours of piped supply. NonTap users accessing water via standpipes can only receive water during hours of supply. The amount of water theoretically available to NonTap users in litres per day is given as

$$\text{NTHPSup} = \frac{\text{HrsSupply} \times 60}{10} \times 15. \tag{A8}$$

NonTap users dependent on standpipes are hit hardest by cutbacks. It takes roughly 10 min to fill a pot of water including time wasted and in transitions between people. Each pot holds 15 L:

$$\text{NTHPUse} = \min(\text{NTHPSup}, \text{NTHPDmd}). \tag{A9}$$

A key assumption is that NonTap households are both supply and demand constrained. They will queue up to collect water but only until their demand is satisfied. Beyond this even if hours of supply are expanded, they will not use more water:

$$\text{TotalHPUse} = \frac{\text{NTHPUse} \times \text{NonTapHH}}{10^6} \tag{A10}$$

$$\text{TPipSup} = \frac{\frac{1}{1.2}(\text{TotalPipSup} - \text{TotalHPUse}).10^6}{\text{TapHH}}. \tag{A11}$$

Assuming that NonTap users wait in line to get water and fill every available pot during the hours water is available, the rest of the water is delivered into the sumps of all piped users. After accounting for the 20 % supplied to commercial and industrial users, the amount of piped water supply available to each TapHH can be calculated.

Infrastructure Sub-model: it was assumed that the deterioration in pipelines and thus increase in leakage over time is proportional to the difference between the tariff and the short-run marginal cost of supply. If the tariff exceeds the operation and maintenance cost (OMCost is Rs 12/kL), then the pipeline leakage gradually improves at a rate proportional to the difference or surplus revenue (RevSurplus) earned on each unit of water delivered:

$$\text{RevSurplus} = \frac{\text{PipedPrice} - \text{OMCost}}{\text{OMCost}} \tag{A12}$$

$$\delta\text{LeakRate} = C1 \times \text{RevSurplus}. \tag{A13}$$

The constant $C1$ was chosen so that the piped system leakage rate deteriorates from 20 % in 1965 to 37 % by 2007 under the current flat-rate tariff structure.

Similarly, it is assumed that if there are surplus revenues, new reservoir capacity can be added to keep pace with population growth:

$$\delta\text{ResMax} = C2 \times \text{RevSurplus} \times \kappa(\text{TotalHH}). \tag{A14}$$

The constant $C2$ was chosen such that reservoir capacity increases at a rate to maintain the initial per capita reservoir capacity, when water is priced to be Rs 15/kL (i.e. Rs 3/kL more than O & M costs). Reservoir inflows are also proportionately increased – i.e. the reservoirs are assumed to have their own catchments which generated inflows using the same equations as the existing reservoir system.

Aquifer Sub-model: the aquifer is simulated as a simple bathtub, so the water level in the aquifer is a simple linear function of the total aquifer storage with specific yield (SYield) of 10 %. When the aquifer is fully saturated, saturated thickness is assumed to be 20 m. The area (ChennaiArea) is 176×10^6 m^2. Thus, the volume of water stored in the aquifer in m^3 when fully saturated is

$$\text{MaxGW} = 20 \times \text{SYield} \times \text{ChennaiArea}. \tag{A15}$$

The groundwater balance equation is

$$\delta\text{GW} = \text{PR} + \text{RR} - \text{SS} - \text{TankerUse} - \text{GWUse}. \tag{A16}$$

PR in m^3 per month is the pipeline recharge depends on leakage from pipelines. RR is rainfall recharge in m^3 per month, which is defined as 10 % of rainfall. Rainfall is in mm month^{-1}. SS is defined as sub-surface flow to the ocean or baseflow to the river which occurs whenever GW is completely saturated. TankerUse and GWUse represent groundwater extractions by tankers and households respectively. These are discussed in the User Agent section:

$$\text{PR} = \begin{cases} \frac{\text{TotalCitySup} \times 30 \times \text{LeakRate}}{1000}, & \text{if Shutdown} = 0 \\ 0, & \text{otherwise} \end{cases} \tag{A17}$$

$$\text{RR} = \text{Rainfall}/1000 * \text{ChennaiArea} * 0.1. \tag{A18}$$

The depth to water is based on the volume dewatered over the period of the model plus an assumed initial depth to water in 1965 (5 m b.g.l.):

$$\text{DepthToGW} = \frac{(\text{MaxGW} - \text{GW})}{\text{ChennaiArea} \times \text{SYield}} + 5. \tag{A19}$$

User Agent Sub-model: a key feature of the model was the representation of user behaviour. Users (households) make two types of decisions. In the short-term, they decide what sources of water to use in a given time period given their income and past investments in wells, sumps etc. In the long-term, households decide what types of investments to make in the water system. In every period when piped supply is less than consumer demand, some fraction of the households (5 % per year or 0.41 % per month is assumed) drill new wells. Long-term investments such as wells are "sticky" and once made remain in place even if they are not used. They permanently alter the options and incentive structure to households:

$$\delta\mathrm{Wells} = \begin{cases} \mathrm{TapHH} * 0.041, & \text{if TPipSup} < \text{TPipDmd} \\ 0, & \text{otherwise.} \end{cases} \tag{A20}$$

The short-term consumption model recognizes that households are often supply constrained and must cope with water shortages. In the short term, households have options – i.e. they can switch sources or buy water. Consumption is constrained both by supply (amount of water available) as well as demand (amount of water they are willing to consume). In the short term, users need a small amount for their potable needs (about 10 L per capita per day). After allocating the best quality water for their potable needs, they allocate the cheapest available source for their non-potable needs:

$$\log(7Q) = \alpha \log\left(\frac{\mathrm{Price}}{1000}\right) + \gamma \log(\mathrm{HHSize}) + \delta I + \kappa, \tag{A21}$$

where α (the price elasticity of water) is -0.49, γ (the coefficient of household size) is 0.48 and δ (the income elasticity) is 0.19. Because α, γ and δ are exponents, they are unitless. A weekly demand function estimated from the household data set was divided by 7 to obtain the daily household water demand Q in litres per day (Srinivasan et al., 2010a).

In understanding short-term user decisions, users were assumed to be rational fully informed agents. The primary principle of the user agent model is that users will use up the lowest cost source accessible to them before moving to the next cheapest source. In other words, water consumption is driven by price and supply constraints. In developing the user agent model, only sources reported in the household survey were included. For instance, no households reported purchasing water from neighbours or using public surface water sources like ponds or temple tanks; so these were not included.

The price of water varies by source (piped, well, and tanker) as described in later sections. HHSize is the average household size in Chennai, which is 4.5 people. I is a binary income variable simply coded as high or low, and N is the number of members in the household. As the presence of indoor plumbing is linked to household wealth, Tap and NonTap categories also serve as way to categorize rich and poor users. Thus, $I = 1$ for Tap households and 0 for NonTap households. Thus, in the model, the demand for each source is different for Tap and NonTap households.

Tap and NonTap households were each assumed to access three sources of water: the piped supply, groundwater (own or shared wells) and purchased water from tankers. For any source, the amount used is the lesser of what is available and what is demanded at the marginal price. The model uses a simple allocation rule to decide which sources the users will use; consumers will use as much of the cheapest source available, then move to the next cheapest source. Thus the inputs to the user agent model are a price, a quantity demanded at that price and quantity available for each of the three sources.

Quantity Demanded: users rank sources in terms of cost from least to most expensive. Purchased tanker water (at Rs 60/kL) is always the most expensive and is the last possible resort. Between groundwater and piped supply, users pick whichever is cheaper. If users have wells, they will compare the marginal cost of groundwater (Rs 7/kL) to the cost of piped water. If piped water is charged at a flat rate, users only take into account the cost of pumping the water to their overhead tank (Rs 2/kL); but if piped supply is metered they must pay the volumetric tariff which may be anything between Rs 5/kL and Rs 15/kL. For each source, the maximum quantity the user would demand at that price was estimated using the demand function in Eq. (A21). For instance, for flat-rate piped supply the quantity demanded was 615 L day^{-1} (TPipDmd), for wells 356 L day^{-1} (TWelDmd) and for tankers 91 L day^{-1} (TTanDmd). The quantity demanded by NonTap households for standpipes and shallow bore wells use was 180 L day^{-1} (NTHPDmd and NTWelDmd).

Quantity Availability: the water available from different sources is obtained from the reservoir and aquifer models. The model assumes a maximum demand for each source of water based on its cost. Then the model calculates the potentially available supply from that source – NonTap use from handpumps (HPUse) and Tap piped supply (PipedSup) as calculated earlier. To estimate water available from wells, Tap households were classified into households without wells or whose wells went dry and those whose with functioning wells. It is assumed that the wells which have not gone dry will yield enough water to meet domestic water needs. So water availability from wells was simply assumed to be 0 for households lacking wells, but households with functioning wells were assumed to be able to satisfy all their residual water demand from wells. Similarly, water available from tankers is assumed to be infinite for all practical purposes.

Tap households – Case 1: if piped supply is the cheapest source and the household has a functioning well, then the household will use all available piped water before turning on their well:

$$1: \begin{cases} \mathrm{TPipUse} = \min(\mathrm{TPipSup}, \mathrm{TPipDmd}) \\ \mathrm{TWelUse} = \max(\mathrm{TWelDmd} - \mathrm{TPipUse}, 0) \\ \mathrm{TTanUse} = 0. \end{cases} \tag{A22}$$

Tap households – Case 2: if piped supply is the cheapest source and the household has no functioning well, then the household will use all available piped water before purchasing tanker water. However, they will only purchase tanker water if there is any "residual demand" after the available piped water supply is used up:

$$2:\begin{cases}\text{TPipUse} = \min(\text{TPipSup}, \text{TPipDmd})\\ \text{TWelUse} = 0\\ \text{TTanUse} = \max(\text{TTanDmd} - \text{TPipUse}, 0).\end{cases} \tag{A23}$$

The percentage of households with dry wells is obtained from the distribution below using the empirically derived equation.

Tap households – Case 3: if well supply is the cheapest source and the household has a functioning well, it is assumed the household will continue to use some piped water (assumed 75 L per household per day) for drinking, cooking and other kitchen uses:

$$3:\begin{cases}\text{TWelUse} = \text{TWelDmd} - 75\\ \text{TPipUse} = 75\\ \text{TTanUse} = 0.\end{cases} \tag{A24}$$

NonTap households – Case 4: NonTap households follow a similar strategy preferring public standpipes if available. However, if supply is restricted, they will use shallow bore well handpumps (locally called "India Mark Pumps"). These shallow bore wells are typically easily accessible on every street, but the quality is not as good as piped water. Bore well handpumps usually function if the water table is shallow (defined in the model as < 15 m). Any residual demand will be met by tankers.

Water use from public handpumps (standpipes) has already been defined in Eq. (A9). Water available and used from shallow bore wells is given as follows:

$$\text{NTWelSup} = \begin{cases}100\,000, & \text{if DepthtoGW} < 15\\ 0, & \text{Otherwise}\end{cases} \tag{A25}$$

$$4:\begin{cases}\text{NTapWelUse} =\\ \min(\text{NTWelDmd} - \text{NTHPUse}, \text{NTWelSup})\\ \\ \text{NTTanUse} =\\ \max(\text{NTTanDmd} - \text{NTHPUse} - \text{NTWelUse}, 0),\end{cases} \tag{A26}$$

where NTHPUse is as defined in Eq. (A9).

The total quantity of the groundwater extractions by users and tanker operators is estimated by summing of HH tanker demand and HH well use across all household types (TapHH with wells, TapHH without wells and NonTapHH). These extractions (TotalTankerUse and TotalGWUse respectively) feed back into the Aquifer model.

Cost of Water Sub-model: because quantity of water consumed is a function of marginal price, monthly cost of water was assumed to be a reasonable indicator of water security. The cost of water is simply the total amount paid divided by the total water use by all HH in Chennai.

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All errors and weaknesses in the model and arguments remain mine.

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