A process-based approach to attribution of historical streamflow
decline in a data-scarce and human-dominated watershed

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Abstract
Human activities have resulted in rapid hydrological change around the world, in many cases producing shifts in the dominant hydrological processes, confounding predictions, and complicating effective management and planning. Identifying and characterizing such changes in hydrological processes is therefore a globally relevant problem, one that is particularly challenging in sparsely monitored environments. We develop a novel, process-based approach for attribution of hydrological change in such scenarios, and apply the approach to the TG Halli watershed outside Bangalore, India, where streamflow has declined considerably over the last 50 years. The approach consists of (1) employing a range of field instrumentation and experiments to identify contemporary streamflow generation mechanisms, (2) using these observations to constrain our understanding and generate hypotheses pertaining to historical changes, and (3) evaluating these hypotheses with a range of evidence including proxies for historical hydrological processes. The body of evidence in the TG Halli watershed indicates the historical presence and subsequent loss of a shallow groundwater table that previously discharged to the stream, meaning that groundwater depletion is the most likely driver of streamflow decline. These findings present a viable path towards improved predictions of future water resources and sustainable water management within the watershed. Our process-based approach to attribution has the potential to improve understanding of human-driven hydrologic change in regions with poor monitoring of hydrologic systems.

Keywords
hydrological change, nonstationary hydrology, attribution, groundwater depletion, data scarcity, streamflow generation

Disciplines
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A process-based approach to attribution of historical streamflow decline in a data-scarce and human-dominated watershed

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Abstract

Human activities have resulted in rapid hydrological change around the world, in many cases producing shifts in the dominant hydrological processes, confounding predictions, and complicating effective management and planning. Identifying and characterizing such changes in hydrological processes is therefore a globally relevant problem, one that is particularly challenging in sparsely monitored environments. We develop a novel, process-based approach for attribution of hydrological change in such scenarios, and apply the approach to the TG Halli watershed outside Bangalore, India, where streamflow has declined considerably over the last 50 years. The approach consists of (1) employing a range of field instrumentation and experiments to identify contemporary streamflow generation mechanisms, (2) using these observations to constrain our understanding and generate hypotheses pertaining to historical changes, and (3) evaluating these hypotheses with a range of evidence including proxies for historical hydrological processes. The body of evidence in the TG Halli watershed indicates the historical presence and subsequent loss of a shallow groundwater table that previously discharged to the stream, meaning that groundwater depletion is the most likely driver of streamflow decline. These findings present a viable path towards improved predictions of future water resources and sustainable water management within the watershed. Our process-based approach to attribution has the potential to improve understanding of human-driven hydrologic change in regions with poor monitoring of hydrologic systems.

Keywords: hydrological change, nonstationary hydrology, attribution, groundwater depletion, data-scarcity, streamflow generation

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1 Introduction

The extent of human intervention in the hydrologic cycle is unprecedented (Ceola et al., 2019; Vorösmarty et al., 2004, 2013), undermining traditional assumptions of stationarity in hydrology (Ehret et al., 2014; Milly et al., 2008; Peel and Blöschl, 2011). Such changes have forced water resources engineers to make predictions and design sustainable management strategies in a nonstationary water cycle continually evolving in response to human drivers (Gleeson et al., 2019; Montanari et al., 2013; Pande and Sivapalan, 2016; Sivapalan et al., 2012). Effective prediction and management of water systems depend on credible understanding of hydrologic trajectories (Sivapalan and Blöschl, 2015; Srinivasan et al., 2016), which must explicitly include ways to account for nonstationarity (Magilligan and Nislow, 2005; Thompson et al., 2013; Walvoord and Striegl, 2007; Wine and Davison, 2019; Yang et al., 2002).

This means that in non-stationary systems, managers need to know what drivers, anthropogenic or environmental, are causing changes in the behavior of the water system: a problem of attribution. Attribution in hydrology commonly follows a process of predictive inference, whereby models are used to infer causal relationships (Ferraro et al., 2019). In this approach, plausible mechanisms of change are incorporated into hydrologic models (Beven, 2012), with the resulting models forming hypotheses about system behavior (Beven, 2019), which can be rejected where they fail to capture relevant drivers of change (Beven and Lane, 2019). Predictive inference rests on the assumption that models which reasonably reproduce observed hydrological behavior sufficiently represent the underlying hydrological processes (Ferraro et al., 2019). A difficulty with this approach is the risk of equifinality between model outcomes, limiting a modeler’s ability to reject hypotheses with confidence (Beven, 2006; Savenije, 2009). Other approaches to attribution include hypothesis testing within econometric frameworks that capitalize on natural experiments (Müller and Levy, 2019), sometimes in large-sample settings (Gupta et al., 2014; Levy et al., 2018), or in paired catchment studies that compare treatment and control outcomes at field sites (Brown et al., 2005). These approaches are powerful tools useful at regional scales, where the relevant variables are measured, and where other experimental design challenges such as endogeneity and reverse causality can be controlled for (Müller and Levy, 2019).

It is not clear that these tools can cope with either small-scale (e.g. individual catchment-level) attribution problems, nor with the particular challenge of highly nonlinear changes in catchment behavior that arise following anthropogenic shifts in hydrological regime. A hydrologic regime shift arises when the internal state of a hydrological system changes, meaning that the relationship between exogenous drivers (e.g. precipitation and potential evaporation) and measured hydrological outputs (typically flow variables) is fundamentally altered. Such shifts produce acute consequences for ecological and social systems (Foufoula-Georgiou et al., 2015), but evade attribution because of the complex processes underlying the shift (Savenije, 2009). Attributing hydrological changes in systems that experience regime shifts, therefore, remains a outstanding task for decision making around water resource management (Gober et al., 2017). It is a particularly challenging task in sparsely monitored watersheds where observations that could support inference of a regime shift may not exist. In these watersheds, urgent need for evidence-based water management demands methodological
approaches that can be applied to individual watersheds, in the absence of rich historical data records, and that can yield a reliable attribution of the history of hydrological change, including regime shifts.

In this paper, we develop a novel, empirical approach to attributing historical hydrologic change by building a scientific narrative of contemporary hydrologic processes which we use to constrain our understanding of historical change. We focus on the strongly nonstationary and human-impacted TG Halli watershed, outside of Bangalore, India (Penny, 2017). Streamflow in the watershed has declined dramatically since the 1970s, reducing inflow to the TG Halli reservoir, which historically served as the primary water source for Bangalore (Srinivasan et al., 2015). The period of streamflow decline coincided with a suite of other hydrologic changes in the watershed, including reduced inflow to the widespread “cascading tank” (Van Meter et al., 2014) rainwater harvesting system in the watershed (Penny et al., 2018), dramatic reductions in groundwater level (Ballukraya and Srinivasan, 2019; Lele et al., 2013a), and abandonment of shallow surface wells and bores. Declines were also coincident with considerable changes in land and water management including expansion of groundwater irrigated agriculture and eucalyptus plantations, rapid urbanization around Bangalore, and widespread watershed management efforts (Lele et al., 2013a; Penny et al., 2018). Previous research determined that the declines in flow cannot be attributed to climatic changes (Srinivasan et al., 2015), suggesting that it is the changes in land and water management that produced the changes in hydrology. We assess hydrological change in the TG Halli watershed by invoking the method of multiple hypotheses (Chamberlin, 1965). This method involves identifying several plausible hypotheses and seeking evidence to falsify each one — in this case, ruling out specific historical mechanisms of hydrologic change.

Investigation into streamflow decline in the TG Halli is particularly important because associations between hydrologic change and human-induced land and water management changes remain unclear. Further, in the TG Halli, management responses to water scarcity from local and state agencies have been largely uncoordinated and at times contradictory (Srinivasan et al., 2015), despite the many symptoms of water crisis in the watershed including escalating costs and reduced predictability of groundwater supplies, rapid land conversion, and near complete loss of surface water resources. In addition to developing a research strategy to understand hydrologic change in human-modified watersheds characterized by lack of hydrologic observations, this research will directly support agriculture and water management in the TG Halli watershed. Prior research efforts in the TG Halli watershed have produced valuable insights regarding potential drivers and hydrologic outcomes of human activity within the watershed (Penny et al., 2018; Srinivasan et al., 2015), but there remains a need to demonstrate the causal processes linking human drivers to the observed drying of the river.

Contemporary hydrological science is confronted with the need to understand non-stationarity and complex interdependencies between physical, biological and human systems, especially in heavily managed watersheds (Blöschl et al., 2019; Montanari et al., 2013). These challenges are sometimes at odds with increasing reliance of researchers on hydrological models to evaluate hypotheses (Pfister and Kirchner, 2017). For example, models often rely on calibration to correct for erroneous or omitted representation of processes, and non-stationarity in these processes can undermine the quality of calibrated values (Schaeffli et al., 2011). Such concerns have prompted calls for revitalizing field-based hydrological research (Burt and McDonnell,
Although field research has a long history of being used to investigate hydrological processes, the use of field observations to identify and characterize hydrological change has been largely confined to long-term observational efforts, such as those occurring in experimental watersheds, LTERs, and water supply catchments (Bhowmik, 1987; Keefer et al., 2008, e.g., see ). These environments are relatively unmodified by direct human activity and unusual in terms of the quantity, longevity, and quality of hydrological data available. In contrast, the challenges posed by nonstationarity are likely to be greatest in heavily modified watersheds and to have the most significant consequences for human populations in the least economically resilient regions, which also tend to be the least monitored (Sene and Farquharson, 1998). We demonstrate here that short-term field investigations not only provide a way to understand hydrological processes but can also be used as a diagnostic tool for attributing hydrologic changes in a sparsely monitored, highly modified, and rapidly changing watershed.

To this end, we develop a novel, threefold approach for process-based attribution of hydrological change. (1) First, we develop an understanding of contemporary hydrological processes through field experimentation and observational research aimed at demonstrating the occurrence or absence of streamflow generation mechanisms including (a) infiltration excess runoff, (b) saturation excess runoff, and (c) groundwater discharge to the stream channel under contemporary conditions (Figure 1). (2) These findings are then used to constrain a conceptual model of past system behavior and generate a range of process-relevant hypotheses. (3) Finally, these hypotheses are tested against historical information about watershed functions derived from a broad range of evidence, including historical flow records, farmer surveys (Srinivasan et al., 2015), and the features of historical infrastructure designed and constructed prior to the observed hydrologic changes.

We describe our field methodology and findings in the Methods (Section 2) and Results (Section 3), respectively. The novelty of this study rests in the synthesis of these findings, which we describe in the Discussion: we use the findings from our field studies to understand contemporary hydrological processes (Section 4.1), generate process-relevant hypotheses of change (Section 4.2), and evaluate these hypotheses with a range of evidence (Section 4.3).

2 Methods

2.1 Study sites

The TG Halli watershed is located in Karnataka, India, spanning 1,447 km² to the northwest of Bangalore (Figure 2). The watershed contains two main river channels, which drain into the TG Halli reservoir at the watershed outlet. The climate is tropical semi-arid and the watershed receives approximately 700 mm of annual rainfall, which arrives mostly during the monsoon season between June and November. Temperatures are fairly consistent throughout the year around 25 °C, peaking prior to the monsoon season in June. The watershed topography is mostly flat or very gently sloping, with 86% percent of the watershed consisting of slopes less than 3% (ISRO and IN-RIMT, 2000).

The eastern portion of the watershed contains the western periphery of the Bangalore urban area, which
was historically supplied with drinking water by the TG Halli reservoir. Urban areas intruded agricultural land at a rate of 2.3 km² per year over the study period, and 3.8 km² per year since 2002, but the majority of urbanization around Bangalore occurred downstream of TG Halli and urban area was still a relatively small (7%) portion of the watershed (Lele and Sowmyashree M.V., 2016). Outside of Bangalore, the landscape is dominated by agriculture, including rainfed and irrigated crops in addition to tree plantations, which primarily consist of eucalyptus plantations (Figure 2). In 2014, agricultural crops and eucalyptus plantations covered 37% and 19% of the watershed, respectively (Table 1 Lele and Sowmyashree M.V., 2016). Remaining land cover included fallow land (18%), perennial irrigated plantations (11%), built-up land (7%), water (5%) and other categories (3%).

Table 1: Land use as a percent of total area in TG Halli and study watersheds.

<table>
<thead>
<tr>
<th>Land use</th>
<th>TG Halli</th>
<th>Doddatumkur</th>
<th>SM Golahalli</th>
<th>Thirumagondonahalli</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crops</td>
<td>36.6</td>
<td>51.0</td>
<td>52.0</td>
<td>38.0</td>
</tr>
<tr>
<td>Eucalyptus</td>
<td>18.7</td>
<td>20.0</td>
<td>24.0</td>
<td>27.0</td>
</tr>
<tr>
<td>Fallow</td>
<td>18.5</td>
<td>8.0</td>
<td>12.0</td>
<td>21.0</td>
</tr>
<tr>
<td>Irrig. plantations</td>
<td>11.7</td>
<td>12.0</td>
<td>8.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Other</td>
<td>14.5</td>
<td>9.0</td>
<td>4.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Total area (km²)</td>
<td>1447</td>
<td>18.9</td>
<td>0.8</td>
<td>7.3</td>
</tr>
</tbody>
</table>

1 Excludes SM Golahalli subwatershed.

The river network in the TG Halli watershed is fragmented by a series of surface water harvesting structures known as tanks (Vaidyanathan et al., 2001), which consist of a shallow bund wall built across natural river valleys (Van Meter et al., 2016). Most of the tanks were constructed centuries ago and formed a “cascading tank system,” in which tanks would fill and overflow downstream, forming a connected network. As surface water flows in the watershed have declined, tanks in the watershed now rarely overflow. Irrigation, historically supplied by stored water in the tanks, is now primarily sourced from groundwater (Lele et al., 2013a). Extensive groundwater pumping has resulted in water table depletion on the order of 100 m (Srinivasan et al., 2015). Numerous check dams have been constructed in headwater channels to increase groundwater recharge. The check dams function like weirs, with the impounded water being lost to evaporation or recharging local groundwater. Farmers have adapted to reduced groundwater availability by converting their fields to eucalyptus plantations, which require no irrigation and little maintenance. Other farmers have abandoned their crops and left their land fallow.

Field studies were conducted in 2014–2016 and focused on three subwatersheds of the TG Halli watershed, each defined by its receiving tank: Doddatumkur, SM Golahalli, and Thirumagondonahalli (Figure 2d,e). The land use characteristics of these study watersheds are representative of much of the TG Halli watershed, with a mix of rainfed crops, groundwater irrigated crops, eucalyptus plantations, perennial irrigated plantations, and fallow land (Table 1). We selected study watersheds with contrasting dominant land uses: more groundwater irrigation in the Golahalli and Doddatumkur subwatersheds, and more eucalyptus plan-
tations in the Thirumagondonahalli watershed. These two land use categories were used to select the study watersheds because they have been suggested as potential drivers of streamflow decline (Srinivasan et al., 2015).

2.2 Field instrumentation

2.2.1 Water level and tank inflow

Streamflow estimates were generated from measurements of tank water level and tank bathymetry. Each of the three study tanks (SM Golahalli, Doddatumkur, and Thirumagondonahalli) was instrumented with an Odyssey Capacitance Water Level Logger (Dataflow Systems Inc, 2017), which was manually calibrated to water levels in the tank.

Remotely piloted vehicles were used to map the bathymetry of the tanks, merging maps generated from aerial vehicles for dry areas and surface vehicles for wetted parts of the tanks (Young et al., 2017). The combined bathymetric surveys and water level measurements were used to calculate tank water storage from the water level timeseries. Streamflow records were then generated from tank storage timeseries for each of the watersheds for the 2014–2016 monsoon seasons. This was possible because the tanks did not overflow.

The capacitance sensors were sensitive to temperature, leading to daily fluctuations in the apparent water level and overestimates of the water level during inflow events as cold water mixed in the tank. As temperature levels equilibrated after the storm, the tank water levels appeared to drop. Because these temperature effects were challenging to separate from any actual changes in tank water storage, sub-daily analyses relied primarily on estimates of the timing of peak inflow, used in Section 2.4, which was unaffected by the temperature fluctuations.

2.2.2 Weather stations

Precipitation measurements were obtained from tipping bucket rain gauges (Davis Instruments Rain Collector 7852) installed near the SM Golahalli tank and the Hadonahalli village (see Figure 2) from April 2014 through November 2016. Data from the rain gauges were compared to 15-minute precipitation data from 2011 through 2016 from the Karnataka State Natural Disaster Management Center (KSNDMC, data collected with VARSHA-TRG-GPRS tipping bucket rain gauges from Spatika) as a quality assurance and control procedure. Rain events reported in our gauges were flagged if they exceeded daily precipitation at the nearest KSNDMC rain gauge by more than 20 mm, or if recorded rainfall intensities exceeded 15 cm per hour. The flagged data were manually removed from the record if rainfall was inconsistent with streamflow or soil moisture records (e.g., when heavy rainfall was not accompanied by any response in streamflow or soil moisture). Overall, 17 events were removed from the Hadonahalli precipitation record and 5 events were removed from the SM Golahalli record. Many of these events occurred in the dry season, likely indicating a sensor malfunction.
2.2.3 Soil moisture

Soil moisture sensors were installed at four agriculture sites with different cropping and irrigation technologies, including a grape site with drip irrigation, a cabbage site with flood irrigation, a rainfed site, and a eucalyptus plantation. At the rainfed, grape, and cabbage sites, four Decagon EC-5 Soil Moisture sensors (Decagon Devices, 2016) were installed, two each at depths of 30 cm and 1 m. The eucalyptus site was instrumented with Decagon EC-5 sensors at depths of 30 cm, 1 m, 2 m, and 3 m, and Campbell Scientific CS650 Water Content Reflectometers (Campbell Scientific, 2014) at depths of 1 m, 3 m, and 3.7 m. Soil moisture sensors at the grape, rainfed and eucalyptus sites reported from the beginning of the 2014 monsoon season through 2016. The cabbage site sensor failed multiple times resulting in large data gaps from October 2014 through March 2015 and ceased collecting useful data in July 2016. The eucalyptus site sensors were potentially influenced by ponded water in a nearby dug pit. The longest, most consistent soil moisture records were obtained at the rainfed and grape sites, which form the primary basis for analysis here.

Soil moisture records were manually checked for quality control, to ensure self-consistency and coherency across sensors. Our analyses rely on relative saturation, $S$, which we calculated as $\frac{VWC}{n}$, where $n$ is the porosity. Local soil porosity at each sensor was estimated as the maximum recorded VWC during the study period. At sensors where the recorded VWC never exceeded 0.3, we set porosity to 0.3.

2.3 Field experiments

2.3.1 Hydraulic conductivity

Hydraulic conductivity at the land surface was measured using a Soil Moisture Equipment (SME) Tension Infiltrometer (Soilmoisture Equipment Corp., 2008), used at all sites, and CSIRO Disk Permeameter (CSIRO, 1988), used at sites measured in 2015. At each SME measurement point, the infiltrometer was used to measure infiltration rates at an unsaturated pressure head (-7 to -12 cm) and near-saturated pressure head (-1 to -3.5 cm). Parameters of soil hydraulic conductivity ($K_{sat}$ and $\alpha$) were calculated using a nonlinear model based on the method developed by Gardner (1958) and Wooding (1968) (Logsdon and Jaynes, 1993). At each CSIRO site, the permeameter was used to measure infiltration rate at a near-saturated pressure head (-1 to -2 cm) and $K_{sat}$ was estimated by applying the same method by including $\alpha$ taken from a tension infiltrometer measurement at the same site.

Sites were selected to cover the different types of land use in the subwatersheds, specifically crops, eucalyptus plantations, and beds of dry tanks (for locations, see Supporting Information Figure S1). At 25 of the locations, we made at least 2 replicate measurements, aiming to capture within-site variability. Overall, 83 measurements were made at 35 locations (19 crop, 10 eucalyptus, 6 tank).

2.3.2 Stable isotope tracer study

Stable isotopes of water were analyzed from samples of rainfall, soil water, and runoff collected near Ekasipura village (see Figure 2e) over the course of two storms, on 28 September 2014 and 30 September 2014. Each storm lasted less than an hour and generated runoff in the local stream channel. Soil water samples were
made from an agricultural field growing corn, and runoff samples collected upstream of a check dam entering the nearest main channel.

Precipitation samples were made continuously during the storm using using a funnel and collector, and stored in a sealed flask to prevent evaporation. Soil water was collected using a suction lysimeter, installed at a depth of 30–35 cm. The lysimeter was installed ahead of time and left under suction to collect water prior to the storm. The first soil water sample, taken at the beginning of the storm, reflected soil water conditions prior to the storm. The lysimeter was fully emptied after each sample was taken, so that each successive sample represented new water in the lysimeter. Runoff samples were collected manually. Deuterium and δ¹⁸O concentrations were obtained from the water samples by the stable isotope laboratory at the University of California, Berkeley.

2.3.3 Overland flow traps

To detect the presence of overland flow, two flow traps were installed September 19–25, 2014, in agricultural fields containing corn, one in SM Golahalli and another near Ekasipura village. Another flow trap was installed October 24–31 in a eucalyptus plantation near the Hadonahalli weather station (see Figure 2d,e). Flow traps consisted of a pan collector (with entry facing uphill) that drained into a storage container, and were constructed using locally available household items. Overland flow from the upstream fields collected in the flow trap and remained stored until removal.

2.3.4 Open well survey

Long-term groundwater level observations in the TG Halli watershed were either unavailable or unreliable (e.g., see Ballukraya and Srinivasan, 2019; Hora et al., 2019). To assess shallow groundwater levels in the study watersheds, we surveyed 99 shallow open wells during the 2014 monsoon season (for locations, see Supporting Information Figure S1). The time period of the survey was coincident with storms that produced significant local runoff. Our expectation was that if this runoff were associated with shallow groundwater tables, this would be reflected in the water levels in these wells. Presence or absence of water in each well were noted, and the depth of the well bottom relative to the local land surface was measured, and converted to a common datum using a local digital elevation model DEM and GPS coordinates of each well. These well base depths were compared to stream-bed elevations determined from the same DEM.

2.4 Storm event analysis

Over the course of the three-year study period, we measured precipitation greater than 1 mm on 174 days at the Hadonahalli station and 107 days at the SM Golahalli station. Daily precipitation was measured for each 24 hour period from 8:30 AM to 8 AM the following day. Because the bulk of precipitation during monsoon season occurred in the late afternoon through the early hours of the morning, we assumed that each 24-hour period with precipitation contained a single storm event. Each day with precipitation greater than 1 mm
was treated as a storm event and associated with a suite of hydrologic metrics, including cumulative tank inflow, timing of peak tank inflow, peak soil moisture, and antecedent soil moisture.

The cumulative tank inflow for any given storm was taken as the tank storage volume at the end of the 24 hour period minus the tank storage volume at the beginning of the 24 hour period. We identified runoff events as those events when there was an increase in instantaneous water level of $>5$ mm over the 24-hour period and an increase in the average water level of $>0$ mm from previous day. Both metrics were needed to ensure runoff was attributed to the appropriate day (instantaneous metric) and that the runoff metric was robust to instantaneous conditions and variability (average metric), given the sensitivity of the sensors to temperature.

Soil moisture measurements were converted to relative saturation, and we noted the peak soil moisture associated with each storm. The peak soil moisture at each depth was set to the maximum soil moisture within the 24-hour storm period across all sensors at that depth in the grape and rainfed monitoring sites. For several subsets of storm events (e.g., events characterized by a given rainfall volume, or by a rainfall volume and peak soil moisture metric), we also calculated “runoff probability” as the number of runoff events divided by the number of precipitation events.

3 Results

3.1 New water and overland flow

The within-storm isotope analyses suggested that streamflow water was comprised of rainwater, with no evidence of mixing between rainwater and pre-event soil water in the measured runoff. In both storms A (in red, Figure 3) and B (in blue), the relative concentration of deuterium ($\delta D$) in runoff tracks precipitation, while the concentration in soil water remains relatively constant and distinct from the values in the rain and runoff. In dual isotope space (not shown), runoff samples fell along the local meteoric water line. The first runoff sample in the second storm was more enriched in $^{18}O$ than rainfall, suggesting the possibility of mixing with evaporatively enriched water at the initiation of the storm, potentially from small amounts of surface ponding carried over between the storms. The bulk of the runoff however, matched the profile of new water, as opposed to old water stored in the soil.

There were 5 storms at the SM Golahalli rain gauge during the period when flow traps were deployed, including 4 which generated runoff into the tank. Overland flow was produced and stored in flow traps during 3 of these storms at the SM Golahalli tank, and 4 in the Ekasipura location. There were 3 storms in the Hadonahalli watershed during the period of flow trap deployment, 1 of which produced runoff into the Thirumagondonahalli tank and 2 of which filled the flow trap (either the runoff was localized away from the tank or not sufficient to qualify as tank inflow).
3.2 Saturated hydraulic conductivity

Saturated hydraulic conductivity ($K_{sat}$) was highest at cropped sites with mean ($\pm$ 1 standard deviation) values of $3.85 \pm 3.49$ cm/hr, followed by eucalyptus plantations ($1.35 \pm 0.93$ cm/hr) and tank beds ($0.84 \pm 0.81$ cm/hr). Precipitation rates were comparable with saturated hydraulic conductivity, and in large storms precipitation rates were greater than $K_{sat}$ at both cropped and eucalyptus sites (Figure 4). Under a simplified scenario in which the landscape is covered by 34% eucalyptus and 66% crops (the relative proportions in the TG Halli watershed), and the assumption that infiltration capacity is equal to saturated hydraulic conductivity (the limiting case), much of the landscape would be producing infiltration excess runoff in heavy storms (Figure 4c).

3.3 Storm dynamics and timing

Over the three year study period, most monsoon season storms at Hadonahalli (61% of 174 storms) were smaller than 10 mm, and considerable rainfall (15%) arrived in just 4 large storms (>45 mm). These 4 storms generated 38% of the total runoff into the Thirumagondonahalli tank.

In comparing the storms that produced runoff to those that did not, we were unable to detect a clear threshold in precipitation rate, volume or antecedent soil moisture that triggered runoff occurrence. We also compared the runoff probability across groups of storms with common peak soil moisture and storm volume (Figure 5). The probability of runoff increased for increasing event rainfall, but did not differ for soils near saturation relative to other soil conditions.

The difficulty in clearly associating runoff generation with soil and storm characteristics likely reflects the hydrologic heterogeneity that was present even in the small subwatersheds studied here. Rainfall intensity and volume, antecedent soil moisture, and check-dam storage levels likely varied between storms and through space, complicating the observed relationship between discharge into the tank and the point measurements in the watershed.

Much of the runoff occurred during a few large storms sharing similar characteristics, which were illustrated by the dynamics in a representative storm occurring on 07 October 2014 (Figure 6). In this event, strong rainfall was followed by considerable inflow to the tank. Peak runoff occurred just before midnight, after which the soil profile continued to saturate over the next 1–3 hours with the upper sensor (30 cm) peaking in soil moisture before the lower sensor (1 m).

In nearly all storms, the peak in soil moisture occurred after the peak in runoff, regardless of soil moisture site or total storm runoff volume (Figure 7).

3.4 Well survey

Ninety-nine wells were surveyed during the 2014 monsoon season. Seventy of these wells were completely dry, containing no water. In the remaining 29 wells, visual evidence of surface channels directing flow from adjacent fields into the well could be seen. These wells therefore appeared to be storing runoff from overland
flow. No similar channels were visible at the dry wells. Runoff occurred and filled nearby nearest tanks both before and after the well survey.

The elevation of the bottom of open wells was, in general, comparable to the elevation of the bed of the nearest stream channel. Relative to the stream, the elevation of well bottoms tended to increase moving further away from the stream (Figure 8).

4 Discussion

4.1 Contemporary streamflow generation

The above field investigations of hydrological processes allow us to proceed with our diagnostic approach to understanding hydrological change. This threefold strategy consists (a) understanding contemporary runoff generation processes, (b) using this information to constrain a conceptual model and generate hypotheses of historical change, and (c) evaluating those hypotheses using a variety of data sources and field observations (Figure 9).

Our results indicate that contemporary runoff generation in the studied subwatersheds is primarily associated with infiltration excess overland flow, not saturation excess overland flow or baseflow from a shallow water table (Figure 9a). Multiple strands of evidence point to this finding.

First, there was clear evidence that overland flow occurred during runoff-producing storms. The flow trap observations detected such flow during all runoff-producing storms in nearly all of the flow traps. The isotope analysis suggested that runoff was composed of new water, rather than containing signals of old water consisting of soil or groundwater. We visually observed overland flows during rainfall events in the study watersheds and saw clear evidence of erosion as flowlines, a precursor to rill formation (Merritt, 1984). The sites where we made these observations were topographically flat, distributed throughout the watershed, and suggest that overland flow generation during storms is widely distributed, rather than being confined to particular topographic positions or land cover types. Simultaneously, we did not observe any evidence of a shallow water table, and noted a downward propagation of wetting fronts into a drier subsoil during storm events. These observations are inconsistent with contemporary flow production from a shallow or perched water table, and suggest that overland flow is the primary watershed-scale mode of runoff response.

Second, a number of strands of evidence suggest that infiltration excess, rather than saturation excess, is likely the dominant mechanism generating the observed overland flow. The observed saturated hydraulic conductivities in soils were relatively low, and observed rainfall intensities exceeded these conductivities for 25% or more of the storms that occurred. The observation of a downward propagating wetting front throughout the storm, and indeed increasing soil saturation well after surface runoff peaks had been generated is also consistent with the occurrence of infiltration excess runoff. Typically at least a fraction of the observed soil columns remained unsaturated during runoff producing events, again consistent with infiltration excess, but not saturation excess, streamflow generation mechanisms. The insensitivity of runoff probability to soil moisture is also consistent with this mechanism. The only finding we made that was inconsistent (or at least
inconclusive) with respect to infiltration excess runoff generation was the absence of a clear threshold in storm intensity around which runoff did or did not occur. We hypothesize that this is likely to be associated with heterogeneity in rainfall intensity across the studied subwatersheds, and potentially also to heterogeneity in water storage in check dams, which fragment the channel network and may obscure the relationship between generation of runoff at field scales and propagation of runoff to the tank at the watershed outlet.

4.2 Conceptual model of historical change

We now apply our understanding of contemporary streamflow generation to constrain a conceptual model of how a change in streamflow generation could have occurred with respect to infiltration excess runoff, saturation excess runoff, and groundwater discharge. Previous analyses found that rainfall and its characteristics were near-stationary in the region over the 20th Century (Srinivasan et al., 2015), suggesting that changes in rainfall intensity are unlikely to have occurred, and observed changes are likely due to with changing hydrological processes within the watershed.

The finding that contemporary streamflow is dominated by infiltration excess runoff suggests the prospect that this mechanism could have declined over time, particularly given the changes in land use that occurred throughout the watershed. We also consider the possibility that there could have been an additional mechanism of runoff generation in the past. Because the occurrence of saturation excess mechanisms are primarily dictated by geology and landform, which have not been substantially altered in the watershed, it is challenging to conceive of a situation where saturation excess runoff occurred in the past but not the present. Conversely, several strands of evidence suggest that the change in surface runoff could be associated with the decline of an historically present seasonal shallow groundwater table.

We therefore consider two hypotheses that could describe the loss of streamflow within the TG Halli watershed: (i) a reduction in infiltration excess runoff due to changing land use and soil properties, and (ii) the loss of a shallow groundwater table that historically discharged to the stream (Figure 9b).

1.3 Evaluation of historical processes

Evaluation of historical hydrological processes in the absence of historical observations presents various challenges. In order to test each of the above hypotheses, we relied on observational research conducted during the course of this study, supplemented by findings from recent research in the TG Halli watershed and historical information from other sources (Figure 9c).

A change in infiltration excess runoff would be associated with widespread changes in soil properties. We do not have access to measurements of historical soil properties, and therefore a direct comparison of historical and contemporary soil properties is impossible. However, because the TG Halli watershed is intensively managed for agriculture, changes in soil would be associated with changes in land use. This means that a space-for-time substitution would be appropriate to evaluate this hypothesis. We ignore urbanization, which generally produced increased impervious surfaces and has been associated with increased runoff downstream of Bangalore (Penny et al., 2018). We focus instead on agricultural land use changes in the TG Halli, which
have largely consisted of transitions from traditional crops to eucalyptus plantations (Lele and Sowmyashree M.V., 2016). Furthermore, eucalyptus plantations often arise in discussions with stakeholders when asked about their perceptions of the drying of the watershed (Lele et al., 2013b). Infiltration excess runoff is determined by precipitation rates, which have not changed over time, and infiltration capacity, which depends strongly on saturated hydraulic conductivity for which we have measurements at cropped sites and eucalyptus sites. Because eucalyptus plantations exhibit lower saturated hydraulic conductivity than traditional cropland (see Figure 4), these changes would be inconsistent with a reduction in runoff generation via an infiltration excess mechanism. We can therefore exclude this hypothesis.

A change in groundwater discharge would require the loss of a shallow water table. The water table is clearly absent from the watershed today, meaning evaluation of this hypothesis requires addressing whether or not a shallow groundwater table existed in the past, and whether or not it discharged to the stream network. Although the presence and subsequent loss of a shallow water table seems likely given the prevalence of groundwater irrigated agriculture in the watershed, direct observations of historical groundwater are not possible. Publicly available groundwater data are biased towards observation wells in which the water level can be observed (i.e., wells that are not dry), meaning that any wells which dry out over time are excluded from the record (Hora et al., 2019). Satellite observations from the GRACE mission are equally ineffective in the TG Halli, both because the data require an excessively large smoothing filter on the order of 300 km (Zhang et al., 2009) and the GRACE satellite record began in 2002 after much of the drying in the TG Halli had occurred (Tapley et al., 2004).

Instead, we consider the open wells surveyed in this study as a proxy for the historical water table. These open wells are large (approximately 5–10 m diameter), manually constructed and widely installed structures, and historically were used for agricultural irrigation. Presumably, such extensive construction and use of shallow surface wells would only be consistent with a hydrologic regime in which those wells regularly intersected the groundwater table. Moreover, a sample of borewell drill logs within the TG Halli watershed obtained from the 1970s (for locations, see Supporting Information Figure S1) indicate that the depth to the water table encountered during this time period was comparable to the depths of the shallow wells, further supporting the hypothesis that the shallow well depth is a reasonable proxy for past groundwater depths (Figure 10). By comparing the contemporary well depths and contemporary channel elevations, it is clear that a groundwater table that was shallow enough to have been accessed by the wells would also have been shallow enough to intersect the contemporary stream channels (Figure 8), and moreover, that a head gradient would have existed between the wells and stream channels, supporting groundwater discharge to the channel.

There are other circumstantial pieces of evidence supporting the notion that a historical shallow groundwater table could have existed and sustained surface flows during the monsoon season. Long-term monthly inflow data to the TG Halli reservoir indicate the historical presence and subsequent loss of protracted baseflow, in some cases lasting for 1–2 months after the cessation of monsoon season rainfall (Srinivasan et al., 2015). A baseflow analysis suggested that the known decline in the water table could represent a large-enough change in watershed storage to explain the ‘missing’ water in contemporary river discharges (Srinivasan et al.,...
2015). Phenomenologically, the extent of groundwater irrigated agriculture in sub-watersheds across the TG Halli watershed is correlated to the magnitude of surface discharge decline since the 1970s (Penny et al., 2018).

4.4 Context and attribution of hydrologic regime change

The evidence presented here attributing the loss of shallow groundwater to the loss of streamflow is necessarily circumstantial, given our inability to directly observe historical runoff generation processes. Nonetheless, the fact that diverse strands of evidence are consistent lends confidence to an interpretation that reductions in surface flow in the TG Halli watershed can be attributed, at least in part, to a decline in shallow groundwater levels. In the absence of a shallow water table to route infiltrated water to streams and sustain baseflow, only episodic runoff production via infiltration excess mechanisms generates streamflow today. Similar changes in runoff dynamics have been observed in other systems. For example, in watersheds in Western Australia where drought caused groundwater levels to drop >5 m below the depths of the stream elevation, runoff ratios never exceeded 0.03, while in watersheds where groundwater remains within 5 m of the stream elevation, runoff ratios were tightly coupled to groundwater depth, exceeding 0.2 in some cases (Hughes et al., 2012; Kinal and Stoneman, 2012). Drops in runoff ratio were noted in 46% of watersheds in Eastern Australia following the 10 year Millennium Drought, which also lead to extensive declines in groundwater levels (Saft et al., 2016, 2015), and following groundwater disconnection induced by pumping for agricultural irrigation in the High Plains aquifer in the USA (Kustu et al., 2010). In larger river systems, prolonged declines in groundwater levels are associated with switches from gaining to losing streamwater-groundwater interactions (Brunner et al., 2009), further altering runoff ratios as streamflow is progressively lost to unsaturated soils beneath the streambed. Regardless of the relative importance of runoff production versus losing conditions in the channel for the TG Halli watershed, large declines in groundwater level have an established ability to change the hydrologic regime and functioning of watersheds at multiple scales (Petrone et al., 2010).

Such changes in hydrologic regime underline the importance of understanding process change in order to develop management approaches for nonstationary systems like the TG Halli watershed. For example, adopting a single, simple runoff parameterization (e.g., via a curve number or solely as infiltration excess runoff) which is commonly done in water resources modeling for management purposes will necessarily be confounded by regimes shifts that alter the relationship between rainfall and runoff and render these parameterizations non-stationary (Neitsch et al., 2011). Understanding process change is therefore an essential precursor to modeling such systems, and to informing restoration or management approaches.

Land and water management changes in the TG Halli watershed are not confined to declining groundwater. Ongoing fragmentation of the flow network by installation of irrigation bunds on farm fields, and installation of check dams in headwater channels are likely to have contributed to the observed surface water declines. Fortunately, the timing of these events (loss of shallow groundwater, installation of check dams, installation of irrigation bunding) is separable, given that groundwater depletion and streamflow decline largely predate other management practices (Srinivasan et al., 2015).
5 Conclusions

Given the widespread changes in the hydrological cycle occurring around the world, hydrology must confront the problem of changing hydrological processes. To this end, we develop a process-based approach for attribution of hydrological change in data-scarce regions. The success of this approach depends on the integration of multiple field investigations to evaluate contemporary runoff generation mechanisms and constrain a narrow set of hypotheses that potentially explain historical changes in the watershed. Final evaluation of these hypotheses can be conducted through the use of proxies and space-for-time substitution. The novelty of this study therefore lies in a synthesis of hydrological processes to understand historical changes, and suggests the value of field research to assist in the identification and attribution of change in hydrological processes.

We apply this approach in the TG Halli watershed, which has exhibited severe hydrological changes since the 1970s. With surface flows into the TG Halli reservoir at <25% of historical levels, groundwater depths continuing to drop more than 100 m below the land surface, and ongoing land conversion in the TG Halli watershed, the present water management situation has many characteristics of an emerging water crisis (Srinivasan et al., 2012). Abandonment and fallowing of crop fields by some farmers (Lele and Sowmyashree M.V., 2016) suggests that collapse and reorganization of the social-ecological system is already occurring at smaller scales and that the system may be in a state of low resilience (e.g., see Holling, 2001; Penny and Goddard, 2018).

In the absence of a process-based attribution of hydrological change that illuminates genesis of this emerging crisis, policy makers and managers were left without a consensus evidence base from which to develop and evaluate management options. Lack of historical hydrological records have prevented conventional attribution methods and required innovation to generate novel datasets (Penny et al., 2018), utilize the method of multiple working hypotheses to identify plausible drivers of change (Srinivasan et al., 2015), and constrain understanding of the process basis underlying the observed changes (this study). Although the method of multiple working hypotheses is necessarily idiosyncratic to the specific problem and datasets at hand, it is also consistent with the production of robust-process explanatory narratives, which Kleinhans et al. (2005) has argued are essential to generalizable knowledge production in the geosciences. While the multiple working hypotheses approach cannot avoid the difficulty of under-determination (i.e., insufficient evidence to fully constrain past processes Kleinhans et al., 2005), it can usefully inform modeling and interpretation of phenomena, reducing the potential for interpretation pitfalls such as equifinality (Beven, 2006) or reverse causation bias (Maclure and Schneeweiss, 2001). In the case of the TG Halli watershed, investigations provide strong, if circumstantial evidence of a hydrologic regime shift from a connected groundwater system sustaining relatively high runoff to a disconnected system in which infiltration excess runoff is the remaining form of flow production. Any future modeling and policy effort should be cognizant of this major driver of nonstationarity hydrologic function in the TG Halli watershed.

Attributing hydrologic change in complex and poorly understood watersheds is clearly a challenging and potentially nebulous task for hydrologists to undertake. Yet such attribution is essential for robust water
resources management given the widespread prevalence of nonstationary in the hydrologic cycle and the need for robust modeling and prediction efforts in water resources management, especially in human-influenced watersheds characterized by hydrologic regime shifts. These watersheds often provide critical support for social, economic and environmental well being. Synthesizing multiple evidence sources needed in a hypothesis testing framework offers a way to understand historical watershed functioning, even after extensive human modification and in the absence of direct historical measurement and observations.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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References


Figure captions

Figure 1: Canonical runoff generating mechanisms (i), potential corroborating evidence (ii), and observational approach (iii). Three runoff generation mechanisms are hypothesized as alternative streamflow generation pathways in the TG Halli watershed: infiltration excess, saturation excess, and subsurface stormflow and groundwater discharge to the channel. Infiltration excess runoff would be supported by the presence of overland flow, by channel flows consisting primarily of “new” water, and by soil conductivities that were regularly lower than rainfall intensities (Horton, 1933). Saturation excess runoff would be supported by the presence of overland flow consisting of a mix of old and new water, by saturation of surficial soils above an impermeable layer prior to runoff, and by soil hydraulic conductivities exceeding rainfall intensities (Dunne and Black, 1970; Hewlett and Hibbert, 1967). Groundwater discharge would be associated with a shallow or perched groundwater table and would result in a discharge of old water to the stream (Whipkey, 1965).

Figure 2: TG Halli location, land use, and instrumentation of the three study watersheds. (a) India. (b) Karnataka. (c) TG Halli watershed land use map with major land use categories from Karnataka State Remote Sensing Application Center (KSRSAC). (d) Thirumagondonahalli study watershed including a lake water level gauge, Hadonahalli weather station, and soil moisture sites. (e) Doddatumkur (large tank) and SM Golahalli (small tank) study watersheds including water level sensors and SM Golahalli weather station. Storm isotopes were taken near Ekasipura village within the Doddatumkur watershed.

Figure 3: Within-storm deuterium isotopes for two one-hour storm events, A and B, including precipitation (P), soil moisture (S), and runoff (Q) isotopic signatures. The signature of runoff tracked precipitation and did not appear to contain a soil water component.

Figure 4: Saturated hydraulic conductivity ($K_{sat}$) and runoff potential. (a) Volume-based probability of exceedance of precipitation, (b) boxplots $K_{sat}$ for crops and eucalyptus land use. (c) Fractional area generating infiltration excess runoff, assuming the limiting case that infiltration capacity is equal to $K_{sat}$. The dashed portion of this line indicates rain rates that exceed the most intense rates observed at the precipitation gauges, but would be required to generate infiltration excess runoff across 100% of the landscape.
Figure 5: Runoff probability for groups of storms. Storms events (N = 173) were binned into four equal-sized groups (Bins 1–4, separated by dashed lines) based on the total precipitation of each storm. The runoff probability was calculated as the fraction of storm events that generated runoff, given the storm bin and relative saturation. For example, Bin 4 contained 42 storms with precipitation in the range of 15–120 mm. Among these storm events, when soil at 30 cm depth was unsaturated (S < 0.8, N = 28), runoff was generated in 86% of events. When the soil at 30 cm was near saturation (S ≥ 0.8, N = 14), runoff was generated in only 71% of events, despite these events having higher average precipitation (41 mm in these storms, versus 23 mm for S < 0.8). Within each precipitation bin, storms with higher peak soil moisture (filled-in circles) are not more likely to generate runoff than storms with lower peak soil moisture (open circles).

Figure 6: Within-storm dynamics for a storm event beginning on 07 October 2014, including 30-minute precipitation at Hadonahalli, inflow to Thirumagordonhalli tank in cubic meters per second, and relative saturation profiles (S) at the rainfed and grape sites. Soil moisture was measured at 30 cm and 1 m (dashed lines) at each site and interpolated to other depths. Peak inflow occurred before peak soil moisture, which occurred first at the upper soil moisture sensor before the wetting propagated to the lower soil moisture sensor. Because rainfall was often highly localized, the initial peak in streamflow at 21:00 likely occurred in response to precipitation somewhere in the watershed but not at the gauge.

Figure 7: Time lag of peak inflow (Q) to peak soil moisture (S) at the grape and rainfed sites. In all but a few cases, peak soil moisture occurred after peak inflow, regardless of the total inflow for the storm event.

Figure 8: Elevation of the bottom of dry open wells relative to the nearest stream channel, with the approximate elevation of the stream bed marked by the blue dashed line. In general, the relative elevation of the bottom of the well increases moving further away from the stream.

Figure 9: Threefold strategy to attribution of hydrological change. a) We evaluate contemporary runoff generation processes and find evidence of (1) infiltration excess runoff, but not (2) saturation excess runoff or (3) baseflow (see Section 4.1). b) Insights from field research are used to generate a conceptual model of historical processes, including two hypotheses that would explain historical changes: reduced overland flow or loss of a shallow water table (Section 4.2). c) We evaluate these hypotheses using information about infiltration capacities, open wells, and historical borewell logs, combined with additional evidence from other studies (Section 4.3).

Figure 10: Boxplots of the depth to the bottom of dry wells in 2014 and depth to the water table taken from borewell drill logs in the 1970s. The distribution of water table depths in the 1970s is similar to the distribution of well-bottom depths surveyed in the 2014 monsoon season.