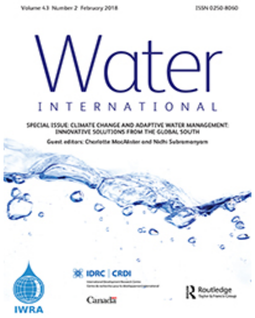

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Adapting to climate change in rapidly urbanizing river basins: insights from a multiple-concerns, multiple-stressors, and multi-level approach

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ABSTRACT
Much of the research on climate change adaptation in rapidly urbanizing developing regions focuses primarily on adaptation or resilience as the goal, assumes that climate change is the major stressor, and focuses on the household or the city as the unit of analysis. In this article, we use findings from two rapidly urbanizing sub-basins of the Cauvery River in southern India (the Arkavathy and Noyyal sub-basins) to argue for a broader analytic and policy framework that explicitly considers multiple normative concerns and stressors, and uses the entire watershed as the unit of analysis to address the climate–water interaction.

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Introduction

The Technical Working group on Water of the Intergovernmental Panel on Climate Change (Bates, Kundzewicz, Wu, & Palutikof, 2008) has suggested that climate change is likely to directly impact the water sector, and through it agriculture, domestic, and other sectors. Understanding the impact of climate change on the water sector has therefore received enormous research attention in the past decade. Most funding agencies have reframed their water-related funding programmes in climate change terms across various geographic contexts, providing an impetus to research in this direction.[1] Indeed, it would be fair to say that 'adapting to climate change' is one the most dominant themes in the water sector.[2] Simultaneously, rapid urbanization is also an important issue in developing countries, especially in Asia (Department of Economic and Social Affairs, 2010, 2015). There is thus increasing interest in understanding how water resource management in urbanizing regions might adapt to climate change. A large body of literature, both academic and policy-oriented, has emerged to address this question (Bartlett & Satterthwaite, 2016; Broto & Bulkeley, 2013; Revi et al., 2014). More recently, a significant subset of this literature has focussed on rapidly urbanizing regions in developing countries with support from cross-national programmes such as the Asian Cities Climate Change Resilience Network (ACCCRN, http://www.acccrn.

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net) and implementation efforts such as 100 Resilient Cities (http://www.100resilientcities.org) and the Urban Climate Change Research Network (UCCRN, http://uccrn.org/).

What approach might best address the issue of climate adaptation in water resource management in an urbanizing developing country context? In an earlier review focusing on barriers to integrated analysis in this field (Srinivasan, Thomas, Jamwal, & Lélé, 2013), we pointed out that the literature is characterized by multiple disconnects, including differing normative concerns, attention to different stressors, and scale mismatches. Specifically, climate–water research often (not always) limits its normative focus to adaptation or resilience, assumes climate change to be the main stressor, and tends to focus on the city as the unit of analysis. While this may be appropriate in a developed-country context, in a developing-country context, such research may run the risk of not speaking to other major normative concerns, such as adequacy, sustainability, or justice, and of overlooking the confounding role of other stressors, such as migration and land use change. Moreover, since cities invariably source water from outside the city and dispose of wastewater outside their boundaries, to understand urban climate adaptation in the context of water, it is important to situate cities within their watersheds or basins.[3] Several authors have flagged one or more of the above issues, but their responses have not yet merged into a comprehensive alternative approach. In Srinivasan et al. (2013), we proposed an alternative framework in which multiple concerns, multiple stressors, and links between the basin, the water supply and sewerage utility and household scales of analysis are explicitly incorporated.

This article elaborates on and demonstrates the usefulness of such a framework in assessing and explaining water-related outcomes in a comprehensive manner. In particular, the framework enables us to clarify whether certain 'adaptive' actions or policy responses synergize or generate trade-offs with respect to other concerns. It also helps identify what the role of non-climate stressors is and whether climate aggravates or reduces stress, given the specific configuration of basin-level resources, inter-basin and intra-basin water transfer and infrastructure, and institutions for allocation and distribution of water and treatment of wastewater.

We illustrate these points by synthesizing results from a large research project covering two rapidly urbanizing sub-basins (hereafter 'basins') in peninsular India: the Arkavathy River basin, overlapping with Bengaluru City in Karnataka State, and the Noyyal River basin, which includes Coimbatore and Tiruppur Cities in Tamil Nadu State. Our research team comprised more than 50 researchers with expertise in hydrology, water quality, remote sensing, economics, political science and gender studies. The team worked together for four years with a variety of data sources and methods of collection and analysis to understand the outcomes and drivers of water management in these two basins.

The article is structured as follows. The next section begins with a brief review of the literature and arguments in favour of adopting a broader framework for understanding the climate–water relationship in rapidly urbanizing regions in developing countries. The section ends with our conceptual framework. A description of the study region and the methods used in various studies to understand the different links in the framework is provided in the following section. The findings are then presented in terms of the multi-dimensional outcomes, the relative magnitudes of and interplay between different stressors, and the role of basin-scale institutions and individual households in responding to water-related stresses. The article ends by reflecting on how the framework provides insights that might have otherwise been missed or only tangentially addressed, and what implications this might have for future research.

The need for a broader framework and its contours

The large literature on the climate–water interface that has emerged in the last two decades has been subjected to some recent critiques. This section briefly summarizes three issues that have emerged in the context of research on the climate–water interface in urbanizing regions of developing countries.

Is adaptation or resilience the only concern?

The secular shifts and increased unpredictability in climatic conditions that the rising concentration of greenhouse gases is creating has sparked a huge interest in the ideas of adaptation and resilience (for reviews, see Adger, Huq, Brown, Conway, & Hulme, 2003; Fabricius, Cundill, Folke, & Schultz, 2007; Kiparsky, Milman, & Vicuña, 2012; Nelson, Adger, & Brown, 2007). Broadly speaking, while 'adaptation' refers to responding to a known change, or 'predict and prevent' (Tyler & Moench, 2012), 'resilience' is best understood as the ability to deal with unknowable future shocks or stresses.

Both concepts, if taken at face value, assume that the condition prior to the predicted change or unpredicted shock was acceptable or desirable (Cretney, 2014). In the context of water, this means assuming that 'these regional ecosystems and human activities are usually reasonably well adapted to the current climate conditions, but may be vulnerable to large or rapid changes' (Nijssen, O'donnell, Hamlet, & Lettenmaier, 2001, p. 144). This may be true in a developed-country(typically temperate) context, where issues of water scarcity, water quality, and to an extent sustainability have been largely resolved over a century of industrialization and urbanization and many decades of relatively stable populations. For instance, the average domestic supply of water in the USA is 333 litres per capita per day (LPCD) (Maupin et al., 2014) and in Canada is 335 LPCD (Shrubsole & Draper, 2007) – more than adequate by any standard. In the face of potentially dramatic shifts in climate, the major goal for these regions has to be to adapt and/or build resilience so as to maintain this (high) level of water availability or water service (see e.g. Moser, 2010).

But this does not hold true for developing countries, where the goals of adequacy, quality and sustainability (among others) are far from being met. For instance, median per capita water availability in Indian cities is a mere 69 LPCD and is very inequitably distributed (Indian Institute for Human Settlements, 2014). Similarly, the problem of poor quality of water supply is widespread (Central Pollution Control Board, 2010), and groundwater levels are rapidly declining in many regions (Central Ground Water Board, 2011) even as surface water bodies are being built over (Centre for Science and Environment, 2012).

Not all research on adaptability and resilience in the climate–water context neglects these other concerns. In particular, the relationship between traditional equity and justice concerns and the new focus on resilience has been the subject of much discussion (see e.g. Cote & Nightingale, 2012; Ziervogel et al., 2017). Several researchers have introduced equity concerns into urban climate–water research by focusing attention on poor and socially marginalized groups in their study of climate impacts, e.g., the attention to slum dwellers in Indore (Bhat et al., 2012) under the ACCCRN. There is a recognition that 'resilience is not a characteristic that is evenly spread through the urban population' (Tyler & Moench, 2012, p. 314). 'Inclusivity' is now even enshrined alongside 'resilience' and 'sustainability' in Sustainable Development Goal 11, which pertains to cities. While a welcome expansion, we would argue that 'increasing the resilience of the poor' is not quite the same as explicitly setting poverty reduction or adequate water supply for the poor as a goal.

Another approach to including equity or justice concerns is based on the argument that rights and justice have 'instrumental value' (Ziervogel et al., 2017). The claim is that attention to rights and entitlements or transparency and accountability in governance (Tyler & Moench, 2012) will further the goal of resilience. But it is not clear that this is always the case – resilience is not guaranteed to be just, nor is justice guaranteed to be resilient (see e.g. Thomas & Twyman, 2005). For instance, increasing resilience in the water sector might be achieved by building more big dams, thereby displacing marginalized groups (Lebel, Foran, Garden, & Manuta, 2009). So unless justice is foregrounded as an independent concern on par with resilience, injustices might not be avoided.

We also believe that democratic governance is best seen as a goal in itself, regardless of whether it leads to 'better' outcomes or not, because many dictatorial regimes may in fact produce better outcomes. Similarly, even long-term sustainability and resilience are not identical goals but are both important for water resource management. Indeed, the broader literature on water resource management shows engagement with a multiplicity of goals, such as sustainability, reliability, adequacy and adaptability (Srinivasan, Lambin, Gorelick, Thompson, & Rozelle, 2012). But the dominance of adaptation/resilience among donors appears to have constrained the discourse, and researchers are now left trying to reintroduce some of the other concerns through various intellectual back doors. We believe that there is a need for climate–water research in developing country contexts to explicitly acknowledge the existence of multiple societal concerns or goals. Acknowledging this will then enable research to examine the synergies and trade-offs between these different goals.

Is climate change the only stressor?

When the theme of research is framed as 'the impact of climate change on water resources', there tends to be a presumption that climate change is the most important stressor acting on the water resource system. In economically developed temperate countries with zero population growth and urbanization already at 90% or more, it does seems likely that climate will be the main stressor. But it would be inappropriate to generalize this assumption across the globe. Vörösmarty, Green, Salisbury, and Lammers (2000) estimate that rising water demand driven by population and economic growth would significantly outweigh climate-induced stress. More specifically, in developing-country contexts, rapid growth of urban populations driven by 'push and pull' migration combines with intensifying agriculture, industrial growth, and increasing incomes to increase the demand for freshwater in multiple ways. A recent four-nation study (Grafton et al., 2012) showed that direct human actions on water, and not climate change, remain the principal drivers of reduced water flows.

Unfortunately, consistent incorporation of multiple stressors in climate change–water research in developing countries seems to be an exception rather than the norm. In an extreme case, a multi-basin simulation of the hydrological impacts of climate change in India assumed the status quo as far as other variables were concerned (Gosain, Rao, & Basuray, 2006). Others have incorporated multiple stresses in a limited way by looking at how a household's ability to respond to climate change may be constrained by other socio-economic stresses, such as disease or a lack of livelihood opportunities (Quinn, Ziervogel, Taylor, Takama, & Thomalla, 2011). O'Brien and Leichenko (2000) proposed the idea of 'double exposure' to identify social groups that are vulnerable to simultaneous impacts of climatic and economic changes. But the idea of starting all climate–water analyses with multiple stressors, identifying objectively the relative importance of climate change *vis-à-vis* other stressors, and examining interactions between different stressors needs to become mainstream in climate–water research in developing regions.

Is focusing on the household or the city enough?

Analyzing the impact of climate change on water users requires working across very disparate scales. What we see in practice are sharp disciplinary disconnects. Climatologists estimate climate change patterns at fairly coarse regional scales. Hydrologists are adept at downscaling these patterns and applying them to basin-scale models to predict changes in streamflow or recharge. They have also applied such downscaled data to models of urban storm runoff to predict urban flooding. However, when it comes to water provisioning, hydrologists seldom go beyond estimating average physical availability in a basin (see e.g. McDonald et al., 2011). On the other hand, social science research on adaptation and resilience in urban water provisioning has focused on households, communities and, where necessary, the municipality or equivalent water service providers. They tend to take the hydrological resource and engineering context as a given.[4] This may work as long as the focus is on (say) how water is distributed within a city.

But the social hydrology of cities is more complicated than that, because cities don't exist in isolation. Cities invariably import large quantities of water from surrounding watersheds or, in the Indian case, from longer distances as they grow bigger (Mukherjee, Shah, & Kumar, 2010). Not only do these withdrawals set up potential conflicts with water users in those watersheds (Narain, 2014), but they are also influenced by what changes take place in the watersheds upstream of the withdrawal point. Equally important, the consumptive use of water in the urban context is fairly low (~25% of total withdrawal). This means that a large quantity of 'return flow' is generated by the city, in polluted form, and is then let out (treated or untreated) beyond city boundaries, where it may get reused. If recycling within the city increases, these return flows decrease. Finally, cities are also linked to peri-urban and rural areas through land, labour, and product markets, and the process of urbanization significantly affects these areas. Thus, if one wants to understand the impact of climate change in an *urbanizing* context, one needs to place cities in their watershed and look at these multiple spatial links.

Researchers are beginning to incorporate the larger watershed in their analysis of urban water resilience. Research on downstream reuse of urban wastewater has already been flourishing for a while (Amerasinghe, Bhardwaj, Scott, Jella, & Marshall, 2013; Drechsel, Scott, Raschid-Sally, Redwood, & Bahri, 2009). Research on urban–peri-urban connections due to water supply systems is also emerging (Narain, 2010; Narain & Singh, 2017). Other studies within ACCCRN have also flagged that climate change will affect the basins from which city water supplies are drawn (Bhat et al., 2012), even though they do not use any hydrological model to estimate what changes in precipitation might mean for the supply. But the hydrological impacts of urbanization on peri-urban watersheds, other than in the form of flooding, have not been examined very extensively. Integrating these dimensions and the actors in those larger regions will enhance our understanding of the water dynamics of urbanizing regions.

A multiple-concern, multiple-stressor, multi-level framework

The above review indicates that in the context of urbanizing regions in developing countries, research should explicitly acknowledge multiple concerns and multiple stressors at the outset, and also seek ways of linking basin-scale analysis to individual actions via infrastructure and institutions where appropriate (Srinivasan et al., 2013).

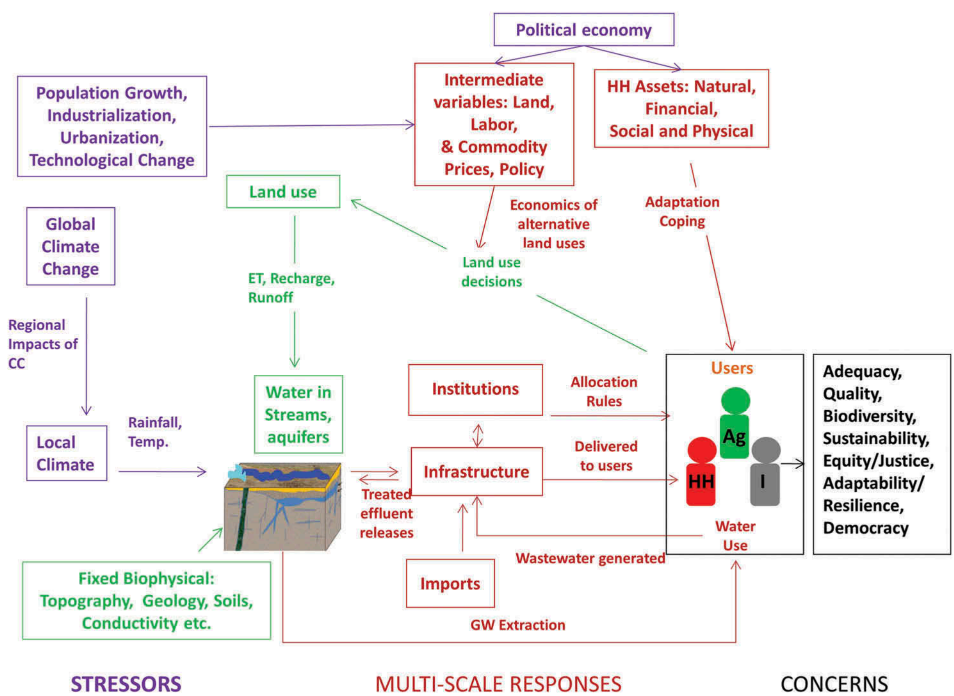

Figure 1. Proposed framework for understanding water management in urbanizing regions in developing countries, incorporating multiple normative concerns, multiple stressors, and multiple scales. HH, Ag, and I refer to domestic, agricultural and industrial water users respectively (revised from Srinivasan et al., 2013).

Our proposed framework is presented in Figure 1. We explain below the different parts of the framework and the rationale behind them.

Since concerns are normative concepts, i.e., important in and of themselves and not instruments for some other goal, the goals of water management cannot be arrived at through 'scientific' debate but rather are based on ethical choices. Different researchers have articulated these concerns in different ways in the broader water governance literature, for instance 'developing, allocating and managing [water] equitably and efficiently and ensuring environmental sustainability' (Rogers & Hall, 2003); 'effectiveness, equality of access and sustainability' (Cleaver & Toner, 2006); or 'progress towards MDGs goals, good governance principles and stakeholder involvement, climate change adaptation, and environmental conditions/quality' (Pahl-Wostl, Lebel, Knieper, & Nikitina, 2012). We propose the dimensions of adequacy, equity and justice, sustainability, adaptability/resilience, quality/public health, biodiversity, and democratic governance.

These dimensions are given in the rightmost box in Figure 1. While necessarily subjective, we believe that this formulation is broad enough to capture most concerns, while still remaining analytically tractable. The explicit formulation enables us to examine the trade-offs and synergies between different normative goals.

Other than climate change, population growth, urbanization (a shift in population from rural to urban), industrial growth and technological change are the major stressors that we think commonly exist across such regions. Also ever-present is the political economy that shapes policies such as agricultural subsidies or real estate markets. These exogenous factors (not all being stressors) are shown on the left side of Figure 1.

Inter- and intra-basin transfers, water transport and distribution systems in agriculture and domestic sectors, and effluent treatment plants are the key physical infrastructure in urbanizing regions. The institutions that manage them may include irrigation agencies, specialized water supply and sanitation boards, municipalities, and pollution regulators. The legal and administrative framework and political process for water allocation across major sectors (e.g., between agriculture and urban users, or between states) and regulating access to groundwater would be part of these institutional arrangements, which are indicated in the middle of Figure 1. These are also the major 'points of entry' for bringing about positive change. Note that the framework has to be dynamic: agencies respond to stressors by creating new infrastructure or modifying rules; individuals may respond by changing crops, adopting new technology, or drilling domestic borewells. The actions of millions of individuals and multiple agencies create cumulative outcomes that may ameliorate or aggravate scarcity, unsustainability or inequity, and over time these outcomes will again drive new responses.

We believe that such a framework provides a useful way of highlighting key elements (concerns, stressors and linkages) without imposing a particular social theory, which would be chosen by the individual researchers based on their inclinations and the specific context. However this theory is fleshed out, our framework will push the researcher towards weighing the relative importance of and interactions between climate and non-climate stressors, tracing their impacts on water users through the institutional arrangements and therefore understanding the space for implementing different policy changes, and identifying whether particular policy changes generate synergies or trade-offs across different normative concerns so as to be characterized as overall enhancement of sustainable development goals or not. Next we demonstrate the application of this framework in our study region, covering two rapidly urbanizing basins in peninsular India.

Applying the framework: the study region and methods

This research focused on two sub-basins of the larger Cauvery River basin in southern India (Figure 2). Both sub-basins (hereafter referred to as 'basins' for convenience) have 600–900 mm of annual rainfall and aquifers underlain by a hard-rock geology. The Arkavathy basin (3314 km^2) is a highly water-stressed, rapidly urbanizing basin overlapping with the city of Bengaluru. The basin covers parts of Bengaluru Urban, Bengaluru Rural, and Ramanagara Districts and includes three towns in addition to about 33% of Bengaluru City, adding up to a total population of 5.3 million, of which approximately 80% lives in urbanized areas per the 2011 census.[5] The Thippagondanahalli (TG Halli) reservoir separates the basin into upper and lower portions and supplies a small portion of Bengaluru's water supply.[6] Bengaluru's wastewater ends up in the Arkavathy through the Vrishabhavathy River, a tributary. En route, the wastewater is used by downstream farmers.

The Noyyal sub-basin (3510 km^2) is also a rapidly urbanizing basin, which includes the cities of Coimbatore and Tiruppur, with a population of 4.2 million, of which more than

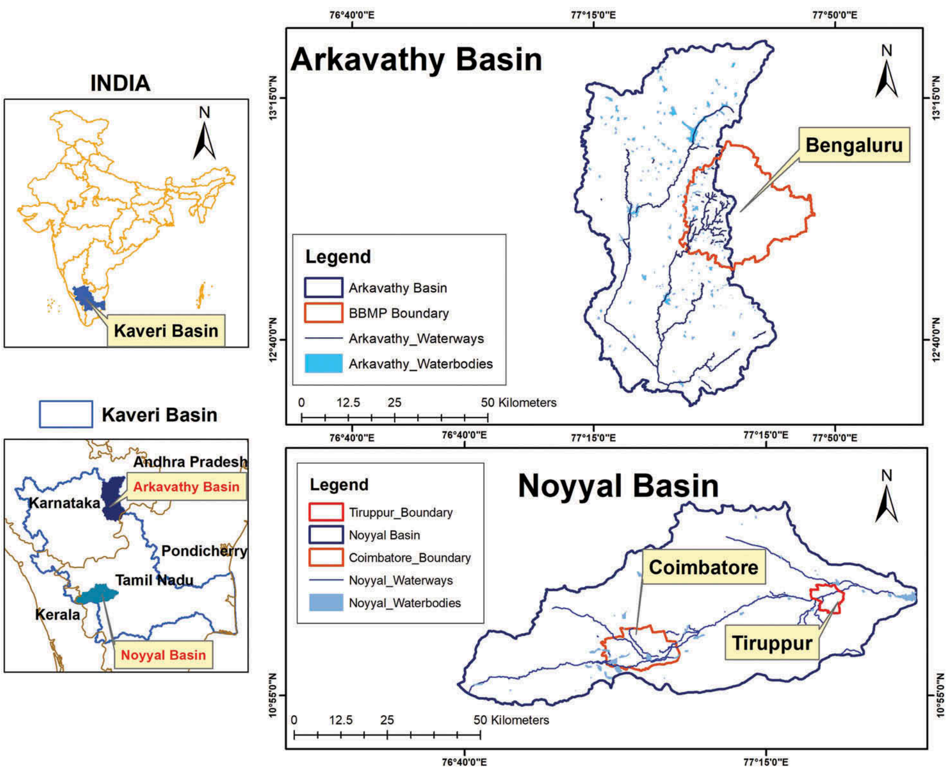

Figure 2. Location of study basins in peninsular India. BBMP = Bengaluru municipality. Source of base map: India-WRIS wiki.

75% lived in urbanized areas per the 2011 census. It is also heavily industrialized, with the township of Tiruppur having more than 3000 hosiery and textile processing industrial units. The study area included only part of the Noyyal basin: the portion downstream of the Orathupalayam Dam, which includes areas served by major surface water irrigation schemes, was excluded. The Noyyal is a highly seasonal river and does not provide any water supply, partly because it is a recipient of sewage and industrial effluents.

We conducted a four-year research project, with support from the International Development Research Centre (Canada), to understand water management in both these sub-basins. We began with situation analyses that summarized the current understanding of water management in the two basins (Lele et al., 2013; Srinivasan et al., 2014). We then conducted studies to understand the different linkages in the conceptual framework, such as factors influencing farmer crop choice and irrigation decisions; patterns of land use change over time; factors influencing urban water consumption; the nature and extent of water pollution, treatment and reuse; trends in surface flows and groundwater levels and the potential drivers of these trends; and agencies involved and modes of water governance in small towns and large cities. These studies involved the collection and analysis of a large variety of primary and secondary data using a variety of methods, including census data, field structured surveys, interviews and focus group discussions, archival and legal data, satellite imagery, field hydrological studies and multi-scale hydrological modelling, water quality sampling and lab analysis, and extensive stakeholder outreach and interaction (see the ACCUWa project page, http://www.atree.org/accuwa for details).

Insights from the two-basin study: outcomes, stressors and responses

The analyses pertaining to individual links and processes have been written up and published (or are in the process of being published) as separate papers and reports. Here, we synthesize some of the insights obtained from these individual studies that throw light on the questions identified above: the role of and interaction between different stressors, the institutional arrangements and policies that iteratively responded to the stressors, and the progress towards and trade-offs between different normative concerns or goals under these different policies. This article's scope is limited to the discussion of the agro-hydrological changes in the source watersheds, the provisioning of water to urban domestic users, and the downstream impacts of urban effluents. We do this in a comparative manner across the two basins, discussing first the progress *vis-à-vis* normative concerns, and then how the stressors and responses (at household, agency, and higher levels) have interactively shaped these outcomes. For brevity, we focus on findings regarding adequacy, quality, equity, and sustainability concerns, not on biodiversity conservation or democratic governance goals.

Status vis-à-vis multiple concerns

Adequacy

Urban domestic water users are facing significant water shortages in both basins. Two of the eight sampled towns fell below 70 LPCD (the norm for the smallest towns) and one other below 90 LPCD (Figure 3). More importantly, within each town, a large

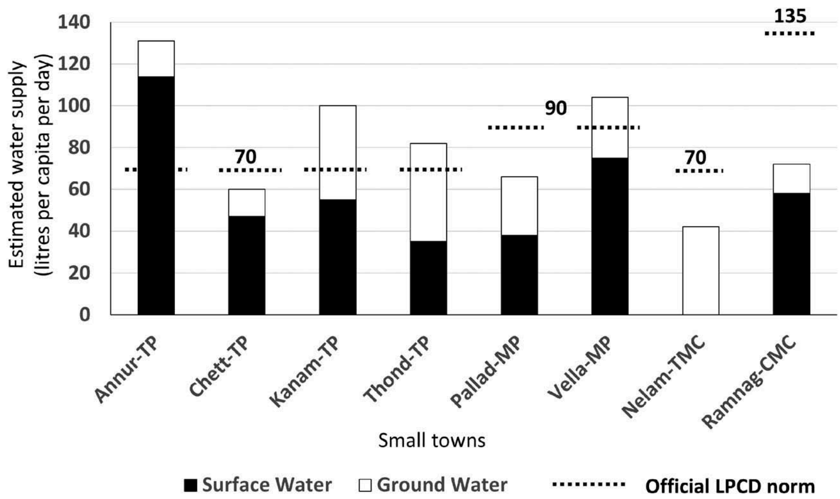

Figure 3. Variation in average household water supply (litres per capita per day) in sampled small towns in the two basins. TP, MP, TMC and CMC refer to different municipal categories. Town names are shortened for convenience. Source: Lele et al., 2018.

fraction of the population received significantly less water than the town average (Lele, Madhyastha, Sulagna, Dhavamani, & Srinivasan, 2018). In the two large metros of Bengaluru and Coimbatore, water supply is somewhat higher, but again in Bengaluru, a large fraction of the population makes do with less than 100 LPCD (Malghan et al., 2016). Further, all these households face greater water stress during the summer months. On the whole, water is more scarce in the urban areas of the Arkavathy basin (rightmost two towns in Figure 3) than in the Noyyal basin (leftmost six towns in Figure 3) – see Lele et al. (2018) for more details.

For agricultural users, 'adequacy' is harder to define. Our farmer surveys in the two basins showed that irrigation water is scarce at least in the Arkavathy basin: the fraction of farmers having access to irrigation (almost entirely groundwater irrigation) is only 15% as compared to 68% in the Noyyal basin. But it must be noted that in the Noyyal basin, 50% of the land is fallow, while this fraction is only 18% in the upper Arkavathy basin. So, it seems that those who do not have access to water have already moved out of farming in the Noyyal basin.[7] Farmers are not experiencing the full scarcity cost because electricity for pumping is still free, but in both basins, focus group discussions with farmers indicated a perception of rising scarcity.

Equity

The estimates in Figure 3 show significant differences across small towns, and there are even bigger differences *vis-à-vis* metropolitan areas, because they attract policy attention. For instance, Bengaluru has invested vast amounts of public money in acquiring Cauvery water without sharing it with its small town neighbours. Policy in the Noyyal basin has been more equitable: every bulk water supply scheme involves supplies to towns and villages. But the bigger inequity is the inter-household inequity within cities, with consumption ranging from below 50 LPCD in slums to above 300 LPCD in villas and apartments in Bengaluru and from 60–70 LPCD in slums to more than 400 LPCD in villas in Coimbatore (Apoorva, Biswas, & Srinivasan, 2018). The inequity is on the whole worse in the Arkavathy basin than in towns in the Noyyal basin.

Access to irrigation is also highly unequal. As mentioned above, in the Arkavathy basin, only 15% of all currently farming households owned a functioning borewell, and borewell ownership correlated positively with landholding and caste status (Patil, Thomas, Lele, Srinivasan, & Eswar, 2018). And as groundwater levels have dropped (see below), access has become more inequitable, as only the wealthy farmers can afford to keep investing in drilling deeper wells, with the probability of failure currently around 50% (Thomas, Eswar, Kenchaigol, Srinivasan, & Lele, 2015).

Sustainability

Even this limited use of water is far from sustainable. Virtually all rural water supply and a surprisingly large fraction of urban water supply – ranging from 10% in a few small towns in the Noyyal basin to 30% in Bengaluru city and 100% in a few towns in the Arkavathy basin – comes from groundwater, a resource which is declining rapidly. For instance, the median depth at which newly drilled borewells struck water declined from 250 ft in 1980–85 to 750 ft in 2010–2015 (Figure 4) in the rural upper Arkavathy basin. The lower Arkavathy basin showed less of a decline because it received return flows from Bengaluru via the Vrishabhavathy River, and so groundwater use was slightly lower in this region.[8] Groundwater in the Noyyal basin also showed a declining trend away from the river, but an overall lower rate of depletion, for reasons outlined later below.

Simultaneously, the contribution of surface water sources *within* each basin to its domestic water supply has become virtually zero after the mid-1990s as surface flows in streams and rivers in both basins have systematically declined. Between the mid-1970s and 2013, the flows in the upper Arkavathy declined from an average of more than 150 million to less than 15 million litres per day (Figure 5, panel A). Consequently, the TG Halli reservoir on the Arkavathy, which was supposed to provide 150 million litres per day of

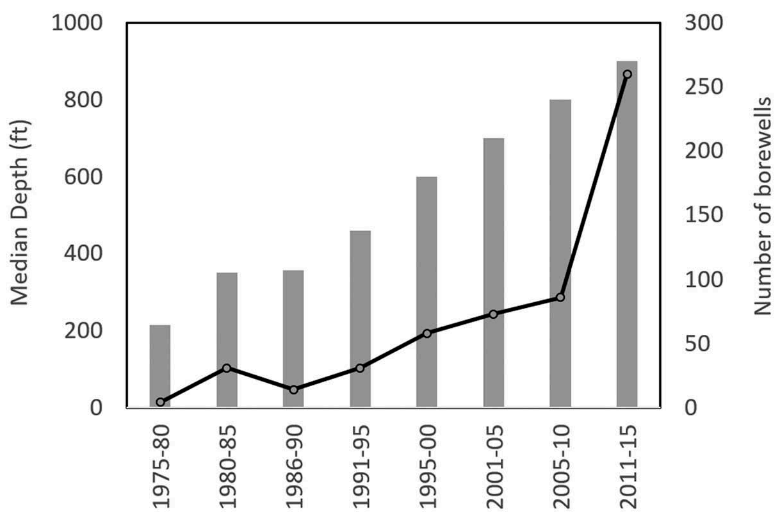

Figure 4. Increasing number of borewells drilled alongside increasing depth to water in the upper Arkavathy basin. (Source: primary data from well censuses in two milli-watersheds.)

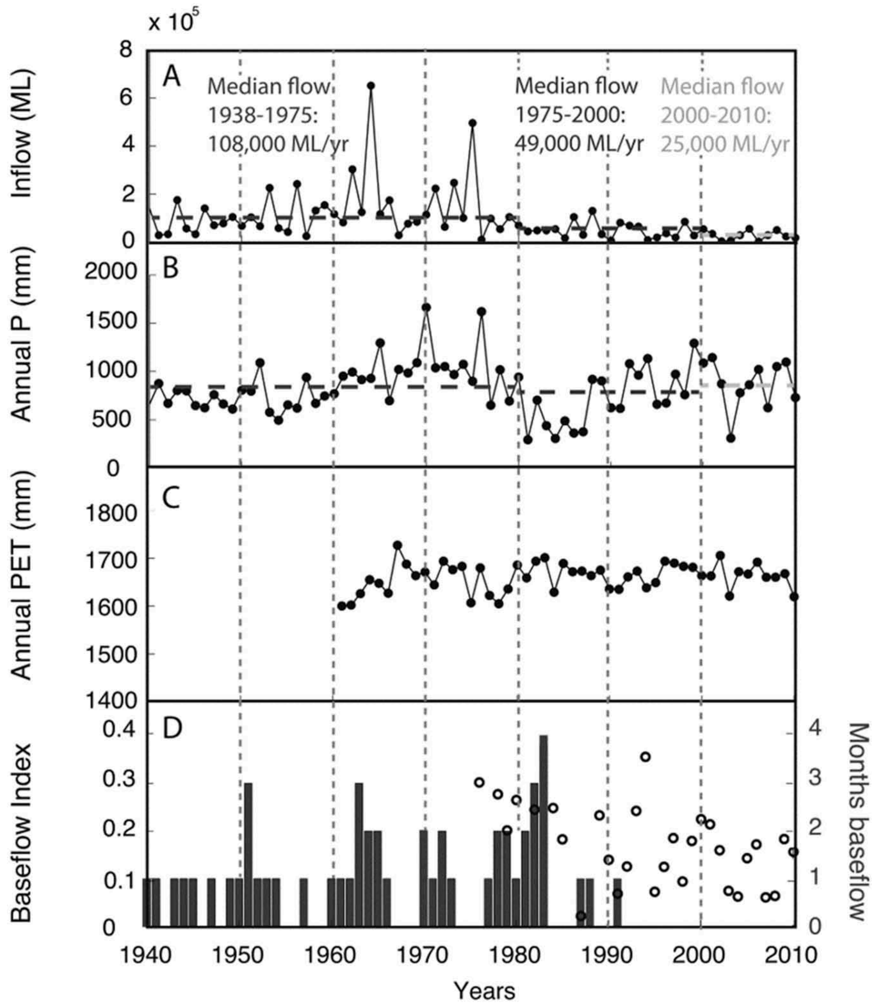

Figure 5. Changes in total streamflow (top) and baseflow (bottom) into TG Halli reservoir since 1940, with no explanatory trends seen in rainfall or potential evapotranspiration (source: Srinivasan et al., 2015).

water supply to Bengaluru, is now not supplying any water to the city. Most other reservoirs meant for irrigation showed a drying trend as well (Penny, Srinivasan, Dronova, Lele, & Thompson, 2016). The Noyyal River is now flowing only episodically.

Resilience/vulnerability

With cross-basin imports of surface water (from the Cauvery to Bengaluru and from the Bhavani, Siruvani and Cauvery Rivers into the Noyyal basin) becoming the only sources of surface water and contributing the major portion of urban water supply, the urban populations in these basins have become highly vulnerable to any disruptions in this source. Climate change may reduce precipitation in the Western Ghats region that feeds the Cauvery. Given that the Cauvery is a closed basin, that interstate conflict over Cauvery waters is already severe, and that the diversion of Cauvery water to supply Bengaluru has already exceeded the total allocation of

Cauvery water for urban use (Jayaraman, 2016), two threats loom on the horizon, especially for urban areas of the Arkavathy basin: climate change–induced reductions in precipitation in the upper (western) reaches of the Cauvery basin; and conflict between farmers in Karnataka and Tamil Nadu States over increased withdrawals from the Cauvery. To a lesser extent, that is also true of populations in the Noyyal basin that are dependent upon continuous transfers from the Bhavani sub-basin, which is fed by high rainfall in the Nilgiris, where again climate change and farmer agitations in the Bhavani are potential threats.

The vulnerability of agriculture, on the other hand, can be said to have decreased in both basins because irrigation shifted from surface irrigation tanks to groundwater, thereby being much less affected by the vagaries of the monsoon (Penny et al., 2016). This is reflected in the steady rise and then stabilization of the area under irrigated agriculture in the upper Arkavathy basin: from 135 km^2 to about 168 km^2 between the early 1970s and 2014, coinciding with a shift in irrigated crops from paddy and sugarcane to horticulture and vegetables (Lele & Sowmyashree, 2016). Similarly, irrigated agriculture in the Noyyal has stabilized, with a shift from tank irrigation to groundwater and a corresponding shift in irrigated crops from paddy and sugarcane to horticultural crops (Lele & Muneeswaran, 2016).

Similarly, rainfed agriculture in the Arkavathy basin saw a dramatic shift from single-season crops such as *ragi* (finger millet), which are highly sensitive to rainfall, to unirrigated tree crops (primarily eucalyptus), which are harvested on a six-to-seven-year cycle and are deep-rooted, thereby insulating the farmer from inter-annual variations in the monsoon. While the single-cropped area in the upper Arkavathy dropped from 50% to 14% of the catchment between the 1970s and 2014, the area under eucalyptus grew from zero to 270 km^2, or 20% of the catchment (Lele & Sowmyashree, 2016).[9]

Water quality and health

Surface water is highly polluted in most urban and peri-urban locations in the two basins. The Vrishabhavathy, the perennially flowing tributary of the Arkavathy, is highly polluted (Jamwal, Zuhail, Urs, Srinivasan, & Lele, 2015), as are almost all surface water bodies in Bengaluru, and the condition of the Noyyal river and water bodies around it is even worse (Srinivasan et al., 2014). Although domestic water users in the two basins are largely insulated from this pollution because they use surface water imported from beyond the basin boundary or deep groundwater, the impacts on aquatic life are significant, as most surface water bodies are polluted with biological and industrial contaminants (Jamwal & Lele, 2017). Moreover, the use of polluted Vrishabhavathy water for agriculture in downstream locations leads to vegetable products and milk (sold back to Bengaluru) being contaminated with heavy metals, along with effects on farmer health (Thomas, Deepthi, & Jamwal, 2017). Although we did not measure water quality in the Noyyal basin, there is a large literature on the pollution of the Noyyal river and surrounding water bodies and its impacts on downstream farming (Srinivasan et al., 2014).

Stressors and responses

How does one explain these problematic outcomes or shortfalls on multiple fronts? One can see from Figure 1 that the ‘stressors’ are those variables over which individuals and agencies have almost no control, but that individuals and agencies can and do take several actions in response that can mitigate and/or aggravate the stresses. We present our analysis of this interaction between stressors and individual/collective responses with respect to different outcomes in three interconnected geographies: the upstream (or away from river), primarily agricultural watershed within small towns, the city itself, and the downstream agricultural and peri-urban watershed.

Upstream agricultural watershed

The sharp and measurable declines in surface flows and in groundwater levels in the upper Arkavathy basin were not caused by a decline in rainfall (Figure 5, panel B), nor by a rise in temperature that could cause increase evapotranspiration (Figure 5, panel C), both of which changed little. Consumptive use of water in agriculture (evapotranspiration) increased dramatically due to two factors: farmers shifted from rainfed cereal cultivation to deep-rooted eucalyptus plantations; and with the advent of borewell drilling technology, farmers dramatically expanded groundwater extraction. The demand for horticultural and vegetable crops and labour in the dramatically expanding Bengaluru market contributed to the expansion of these new irrigated crops on the one hand and of low-labour eucalyptus cultivation on the other. The higher population in the basin also accounted for an increase in groundwater extraction, but in terms of consumptive use, its contribution was small (Srinivasan, Penny, Lele, Thomas, & Thompson, 2017). Groundwater declines completely dried up baseflows (Figure 5, panel D) and have also undermined groundwater availability for small towns in the watershed.

State policies shaped individual farmer behaviour – the government initially supported groundwater prospecting and continues to supply electricity for agricultural pumping virtually free of charge. Moreover, it has refused to implement any other form of controls on groundwater extraction. A further positive feedback was provided by the state response to declining groundwater levels – it initiated widespread construction of ‘check dams’ in streams to increase groundwater recharge. This only temporarily mitigated the decline, as extraction continues in an unregulated manner, but it did significantly contribute to further retarding surface flows (Srinivasan et al., 2015). Similarly, the shift to eucalyptus was initially triggered by a World Bank–funded ‘farm forestry’ project but then sustained by the market that had developed for this crop in rapidly growing Bengaluru and in the economy at large. Thus, urbanization and expanding product markets, compounded by state policy on groundwater (non-)regulation, electricity subsidies, check dam construction and eucalyptus promotion, rather than climate change, turned out to be the most important drivers of land use change and linked hydrological change. Note that what were and still are considered adaptive responses at the level of individual farmers, such as switching to eucalyptus in the face of rising labour costs, switching to borewell technology, and constructing check dams in the face of declining groundwater levels, turned out to be maladaptive at the scale of the basin. These connections between stressors, responses, and salient outcomes for this geography are shown schematically in Figure 6.

The trajectory of the Noyyal basin was very similar. The only difference was that eucalyptus was not promoted by the government here, and so farmers simply quit farming, migrated to the towns, and left the land fallow, which meant less evapotranspiration in rainfed cropping and hence, slower depletion of groundwater.

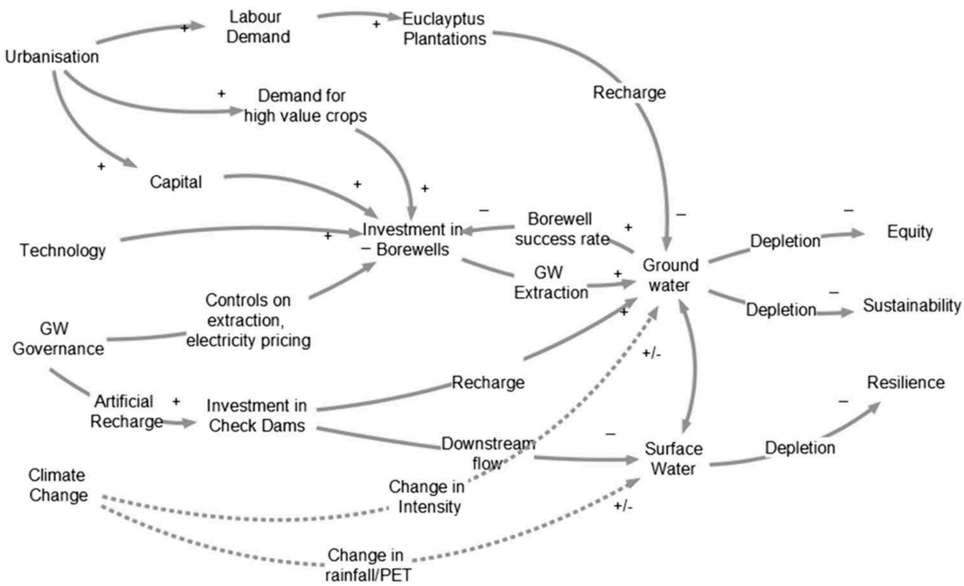

Figure 6. Connections between stressors, responses and outcomes in the upper Arkavathy rural watershed. The signs show the direction of the effect, and dotted lines represent effects that were relatively weak.

Going forward, our simulations for both basins show that the effects of climate change on agriculture in both basins will be small and will be overshadowed by the effects of urbanization. Predicted increases in total precipitation and rainfall intensity will increase surface runoff. But both basins are also moving away from rainfed seasonal crops and depend only on groundwater or tree crops, which average out inter-annual effects, so the net effects on existing irrigated agriculture and on surface flows may be small. Policies to promote drip irrigation may slow down the pace of groundwater decline (or borewell failure rates) but by themselves cannot rectify the long-term problem if total extraction by agriculture continues as it is.

The city

The problem of scarcity in the urban domestic sector is driven by the phenomenal growth in urban population, which was 118% in the Arkavathy basin and 300% in the Noyyal basin between 1991 and 2011. But several state policies have sought to mitigate the effect of this stressor. First, new pipelines brought more water from outside the basin to urban centres in both basins. Second, a systematic programme of groundwater (borewell)–based rural water supply was implemented in both basins.[10] Third, Bengaluru and later Coimbatore implemented metering and rising slab-rate water pricing fairly early on. Fourth, in Bengaluru, regulators made attempts to enforce water reuse in large apartment complexes, albeit with very limited success (Kuttuva, Lele, & Mendez, 2016). Finally, individuals responded by drilling borewells where they did not have access to adequate public supply. But in the Noyyal basin, municipalities drilled these public borewells to augment imported river water supplies and engaged in dual supply on all streets, thereby significantly limiting the growth in private household

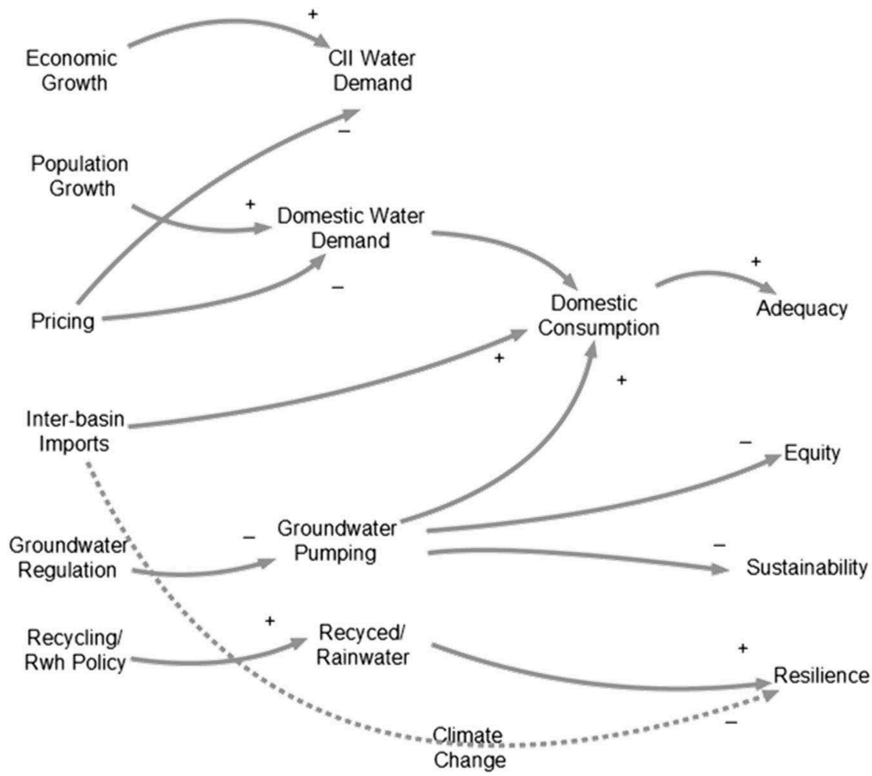

Figure 7. Connections between stressors, responses and outcomes in Bengaluru City. The signs show the direction of the effect, and dotted lines represent effects that were relatively weak. Rwh = rainwater harvesting; CII = commercial, industrial and institutional water users.

borewells and better distributing available surface water. In the Arkavathy basin, where water distribution was controlled by dedicated engineering agencies, the approach was to focus exclusively on supplying imported surface water, resulting in more inequity and more indiscriminate private borewell drilling and pumping, and bigger tanker markets. Increasing public borewell supply did alleviate inequities in access, but this quick fix could not address questions of biophysical or financial sustainability.

Admittedly, any agency would have difficulty responding to the demands of a rapidly growing population. But it is clear that agency responses failed on one front: protecting local surface water sources and protecting local groundwater from decline. The Bengaluru Water Supply and Sewerage Board, the owner of the TG Halli reservoir, simply abandoned it. It also did not introduce any regulations on urban groundwater pumping nor try to pump groundwater itself – in contrast to the agencies in the Noyyal basin. In both basins, municipalities have made only cursory attempts to promote rooftop rainwater harvesting (Rwh in Figure 7). And all municipalities in both basins have allowed local surface water bodies to either dry up or become repositories of sewage (Lele et al., 2018).

Agencies have a mixed record when it comes to addressing social inequality and its implications for water access. When water supply is handled by municipalities (as dedicated engineering agencies), the needs of the poor seem to be met better by the

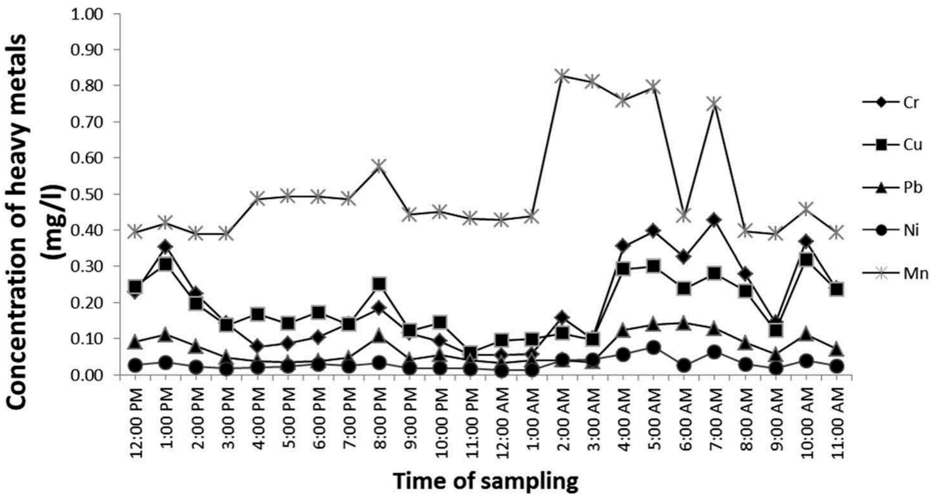

Figure 8. Variation in heavy metal content in the Vrishabhavathy River during a 24-hour monitoring exercise in January 2015 at a site closest to a designated industrial area. The night-time/early-morning peaks of heavy metal concentration in the river are far above the permissible concentrations at the point of discharge (source: Jamwal, Idris, Urs, & Lele, 2015).

deployment of extensive public standpipe networks and public tanker support. The push towards fully piped (and eventually fully metered) supply overlooks the importance of household ownership of water storage assets (sumps/overhead tanks) in the context of interrupted supply, which is the norm in all urban areas. Our research showed a clear decline in consumption in households having less storage (Apoorva et al., 2018).

The metropolitan water supply agencies have also not figured out how to make rising slab rate tariffs work equitably. Metered pipe connections are given to each dwelling unit or building. Typically, poorer households live in multi-family dwellings, whereas richer households own separate dwellings or houses. Consequently, poorer households that share a single connection end up paying a much higher average tariff for the same per capita consumption than a rich family living by itself (Malghan et al., 2016).

These connections between stressors, responses and salient outcomes for this geography are shown in Figure 7. Going forward, the effects of changes in precipitation patterns *within* the basins on urban domestic water supply are likely to be small and again overshadowed by the pace of urbanization. The dependence on imports from basins which are likely to face declines in precipitation will, however, significantly threaten water supply systems that are already precariously placed *vis-à-vis* meeting basic adequacy norms and have drawn down or polluted their local resources (groundwater and surface water bodies respectively). Recycling norms imposed by regulators on a small section of the population (apartment-dwellers) are unlikely to be effective unless they become part of a much larger shift towards managing local resources, recycled water and imported water as an integrated whole and create infrastructure and institutions for it at multiple scales (households, apartments, neighbourhoods and city). Measures focused on increasing imports from the Cauvery or other rivers that also originate in the Western Ghats will only increase

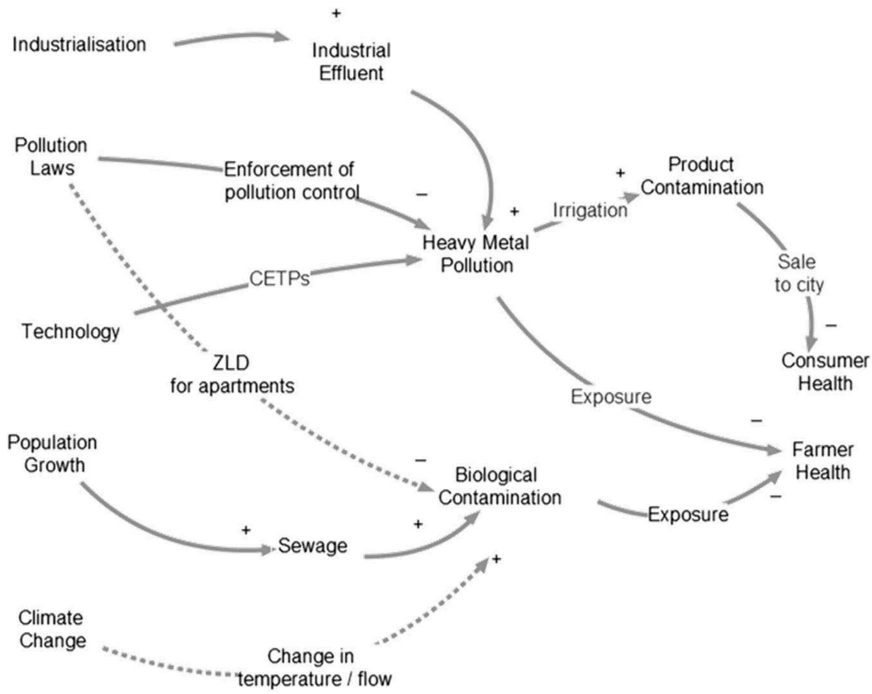

Figure 9. Connections between stressors, responses and outcomes in the downstream agricultural and peri-urban watershed. The signs show the direction of the effect, and dotted lines represent effects that were relatively weak. CETP = common effluent treatment plants for industry; ZLD = zero liquid discharge policy.

vulnerability in the long run, not to mention conflict with downstream populations in those basins.

Downstream watershed

The increasing water pollution is due to both increasing industrial growth (causing chemical and heavy metal contamination) and rising population (causing biological contamination). Pollution laws were passed nation-wide in the mid-1970s to regulate water pollution. The regulatory process was primarily based on ex ante consent, much less on post facto monitoring, and with no specification of ambient water quality goals. The focus of regulation was industries; domestic sewage went largely unregulated (Jamwal, Lele, & Menon, 2016).

The effects of weak monitoring are visible in Figure 8, which shows that heavy metal concentrations in the monitored stream in an industrial sub-catchment of the Vrishabhavathy river increased dramatically at night and early morning. We also found that the biological contamination of the Vrishabhavathy River was because the oldest sewage treatment plant in Bengaluru did not meet effluent discharge standards and also worked far below capacity, even as sewage is discharged untreated (Jamwal et al., 2015). The story in the Noyyal basin is essentially similar – sewage treatment is far below the requirement, and industrial pollution is poorly monitored and regulated (Srinivasan et al., 2014). Sustained public interest litigation in the Noyyal basin led to the shutting down of some industries and tightening of some regulations, but improvements in water quality are yet to be seen. The continued under-investment in monitoring is clearly linked to the poor track record of enforcement and the lack of structures of accountability of the regulating agency to the public (Lele, Heble, Thomas, & Jamwal, 2014).

Once these 'endogenous' factors and their magnitudes are recognized, the role of climate change in aggravating the water pollution hazard (due to higher bacterial activity in warmer water), as sought to be estimated by some researchers in other rivers (Delpla, Jung, Baures, Clement, & Thomas, 2009; Rehana & Mujumdar, 2011), becomes insignificant, and the focus has to be on anthropogenic pollutants and improving their regulation. Current policy responses have been in the form of tightening discharge standards, but these efforts are misplaced. Tightening norms in the absence of strong monitoring and enforcement is useless at best, and extreme tightening, such as unrealistic 'zero-discharge' rules for apartment complexes (Kuttuva et al., 2016) or industries, spurs rule evasion, corruption, and distrust of the regulator. These connections between stressors, responses, and salient outcomes for this geography are shown in Figure 9.

Summary

The results of four years of interdisciplinary research across two basins are not easy to capture in one article. We have sought here to highlight some of the key findings in a way that illustrates the insights that a multiple-concerns, multiple-stressors, and multiple-scales framework might provide. Since the processes involved are dynamic and have feedbacks, snapshots and linear narratives are inadequate. Nevertheless, the key message may be summarized as follows.

Instead of asking whether Bengaluru or Coimbatore city water management is resilient to climate change, we asked whether the basins in which these cities (and their urban neighbours) reside are being managed in ways that meet multiple goals (including resilience), in light of multiple pressures that are driving (interlinked) changes in the urban and rural parts. Our research shows that households and agencies in these basins are struggling to meet basic adequacy norms and have largely neglected questions of sustainability, equity and water quality. Rapid population growth, urbanization and industrialization are by far the major stressors. The effects link the urban and rural parts in both directions. Urban centres suck labour and create demand for certain agricultural products (leading to fallowing-*cum*-intensification), while also emitting large quantities of effluents that again provide mixed blessings to downstream farmers. Indiscriminate pumping on the other hand depletes groundwater, which then affects not just farmers themselves but the groundwater supply in small towns in the basin. The effects of future climate change *within* these basins may not be significant. But the anticipated declines in precipitation in the basins from which they import large quantities of water for domestic supply are likely to threaten the already precariously placed systems in both basins.

Piecemeal policies to address stresses, whether by increasing groundwater recharge without regulating extraction, increasing imports while neglecting local rainfall as a source, or tightening of discharge standards while neglecting monitoring and enforcement, will at best be ineffective and in some cases, increase systematic vulnerability or unsustainability. These policies, as crafted, also tend to have unequal benefits or costs. In the above cases, only borewell-owning farmers or urban households with piped supply tend to benefit while apartment dwellers bear the costs.

Concluding remarks

Rapidly urbanizing regions in developing countries pose special challenges for climate–water researchers. Not only are such regions struggling to meet basic adequacy and sustainability norms in highly unequal societies but they are also facing a situation in which 'everything changes' rather than just the climate – populations are growing and migrating, surrounding agriculture is shifting, even the physical landscape is being reshaped rapidly. How then does one understand the climate–water interaction? It may be tempting, given donor pressures and the paucity of good biophysical and socio-economic data in these contexts, to replicate simple models with climate change as the input and city limits as the unit of analysis, and ask how resilience might be enhanced. This may even work when one is examining the impact on (say) flooding, although even here other ongoing processes in the urban space and social differences in the affected population play major roles (Energy and Resources Institute, 2012).

Water use, however, is a complex activity, involving drawing water from near and far into the city, from hinterlands that are also being affected by urbanization and are in turn affecting water resources, accessing water individually or organizing its distribution in various ways to different users, and then disposing the wastewater back into the hinterland, or maybe the next town downstream. Engaging with this complexity is crucial, because the interconnected nature of water and the interaction between multiple stressors can make simple solutions ineffective or sometimes even counter-productive. This is especially true once we understand the multiple concerns that the decision makers try to (or ought to try to) address. Climate resilience per se is not the first thing on their minds, even though there may be some commonalities between this and other objectives. Elucidating the synergies as well as trade-offs across different concerns and the long-term basin-wide versus short-term local impacts of different policies is vital and can be enabled by broad frameworks such as the one adopted for this research. Implementing such a broad framework is not easy, and even our implementation is incomplete in many ways, but framing the research in this manner makes important concerns alive and foregrounds important connections.

Notes

1. See e.g. http://climate-adapt.eea.europa.eu/ and https://www.epa.gov/climate-change-water-sector.
2. The other perhaps being WASH (water, sanitation and health).
3. Technically speaking, watersheds, sub-basins, and basins are progressively larger units, but we use the term 'basin' through the rest of the article while reserving the term 'catchment' for parts of the basin.
4. For instance, Engle and Lemos (2010) examine the relationship between quality of governance and adaptive capacity but without bringing in the resource context.
5. Urbanized areas comprise towns and cities recognized by the state as well as 'census towns' that represent highly urbanized villages.
6. When we refer to the upper Arkavathy basin, we mean the 1447 km^2 catchment at TG Halli reservoir.
7. This shift is probably an interactive effect of rising land values, increasing off-farm job opportunities and water stress, rather than of water stress alone.

8. These findings are based on a village-wise comparison of trends in irrigated land across 1991, 2001 and 2011 census data.
9. Both land use change analysis and farmer survey data confirm that millet cultivation was replaced either by eucalyptus or by fallows.
10. http://indiawater.gov.in/imisreports/nrdwpmain.aspx.

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