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Coevolution of water security in a developing city

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Abstract

The world is rapidly urbanizing. One of the challenges associated with this growth will be to supply water to rapidly growing, developing-world cities. While there is a long history of interdisciplinary research in water resources management, relatively few water studies attempts to explain *why* water systems evolve the way they do; *why* some regions develop sustainable, secure well-functioning water systems while others do not and which feedbacks force the transition from one trajectory to the other. This paper attempts to tackle this question by examining the historical evolution of one city in Southern India.

A key contribution of this paper is the co-evolutionary modelling approach adopted. The paper presents a "socio-hydrologic" model that simulates the feedbacks between the human, engineered and hydrologic system for Chennai, India over a forty year period and evaluates the implications for water security. This study offers some interesting insights on urban water security in developing country water systems. First, the Chennai case study argues that urban water security goes beyond piped water supply. When piped supply fails users first depend on their own wells. When the aquifer is depleted, a tanker market develops. When consumers are forced to purchase expensive tanker water, they are water insecure. Second, different initial conditions result in different water security 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 achieving water security. Third, the effects of mismanagement do not manifest right away. Instead, in the manner of a "frog in a pot of boiling water", the system gradually deteriorates. The impacts of bad policy may not manifest till much later when the population has grown and a major multi-year drought hits.

1 The urban water problem in the developing world

The world's population is rapidly urbanizing. One of the challenges associated with this growth will be to supply water to rapidly growing, developing-world cities. 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). However, many developing cities are not equipped to meet even current demands, let alone future growth. Inadequate piped supply in developing world cities has measurable impacts on water security and human well-being (Srinivasan et al., 2010; Baisa et al., 2010).

But this is not an inevitable trajectory; not all developing world urban systems end up becoming unreliable. For instance, some water utilities such as in Istanbul (Varis et al., 2006) which have experienced explosive population growth have successfully managed the transition to reliable piped supply. Moreover, unreliable piped supply does not automatically mean that users suffer from water insecurity. In reality, many users in developing world cities are able to rely on their own private wells for at least the non-potable component of their needs. As a result, unreliable piped supply system have differential impacts depending on the productivity of the aquifer, density of population, and how easily water can be transported from distant sources and so on (Srinivasan et al., 2013).

This paper attempts to tackle the question of what makes cities evolve differently by examining the historical evolution of one city in Southern India. The paper models feedbacks between the human, engineered and hydrologic system over a forty year period and evaluates the implications for water security. There is a long history of interdisciplinary research in water resources management. Traditionally, the focus of this type of research has been on policy prescription and/or infrastructure planning (Gober et al., 2011; Cai et al., 2003; Booker et al., 2005; Baisa et al., 2010). Researchers use economic arguments and water resources systems models to make the case for new infrastructure projects, demand-side management programs or alternative pricing policies. Such studies fall broadly into the category “Water Resources Management (IWRM)” or “Integrated Assessment (IA)”. They identify stakeholder priorities; 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). The purpose of such 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 WRM is to enable decision-makers in deciding *how* to manage the system (Liu et al., 2008). The problem is many WRM studies frequently suffer from a fundamental weakness – they presuppose relationships and linkages within the system. While model parameters are calibrated, the validity of the model structure itself is rarely challenged. On one hand, carefully developed site-specific customized models (Gober et al., 2011) are highly dependent on the skills and disciplines of the individual researchers; on the other using standardized software packages such as WEAP (Raskin et al., 1992; Lévite et al., 2003) limit the types of feedbacks and sub-systems that may be included. There is very little systematized knowledge which a researcher can draw on to prioritize which feedbacks and links are most critical to understanding a study site.

Relatively few water studies attempts to explain *why* water systems evolve the way they do; *why* some regions develop “sustainable”, secure, well-functioning water systems while others do not and which feedbacks shift the transition from one trajectory to the other. Even when such models are developed the insights can rarely be abstracted beyond the specific case study site to inform research, management and policy elsewhere. Socio-hydrology (Sivapalan et al., 2012) has been proposed as a “new science of humans and water systems” specifically to address this gap. Socio-hydrologic research explores alternative hypotheses and feedbacks in order to explain observed dynamics. Thus, socio-hydrology is *backward looking, descriptive* and seeks to *enhance explanatory power*, while WRM is *forward looking, prescriptive* and seeks to *improve management capability*. Socio-hydrologic modelling involves developing an understanding of the dynamics of coupled human-water systems over large spatial and temporal scales in a generalizable way necessitates inclusion of changes in climate, land use, technology, and social systems (Thompson et al., 2013). This requires modeling feedbacks across multiple scales, sectors and agents so as to explain in the most meaningful but parsimonious way, trajectories exhibited by a range of coupled human-water systems.

Methodologically, this paper illustrates how a "socio-hydrologic" model (Sivapalan et al., 2012) that explores bi- feedbacks between the societal, engineered and hydrologic components water systems may be applied to glean such insights. This paper presents a model of the coupled human-water system in Chennai over a time span of 30–40 yr and explores what factors drive the evolution of urban water security over time. The paper is organized as follows: it begins with an exploration of possible socio-hydrologic modelling approaches. Next it describes the Chennai case study and the "stylized" model of the water system in Chennai, India. The model results then explore Chennai's actual trajectory and its implications for water security.

2 Socio-hydrologic model conceptualization

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 complex coupled models that link agent based and hydrologic models and validate them against a variety of detailed empirical observations (Srinivasan et al., 2013).

Each of these approaches has advantages and disadvantages. Toy models are relatively inexpensive to develop but are by design abstract and therefore 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 is often difficult to characterize in generalizable terms. In contrast, models coupling agent behaviour to hydrologic models that are carefully calibrated and tested against empirical observations may generate reliable results but often lack abstraction and comparability beyond the study site. This paper proposes a third approach: a “stylized model” (Kilgour and Dinar, 2001; Chakravorty and Umetsu, 2003) commonly used by economists in both natural resources and other contexts. A stylized model is a simplified representation that aims to replicate the *essential dynamics* observed in one or more real-world study sites focusing on the behaviour of key variables rather than behaviour of individual agents or detailed spatial disaggregation.

There are two challenges with such stylized models over what aspects to include in the model. First, the problem of deciding which outcomes are worth explaining; i.e., the act of “framing” the model involves making choices on which aspects to include and which ones to exclude (Lane, 2013). This choice is not a purely scientific one but one which involves normative judgements about whose problems matter and why (Lane, 2013). Second, once the “system of interest” is defined to extend beyond the biophysical or engineered systems, every aspect of human society – culture, politics, economic trends, technology, social movements etc., and every related sub-sector – energy, food, public health, biodiversity etc. is a candidate for inclusion. How can the socio-hydrology study be bounded to avoid devolving into a general system dynamics model of the entire world economy? In order to address these challenges, the modeller needs makes a choice about how to “frame” the problem and decide which human well-being/biophysical outcomes are of interest, and which aspects of the dynamics are the most compelling.

With regards to the first challenge, one approach that has been taken is to embed the research process within a stakeholder dialogue and let the definitions and variables of interest emerge (Tidwell and Van Den Brink, 2008). However, it is not always feasible to embed every socio-hydrology research project within a stakeholder process. This paper adopts a softer approach; simply justifying the choice of outcome variables by referencing contemporary debates over water security and acknowledging the limitations of the choice made. The second challenge involves deciding which feedbacks to include. Here Lane (2013) argues that predictive socio-hydrological models are tricky because social futures are not well-defined. If socio-hydrologic models are intended to feed into the policy process, the researchers cannot truly remain an external observer of the system. The very process of deciding what to model, which model variables are static and which ones may be changed in the model could inadvertently influence which futures are possible making the model a self-fulfilling prophecy. Thus the researcher is not an impartial observer but a social engineer as well (albeit unintentionally).

This is an extremely difficult challenge to address and merits attention. This paper sidesteps the issue by focusing strictly on past trajectories. The approach adopted in this paper is that the explanatory power of the model and the sub-systems to be simulated depend on the time-span of model, which in turn depends on the scale of system behaviour that needs to be understood (Fig. 1). Over one year (e.g. a specific drought event), infrastructure, coping ability, and political structures can be assumed to be constant – but water availability and short-term markets may change. Over one decade, infrastructure and political change, incremental improvements in technology and market adjustments could occur but the structure of an economy or cultural beliefs are unlikely to change. Over hundred years, all these factors could change along with hydro-climatic patterns.

This paper attempts to explain how urban water security evolves with urban growth using a stylized model of Chennai, India. Water security is defined in a very narrow manner as access to a sufficient quantity of affordable supply. The evolution of the urban water supply system is traced over a 40 yr period from 1965 to 2005.

3 Case study: Chennai, India

Chennai, formerly Madras, is India's fourth largest city. As per the 2011 census, about 8.9 million people reside in the urban agglomeration, which includes peri-urban areas, towns and villages. The public water utility supplies only the municipal area, which, with a population of 4.8 million, although the network is gradually being expanded. The water utility supplies water to households within the municipal corporation area via a piped network, which obtains water from rain-fed reservoirs and well-fields outside the city (Metrowater, 2008). More than two-thirds of Chennai's households have private wells as a supplementary water source. Peri-urban towns and villages are served by several different agencies. Some of these towns and villages receive bulk supply from Chennai's water utility, while others rely entirely on borewells. The city is expected to continue to grow rapidly (CMDA, 2007), driven by private sector investment in housing and commercial property in peri-urban areas (Dupont and Sridharan, 2006). Peri-urban areas are expected to be eventually supplied with water and sewerage services via the city municipal supply agency.

4 Model conceptualisation and parameterization

The coupled human-environment systems model of Chennai covers the 2550 sq. km area. The model described in this paper is a "stylized" version of a detailed, spatially-explicit coupled human-hydrologic model developed and published previously (Srinivasan et al., 2010). The previous coupled model was run and calibrated using a variety of hydrologic and socio-economic data from the period 2002 to 2006, which included one of the worst droughts and one of the wettest periods in history. As a result the model was able to simulate both hydrologic and user 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 yr period. The parameters for shorter term processes were based on the earlier calibrated and validated coupled model. The parameters that were imported from the earlier model (Srinivasan et al., 2010) include – the consumer demand function, the response of the aquifer system to recharge and pumping, the rainfall-inflow model into the reservoir system, reservoir operations, the behaviour of consumers and the tanker market.

This paper, takes the previous Chennai model as a starting point, but the spatial component is eliminated entirely. Instead, the paper explores *temporal dynamics over* *a much longer period*. Importantly, because 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 which was run over a 5 yr period. The new feedbacks added include growing income, penetration of indoor plumbing, private wells, the impact of pricing policies on the water utilities finances and thus its ability to expand and maintain infrastructure. The socio-hydrologic model back-casts (replicates the past) the actual trajectory of Chennai's water supply system and also explores "counter-factual" trajectories (what might have occurred if different decisions had been taken).

The dynamics of the urban water system is conceptualised in a simplified way, through a set of differential equations. The model simulates both centralized and decentralized infrastructure depending on incentives and financial ability of the water utility and individual users. 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, total population and user investments in borewells were all state variables. Water supplied, pipeline leakages and water extraction and use by users are flows or fluxes. In setting up the model, rainfall, population and economic growth, prices and user demand function were assumed to be *exogenous* or external to the model. I.e., the presence or absence of water was not a significant determinant in Chennai's growth, which was instead driven by other macro-economic factors. Investments in infrastructure both by the water utility and private users were treated as *endogenous* or determined within the model. The initial conditions specified the level of reservoir storage and the coverage and efficiency of the piped system were based on actual data. Actual water tariffs fixed by the government were used for the back-cast. In developing these counter-factual trajectories, one relatively simplistic assumption made is that improved finances will indeed result in better infrastructure and maintenance (this is not always true).

4.1 Population model

Population growth of Chennai was based on actual historical projections, and the average household size of 4.5 persons per household based on census data (Srinivasan et al., 2010) was assumed to hold for all households. It was assumed that indoor plumbing gradually increased as the residents became wealthier. Households with indoor plumbing, "tap households", access water via indoor taps. Whereas households lacking indoor plumbing, "non-tap households", access water through yard or street standpipes. The total number of households in Chennai is the sum of the number of tap and non tap households.

$$\mathrm{TotalHH}(t) = \mathrm{NonTapHH}(t) + \mathrm{TapHH}(t) \tag{1}$$

It was assumed that the fraction of non-tap 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.

4.2 Reservoir model

Monthly change in reservoir storage was modelled as an exponential function of monthly rainfall $R(t)$. This equation was derived empirically from actual historical rainfall data.

$$\frac{\partial S}{\partial t} = k + e^{\alpha R(t)} - \mathrm{Ev}(t) - C(t) \tag{2}$$

Here, $S(t)$ is the total reservoir storage at the beginning of the quarter, $C(t)$ is the water supply diverted for city supply and $\mathrm{Ev}(t)$ is the average lake evaporation for a given month in Chennai.

4.3 City water supply model

$$C(t) = Cf \cdot p \cdot S(t) \tag{3}$$

It was assumed that the city managed the reservoir system by releasing a fixed fraction of storage each month (p %). Throughout the particularly wet decade of 1970 s and through to 1980, p was approximately 4 %. After 1980, the reservoir management became more aggressive to meet the increased demand, until p had reached 7 % by 2005. Diverted reservoir must be shared between Chennai and the surrounding towns, so the water available for domestic city supply is only a fraction (Cf) based on historical data this domestic supply was assumed to be about 66 % after subtracting industrial and commercial water use.

Additionally, Chennai received water from emergency imports, local well-fields and, after 1996, the Telugu Ganga and Veeranam inter-basin import projects.

$$\mathrm{Piped}(t) = (C(t) + \mathrm{Emergency}(t) + \mathrm{TG}(t) + \mathrm{Other}(t))\cot(1 - \mathrm{LeakRate}) \tag{4}$$

The amount of water available for piped supply is a function of diversions from the reservoir system $C(t)$, plus additional imports from an inter-state scheme TG(t), local well-fields Other(t) and emergency imports brought in via tankers during severe droughts when the city is not able to meet a minimum supply of 40 L per capita per day (LPCD). A percentage of the water – LeakRate(t) – is lost via pipeline leakage and in turn recharges the shallow aquifer.

The available water Piped(t) is distributed via the piped distribution system to non-tap households dependent on standpipes and tap households via private piped connections. However, because the two types of consumers access water very differently the water delivered 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 delivered and stored in overhead tanks and flows by gravity to the taps in the house when they are turned on. Because of the lack of storage and effort involved in moving water around, users who depend on standpipes generally end up accessing a much smaller share of the total available supply.

4.4 City water distribution model

During droughts, Chennai's water utility rations piped water supply by cutting back on hours of supply. non-tap users dependent on standpipes are hit harder by cutbacks in supply because they lack in-house storage capacity. It takes roughly 10 min to fill a pot of water and a standpipe is typically shared by about 20 households. Often this results in fights at the standpipe and typically each household ends up getting less water. Therefore, in the model, the amount of water accessed by non-tap households depends on how many hours of piped supply is provided, which in turn depends on the availability of water from all sources combined – the reservoir system, well fields etc. It is assumed that the rest of the available piped water is assumed to be equally distributed among tap households with private connections.

To simulate this we assumed that the total water supply could be translated to hours of supply.

$$\mathrm{Hours}\,(t) \propto \mathrm{Piped}\,(t) \tag{5}$$

$$\mathrm{NonTapHH}_{\mathrm{WaterSupply}}\,(t) = \frac{\mathrm{Hours}\,(t) \cdot 60}{20} \tag{6}$$

$$\mathrm{TapHH}_{\mathrm{WaterSupply}}\,(t) = \frac{\mathrm{Piped}\,(t) - \mathrm{NonTapHHp}_{\mathrm{WaterSupply}}\,(t) \cdot \mathrm{NonTapHH}}{\mathrm{TapHH}} \tag{7}$$

$\mathrm{NonTapHH}_{\mathrm{WaterSupply}}$ and $\mathrm{TapHH}_{\mathrm{WaterSupply}}$ is the amount of water available per HH to NonTap and Tap HH.

4.5 Operation and maintenance model

$$\frac{\partial I}{\partial t} = \gamma \cdot \frac{\left(\mathrm{SMC} - \mathrm{Pr}_{\mathrm{Piped}}\right)}{\mathrm{SMC}} \quad \text{if } \mathrm{Pr}_{\mathrm{Piped}} < \mathrm{SMC} \qquad (8)$$
$$= 0 \quad \text{otherwise}$$

It was assumed that the deterioration in the integrity of the pipeline (and thus increase in leakage) over time is proportional to the difference between the tariff and the short-run marginal cost of supply, i.e. the cost of operating and maintaining the piped network. If the tariff covers the cost of supply then the pipeline leakage rate remains at 15 %. In the current low tariff situation, the piped system deteriorates and the leakage rate rises to 37 % by 2007. This figure is based on conversations with utility officials.

4.6 Aquifer model

$$\frac{\partial A}{\partial t} = \mathrm{LeakRate}(t) \cdot \mathrm{Piped}(t) + iR(t) - \mathrm{Ex}(t) \qquad (9)$$

$A(t)$ is storage in the aquifer. Recharge is a fixed fraction of rainfall and pipeline leaks.

$$\mathrm{WL}(t) = \tau \cdot \frac{(A_{\mathrm{m}} - A(t))}{A_{\mathrm{m}}} \qquad (10)$$

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 of 10 %. When the aquifer is fully saturated $A(t) = A_{\mathrm{m}}$ and the depth to water level is 10. When the aquifer is "empty", the depth to water level is $\tau = 60$ m.

$$\mathrm{Ex}(t) = \mathrm{Wells}(t) + \mathrm{Tankers}(t) \qquad (11)$$

4.7 User agent model

Households make two types of decisions. In the short-term, they decide what sources of water to use in a given time period. In the long-term, they decide what types of investments to make in the water system. These decisions occur both privately and through exercising political pressure, which helps to determine social investment in the public piped delivery system. New wells are added in every period when piped supply is deficient. Long-term investments are "sticky" and once made remain in place even if they are not used.

The short-term consumption model recognizes that households are often supply-constrained and must cope with water shortages. Consumption is constrained both by demand (amount of water available) as well total supply (amount of water available). In the short term, users need treated water for their potable needs (20 L per capita per day or 90 L per household per day) but they choose the cheapest available source for their non-potable needs.

The total demand for non-potable water changes as a function of the price of the marginal source.

$$\mathrm{PotDemand} = 90 \tag{12}$$

$$\mathrm{NonPotDemand} = D(t) = (\mathrm{C}P^{\alpha} N^{\beta} I^{\delta})/7 \tag{13}$$

Where $\alpha = -0.49$, $\beta = 0.28$, $\alpha = 0.19$ and $C = 78.3$. The demand function was estimated per week and so needed to be divided by seven to estimate the daily demand function. Finally, the total amount of water used, by source, was determined by minimizing the costs to the consumer as specified below.

$$\begin{aligned}
&\mathrm{MinCost}^{N}(P,Q) = \sum\nolimits_{i}^{N} p_k q_k \\
&s \cdot t p_1 < p_2 < \ldots < p_N \\
&\sum_k q_k < D(t) \\
&\text{And } q_k < Q_k
\end{aligned} \tag{14}$$

Where $p_1, \ldots, p_N$ are the prices of water from different sources, $q_1, \ldots, q_N$ are the quantities *actually used* from various sources and $Q_1, \ldots, Q_N$ are the quantities *theoretically available* to the user from various sources. In other words the user chooses the lowest cost source subject to the constraint that the amount consumed from a given source may not exceed what is available from that source and the total amount consumed may not exceed what the total demand of the consumer $D(t)$.

I is a binary income variable simply coded as high or low, and N is the number of members in the household. Because the presence of indoor plumbing is linked to household wealth, tap and non-tap categories also serve as way to categorize rich and poor users. Thus, in the model, the demand function is slightly different for tap and non-tap households.

The water available from different sources is obtained from the reservoir and well supply models.

$$Q_{\text{piped}} = \mathrm{TapWaterHH}(t) \tag{15}$$

Q_{Well} = 0 for households lacking wells or households whose wells have gone dry.
= 10 000 L for households with wells that still have water. The 10 000 L assumption simply ensures that these households are not constrained by groundwater availability.

The ordering of Q_{piped}, Q_{Well} as Q_1, Q_2 etc. depends on the relative cost of water from these sources which in turn depends on the tariff policy.

A crucial link between short-term decisions, long-term decisions and the response to groundwater hydrology lies in the variation in user well-depths. As the water level in the wells drop, an increasing fraction of consumers lose access to groundwater. The distribution of well depths was based on an actual distribution obtained from a comprehensive households survey of ∼ 1500 households and was fitted to obtain the following empirical equation.

$$\begin{aligned}\%\mathrm{WellsDry} = {} & -2.94\times10^{-9}\mathrm{WL}^5 + 8.77\times10^{-7}\mathrm{WL}^4 - 9.39\times10^{-5}\mathrm{WL}^3 \\ & + 4.09\times10^{-3}\mathrm{WL}^2 - 4.32\times10^{-2}\mathrm{WL} + 0.0697\end{aligned} \tag{16}$$

In the absence of piped supply, households whose wells went dry became dependent on tanker water.

The total amount of water extracted via wells and tankers is simply obtained by scaling up the quantity consumed per household by the number of households with wells. E.g.

$$\begin{aligned}\mathrm{Wells}(t) = {} & (1 - \%\mathrm{WellsDry}(t))\cdot(\mathrm{HH}_{\mathrm{Wells}}\cdot\mathrm{TapHH}(t)\cdot q_{\mathrm{Tapwells}} \\ & + \mathrm{NonTapHH}(t)\cdot q_{\mathrm{NonTapwells}})\end{aligned} \tag{17}$$

These feed back into the aquifer model and determine the available storage in the next period and therefore the number of dry wells in the next period.

The long-term agent model recognizes that households are able to make coping investments in wells.

$$\begin{aligned}\mathrm{HH}_{\mathrm{Wells}}(t) & = \mathrm{HH}_{\mathrm{Wells}}(t-1) + 0.001042\cdot\mathrm{TapHH}(t) \quad \text{if } \mathrm{TapHH}_{\mathrm{WaterSupply}}(t) < 75\,\%\cdot D(t) \\ & = HH_{\mathrm{Wells}}(t-1) \quad \text{Otherwise}\end{aligned} \tag{18}$$

$\mathrm{HH}_{\mathrm{Wells}}$ represents the percentage of households with indoor plumbing that also own wells. We assume that about 1.25 % of the households with indoor plumbing drill wells each year piped supply drops below their needs. This was calibrated to ensure that about 70 % of the households would have wells (known based on our household survey) by 2005.

4.8 Urban water security (cost of water) 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.

$$\mathrm{Cost}(t) = 30 \cdot \sum_k p_k q_k \tag{19}$$

Where Cost(t) is the monthly cost water users pay for water.

5 Model results

The model explored three possible co-evolutionary trajectories that Chennai's water system could have taken. The first scenario is the real trajectory validated based on a previous detailed spatial model (Srinivasan et al., 2010a) – called "Bad Engineering, Bad Policy". In this scenario, Chennai starts in 1965 with a relatively low level of surface storage and a flat-rate tariff which does not cover either the short-run or long-run cost of supply. Over time the piped system cannot be maintained; pipeline leakages become worse and less and less of the water reaches the consumer. Very little new storage is added. This scenario is essentially replicates historical reservoir storage, tariff and population.

The second scenario, called the "Good Engineering, Good Policy" is a counterfactual trajectory or a model experiment. Here, Chennai starts in 1965 with a double the water storage and low leakage rates – but still much lower than comparable US cities. The tariff is high enough to cover both the short and long run cost of supply and so the infrastructure keeps pace with the population. The third scenario is called the "Good Engineering, Bad Policy" is a second counterfactual trajectory. In this scenario, the city starts with substantial reservoir capacity, but weak tariff policy which does not recover the short or long run marginal costs. Here although the population does well initially, the infrastructure gradually deteriorates.

5.1 Current co-evolutionary trajectory: bad engineering, bad policy

In this scenario, Chennai's population rises exponentially from just 400 000 households in 1965 to over 1.2 million in 2001. The main driving assumptions in this scenario are (1) the rainfall record; i.e., the second half of the actual rainfall record was much more variable than the first half. (2) The utility adopted a flat-rate tariff system which did not allow it to invest in expensive infrastructure projects or maintain the piped network. (3) During the same period, reservoir storage increases by just 20 % and leakage worsened. (4) 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 scenario results (Fig. 2) suggest that as the utility was unable to expand storage capacity to keep up with population, the piped supply system became unreliable. It was economically rational for households to invest in private wells instead of storing or buying water, so well ownership rates gradually increased. At first, only the wealthiest few households owned wells. These households are able to use groundwater whenever piped supply falls short. However, as incomes rose more and more households could afford wells. Because piped supply did not improve, more and more wells were drilled, the groundwater level began to drop faster during dry periods.

5.2 Counterfactual trajectory 1: good engineering, strong management

The second trajectory was developed using different initial conditions – relatively high reservoir storage (see Appendix A). The initial storage assumed was double Chennai's actual storage, but nevertheless comparable to many developing country cities with a sound management policy. Chennai's population growth is as historically observed – water was assumed not to be a significant determinant of urban growth. The main driver in this scenario is that water is fully metered and price is set at the long-run marginal cost of supply (Rs 13/kL) and the additional revenue is used to maintain the system and invest in new storage and transfer projects (as opposed to being lost to corruption).

In this scenario, reservoir releases are based on actual demand. Because water is metered and priced, the utility is able to control demand and therefore the reservoir does not dry up as often. Except for a severe multi-year drought during the 1980s, when a tanker market develops, the city enjoys water security (Fig. 3). Although the rate of ownership of private wells increases during the drought, well-drilling stops once piped supply is restored as no new wells are dug. Consumers incur much higher costs each month on average over the 40 yr period, but there is very little variability in the cost of water.

5.3 Counterfactual trajectory 2: good engineering, weak management

The second counterfactual has mostly similar assumptions as the previous scenario – Chennai begins with robust infrastructure, but in this case the management is weak – 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 eventually deteriorates. In each consecutive drought, the city is unable to control demand and the reservoir dries up.

For the first 20 yr, from about 1965 to 1985, the city does not feel the effects of the bad policy (Fig. 4). Rainfall is good, there are no major droughts and very few households own wells. When the first drought hits Chennai in the 1980s, well ownership increases – but not enough people have wells for the aquifer to dry up. However, when the second multi-year drought hits in the early 2000s, the aquifer no longer has the buffering ability. Over 60 % of the households now have wells – groundwater levels fall rapidly, many wells go dry and a tanker market develops. The cost of water is much high during droughts because water users must depend on tankers.

6 Conclusion

This paper describes coevolution of an urban water system using a socio-hydrologic model of Chennai, India. The model simplifies the complexity of hydrological, economic, technological, and social processes in Chennai. A simple stylized model attempts to replicate the essential dynamics of the actual evolution of Chennai's water system. Then two counter-factual trajectories are explored.

This study offers some interesting insights on urban water security in developing country water systems. First, the Chennai case study shows that urban water security goes beyond piped water supply. Instead the aquifer provides a buffer. When piped supply fails users first depend on their own wells. When the aquifer is depleted, a tanker market develops. When consumers are forced to purchase expensive tanker water, they are 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 achieving water security. Indeed, if storage capacity had to keep up with population, Chennai's reservoir storage would be ten times the actual storage today and comparable to cities like Boston, MA. This raises the issue of path-dependence that 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 other studies have showed (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 till much later when the population has grown and a major multi-year drought hits.

This paper presents an example of a socio-hydrologic modelling study as distinct from a WRM model in several ways. The paper does not attempt to prescribe policy.

Instead the objective is to explain historically observed dynamics and explore alternative trajectories Chennai's water supply might have taken. For instance, where optimal reservoir storage is usually prescribed by a water resources management model, here reservoir storage is an *emergent property* of the system. The model allows the water utility to develop reservoir storage based on its finances and allows water security to evolve based on infrastructure and pricing by the water utility and corresponding coping investments by consumers based on their income. However, it is important to note, that although the model does not directly generate management or policy recommendations, the insights are nevertheless useful. The "outcome variables" (cost of water, depth to groundwater, etc.) in the model have been carefully chosen to reflect variables of interest to stakeholders. Doing so might ensure that the insights gleaned could inform prescriptive, policy-oriented water resources management models.

Any simplistic conceptualization including the one in this paper has several limitations. First, the model is weak on politics. A major assumption is that human responses are primarily economic. While most households in Chennai do respond by making coping investments, water users are in fact also citizens who also engage in the political process. Indeed in my own field work, I encountered several examples of communities using an array of strategies to lobby with the local government to improve water supply. Second, the narrow definition of water security in terms of average costs of water to users also overlooks the nuances of reliability, inequity, uncertainty of the amount and timing of supply etc. Yet it is well known that equity and distributional impact often matter more as certain sections of society are disproportionately affected.

As socio-hydrology evolves as a field, a greater attention to normative lenses and how the choice of outcomes influences the conclusions drawn is urgently. However, such a treatment was beyond the scope of this paper but could be the basis of future work.

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

References

Baisa, B., Davis, L. W., Salant, S. W., and Wilcox, W.: The welfare costs of unreliable water service, J. Dev. Econ., 92, 1–12, 2010.

Booker, J. F., Michelsen, A. M., and Ward, F. A.: Economic impact of alternative policy responses to prolonged and severe drought in the Rio Grande Basin, Water Resour. Res., 41, W02026, doi:10.1029/2004WR003486, 2005.

Cai, X., McKinney, D. C., and Rosegrant, M. W.: Sustainability analysis for irrigation water management in the Aral Sea region, Agr. Syst., 76, 1043–1066, 2003.

Chakravorty, U. and Umetsu, C.: Basinwide water management: a spatial model, J. Environ. Econ. Manage., 45, 1–23, 2003.

Di Baldassarre, G., Kooy, M., Kemerink, J. S., and Brandimarte, L.: Towards understanding the dynamic behaviour of floodplains as human-water systems, Hydrol. Earth Syst. Sci., 17, 3235–3244, doi:10.5194/hess-17-3235-2013, 2013.

Feldman, D. L.: Preventing the repetition: or, what Los Angeles' experience in water management can teach Atlanta about urban water disputes, Water Resour. Res., 45, W04422, doi:10.1029/2008WR007605, 2009.

Gober, P., Wentz, E. A., Lant, T., Tschudi, M. K., and Kirkwood, C. W.: WaterSim: a simulation model for urban water planning in Phoenix, Arizona, USA, Environ. Plan. B, 38, 197–215, 2011.

Jakeman, A. J. and Letcher, R. A.: Integrated assessment and modelling: features, principles and examples for catchment management, Environ. Modell. Softw., 18, 491–501, 2003.

Kilgour, D. M. and Dinar, A.: Flexible water sharing within an international river basin, Environ. Resour. Econ., 18, 43–60, 2001.

Lane, S. N.: Acting, predicting and intervening in a socio-hydrological world, Hydrol. Earth Syst. Sci. Discuss., 10, 10659–10717, doi:10.5194/hessd-10-10659-2013, 2013.

Lévite, H., Sally, H., and Cour, J.: Testing water demand management scenarios in a water-stressed basin in South Africa: application of the WEAP model, Phys. Chem. Earth, 28, 779–786, 2003.

Liu, Y., Gupta, H., Springer, E., and Wagener, T.: Linking science with environmental decision making: experiences from an integrated modeling approach to supporting sustainable water resource management, Environ. Modell. Softw., 23, 846–858, 2008.

Lundqvist, J., Appasamy, P., and Nelliyat, P.: Dimensions and approaches for Third World city water security, Philos. T. Roy. Soc. London B, 358, 1985–1996, 2003.

Raskin, P., Hansen, E., Zhu, Z., and Stavisky, D.: Simulation of water supply and demand in the Aral Sea Region, Water Int., 17, 55–67, 1992.

Sivapalan, M., Savenije, H. H. G., and Blöschl, G.: Socio-hydrology: a new science of people and water, Hydrol. Process., 26, 1270–1276, doi:10.1002/hyp.8426, 2012.

Srinivasan, V., Gorelick, S. M., and Goulder, L.: A hydrologic-economic modeling approach for analysis of urban water supply dynamics in Chennai, India, Water Resour. Res., 46, W07540, doi:10.1029/2009WR008693, 2010.

Srinivasan, V., Seto, K. C., Emerson, R., and Gorelick, S. M.: The impact of urbanization on water vulnerability: a coupled human–environment system approach for Chennai, India, Global Environ. Change, 23, 229–239, doi:10.1016/j.gloenvcha.2012.10.002, 2013.

Tidwell, V. C. and Van Den Brink, C.: Cooperative modeling: linking science, communication, and ground water planning, Ground Water, 46, 174–182, 2008.

Varis, O., Biswas, A. K., Tortajada, C., and Lundqvist, J.: Megacities and water management, Water Resour. Dev., 22, 377–394, 2006.

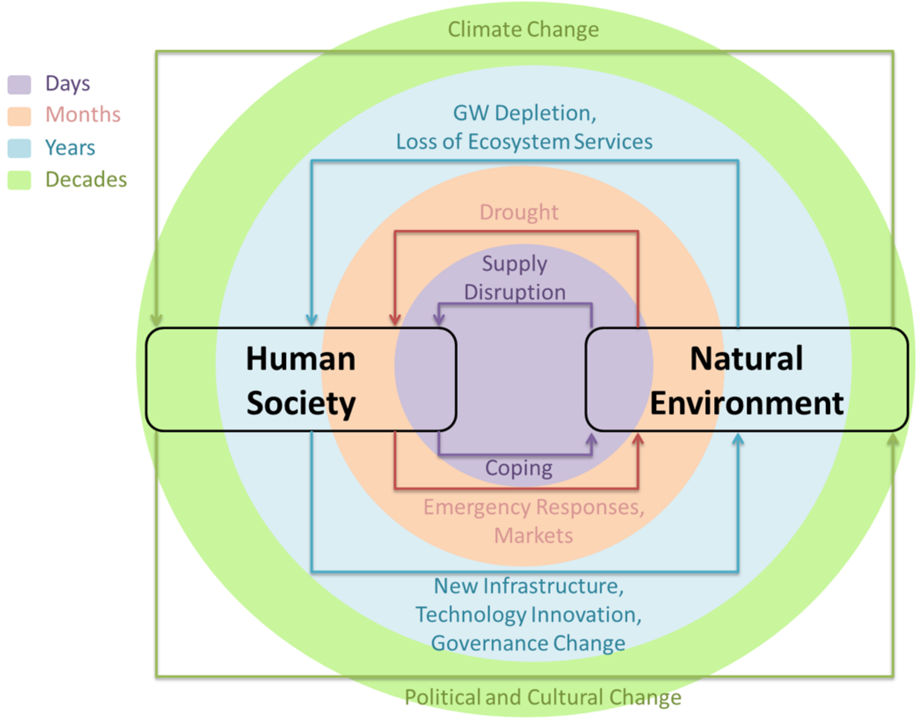

Fig. 1. Feedbacks in coupled human-water systems.

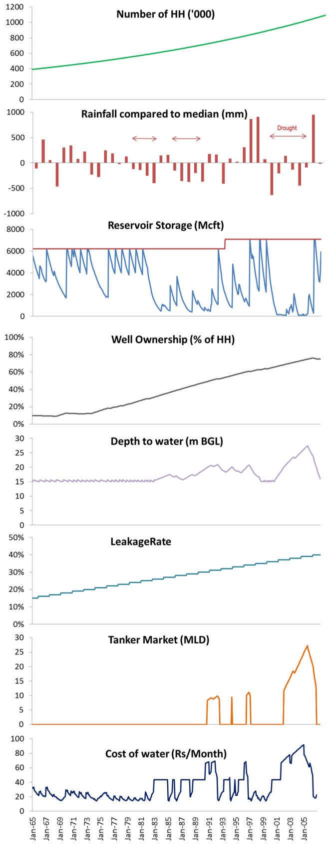

Fig. 2. Actual trajectory – poor infrastructure, weak management.

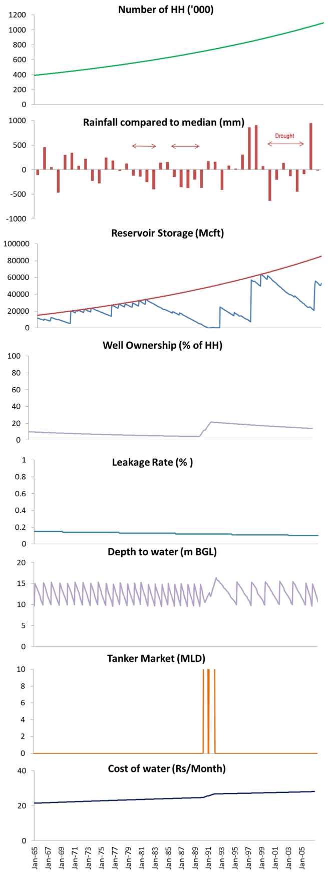

Fig. 3. Counterfactual trajectory – good infrastructure, strong policy.

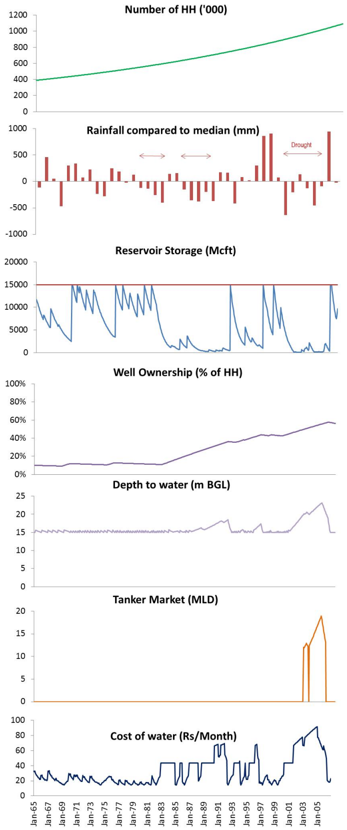

Fig. 4. Counterfactual trajectory – good infrastructure, weak management.