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Why is the Arkavathy River drying? A multiple hypothesis approach in a data scarce region

V. Srinivasan[1], **S. Thompson**[2], **K. Madhyastha**[1], **G. Penny**[2], **K. Jeremiah**[1], **and S. Lele**[1]

[1]Ashoka Trust for Research in Ecology and the Environment, Royal Enclave Sriramapura, Jakkur Post, Bangalore, Karnataka, India
[2]Department of Civil and Environmental Engineering, University of California, Berkeley, Berkeley, California, USA

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Correspondence to: V. Srinivasan (veena.srinivasan@atree.org)

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Abstract

The developing world faces unique challenges in achieving water security as it is disproportionately exposed to stressors such as climate change while also undergoing demographic growth, agricultural intensification and industrialization. Investigative approaches are needed that can inform sound policy development and planning to address the water security challenge in the context of data scarcity.

We investigated the “predictions under change” problem in the Thippagondanahalli (TG Halli) catchment of the Arkavathy sub-basin in South India. River inflows into the TG Halli reservoir have declined since the 1970s, and the reservoir is currently operating at only 20 % of its built capacity. The mechanisms responsible for the drying of the river are not understood, resulting in uncoordinated and potentially counter-productive management responses. The objective of this study was to investigate potential explanations of the drying trend and thus obtain predictive insight.

We used a multiple working hypothesis approach to investigate the decline in inflow into TG Halli reservoir. Five hypotheses were tested using data from field surveys and reliable secondary sources: (1) changes in rainfall amount, timing and storm intensity, (2) rising temperatures, (3) increased groundwater extraction, (4) expansion of eucalyptus plantations, and (5) increased fragmentation of the river channel. Our results indicate that proximate anthropogenic drivers of change such as groundwater pumping, expansion of eucalyptus plantations, and to a lesser extent channel fragmentation, are much more likely to have caused the decline in surface flows in the TG Halli catchment than changing climate.

The case study shows that direct human interventions play a significant role in altering the hydrology of watersheds. The multiple working hypotheses approach presents a systematic way to quantify the relative contributions of anthropogenic drivers to hydrologic change. The approach not only yields a meaningful contribution to the policy debate, but also helps prioritize and design future primary research. The paper represents a first step toward “use-inspired” socio-hydrologic science.

1 Introduction

Developing regions face unique challenges in achieving water security (Bakker, 2012) as they are disproportionately exposed to stressors such as climate change while also undergoing demographic growth, agricultural intensification and industrialization. The impact of these stressors falls upon already food and water insecure populations (Grafton et al., 2013; Milly et al., 2002; Sheffield and Wood, 2008; Srinivasan et al., 2013). As these regions engage in a massive project of water resources development, they face planning and policy choices that must reconcile the ability to meet the basic needs of their populations with potential impacts on the well-being of downstream users, ecosystems and/or future generations. Yet, many developing countries lack the scientific basis to articulate these trade-offs. This leads to water policies that at best, address only part of the problem, or at worst, have negative or paradoxical outcomes (Sivapalan et al., 2014).

1.1 Challenges in developing regions

To make sound choices, developing regions urgently need policies underpinned by sound science that illuminates the trade-offs involved. A first step is to be able to make reasonable predictions of future water availability or to explain observed trends in water availability. Making predictions is a non-trivial problem in any context, but in developing regions it is confounded by three issues that are poorly addressed by traditional, developed world hydrologic models: (i) non-stationarity arising from multiple drivers of change, (ii) the sparse availability of environmental data in most regions, and (iii) inadequate original scientific research so that water management and policy decisions are based on the perceptions of multiple stakeholders (e.g. subsistence farmers through to state officials) about hydrological processes rather than careful research.

1.1.1 Multiple drivers of change

Water resources planning and development is predicated on the ability to predict the likely direction and magnitude of changes to future water flow with some degree of certainty (Kumar, 2011). Most current water resources models are based on assumptions of stationarity of flows. The idea that natural systems fluctuate within an unchanging envelope of variability – stationarity – is a foundational concept in water-resource engineering, and has historically driven design of infrastructure and water policy (Milly et al., 2008). Current models are poorly suited to accounting for human interventions and forecasting their effects on water supply. However, human interventions are increasingly recognized as undermining the stationarity assumption – whether directly through modification of land and waterscapes or indirectly through climate change. The amplified role of humans as drivers of the water cycle has been identified as a defining challenge for hydrology in the Anthropocene (Thompson et al., 2013).

Making predictions under change therefore requires accounting for the effects of multiple drivers of change and their interactions on the availability of water (Srinivasan et al., 2012a). In recent years, the potential impact of climate change on the hydrologic cycle has received enormous attention from researchers and decision makers (Stocker and Raible, 2005; Huntington, 2006). However, it is increasingly being recognized that while climate change will aggravate hydrological impacts on river systems, human water extractions are likely to remain the principal contributor to reduced freshwater flows globally (Vörösmarty et al., 2000; Grafton et al., 2013). Yet, human abstractions are particularly difficult to account for in developing regions, where they are decentralized and poorly regulated. In particular, rather than a few large centrally controlled dams, in many developing regions the cumulative actions of millions of small water users could have significant impacts on the watershed hydrology.

1.1.2 Data sparseness

The task of determining cause and effect relationships with respect to hydrologic behavior is further complicated in developing countries with very sparse or recent hydrologic records (Maeda and Torres, 2012). Hydrologic records are often of poor quality and are difficult to access. Despite several decades of global calls to improve data sharing and transparency (Arzberger et al., 2004; Sivapalan et al., 2003; Bonell et al., 2006; Reichman et al., 2011; Dunne, 1978), data scarcity acts as a major impediment to water security and resource sustainability. Data scarcity has motivated concerted research efforts on hydrologic predictions in data-limited environments, such as the Predictions in Ungauged Basins (PUB) effort of IAHS (Wagener et al., 2004; Sivapalan, 2003; Sivapalan et al., 2003). But these efforts have generally not been suitable for predictions in non-stationary hydrology situations. For example, PUB relies on extrapolation of information from gauged to ungauged basins (Blöschl et al., 2013), through statistical "regionalization" techniques (He et al., 2011). This approach is difficult to apply to human-impacted basinsundergoing rapid change (Srinivasan et al., 2012b; Sivapalan et al., 2012). Lack of data not only confounds the formulation of quantitative models, but also clouds the development of conceptual models of "how a water system works", meaning that the suitability of even basic management strategies can be difficult to evaluate.

1.1.3 Pre-existing perceptions

Despite the scarcity of scientific knowledge, decision-making and investments in the water sector are nevertheless occuring in developing regions. In the absence of reliable historical hydrologic records, models relying on conventional data sources often make unrealistic assumptions or oversimplications, which result in questionable predictions. In other cases, researchers make assumptions about the drivers of change based on other study sites. For instance, Gosain et al. (2006) determine the water availability in space and time in several Indian river basins under climate change, without incorporating any man-made structures like dams, diversions, etc. Mujumdar and Ghosh (2008) model flows in the Mahanadi river of eastern India; they consider the decrease in the streamflow in the recent past to be considered as an impact of "climate signal", essentially precluding the possibility of proximate anthropogenic influences like groundwater pumping. Even without addressing anthropogenic signals, model choices can inadvertently exclude potentially important hydrologic processes. For instance, numerous water resources modeling projects in India rely on the SWAT model, which does not allow for coupling of surface water to deep groundwater resources, and thus effectively decouples any effects of groundwater mining from surface water responses (Kelkar et al., 2008; Gosain et al., 2011; Garg et al., 2013). Any scientific research must address the validity of existing perceptions about what drives system behavior. However, most developing world research studies are focused on identifying trends (rather than the underlying causes) (Rekha et al., 2012) or applying existing models or tools (rather than proposing new models) (Sekhar and Pradeep, 2003) in ways that do not always address policy relevant knowledge gaps.

1.2 Use-inspired science in data-scarce regions

Water users and managers require action; but the mismatch between their needs and what conventional water resources models can generate is not sufficient reason for inaction or ad-hoc decisions. There is an urgent need to formulate new approaches to frame and conduct hydrologic investigations in human impacted, data scarce situations. Rapdily changing conditions make extrapolations from other gaged basins (the PUB approach) inapplicable. The conventional response would be to initiate primary data collection in the basins of interest and build new models. However, primary data collection is expensive, human resource intensive and slow; whereas, often the resources available are limited.

How should hydrologists proceed in these circumstances? First, as Thompson et al. (2013) suggest, hydrologists should adopt a "use-inspired science" approach, with the goal of contributing to major policy debates in the water sector while simultaneously pursuing new scientific understanding. This requires identifying the most pressing societal problems and working backwards from them. Second, as Buytaert et al. (2014) suggest, we need to recognize that hydrological knowledge is likely to be dispersed amongst multiple parties: while researchers and managers may hold some expert knowledge, citizens who have lived through change in the basin may also have insights that could be utilized. New approaches to data gathering that explicitly access this knowledge and incorporate it into scientific inquiry are needed. Third, it should be possible to use this multi-level knowledge to identify working hypotheses (Chamberlin, 1965) that might explain the hydrological phenomenon of interest, and then use the sparse data to test and reject some of them so as to narrow down the focus of primary data collection efforts and limit the range of policy interventions.

Responding to these challenges, we propose an approach to use-inspired science in the context of the data-sparse, human-dominated and rapidly changing Arkavathy sub-basin in South India. The proposed method focuses on using the limited available data sources to narrow down possible causal mechanisms for hydrologic change in order to prioritize further collection of primary data. A key contribution is that the multiple working hypotheses are derived from (i) the academic literature/theoretical considerations, (ii) citizen perceptions and (iii) hydrologic process assumptions that underpin current and proposed policies. The approach explicitly addresses the challenge of multiple stressors by evaluating their potential impacts separately. It requires researchers to treat perceptions of the policy makers and lay people regarding the drivers of water problems as providing equally valid, alternative hypotheses for exploration. This is essential both in terms of exploring the broadest possible suite of possible drivers and in terms of building trust in science among stakeholders and policy makers.

Five possible hypotheses that link anthropogenic and climatic changes to the water scarcity in the basin are outlined. Testing of these hypotheses provides an initial framework by which to narrow down future research questions and provide a basis to frame detailed hydrologic investigations.

2 The problem: drying of TG Halli reservoir

2.1 Description of study area

The Arkavathy River is located in Karnataka State in southern India (Fig. 1). The river's catchment overlaps with the western portion of the rapidly growing metropolis of Bengaluru (Bangalore). The region is seasonally monsoonal, receiving approximately 830 mm of precipitation annually. The main stem of the Arkavathy River has its headwaters in the Nandi Hills north of Bengaluru and is joined by its first major tributary, the Kumudavathy River at Thippagondanahalli village. A reservoir called the Chamarajsagar reservoir but commonly referred to as the TG Halli TG Halli reservoir was constructed in 1935 to supply water to Bengaluru. The reservoir is commonly known as TG Halli reservoir has a catchment area of approximately 1447 km^2.

The TG Halli catchment contains an older water supply reservoir called Hesarghattaan as well as an estimated 617 small surface storage structures called "tanks". Tanks are traditional rainwater harvesting systems that were commonly built in South India and Sri Lanka over the last six centuries, and historically captured a proportion of the surface flows, feeding downstream takes via overflows in a "cascade" (Vaidyanathan, 2001; Shah, 2003). The cumulative storage of all these tanks and Hesarghatta reservoir is 143 million cubic metres (MCM); about one and a half times the storage of TG Halli reservoir (ISRO and IN-RIMT, 2000).

Most of the TG Halli catchment is underlain by hard-rock, consisting of gneiss and granite. Highly weathered soils extend from the land surface to about 20 m below grade level (b.g.l.), and form a shallow aquifer in which seasonal perched water tables can develop. From 20–50 m b.g.l. lies a fractured rock zone with considerable jointing and cracking, acting as a deeper aquifer. Groundwater yields decline rapidly beyond 60 m b.g.l., although some joints and fractures have been enlarged by dissolution at depth.

2.2 The problem

From 1937 up to the 1980s, TG Halli reservoir was a major source of water for Bengaluru. However, inflow to the reservoir has steadily declined since the 1970s (Fig. 2a), and today it supplies only 30–40 megalitres per day (MLD), 20–25 % of its design capacity. Average inflows into TG Halli reservoir have decreased from 385 MLD (140 000 ML year^{-1}) pre 1975 to about 65 MLD post 2000 (24 000 ML year^{-1}) – a decline of 320 MLD. Although there is minimal gauging of the Arkavathy River, the reduction in flow can also be observed in the catchment more broadly in changes in the behavior of a network of cascading irrigation tanks. Today, this network of irrigation tanks is also largely dry, indicating that the loss of surface runoff has occurred throughout the catchment. (Lele et al., 2013).

The drying of flows into TG Halli reservoir and tanks in the catchment has clear implications for the water security of the people that live in the catchment – both in terms of the security of surface water supply and because the changing surface water hydrology may be an indicator of the overall sustainabilty of water allocation and use in the basin. Scientific research that can determine the drivers of the drying trend and its implications is critical to sustaining livelihoods and economic growth of the 800 000 people residing in the watershed.

2.3 The policy debate

The identified gaps in scientific knowledge addressed in this article were derived both from the academic literature as well as by following the policy debate. In the following discussion of the different policy positions, we rely meetings with givernment officials as well as written policy documents and reports. Additionally, we held more than sixty "Water Literacy Meetings" between January and October 2014, attended by over 500 farmers throughout TG Halli catchment.

There have been several activist and policy efforts to understand and address the problem of declining flows into TG Halli reservoir. The Bangalore Water Supply and

Sewerage Board (BWSSB), which operates TG Halli reservoir, commissioned a study of the TG Halli catchment. The study (ISRO and IN-RIMT, 2000) identified several possible causes for the decline of inflows into TG Halli including declines in rainfall, groundwater pumping, and obstructions in streams. However, the study did not attempt to quantify the magnitides of the contributions from the different causes or identify those that were more plausible that others. The recommendations also did not prioritize actions other than guidelines to protect water quality.

More recently, the Cauvery Neeravari Nigam Ltd. (CNNL), the state government agency responsible for "rejuvenating" the Arkavathy River conducted its own preliminary study of the river system (CNNL, 2010), which indicated that the primary reason for reduced inflow into TG Halli is a suite of obstructions to flow within the channel network. These obstructions include agricultural cultivation, check dam construction and vegetative growth. CNNL's policy response has been to identify these obstructions and engage bulldozers to remove them and to desilt the channels. However, whether removal of obstructions alone can contribute to increase of inflows into TG Halli remains in question.

A number of citizen's groups and social movements have emerged with the objective of "Rejuvenating the River" or "Saving Bangalore's Lakes" (see http://www.artofliving.org/kumudvathi-river-rejuvenation-project and https://www.facebook.com/arkavathi.rejuvenation). These citizen's groups are primarily focused on reviving lakes as recharge and recreational structures by removal of eucalyptus trees and other channel encroachments, by desilting lake beds and by diverting or treating wastewater flows into lakes. Simultaneously, many village councils have also invested in desilting tanks and constructing check-dams. Through these mechanisms, they hope to recharge the shallow aquifer and ostensibly restore baseflow in the stream.

In response to widespread concerns over groundwater depletion, the Karnataka Groundwater Authority was created by an Act in 2011. The Authority was given the mandate to regulate groundwater in the state but has yet to put in place any rules to regulate pumping. At present, the only action undertaken is a requirement for voluntary registration of all borewells in the state. However, to date, even these rules do not appear to be enforced. This Authority is yet to put in place any effective measures to control groundwater extraction.

In contrast, in a meeting held in April 2013 in Bengaluru between the research team and the heads of all major water related departments and agencies, the head of the water resources department argued that climate change is likely responsible for the drying of the river. This perception is also held by most farmers we interacted with during the course of sixty "Water Literacy Meetings". The vast majority of the Water Literacy Meeting participants believed that rainfall declines were responsible for lower streamflow and tank levels and inter-basin imports were the only solution.

The range of policy responses described above have not emerged as a coordinated plan, but instead reflect both different *stakeholder interests* and *different perceptions* of the hydrologic causes of the declining river flow. However, the responses can contradict each other. For instance, building of check dams will certainly reduce surface flows, whereas the removal of obstructions along the stream is meant to restore stream flow. Part of the reason for uncoordinated and potentially contradictory actions is that the main causes of the inflow reductions to TG Halli reservoir remain unknown.

2.4 The multiple working hypotheses approach

Based on the policy-level and lay perceptions of the drivers of change in the Arkavathy, as well as a consideration of water balance and runoff generation mechanisms, a suite of hydrological hypotheses can be advanced to explain the observed changes in the Arkavathy Basin. This study considers five such hypotheses positing that reduction in river flows in the Arkavathy are driven by:

- Changes in rainfall patterns (including potential declines in total rainfall, changes in the seasonality of rainfall or changes in the characteristics of storms),
- Increasing potential evapotranspiration driven by an overall trend of increasing air temperature in the Basin,

- Declining groundwater levels leading to changes in runoff generation mechanisms and reductions in baseflow,
- Increasing actual evapotranspiration, driven by land use change, and particularly the expansion of plantation forestry, or
- Increased channel storage due to obstructions, check dam construction and other obstacles to flow – the so-called “Million puddle theory.”

2.4.1 Hypothesis 1: declining rainfall

Changes in rainfall as the primary driver of streamflow could certainly induce changes in surface runoff generation. This could obviously arise due a decline in total annual rainfall. Independently of a change in annual rainfall, the climate change literature for this part of Karnataka mentions a possible shift in the monsoon such that the south-west monsoon June-July-August-September (JJAS) season rainfall probably would decline and post-monsoon October-November-December (OND) rainfall might increase.

Such a change in the timing of precipitation could result in a change in rainfall partitioning to runoff, because of a greater fraction being partitioned to evaporation and transpiration. Finally, even if both seasonal and annual rainfall patterns are unchanged, a reduction in the mean storm intensity or depth could result in a failure to trigger specific runoff generation mechanisms. For example, infiltration-excess runoff may become impossible under low-intensity storms, or saturation-excess runoff generation may be avoided if storm depths are reduced. The previous study commissioned by BWSSB found that rainfall in excess of $20\,\mathrm{mm\,day^{-1}}$ is needed to generate significant inflows into TG Halli (ISRO and IN-RIMT, 2000).

2.4.2 Hypothesis 2: increasing potential evaporation due to climate change

Increases in potential evaporaion could result in an increase in actual evaporation, reducing the partitioning of rainfall to river flows. Of the major drivers of potential evaporation (temperature, humidity, solar radiation and wind speed), it is known that temperature has been increasing in south India over the past century, with most stations reporting temperature increases on the order of 1 °C $(100\,\text{years})^{-1}$ (Arora et al., 2005; Hingane et al., 1985). On the other hand, solar radiation trends in the region have been negative, in association with the formation of Atmospheric Brown Clouds (Ramanathan et al., 2005) and wind speed trends in India also appear to also be declining (McVicar et al., 2012). Empirical evidence from evaporation gauges throughout India also suggests that pan evaporation has declined over the twentieth century (Chattopadhyay and Hulme, 1997). Nonetheless, there is a perception amongst some agencies that temperature-driven increases in evaporative demand could have altered rainfall–runoff partitioning in the Arkavathy and contributed to the reduced streamflow.

2.4.3 Hypothesis 3: declining baseflow due to groundwater depletion

Detailed analysis of streamflow sensitivity to groundwater pumping in well-monitored basins indicates that groundwater depletion can reduce the contribution of baseflow to streamflow, reducing overall flows (Lélé et al., 2007; Wang and Cai, 2009; Zeng and Cai, 2014). Our hypothesis is that reduction in groundwater storage induced by pumping also lowers the seasonal water table, resulting in the water table intersecting the river channel less frequently, for shorter periods of time, and ultimately reducing the baseflow contribution to the Arkavathy. The decline in the Arkavathy River flow has occurred concurrently with an expansion of groundwater extraction in the basin and across Karnataka.

A groundwater balance of TG Halli catchment, done using the Central Ground Water Board's Groundwater Estimation Method (CGWB, 1997) suggests that groundwater extraction increased five fold between 1975 and 2005 and that the groundwater balance has become increasingly negative since the mid-1990s (Shilpa, 2014). While groundwater monitoring in the region is minimal, irrigation data clearly indicate that surface water and shallow groundwater (open wells) are no longer used as an irrigation water source in the region (Fig. 3a and b), as reported in the Annual Season Crop Report of the Department of Economics and Statistics (DES, 2012). There is little clarity, however, on the possible connection between groundwater pumping and other hydrologic changes in the basin.

2.4.4 Hypothesis 4: increasing actual evapotranspiration due to expansion of plantations

Numerous studies indicate that where the catchment area occupied by rainfed, deep-rooted, perennial vegetation increases, flow decreases can result (Brown et al., 2005). The area under tree crops in the TG Halli catchment has certainly increased. In particular, eucalyptus cultivation was actively promoted among farmers by the state government under its farm forestry programme in the 1980s (Shiva et al., 1981). Field surveys within TG Halli catchment indicate a significant increase in eucalyptus plantation area in the past 40 years. Several studies have documented that eucalyptus plantations create unsaturated conditions over a deep root zone, and can thus reduce subsurface contributions to streamflow (Calder et al., 1993; Farley et al., 2005).

2.4.5 Hypothesis 5: Million Puddle Theory

The final hypothesis is that the largely illegal expansion of agriculture into the stream channels and/or construction of buildings in the channel, along with construction of check dams and unculverted roads have resulted in the channels in the upper catchment becoming disconnected. In other words, a once connected flowing river has replaced by a “million puddles”. Water in these puddles is hypothesized to evaporate or be transpired by riparian vegetation, or to infiltrate and recharge the local aquifer, rather than flowing into the tanks or the TG Halli reservoir.

3 Methods

3.1 Data sources and quality assurance

To test these hypotheses, we collected available secondary data within and around the Arkavathy Basin. Data were quality checked and triangulated against other sources to maximize the reliability of subsequent analysis and supplemented with field surveys when needed (Table 1).

Precipitation: data from four long-term rainfall gauges within the TG Halli catchment were available for analysis. These gauges are located in Devanahalli, Doddaballapura, Magadi and Nelamangala towns and span the TG Halli catchment (see Fig. 1 for gauge locations). These gauges provide daily rainfall data over 75 years (1934–2010). Although 18 additional rainfall gauges, operated by various government agencies, are available within the catchment, these gauges do not provide continuous data over a sufficient time period to allow trend analysis. As a quality control procedure appropriate to trend analysis, we performed double mass plots, compared the total number of rainy days between the gauges, and excluded years where the total number of rainy days represented a low outlier (indicating a likelihood of missing data). Outlier years were determined to be those where the number of recorded rain days was less than $f_{25} - 1.5(f_{75} - f_{25})$, where f_{75} represents the 75th percentile and f_{25} the 25th percentile of the total number of rain days.

Temperature: temperature data for the period 1901 to 2001 were obtained for one station each in Bangalore Urban and Bangalore Rural districts from the Indian Meterological Department. The data were checked to ensure that there were no missing data and that temperatures were within expected ranges.

Solar radiation: extraterrestrial solar radiation was computed using the equation provided by Spencer (1971), which has an accuracy of 0.01 % (Duffie and Beckman, 2013) and has been implemented in an online radiation calculator (Maurer, 2014) that uses the latitudes of the weather stations.

Surface flows: monthly inflow data for TG Halli reservoir were obtained from Bangalore Water Supply and Sewerage Board (BWSSB) for the period 1937 to 2010. Additionally, daily records of inflows from 1970 onwards were obtained from the local BWSSB offices and digitized. The daily and monthly data were cross-validated and any errors in data entry or addition were corrected.

Historical land use: for estimating changes in the land area under eucalyptus, we used two sources: a land use map provided by Karnataka State Remote Sensing Application Centre (KSRSAC) and Survey of India topographic sheets. The KSRSAC land use map, derived from IRS LISS3 and PAN merged data (pseudo-6m resolution), reported the area under eucalyptus plantations in 2001. For other years, no such maps were available off the shelf. However, because it is well known that there were virtually no private eucalyptus plantations till the early 1980s, we digitized 1 : 50 000 scale topographic maps prepared by the Survey of India during the 1970s (1973 to 1979). These show eucalyptus plantations on public lands.

To estimate the changes in irrigated area, we triangulated data from three sources (Shilpa, 2014). The Annual Season Crop Report (ASCR) published by the Directorate of Economics and Statistics (http://des.kar.nic.in/) provides areas under each crop in each season with irrigation status at the taluka (sub-district) scale. The Census of India's Village Amenities dataset available for the years 1991 and 2001 provides village-wise net cultivated area and the irrigated area within that. The land use map from KSRSAC for 2001 provided a basin-scale estimate of net cultivated area and also of the irrigated horticultural crops. We found that the ASCR figures (pro-rated for the TG Halli catchment area) suggested that only 2 % of the net cultivated area was being irrigated in 2001. Conversely, the Census Village Amenities data and the land use map both indicated that 10–15 % of the net cultivated area in the basin was irrigated in 2001. The latter estimate is more consistent with field investigations, the KSRSAC land use map and discussions with farmers. We therefore derived the land area of each crop by scaling the relative proportions from the ASCR figures so that the total irrigated area matches the Census Village Amenities estimate. Virtually all the irrigation in the catchment is groundwater based.

Trends in groundwater use and levels: groundwater extraction was estimated using groundwater irrigated area and cropping patterns as derived in the previous section and FAO's crop coefficients (Allen et al., 1998). Long-term groundwater level data (> 10 years) existed for only two shallow wells within a 5 km buffer of TG Halli catchment. These wells continue to report water levels of 10–30 m b.g.l.. However, in the course of extensive field visits, no water was visible in any other open well in the region. We concluded that the two monitoring wells that have water at shallow depths are not representative of surrounding conditions. There are no deep borewell piezometers with long-term water level data in the catchment area. To infer potential changes in groundwater levels, we obtained information on the depths of new drinking water wells drilled by district authorities. These indicate that the median borewell depth is now 300 m (Fig. 3c). Comparable data were obtained for wells drilled in the 1970s throughout the TG Halli catchment (P. N. Ballukraya, personal communication, 2014). We also conducted a census of borewells in a 26 km^2 area in TG Halli catchment in the summer of 2014. Data for a total of 472 borewells were recorded. For each borewell, the owner was interviewed to obtain details of the year of construction, use, status, depths of yielding fractures and year of failure (if applicable) (Srinivasan and Ballukraya, 2014). Together, these datasets provide an understanding of how groundwater levels have changed in the last four decades.

Channel obstructions: data on the number of channel obstructions in the TG Halli catchment were available in a report commissioned by Cauvery Neeravari Nigam Limited (CNNL) (CNNL, 2010). A total of 344 obstructive structures were recorded including roads, bridges and unculverted roads) of which 277 were small check dams. The density of check dams estimated from the report is 0.2 km^{-2} of watershed.

To validate these data, we conducted a smaller survey of check dam density covering an area of 26 km^2 in TG Halli catchment. Research team members walked the length of every stream in two small watersheds within the TG Halli catchment taking photographs, measuring and geo-tagging the locations and types of check dams. Over 40 check dams were found in the 26 km^2 area, with ponding of water found behind the check-dams in many locations indicating a check-dam density of 1.35 km^{-2}. Of the structures censused in the two milli-watersheds, about 20 % were leaky or silted. On comparing data for specific villages covered by our stream survey with the CNNL data for those villages, we found that the CNNL report consistenly under-reported the number of check dams. We therefore assumed a check dam density of 1.35 km^{-2} as the more appropriate estimate for the current analysis.

The volumes of the typical obstructions were estimated based on photographs taken during the validation stream surveys, stream profiles made every 1 to 5 m intervals using a Dumpy-Level instrument on a subset of three check-dams.

3.2 Analysis techniques

The goal of the analysis was two-fold: (i) to determine whether the perceived changes in hydrological drivers have occurred, and (ii) whether the observed changes in the drivers could explain the magnitude of the change in flow in the Arkavathy basin (i.e. are the changes large enough to be consistent with the observed 320 MLD reductions in flow).

3.2.1 Hypothesis 1: declining rainfall

Annual rainfall was computed over the water year (June to May). Seasonal rainfall totals were computed in terms of Pre-Monsoon (January-February-March-April-May), Monsoon (June-July-August-September) and Post-Monsoon (October-November-December) rainfall totals. To identify changes in rainfall depths at daily timescales, the number of days per year in which rainfall volumes exceeded 10, 25 and 50 mm were determined for the 1934–2009 period. Trend detection was undertaken for each of the above datasets in two ways: first we determined if a trend was present over the full timeseries. Because the data generally did not conform to the assumptions for least-squares regression we evaluated the trends using a non-parameteric Mann–Kendall test. Second, we evaluated whether a change in the mean values of the meteorological parameters had occurred from the pre-1970 and post-1970 period, taking 1970 as a nominal point after which the Arkavathy River flows obviously declined. Where the data were normally distributed we made these comparisons with *t* tests, otherwise non-parameteric Mann–Whitney-Wilcoxon tests were used.

3.2.2 Hypothesis 2: increasing potential evaporation due to climate change

In the absence of detailed meteorological data in the Arkavathy Basin, we estimated changes in the mean daily potential evaporation rate as a function of temperature using the modified 1985 Hargreaves Evapotranspiration Equation (Hargreaves and Samani, 1985). This procedure is widely used to estimate PET when only limited ground data (temperature) are available. Despite the simplicity of the method, which relies on the diurnal temperature range to provide a surrogate for solar radiation, the Hargreaves Equation has been shown to provide PET estimates within 10 % or better of those derived from lysimeter or Penman–Monteith methods, particularly when results are averaged over 5 day or greater time periods (Hargreaves and Allen, 2003). Here, we averaged all results to the annual timescale. Limitations of the method lie in the fact that the relationship between diurnal temperature range and other drivers of potential evaporation (e.g. net radiation and vapor pressure deficit) may not be stationary over long time periods. In South India, such non-stationarity is likely to be associated with so-called "solar dimming" due to increased upper atmospheric pollution (Chattopadhyay and Hulme, 1997). We therefore anticipate that errors due to non-stationarity are likely to lead to an over-estimation of potential evaporation in this region.

The Hargreaves equation is given by:

$$\mathrm{PET} = 0.0023 \times R_a \times (\mathrm{TC} + 17.8) \times \mathrm{TR}^{0.5}, \tag{1}$$

where R_a is the extraterrestrial solar radiation (mm day^{-1}), TC is the average daily temperature (°C) calculated as $(T_{\mathrm{Max}} + T_{\mathrm{Min}})/2$ and TR is the temperature range (TR =

$T_{\text{Max}} - T_{\text{Min}}$, where T_{Max} is the maximum daily temperature and T_{Min} is the minimum daily temperature). The resulting PET timeseries was analyzed to determine the presence of trends or step-changes in the mean PET.

3.2.3 Hypothesis 3: declining baseflow due to groundwater depletion

In the absence of timeseries data about groundwater levels, we undertook two different analyses to explore whether changes in groundwater were compatible with the observed changes in surface flow. In one analysis we used a baseflow recession technique to benchmark the changes in mobile subsurface water storage that would be needed to account for the decline in annual flows and then estimated how these changes might manifest as a decline in groundwater levels. If this change in storage greatly exceeds observed well declines in the catchment, then the hypothesis that lower groundwater levels have lead to streamflow reductions could be rejected. In a second analysis, we performed a baseflow separation on the daily runoff data from 1970 onwards to determine how the trends in total streamflow were reflected by changes in quickflow and baseflow.

Recession analysis: We follow Brutsaert and Nieber (1977) in positing a nonlinear relationship between storage (S, [ML]) and discharge (Q, [MLD]) of the form:

$$S = aQ^b. \tag{2}$$

A mass balance during periods of flow recession (i.e. when rainfall P is negligible) would be given by:

$$\frac{\mathrm{d}S}{\mathrm{d}t} = -\mathrm{ET} - Q, \tag{3}$$

where recharge to groundwater and inter-basin transfers are assumed negligible and ET represents evapotranspiration. If Eqs. (2) and (3) are coupled and differentiated, then the following expression is obtained relating flow to its rate of change:

$$abQ^{b-1}\frac{\mathrm{d}Q}{\mathrm{d}t} = -\mathrm{ET} - Q, \tag{4}$$

under the assumptions that ET is slow in comparison to flow, so ET → 0, Eqs. (3) and (4) simplify to

$$\frac{\mathrm{d}Q}{\mathrm{d}t} = -\frac{1}{ab}Q^{2-b}, \tag{5}$$

taking the logarithms of the absolute values of this expression, one obtains:

$$\log\left(\frac{\mathrm{d}Q}{\mathrm{d}t}\right) = \log\left(\frac{1}{ab}\right) + (2-b)\log(Q). \tag{6}$$

That is, a plot of the logarithms of the rate of change of the discharge against the logarithms of the actual discharge at any point in time contains sufficient information (in the form of an intercept and slope) to estimate the parameters of the original storage-discharge expression. To do this the lower envelope of the expression must be fitted in order to minimize the effects of neglecting evaporation (Brutsaert and Nieber, 1977).

This methodology was applied to the monthly flow data from the Arkavarthy at TG Halli, focusing on the seasonal recessions between 1937–1970 (i.e. prior to the discernible reductions in river flow). There are two major limitations to using monthly data for this analysis. First, the estimation of the rate of change of the flow is coarse. Second, the contribution of rainfall to runoff events is unlikely to be negligible, even during the seasonal recession. However, since the daily flow data were only available for the post-1970 period, the monthly analysis provides the only opportunity to evaluate the storage–discharge relationship when the river was flowing “normally”. As outlined in the results, the calibrated model had an exponent $b = 1.43$, very close to the theoretical value of 1.5, offering some reassurance that the results are reasonable. Given the parameterized storage-discharge equation, the mobile storage needed in the catchment to produce the observed flows of the Arkavarthy River can be estimated: we estimated the mobile storage, averaged over the catchment area, needed to produce the mean of the peak monthly flows for all years prior to 1970. The resulting storage volume can be normalized by the mobile porosity of the aquifer sediments to generate an estimate of the drop in the surface water table depth required to explain the “missing” flow volume post 1970.

Baseflow trends: we analyzed baseflow trends in both the monthly data from 1937–2008, and in the daily data available for 1970 onward. For the monthly data, we defined a “baseflow month” as a month when there was streamflow, but no rainfall. For the daily data, we undertook a baseflow separation using a digital filter (Nathan and McMahon, 1990) and computed the annual baseflow and the baseflow index for each water year. Again, we analyzed trends in these indices using the methods described previously.

3.2.4 Hypothesis 4: increasing actual evapotranspiration due to expansion of plantations

We calculated the change in eucalyptus plantation area from 1973 to 2001 by comparing the mapped land uses in both years. We made two assumptions about water use by eucalyptus plantations. First, the plantations could not themselves have led to groundwater mining (as has been claimed to have occurred in other parts of Karnataka Calder et al., 1993); shallow groundwater in the region had largely disappeared by the early 1980s and eucalyptus plantations did not really become common till the World Bank aided Social Forestry Program was introduced in the early 1980s. Second, we assumed that eucalyptus transpires at a rate of 830 mm year^{-1} (the annual average rainfall). In effect the trees were perfectly efficient in utilization of rainwater, given that potential evaporation of 1650 mm yr^{-1} greatly exceeds annual rainfall and that many plantations implement practices to limit surface runoff. Third, to estimate the net increase in water utilization associated with expansion of eucalyptus plantations, we assumed the plantations displaced rainfed cereal crops; i.e., coarse cereals such as maize or millet which have a seasonal ET of about 290 mm year^{-1} for a single crop and 540 mm year^{-1} for a double crop (Allen et al., 1998). Based on the estimated change in evapotranspiration due to eucalyptus conversion and the projected area of land conversion, we estimated the total potential change in runoff that could be induced.

Although it is clear the area under eucalyptus plantations has expanded, the impact on stream-flow remains uncertain. Previous studies in the region, have suggested that eucalyptus trees *can* transpire up to 2100 mm year^{-1} (Calder et al., 1993) in other forested parts of Karnataka. Given PET is about 1650 mm year^{-1}, the actual evapotranspiration from Eucalyptus plantations could not exceed PET. Additionally, it is unlikely that the actual ET could exceed rainfall; given the absence of shallow groundwater in the region, the Eucalyptus roots could not be mining groundwater as some earlier studies in Karnataka have claimed (Calder et al., 1993). Unless most of the new eucalyptus plantations are occurring along the streams and preventing connectivity between channel and catchment, the maximum amount of water the eucalyptus plantations can transpire and consequently runoff reduction from eucalyptus plantations should be bounded by annual rainfall.

3.2.5 Hypothesis 5: million puddle theory

We estimated the total storage volume within channel impoundments, based on the observed density of channel obstructions (1.35 km^{-2}) and an estimated range of storage volumes associated with each. Interpolation of the stream profiles allowed us to estimate the maximum storage volumes as ranging between 300 and 500 M^3. We multiplied this storage by the basin area and density of obstructing structures to obtain a peak storage volume for the whole basin.

We then plotted the cumulative density function of the daily inflow events into TG Halli for 15 years from 1976–1990 (the period before check-dams and unculverted roads were constructed for which we had daily inflow records). We took all flow events less than or equal to the peak storage volume and assumed that the entire flow would be impounded. For events that generated inflows greater than the peak storage, the volume impounded was capped by the peak storage the catchment; anything higher would have overflowed. The volumes impounded were summed to estimate the total loss downstream. This calculation is likely to overestimate the total volume of water impounded behind check dams and unculverted roads, since the structures are unlikely to be empty at the beginning of every rain event.

4 Results

Results are presented separately for each of the tested hypotheses.

4.1 Hypothesis 1: declining rainfall

Annual rainfall trends: Fig. 2b shows the area-averaged monthly and annual rainfall over the basin for the years 1934–2010. With an average of 830 mm year^{-1} and SD of 210 mm year^{-1}, the monthly rainfall time series does not show any trend, and no statistically significant trend emerges in the annual rainfall. Similarly, no significant changes are visible by the pre- and post-1970 in mean annual and monthly rainfall totals. The data do exhibit high decadal variability in rainfall, and it is clear that the 1970–1980 period was exceptionally wet. However, there is no evidence that total rainfall volumes have changed in the region.

Seasonal rainfall trends: with the exception of Devanahally, we did not identify any statistically significant shifts in the timing of the rainfall over the last 80 years. The observed trend in Devanahally was for an increase in JJAS rainfall, contrary to the predictions of climate models, and an increase that is inconsistent with a decline in flow production at other times of the year.

Change in rainfall intensity: no statistically significant trends in daily rainfall volumes exceeding threshold values of 10, 25 or 50 mm could be identified at the 95th percentile level at any of the four gauges. Although we cannot exclude the possibility of changes in sub-daily rainfall intensities, analysis of rainfall data in the TG Halli catchment area shows no meaningful historical trends in precipitation volumes, timing or storm characteristics. We find no evidence that rainfall-driven changes could be responsible for the change in flow in the TG Halli catchment.

4.2 Hypothesis 2: increasing ET due to increase in temperature

Monthly maximum and minimum temperatures (T_{max}, and T_{min}) showed a small but statistically significant increase in minimum temperature, from the period 1901 to 2001, but no change in maximum temperature. The rise in temperature of about 0.6 to 1 °C (100 years)$^{-1}$ was within the range predicted by other studies (Kothawale and Rupa Kumar, 2005; Arora et al., 2005). The estimated PET from the Hargreaves equation averaged to the annual scale is shown in Fig. 2c. As indicated in the figure, there is no statistically significant trend in PET within the basin. We conclude that there is no evidence to support the hypothesis that increasing temperature is increasing potential evaporation and leading to a decline in streamflow.

4.3 Hypothesis 3: declining baseflow due to groundwater depletion

Recession analysis: the fitted storage discharge relationship for the pre-1970 period was:

$$S = 595Q^{0.57} \tag{7}$$

Where S and Q are given in units of ML per month, consistent with the monthly timestep. The slope of the lower envelope was 1.43, very close to the 1.5 slope predicted by the nonlinear Dupuit-Boussinesq theory and found by Brutsaert and Nieber (1977) in their original analysis. We estimated S for the mean of the peak monthly flows from the years prior to 1970 (65 000 ML) using Eq. (7), and normalized this total stored volume by the catchment area of 1453 km^2. This leads to a prediction that on average, mobile storage would need to decline by 0.24 m across the catchment to reduce the peak monthly flow rates to zero.

While the location of this storage decline (e.g. from the unconfined or from the fractured rock aquifer) is unknown, we can use porosity estimates of 20 % for the unconfined sediments, and 1 % for the fractured rock to estimate the order of magnitude of the groundwater declines that could effectively remove 0.24 m of mobile water from being in connection with the surface channels – namely a decline on the order of 1.25 m in the surficial aquifer, or a decline of 25 m in the fractured rock aquifer. The complete loss of storage in the surficial aquifer (surface 20 m) suggests that a 1.25 m loss of storage in this region is entirely plausible. While declines in groundwater level are not as well known, most recent well construction is now to depths of 400 m b.g.l. (see Fig. 3), suggesting that declines in the water table on the order of 10 s of meters are plausible in this zone

As can be seen from Fig. 2d, baseflow started declining after the early 1980s but there was not a single month after 1992 when there was baseflow into the reservoir. The baseflow index, which was computed from daily data and indicates the share of baseflow in the total annual inflow, also declined consistently from 1970–2010. The loss of storage observed in the Arkavarthy Basin is of the correct order of magnitude to explain the contemporary absence of surface flow, and that the hypothesis that loss of groundwater storage in the surface aquifer should be retained as a hypothesis for further investigation.

4.4 Hypothesis 4: increasing actual evapotranspiration due to expansion of plantations

The area under eucalyptus plantations in 1973, as indicated by Survey of India toposheets was only 11 km^2, all of it within the boundaries of state Reserve Forests. By 2001, the area under eucalyptus plantaions had increased to 104 km^2 (Fig. 4).

Conversion of 93 km^2 of rainfed crops to eucalyptus plantations would thus translate to a loss of runoff of 75–135 MLD by the year 2001. This figure is significant compared to the observed runoff decline of about 320 MLD, suggesting that expansion of eucalyptus could be a significant contributor to the observed runoff declines.

4.5 Hypothesis 5: million puddlel theory

Based on the assumptions about check-dam and encroachment water storage and the estimated 1.35 obstructions km^{-2} outlined above, the total loss in runoff at the basin scale attributable to channel encroachment is on the order of 27 MLD. We note that because the analysis does not include other sources of surface water storage (e.g. within-farm impoundments or impoundments in housing plots), this figure may remain an under-estimate. Nonetheless, it suggests that while the million puddle theory could have contributed to a fraction of the loss in runoff, it cannot account for the entire loss of inflow into TG Halli.

5 Discussion

Analysis of the secondary data suggests that rainfall and temperature cannot account for any significant fraction of the loss of inflows into TG Halli reservoir. The million puddle theory can explain only a fraction of the decline, while the hypotheses relating to groundwater decline and expansion of eucalyptus plantations are the most plausible. The results show that the primary causes of drying of the Arkavathy River flows in the TG Halli catchment – groundwater extraction, eucalyptus plantation expansions and increased obstructions along the stream course – are anthropogenic in origin. Although in the future, climate change could play a critical role in further exacerbating water stress, climate stressors will only add to existing anthropogenic stresses. Importantly, policy approaches currently under consideration do not reflect the major underlying causes of the drying of the Arkavathy River, and in some cases (check dam construction) are clearly counter-productive.

The analysis presented here is preliminary. Further work is needed to understand the hydrological functioning of the catchment, including the contemporary and historical flow generation pathways and their changes. There are however suggestive coincidences of timing that suggest a potential working hypothesis for the flow generation mechanisms.

Expansion of electricity and installation of wells began to increase in the 1960s, prior to any drying trend being evident in the Arkavathy – although this period also coincided with a period of relatively high rainfall and streamflow. Flow declines began to emerge in the 1970s, with baseflow indices and numbers of "baseflow months" plummetting in the early 1990s, approximately at the same time that open wells went dry and deeper borewells become more prevalent (based on farmer narratives) (Fig. 3a and b). During this period, the baseflow index declined, suggesting that less and less of the streamflow entering TG Halli reservoir was associated with groundwater inputs. These trends are highly reminiscent of those projected by models of the Republican River Basin (Zeng and Cai, 2014) as a function of increasing groundwater extraction – reduced baseflow and an increasingly erratic quickflow response.

Inflows declined further after 1992, suggesting that additional mechanisms must be considered beyond the decline in baseflow. Possible additional mechanisms include the conversion of the Arkavathy River into a "losing" river, which provides a source of recharge to the local aquifers, the continued expansion of eucalyptus plantations and increasing implementation of management techniques that prevent surface runoff from leaving farm fields, and increasing obstruction of the stream channels. Based on these observations, further research targeting runoff generation mechanisms, establishing the pathways for surface–groundwater connections, evaluating the effect of land use on water balance and estimating groundwater extraction rates has now been initiated in the catchment (see www.atree.org/accuwa).

From a policy perspective, the lack of co-ordination between agencies and different perceptions of the drivers of hydrologic change result in contradictory policy approaches. For instance, even as the Cauvery Neeravari Nigam Ltd. (CNNL) is removing encroachments and blockages under the "Rejuvenation of Arkavathy River" Program, new check dams continue to be authorized the under the Mahatma Gandhi Rural Employment Guarantee Scheme (MNREGA). Funds are disbursed by agencies working at different scales; CNNL, an independent state-level agency pays contractors directly while MNREGA disburses funds through the Gram Panchayats (village councils). Different views of the hydrologic causes of the drying of the Arkavathy result in conflicting implementation approaches. The agencies involved have not made any concerted and substantive efforts to scientifically test and reconcile these views, resulting in significant wasted investment.

6 Conclusions

The TG Halli catchment case study shows that humans can play a significant role in altering the hydrology of watersheds (Wang and Cai, 2009; Grafton et al., 2013) in a variety of ways. Indeed, the results presented in this paper suggest that immediate drivers like groundwater pumping and land use change, rather than just climate change, are the most plausible causes of the drying of the Arkavathy River.

The article strengthens the case for sociohydrology as a use-inspired science of water and society that explicitly treats watersheds a complex systems and includes human feedbacks on hydrologic processes (Sivapalan et al., 2012). In particular, the paper make three contributions to this nascent field.

First, the study highlights the importance of accounting for multiple anthropogenic drivers of change. There has been a tendency within the hydrology community to understate the role of humans in altering hydrology beyond large structures like dams. The dominant conceptualisation remains that of the water system as being external to and separate from society. The case study of the Arkavathy shows why such an approach is flawed.

Second, traditional hydrology does not offer much guidance on how human feedbacks outght to be addressed, particularly in a developing world region where data are scarce and unreliable. By adopting a broad, multiple-working hypothesis approach, we illustrate how even limited data sources can be marshalled to address critical knowledge gaps. The study offers a basis to focus primary investigations.

Third, the hypotheses themselves are derived, not just from the academic literature, but by referencing the policy debate and through stakeholder interactions. This ensures the legitimacy and usefullness of the scientific research. Interestingly, the case study illustrates that the reluctance to acknowledge human feedbacks is not limited to hydrologists, since the human agents living in the catchment, often do not fully perceive or acknowledge their potential role in altering the hydrology.

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Table 1. Details of various data sets used.

Parameter	Type of data	Source of data
Precipitation	Daily rainfall data over 75 years for four long-term rainfall gages	Indian Meterological Department
Temperature	Monthly Max. and Min temperature	Indian Meterological Department
Surface flow	Daily and Monthly Inflows into TG Halli reservoir	Bangalore Water Supply and Sewerage Board
1973 Land use	Topographical sheet	Survey of India
2001 Land use	Land use map	Karnataka State Remote Sensing Applications Centre
Groundwater levels	Well Census	ATREE hydrology team field survey
Groundwater extraction	Irrigated Area	Annual Season Crop Report
	Irrigated Area	Census of India
Channel obstructions	Number of check dams and unculverted roads	Primary Survey by Zoomin Tech.
	Number of check dams	ATREE hydrology team field survey

Table 2. Number and type of stream encroachments in each section TG Halli catchment Source: Zoomin Tech Report to CNNL (2011).

Type	Hesarghatta	Kumudavathy	Arkavathy
Check dam	70	65	142
Bridge	4	23	31
Road	0	2	7

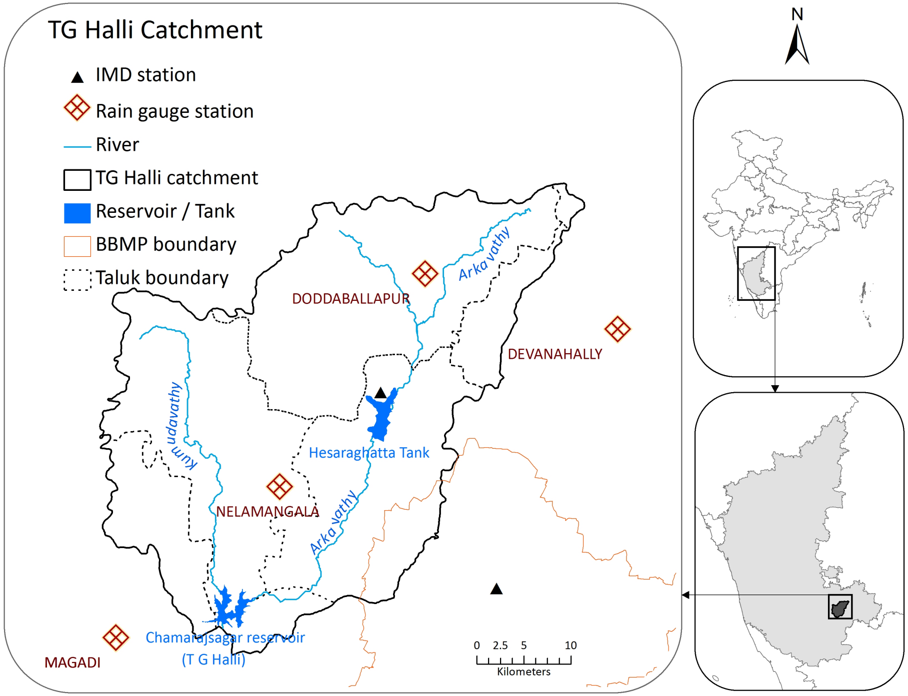

Figure 1. The TG Halli catchment with major features. BBMP is the Greater Bangalore Municipal Corporation Boundary. (Data source: survey of India toposheets at 1 : 50 000 scale; ASTER DEM imagery, maps prepared at the ATREE EcoInformatics Lab.)

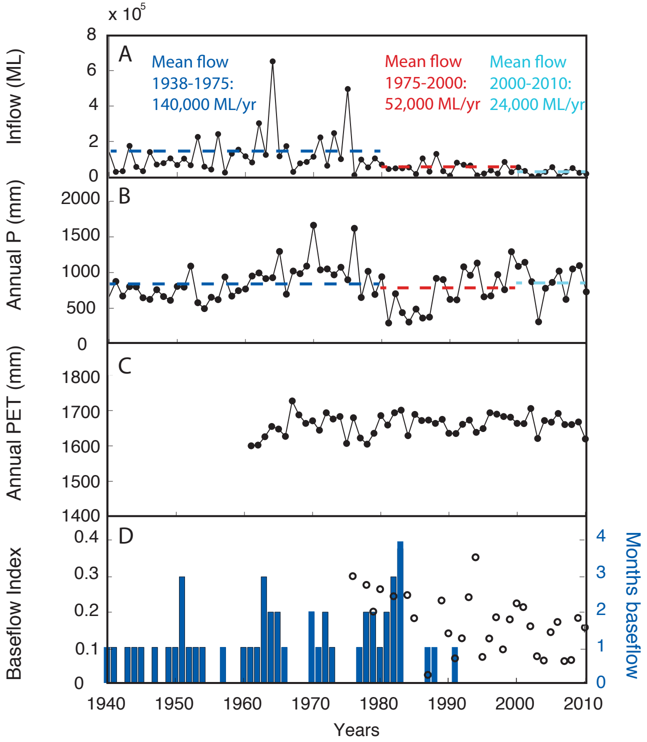

Figure 2. Changes in hydrology and hydrometeorology of the Arkavathy Basin, 1970–2010. **(a)** Annual inflows into the TG Halli reservoir. The 1938–1975 and 1975–2010 mean annual inflows are indicated and illustrate the decline in inflow that has occurred in recent decades. **(b)** Areally averaged annual rainfall over the 7 Taluk (local government areas) comprising the TG Halli catchment. **(c)** Potential Evapotranspiration as estimated from the Hargreaves Equation for the TG Halli catchment. **(d)** Two estimates of baseflow contribution to TG Halli inflows: the number of months year^{-1} when 100 % of flow was derived from baseflow (bars) and the baseflow index computed from daily inflow data (dots).

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀▮
▶▮
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

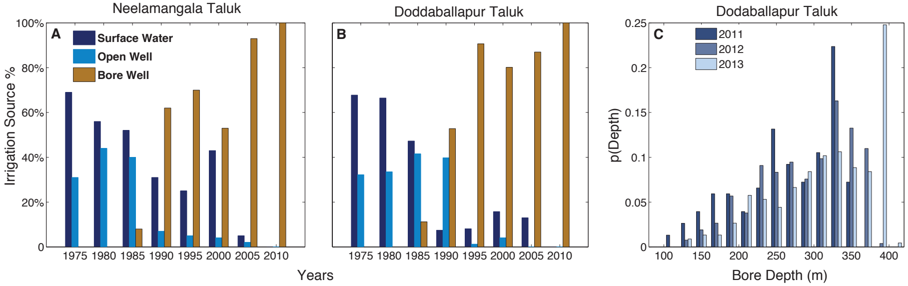

Figure 3. Water use in TG Halli Catchment. **(a, b)** show sources of irrigation water used over time in two Taluks (Local Government areas), indicating the reduction in surface and shallow well use and their replacement by deep bore wells over time. Data Source: Department of Economics and Statistics, Karnataka. **(c)** shows the depths of Gram Panchayat (village council) wells drilled in Doddaballapur Taluk in TG Halli catchment from 2011–2013, indicating that groundwater is now accessed at great depth, and may be continuing to fall in this Taluk (Data source: Doddaballapur Taluk Office, Karnataka).

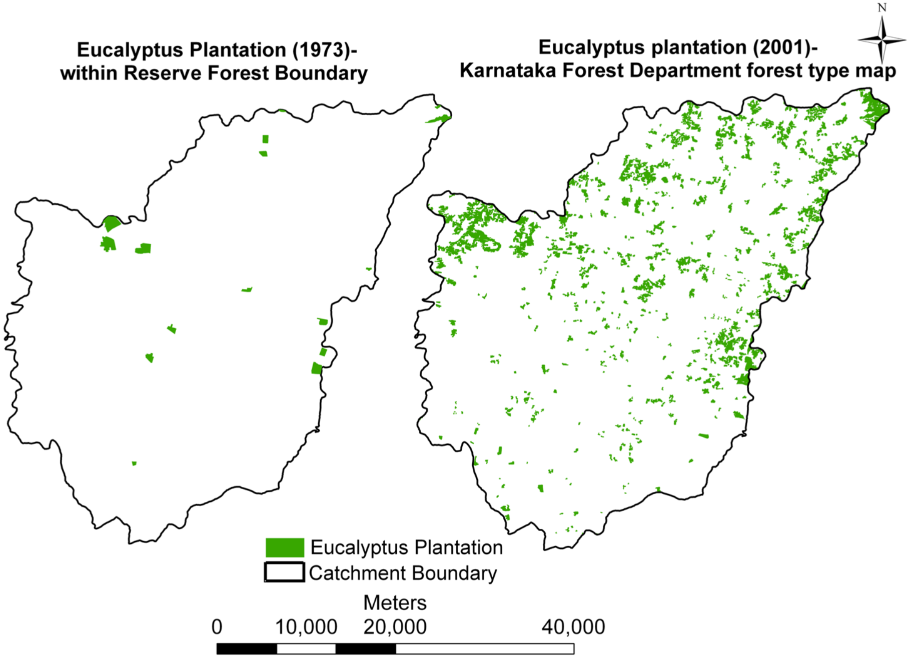

Figure 4. Change in Eucalyptus Area in Arkavathy basin between 1973 and 2001.