Journal of Hydrology X 15 (2022) 100121

Contents lists available at ScienceDirect

Journal of Hydrology X

journal homepage: www.sciencedirect.com/journal/journal-of-hydrology-x

Research papers

Assessing the role of groundwater recharge from tanks in crystalline bedrock aquifers in Karnataka, India, using hydrochemical tracers

Bentje Brauns[a,*], Somsubhra Chattopadhyay[b,1], Dan J. Lapworth[c], Sian E. Loveless[c,2], Alan M. MacDonald[d], Andrew A. McKenzie[c], Muddu Sekhar[e], Siva Naga Venkat Nara[f], Veena Srinivasan[b]

[a] British Geological Survey, Environmental Science Centre, Keyworth NG12 5GG, UK
[b] Ashoka Trust for Research in Ecology and the Environment, Bengaluru, Karnataka 560064, India
[c] British Geological Survey, Maclean Building, Crowmarsh Gifford, Wallingford OX10 8BB, UK
[d] British Geological Survey, The Lyell Centre, Edinburgh EH14 4AP, UK
[e] Department of Civil Engineering, Indian Institute of Science, Bengaluru, Karnataka 560012, India
[f] Interdisciplinary Centre for Water Research, Indian Institute of Science, Bengaluru, Karnataka 560012, India

ARTICLE INFO

Keywords:
India
Groundwater recharge
Fractured rock
Hydrochemistry
Stable isotopes
Tanks

ABSTRACT

The majority of India's rural drinking water supply is sourced from groundwater, which also plays a critical role in irrigated agriculture, supporting the livelihoods of millions of users. However, recent high abstractions are threatening the sustainable use of groundwater, and action is needed to ensure continued supply. Increased managed aquifer recharge (MAR) using the > 200,000 existing tanks (artificially created surface water bodies) is one of the Indian government's key initiatives to combat declining groundwater levels. However, few studies have directly examined the effectiveness of tank recharge, particularly in the complex fractured hydrogeology of Peninsular India. To address this gap, this study examined the impact of tanks in three crystalline bedrock catchments in Karnataka, southern India, by analysing the isotopic and hydrochemical composition of surface waters and groundwaters, combined with groundwater level observations. The results indicate that tanks have limited impact on regional groundwater recharge and quality in rural areas, where recharge from precipitation and groundwater recycling from irrigation dominate the recharge signal. In the urban setting (Bengaluru), impermeable surfaces increased the relative effect of recharge from point sources such as tanks and rivers, but where present, pipe leakage from public-water-supply accounted for the majority of recharge. Shallow groundwater levels in the inner parts of the city may lead to groundwater discharge to tanks, particularly in the dry season. We conclude that the importance of aquifer recharge from tanks is limited compared to other recharge sources and highly dependent on the specific setting. Additional studies to quantify tank recharge and revisions to the current guidelines for national groundwater recharge estimations, using a less generalised approach, are recommended to avoid over-estimating the role tanks play in groundwater recharge.

1. Introduction

It is estimated that nearly 700 million Indians living in villages (50% of India's population) depend on groundwater for basic needs (Kulkarni et al., 2015). Groundwater is also the primary water source for over 50% of India's irrigated agricultural land (GoI, 2015). As such, it is a vital resource both for public health and economic growth (Kulkarni et al., 2015; Pahuja et al., 2010; Shah et al., 2003). The Indian Government reports that, on a national scale, groundwater abstraction (of which 90% is used for irrigation) was 249 billion cubic metres (BCM) for the year 2017 — approximately two thirds of the estimated annual net extractable groundwater of 393 BCM (CGWB, 2019a). The scale of groundwater abstraction differs across the country, and since the 1980s, groundwater levels have declined in several regions as a result of increased

* Corresponding author.
E-mail address: benaun@bgs.ac.uk (B. Brauns).
[1] Present address: Department of Hydrology, Meteorology and Water Management, Warsaw University of Life Sciences, Poland.
[2] Present address: Environment Agency, Crowmarsh Gifford, Wallingford OX10 8BD, UK.

https://doi.org/10.1016/j.hydroa.2022.100121
Received 4 June 2021; Received in revised form 24 November 2021; Accepted 21 January 2022
Available online 29 January 2022

abstraction due to enhanced and more affordable pump technology. Nearly a third of the groundwater assessment units in peninsular India are therefore in 'semi-critical' (14%), 'critical' (5%), or 'over-exploited' (17%) status (CGWB, 2019a), with strongest declines observed in the sedimentary basins in the northwestern states (Ambast et al., 2006; CGWB, 2019a; MacDonald et al., 2016; Rodell et al., 2009) and in parts of southern India's crystalline basement aquifers (e.g. in the states of Karnataka and Tamil Nadu), which cover about 60% of the country (CGWB, 2019a; Sharma et al., 2018).

The importance of enhanced groundwater management in India has clearly been recognized by the Government of India, acknowledging in the *Third National Water Policy* document (GoI, 2012b) that water governance needs to be improved to alleviate "a critical situation in many parts of the country". One of the key suggestions is to enhance water availability by using 'tanks' — the local term for typically small, surface water storage structures, such as farm ponds, but also larger lakes — for water harvesting and managed aquifer recharge (MAR) (CGWB, 2007; CGWB, 2013). The use of tanks is a long-standing tradition especially in southern India since ancient and medieval times (Dixit et al., 1993), and they are said to provide flood protection, water storage, ecosystem services, as well as recreational and aesthetic value and potential recharge to local groundwater (D'Souza and Nagendra, 2011; Dixit et al., 1993; EMPRI, 2018; Esha, 2008; Nagendra and Ostrom, 2014; Patil, 2011). Though it is difficult to know the precise number of functional tanks in India (Pant and Verma, 2010), it is estimated that there are between 200,000 (Palanisami et al., 2010; Sharma, 2003) and 500,000 (Reddy, 2015). Recent tank restoration and promotion efforts, with a goal to enhance groundwater availability by means of MAR, have been undertaken by the national and local governments (e.g. Tamil Nadu and Karnataka, often supported by local NGOs), and also received substantial support by international institutions such as the European Union (EU), the National Bank for Agricultural and Rural Development (NABARD), the World Bank, and the International Water Management Institute (IWMI) (Richard-Ferroudji et al., 2018).

However, there are few studies that directly evaluate recharge from tanks or investigate tank-groundwater connectivity in India's basement setting, and therefore, little is known about the effectiveness and potential groundwater quality implications of tank restoration and promotion. In the suggested methodology for groundwater recharge estimations used for national groundwater resource assessment and planning, the Indian Government's Groundwater Resource Estimation Committee (GEC) acknowledges the limited availability of field studies. As a temporary measure, they suggest a recharge estimation method using a fixed recharge rate of 1.4 mm/day/tank-area as approximation (GEC, 1997). This approach was carried forward into the most recent GEC guideline (GEC, 2017) and the latest national groundwater review (CGWB, 2019b). However, while recharge from tanks in the north Indian alluvial plains is relatively high and homogeneous (Bhanja et al., 2019), recharge to the lower-permeability crystalline aquifers dominant in southern Peninsular India is more complicated and likely much more spatially variable. Crystalline basement aquifers are formed by a combination of weathering and tectonic forces and can be best conceptualized as zones of varying degree of weathering, i.e. a weathered upper zone termed 'saprolite', which overlies a less weathered, but fractured rock layer, followed by fresher basement rock (Collins et al., 2020; Singhal and Gupta, 2010). In the southern Indian context, the thickness of the weathered zone is typically a few to several tens of meters, with fracture zones extending to depths of 200 to 300 m (CGWB, 2012). Below the relatively permeable weathered zone, recharge to the crystalline basement depends on the size (aperture) and distribution (connectivity) of fractures. Lateral connectivity varies spatially with depth and depends on the vertical extent of the weathered zone and layout of the fracture network at depth (Banks et al., 2009; Guihéneuf et al., 2014; Ofterdinger et al., 2019). The connectivity may also depend on the type of fissure network, for example on whether the bedrock is fractured or sheared.

Few studies report the local impact of tanks in these crystalline basement settings in India. Investigating recharge from mostly small tanks with < 0.4 km^2 zone of influence ('command area') in Andhra Pradesh, Reddy and Behera (2009) found farmers reported shallower groundwater levels and fewer dry wells in areas with restored tanks than in areas without tanks. A study using macro level data from West Bengal to model the linkage between groundwater levels and tanks found an inverse relationship between tank density and depth to groundwater (Chowdhury and Behera, 2018). However, in both of these studies, it is not clear if the difference in groundwater level can be attributed to recharge by tanks, or is influenced by other factors, such as decreased groundwater abstractions in areas with higher surface water availability (i.e. tanks). Other studies, mainly using water balance approaches, have quantified average daily percolations rates of 5.5–18.4 mm/day (Boisson et al. 2014; Perrin et al., 2012; Singh et al., 2004), and percolation efficiencies, defined as the percolated fraction of tank water depletion over a given time period, of 35–68% (Boisson et al. 2014; Massuel et al., 2014; Metha and Jain, 1997; Perrin et al., 2012; Singh et al., 2004; Sukhija et al., 1997). However, little is known about how much of the infiltrated water actually recharges groundwater, as not all water lost through the base of a tank can be expected to reach the groundwater table, but some may be stored in the vadose zone or taken up by evapotranspiration (De Vries and Simmers, 2002). This is in particular discussed in a study by Boisson et al. (2014), which proposed a combined surface water and groundwater balance method in order to better consider flow within the unsaturated zone and found that only 53–88% of the potential recharge from the tank percolate reach the groundwater table. In summary, while some studies have assessed groundwater recharge from tanks in the Indian crystalline basement using a variety of approaches, most have focussed on quantifying the percolation rates of the tanks. There remains significant uncertainty on how much of this infiltrated water is recharging to deeper groundwater and how much of the water is lost in the unsaturated zone. Therefore, more site-specific studies are necessary to understand the effects of tanks on groundwater recharge in the crystalline basement.

In this study, a suite of direct measurements, i.e. water isotopic ratios, hydrochemistry and water level observations were used to investigate the degree of groundwater recharge and its impact on water quality from tank structures in three study areas in Karnataka State. The areas reflect agricultural land use and different geological settings (fractured versus sheared crystalline basement). Because tanks are traditionally part of both the urban and rural landscape in southern India, we also considered the city of Bengaluru — well known for its numerous interconnected tanks — in this study. Specific aims were to:

1) Assess the connectivity of the deeper (fractured) basement aquifer to modern recharge processes from tanks and other sources;
2) assess the significance of tank recharge compared to other recharge sources, and;
3) identify the contamination risk posed by tanks and other recharge sources to groundwater.

2. Methods

2.1. Study locations

This study focuses on three areas in south and southeastern Karnataka. There are seven perennial river basins in Karnataka, but due to the high inter-annual variability of monsoon rainfalls and river flow, and high vulnerability of local surface water sources to contamination, groundwater is used as primary drinking water source in most of the state's rural area (EMPRI, 2018). Groundwater resources in Karnataka are also heavily used for industrial and domestic water supply in major cities such as Bengaluru (population about 8 million) and Mysore (population about 0.9 million), and for agricultural production across the state. Recent (2017) estimates of groundwater withdrawals are 70%

of total extractable groundwater (compared to 63% on the national scale), and about 26% of Karnataka's 'taluks' (administrative divisions) are classified as 'over-exploited' with respect to groundwater use, which is 9% higher than on the national scale (CGWB, 2019b).

The selected sites for this study are the city of Bengaluru, two sub-catchments (Aralamallige and Hadonahalli) in the rural area of the Thippagondanahalli (TG Halli) catchment about 30 km north of Bengaluru, and the rural Berambadi catchment in the southern part of Karnataka (Fig. 1). All study areas are located in the Cauvery River Basin, with exception of the north-eastern part of Bengaluru, which falls into the South Pennar basin. Table 1 lists key characteristics, such as size, tank density, and climatology of the study areas. Mean annual precipitation in the areas ranges 800–900 mm/year, but with high annual variations (Fig. 1E), and its pattern is composed of two distinct monsoon periods, namely the dominant southwest summer monsoon (June-September) that typically produces most of the annual

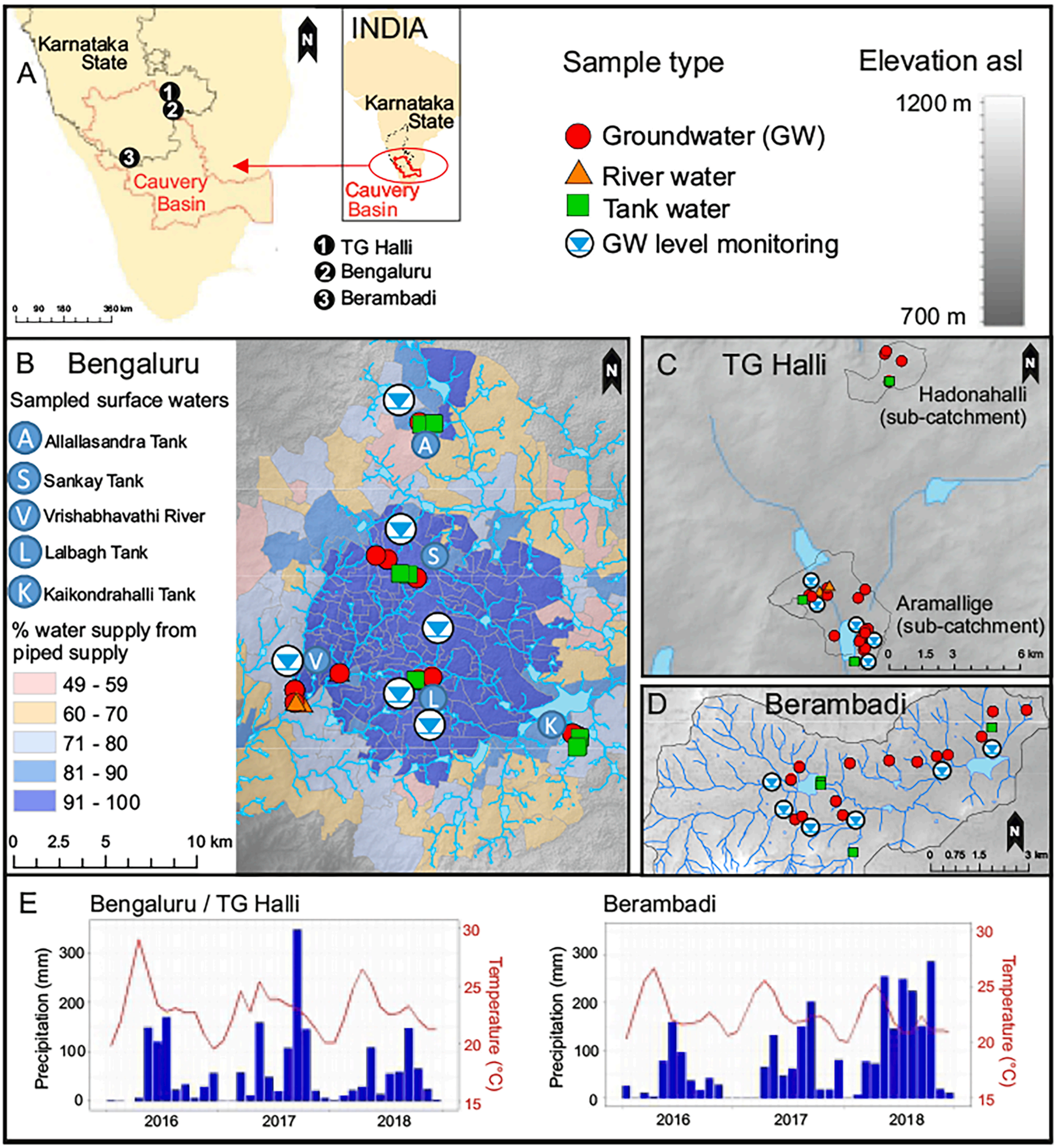

Fig. 1. Overview figure showing: (A) Map indicating the location of the three study areas in respect to the Cauvery Basin and Karnataka State, (B-D) water sampling and groundwater monitoring locations in each catchment, (E) monthly precipitation and temperature 2016–2018 for Bengaluru/TG Halli and Berambadi. Areas of low/high percentage of household water supply from piped mains water are indicated in Bengaluru (B), highlighting the high percentage of piped water supply (imported mainly from the Cauvery River) in the inner city. Where samples were taken nearby larger surface water features in Bengaluru, the names of these features are indicated by letter, and fully stated in the legend. Data sources: % piped water coverage in Bengaluru based on (GoI, 2012a), rainfall data provided by the Kabini CZO and ATREE (see acknowledgement), elevation data from USGS SRTM data (http://earthexplorer.usgs.gov).

Table 1
Basic information on the study areas.

Catchment Name	Size (km^2)	Number of tanks	Tank density ($tanks/km^2$), Percentage of catchment size (%)	Mean annual rainfall (mm)	Climate region (Koeppen-Geiger)
Bengaluru	1307	681	0.52, 5%	900	Equatorial desert (Aw)
TG Halli	1447	617	0.42, 4.8%	830	Equatorial desert (Aw), parts hot-arid steppe (BSh)
Berambadi*	89	53	1.67*, 1.3%	800	Equatorial desert (Aw)

Data Bengaluru (numbers for Bengaluru Metropolitan Area, disused tanks excluded): (EMPRI, 2018).
Data Berambadi: (Robert et al., 2017; Sekhar et al., 2016), calculation of Berambadi tanks based on satellite imagery.
Data TG Halli: (EMPRI, 2015; Srinivasan et al., 2015).
Climate regions: (Kottek et al., 2006).
* in addition to the rain-fed tanks, about a third of farmers use small-scale ponds for groundwater storage during the day Robert et al. (2017), which are not included in this table.

precipitation (~85%), and the northeast winter monsoon from October to December (Rahul et al., 2016). Mean temperatures are around 23 °C, and potential evapotranspiration usually exceeds the annual rainfall with mean values of approximately 1100–1650 mm/year across the study areas (Sekhar et al., 2016; Srinivasan et al., 2015).

Numerous long-established water tanks are characteristic of all three study areas (see Table 1) with region-specific distribution in size and set-up. Tanks can be divided into the following broad categories; river-fed tanks constructed by using dams (locally termed *anicuts*) to check water along a hydraulic gradient, or rain-fed tanks constructed by digging a square cavity of shallow (few metres) depth into the ground (EMPRI, 2018). Tank embankments can be site-specific, but typically, river-fed tanks have little embankment aside from the check dam, while smaller, rain-fed tanks are usually without raised embankments.

Bengaluru has mostly cascading, large (> 1.2 ha), medium (0.4–1.2 ha), and small size (< 0.4 ha) tanks with seasonal to perennial water storage. The city is naturally divided into three main river valleys, and most of the city's tanks have been established by the use of anicuts to intercept rainwater and dam existing streams along topographic gradients; often with drains connecting a series of cascading tanks to each other (D'Souza and Nagendra, 2011). Nowadays, the main tank inflows are from rainfall, and urban runoff, including waste waters (Rao et al., 2020). The depth of water bodies in Bengaluru ranges from 0.5 m to a maximum of 9 m (Sankay Tank). The TG Halli catchment is dominated by two large reservoirs, namely TG Halli reservoir itself (in the most southern part of the catchment) and Hesaraghatta Tank, which is located about 30 km upstream from TG Halli along the Arkavathy River (a tributary to the Cauvery River). In addition, there are an estimate of about 600 smaller, often cascading in-stream tanks, of which most have been constructed by checking monsoon runoff (Srinivasan et al., 2015). In the Berambadi catchment, most of its 53 tanks — other than the Berambadi tank — are ephemeral and only fill up for short periods after strong monsoon rains (Collins et al., 2020; Sharma et al., 2018). There is no detailed bathymetry available for small tanks in TG Halli and Berambadi, but the depth of these smaller ponds observed in similar studies ranges around 4 m (Boisson et al., 2014, Massuel et al., 2014, Sharda et al., 2006).

2.1.1. *Hydrogeology*

Previous hydrogeological studies have been undertaken in all three areas: Sekhar et al. (2018) investigated groundwater level dynamics in Bengaluru for the period 2015–2017. At TG Halli catchment, Ballukraya and Srinivasan (2019) investigated variations in groundwater levels in the two sub-catchments Aralamallige and Hadonahalli (about 7 km and 20 km north of Hesaraghatta Tank, respectively), which corresponds to the areas used in this study. The Berambadi catchment is the site of the Kabini Critical Zone Observatory (Sekhar et al., 2016).

The three study areas are dominated by weathered and fractured bedrock aquifers of the Banded Gneiss Complex, with local variations in rock-composition. Bengaluru is mainly underlain by Precambrian migmatites, granodiorites, tonalites and gneiss, with local granitic intrusions, especially in the central part of the city (near Lalbagh Lake). The weathered horizon is about 15 m in thickness and overlain with red loamy to gravelly superficial deposits of varying thickness (Hedge and Chandra, 2012). A particularly thick saprolite formation of about 60 m can be found in the eastern parts of Bengaluru (Hedge and Subhash Chandra, 2014). Groundwater levels in Bengaluru are observed from extremely shallow depths of only 1 m below ground level (bgl) to about 70 m bgl (Sekhar et al., 2018). The nearby TG Halli catchment likewise consists of weathered (to a depth of about 20 m bgl), fissured and fractured granite and gneiss (Srinivasan et al., 2015). Boreholes are often deep (200–300 m), but may recharge from water-bearing joints at shallow depths as well as from deeper fractures, thus creating a complicated flow system with many of the water bearing fractures at shallow depths. An extensive study in TG Halli from borehole scans and groundwater levels of 83 boreholes revealed that groundwater levels vary considerably between 28 and 222 m bgl, often with large differences between adjacent (proximities of < 100 m) boreholes (Ballukraya and Srinivasan, 2019). The Berambadi catchment, 200 km southwest of Bengaluru, is dominated by massive to extensively sheared gneiss, overlain by about 1 to 5 m of regolith (Collins et al., 2020), which is a thinner weathered zone than in the other catchments. Groundwater levels in Berambadi have been monitored since 2010, and the observed depths to groundwater range from 10 to 70 m (Sekhar et al., 2016).

2.1.2. *Water and land use*

Water demand in Bengaluru has risen in recent decades and cannot be met using local water resources. To overcome acute water shortages, additional water is drawn from the Cauvery River, and imported to the city via a large pipeline. River Cauvery water is now the city's main drinking water source, particularly in the centre of Bengaluru where the density of the piped mains network is the greatest. Additionally, numerous boreholes have been drilled after the onset of more advanced and affordable pump technology in the 1980s to increase access to groundwater across Bengaluru. In the outskirts of the city, these are often used for drinking water as well as for small-scale agricultural activities. In the more rural study area of TG Halli, groundwater abstraction has similarly increased in recent decades, and is likely one of the causes of strong decline in surface water flows (Srinivasan et al., 2015). In the Berambadi catchment, groundwater is the primary source of water for most water uses. Increasing groundwater abstraction for agricultural production has led to water table declines of up to 50 m (Sharma et al., 2018). However, the recent strong monsoon of 2018 has resulted in significant recoveries in groundwater levels across the catchment (Collins et al., 2020). Agricultural activities in the rural catchments are intensive, with 2–3 cropping seasons a year, namely in summer (January to May, always irrigated), kharif (May to September, frequently irrigated), and rabi (September to January, only irrigated if rainfalls are insufficient) (Sekhar et al., 2016). The irrigation pattern means that the highest groundwater abstraction for the summer irrigation coincides with the period of deepest groundwater levels.

2.2. *Sampling and analysis*

Repeat samples (total n = 112) were collected from surface water (piped mains water, river water, and tank water) and boreholes from shallow (a few metres) to about 300 m depth (Table 2) during two sampling periods, reflecting post-monsoonal (October 2017) and pre-

Table 2
Overview of number of sites sampled in both sampling campaigns and additional one-off samples (indicated in parenthesis) taken from surface water and groundwater in each round, and total number of samples collected. In addition to the listed samples, a total of 51 rainwater samples were taken in weekly to monthly intervals (35 in TG Halli and 16 in Berambadi).

	Catchment	Piped water	River/canal	Tank	Groundwater (by borehole depth)				
					< 50 m	51–150 m	151–250 m	>250 m	Total
post-monsoon (Oct '17)	Bengaluru	3*	1	4 (+5)	2	6	2 (+1)	1	19 (+6)
	TG Halli		(+2)	3 (+1)	1	2	3	12	21 (+3)
	Berambadi			3 (+1)	2	10 (+1)	1		16 (+2)
pre-monsoon (Mar-May '18)	Bengaluru	3*	1 (+2)	4	2	6 (+1)	2	1	19 (+3)
	TG Halli			3	1	2	3	12	21
	Berambadi			3	2	10	1		16
	All areas	6*	2 (+4)	20 (+7)	10	36 (38)	12 (13)	26	112 (+14)

* Only one of the three piped water samples in each round was collected from precisely the same location. However, as the piped water composition is presumed to be independent from the sampling location, all three samples in each round are considered in the repeat-dataset.

monsoonal (March-May 2018) conditions. Groundwater samples were collected from boreholes (and in two locations from open wells), and surface water — where possible — from nearby tanks, and in few cases from rivers (Vrishabhavathi River in Bengaluru) or canals. Additionally, 14 one-off samples (groundwater and surface water) were taken at different locations (numbers indicated in parentheses in Table 2). The surface water samples were obtained as grab samples (using a sampling beaker attached to a rod) at about 10–20 cm depth below the water surface and about 2–3 m off the river/tank edge. Samplers were faced upstream where applicable, and there was no disturbance to the bottom sediment immediately prior, or during sampling. Care was taken to avoid tank locations that appeared stagnant (based on visual evaluation), and sampling was undertaken near outflows where possible. No detailed information is however available on the potential degree of stratification within the surface water bodies. The samples for inorganic chemistry were filtered (0.45 µm cellulose membrane) into two 30 mL Nalgene™ bottles without airspace, and un-acidified, but prior to analysis, cation samples were acidified and preserved with Aristar™ grade concentrated nitric and hydrochloric acid (0.5% v/v). Water chemistry samples were stored at 4 °C, except during transportation to the UK (24 h at ambient room temperature).

Bulk rainwater samples (n = 51) were collected for isotope analysis (δ^2H and $\delta^{18}O$) in two of the study areas (TG Halli and Berambadi) for the one-year period September 2017 to September 2018 using a specifically designed totalizer that minimizes evaporation effects (based on IAEA/GNIP, 2014). Sampling intervals of the rainwater varied slightly depending on rainfall events, but were approximately every two weeks. Because of the close proximity (about 30 km) and similar altitude and climatology of TG Halli to Bengaluru, rainfall samples from TG Halli are considered as representative for the Bengaluru region as a whole in this study. Unfortunately, one sample for the period 11/11/2017 to 29/12/2017 (constituting about 10% of the annual rainfall) from Berambadi was lost in transport before analysis.

In each sampling round, dissolved oxygen (DO), redox potential (Eh), temperature, pH, and specific electrical conductivity (SEC), were measured in the field where possible in a flow cell, with bicarbonate alkalinity (HCO_3) concurrently determined by micro-titration. All surface waters and groundwaters were analysed for inorganic (major, minor, trace) elements using ICP-MS (Agilent 8900) and Ion chromatography (Dionex ICS5000), and for stable isotopes (δ^2H and $\delta^{18}O$) using an isotope ratio mass spectrometer (VG-Optima) at the Centre for Environmental Geochemistry (CEG), UK. The δ^2H and $\delta^{18}O$ ratios were reported in reference to the Vienna Standard Mean Ocean Water (VSMOW), with measurement precision within ± 0.05‰ for $\delta^{18}O$ and ± 1‰ for δ^2H. Deuterium excess (d-excess) was calculated using d-excess $= \delta^2H - 8 * \delta^{18}O$ according to Dansgaard (1964). Results were visualised using R version 3.6.1 (The R Foundation) and the ggplot2 package. Spatial plots were undertaken using ARCGIS®.

In addition to the hydrochemical investigation, pressure transducers were installed at six locations in Bengaluru and in one location in Berambadi to record water level variations at high frequency (15-minute intervals). Additional manual water level measurements (dip meter) were taken manually at approximately monthly intervals for five of the sampling boreholes in Berambadi and five boreholes in the southern subcatchment of TG Halli (see Fig. 1 B for detailed locations of all monitored sites, and Supplementary Material Table S1 for additional information on borehole elevations and depths). More comprehensive water level observations for the same period from the Kabini observatory (Berambadi) are available in Collins et al. (2020).

3. Results

3.1. Stable isotopes

Results of the stable isotope analysis (including one-off samples) are presented in Fig. 2 for rainfall samples (Panel A) and groundwaters and surface water by sampling round (Panel B-C), along with the amount weighted mean rainfall composition for TG Halli (also used for Bengaluru given the proximity of ~ 30 km) and Berambadi. Tabularized data, such as mean values and standard deviations for $\delta^{18}O$, δ^2H, and d-excess of surface waters and groundwaters by study area and sampling round are provided in Table S2 in the Supplementary Material.

The $\delta^{18}O$ ratio of the rainfall samples (n = 51) ranged between −9.3‰ and + 1.6‰ (median −5.3‰), and that of δ^2H between −65.9‰ and + 22.3‰ (median −28.5‰). The amount weighted average for the TG Halli rainfall samples was −5.2‰ for $\delta^{18}O$ and −30.3‰ for δ^2H, and the (incomplete, i.e. missing data from one sample) amount weighted average in Berambadi was −3.7‰ for $\delta^{18}O$ and −20.0‰ for δ^2H. The overall distribution of $\delta^{18}O$ and δ^2H for the rainfall samples is similar to the local meteoric water line ($\delta^2H = 11.74\ \delta^2H + 7.82$) established by Kumar et al. (2010) in an earlier study in Karnataka and the global meteoric waterline (GMWL with $\delta^2H = 8\ \delta^2H + 10$) (Fig. 2, note that the local and global meteoric waterlines are nearly identical).

Surface water samples in Bengaluru (from piped mains, Vrishabhavathi River, and tanks) have similar isotopic compositions to each other in the post-monsoon season (reflecting wet conditions), but there is a slightly higher evaporative signal in the tanks compared to the piped mains and river water in the drier pre-monsoon sampling. This is indicated for example visually by the slightly more positive $\delta^{18}O$ (Fig. 2C) of the Bengaluru tank samples, and the lower pre-monsoon median d-excess of the Bengaluru tanks (-8.3‰) compared to the piped and river water (0.7 and 2.9‰, respectively, see Table S2 and Figure S1 in the Supplementary Material). Surface waters in the rural catchments have slightly isotopically lighter composition than groundwaters in the post-monsoon (Fig. 2B), and a stronger, but not significant (Wilcoxon rank sum test) pre-monsoonal enrichment in heavier isotopes (median d-excess of −28.7 and −23.9‰ for TG Halli and Berambadi, respectively, compared to only −8.3‰ in Bengaluru, Figure S1, Table S1). Groundwater isotopic compositions show a marked difference in spread between the urban and the rural catchments, with a larger variation

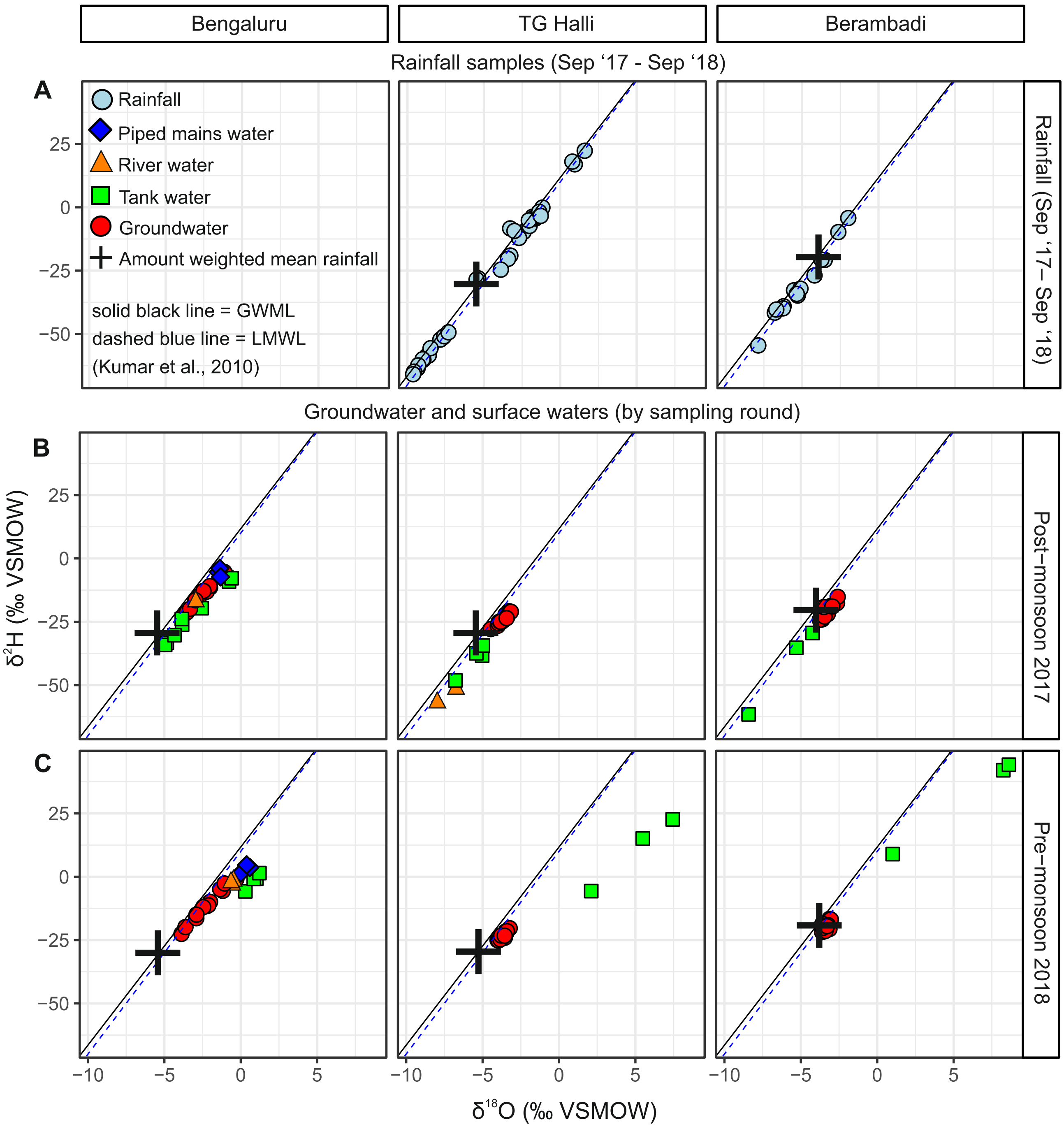

Fig. 2. Stable isotope composition (δ^2H versus $\delta^{18}O$) for (A) rainfall sampled in about 6-weekly intervals from September 2017-September 2018, and (B-C) groundwaters and surface water by sampling round (post-monsoon 2017 and pre-monsoon 2018). Water types are indicated by colour and symbol, and the weighted mean rainfall refers to the one-year amount weighted rainfall mean (September 2017 to September 2018) for TG Halli and Berambadi (due to a data gap in rainfall collection in Berambadi, the weighted average for this area may be slightly skewed). Note that the local meteoric water line (LMWL, dashed blue line) and global meteoric waterline (GMWL, solid grey line) are nearly identical. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

between sample locations in Bengaluru compared to a very homogenous compositions in the rural catchments TG Halli and Berambadi (Fig. 2), plotting close to the amount average weighted rainfall. This is reflected for example by the higher (three-fold) standard deviation for $\delta^{18}O$ in Bengaluru of ± 0.9‰ compared to ± 0.3‰ for TG Halli and Berambadi (Table S1, Supplementary Material). The observed variations in Bengaluru seemed to be slightly greater in shallower boreholes, but there is no significant correlation between isotopic composition and borehole depth at either study area (Fig. 3, *R = -0.27 for* $\delta^{18}O$ versus borehole depth).

Closer examination of groundwater samples from Bengaluru seems to suggest that samples fall into two separate groups (with distinct behaviour, namely an 'inner-city group' (sampling sites near Lalbagh, IISc, and Sankay tank, Figure 4 right column), which consists of groundwater samples that are more isotopically enriched (i.e. more evaporated) and have similar isotopic ratios to piped and tank waters, and a second group of groundwater samples from the outskirt areas (Allalasandra tank, Vrishabhavathi, and Kaikondrahalli tank, Figure 4

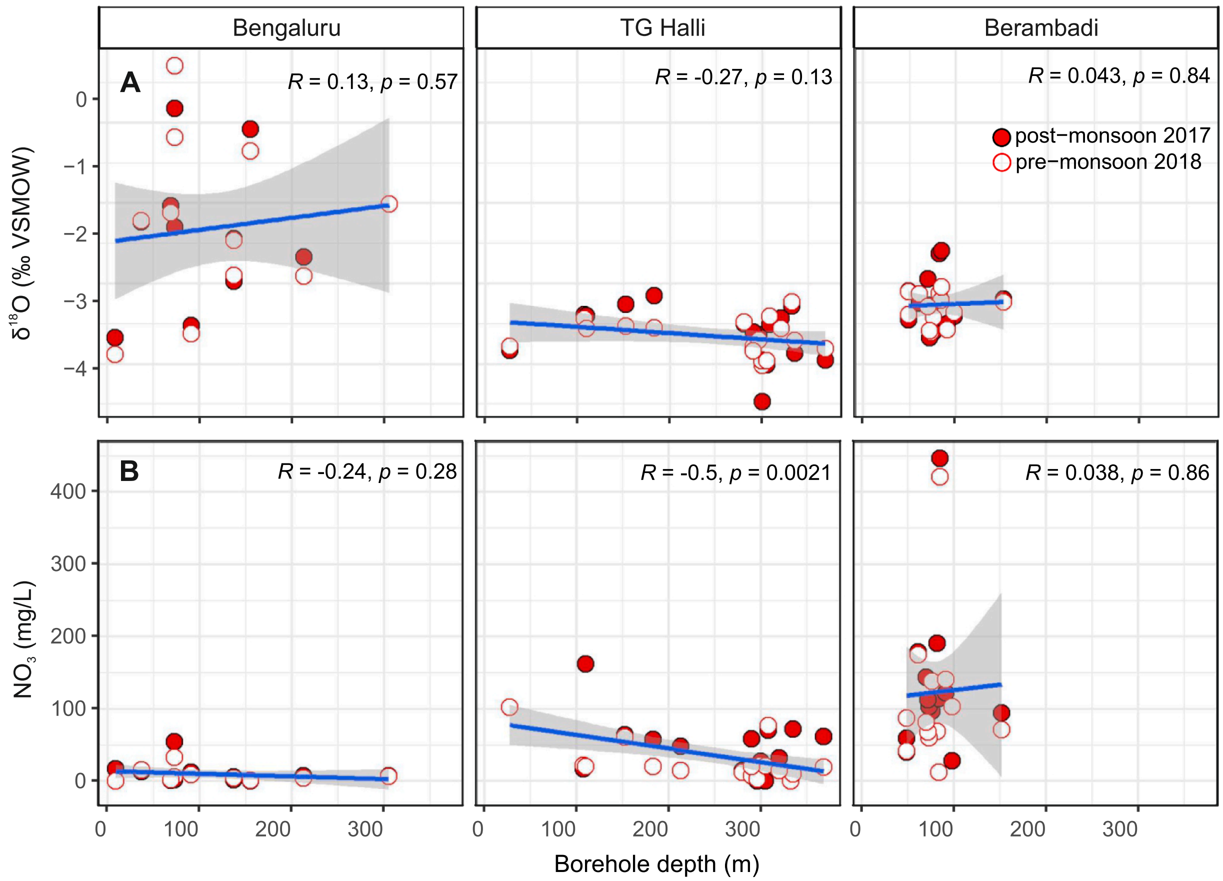

Fig. 3. Covariant plot of (A) $\delta^{18}O$ and (B) NO_3 concentration in groundwater versus borehole depth. Both plots demonstrate the lack of strong correlations between concentrations and borehole depth (all R < 0.7, Pearson correlation).

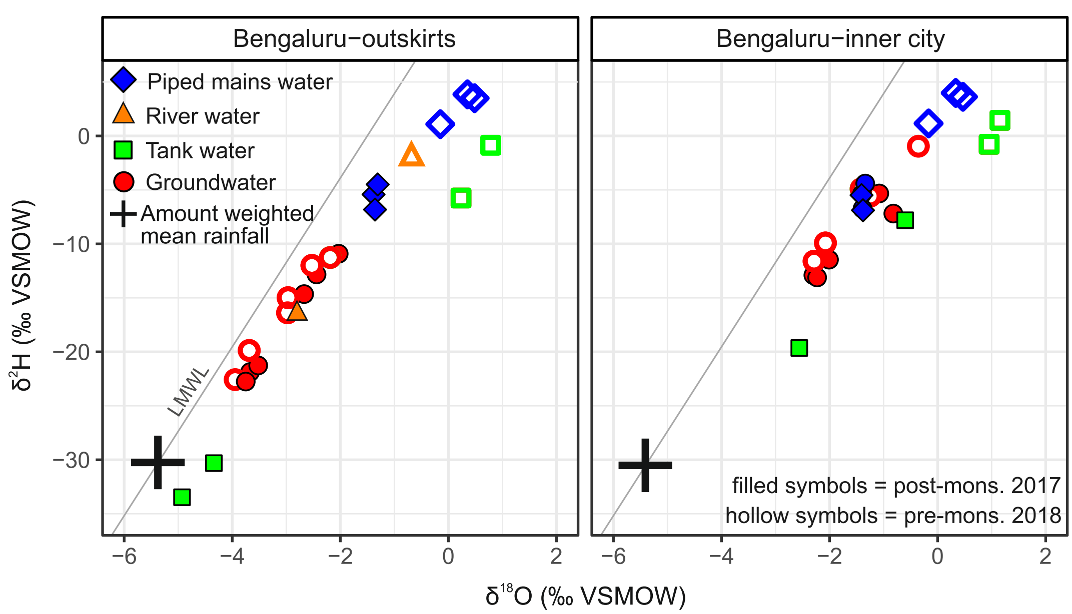

Fig. 4. Plot of δ^2H versus $\delta^{18}O$ of sampled waters in Bengaluru, comparing the outskirts (sampling locations Allalasandra tank, Vrishabhavathi, and Kaikondrahalli tank) and the inner-city region (sampling sites Lalbagh, Sankay, and IISc, located within ~ 1 km west of Sankay Tank; Fig. 1). Piped mains water and the amount weighted mean rainfall is shown for both inner city and outskirts. The local meteoric water line (LMWL) is added in grey.

left column, refer to Fig. 1 for detailed locations). Samples from the outskirts are significantly (Wilcoxon rank sum test < 0.05 for d-excess and $\delta^{18}O$) less isotopically enriched, as indicated for example by the lower mean $\delta^{18}O$ of tank groundwaters from the outskirts (-2.9‰ post-monsoon 2017 and −3.0‰ pre-monsoon 2018) compared to the inner-city samples (-1.7‰ and −1.4‰, Fig. 4).

3.2. Hydrochemistry

3.2.1. Water types and major ion chemistry

A piper plot (Fig. 5) of all analysed samples by study area and source type demonstrates that the rural catchments are almost entirely dominated by alkaline earth elements (Ca, Mg), while some samples in the urban setting (Bengaluru) are dominated by Na. The dominant water type in Bengaluru is Ca-Na-HCO_3, with exception of piped water (Ca-Mg-HCO_3 type) and eight samples with Cl as dominant anion (most of these near Kaikondrahalli tank). The rural catchments (TG Halli and Berambadi) exhibit a more diverse range of water types, with higher proportions of Mg both in tank water and in groundwaters. Contrary to Bengaluru, Cl dominance in the rural catchments only occurred in two pre-monsoonal tank samples in TG Halli, and in none of the samples in Berambadi (for more detailed information on water types by study area, water source, and sampling round see Supplementary Material Table S3).

3.2.2. Surface water major ion chemistry and field parameters

Piped water in Bengaluru has median concentrations of Ca, HCO_3, and SO_4 similar to the city's tank water, but is generally lower in concentrations of K, Na, and Cl (Fig. 6, with tabular data given in Supplementary Material, Table S4). Mg concentrations in piped water (medians around 19 mg/L) are about twice as high as in the city's tank water. Most noteworthy, NO_3 was detected in the post-monsoonal piped water in concentrations of up to 19.7 mg/L, while little NO_3 was observed in Bengaluru's tank water in either sampling round (all concentrations < 1 mg/L NO_3). River water samples from Vrishabhavathi River showed generally higher concentrations of all major ions and SEC of around 1400 μS/cm (Fig. 6). Tank waters are relatively similar in composition for the three studied catchments, though the Bengaluru tanks have slightly higher ion concentrations with regards to Ca, Mg, HCO_3, and most noteworthy higher Na and Cl (Fig. 6). The higher Cl concentrations in Bengaluru exceed those of the rural catchments roughly by 30 mg/L and with higher concentrations at Kaikondrahalli Tank (>90 mg/L in both sampling rounds).

Pre-monsoonal Cl medians are higher than post-monsoonal ones in all study regions. In Bengaluru, this is mainly caused by strong increases in Cl concentrations in the two tanks in the outskirts (increase by 101% and 73% at Kaikondrahalli and Allalasandra Tank). The inner-city tanks Sankay and Lalbagh, surrounded by a more densely piped mains network (Fig. 1B), only show increases in Cl by 19% and 39%,

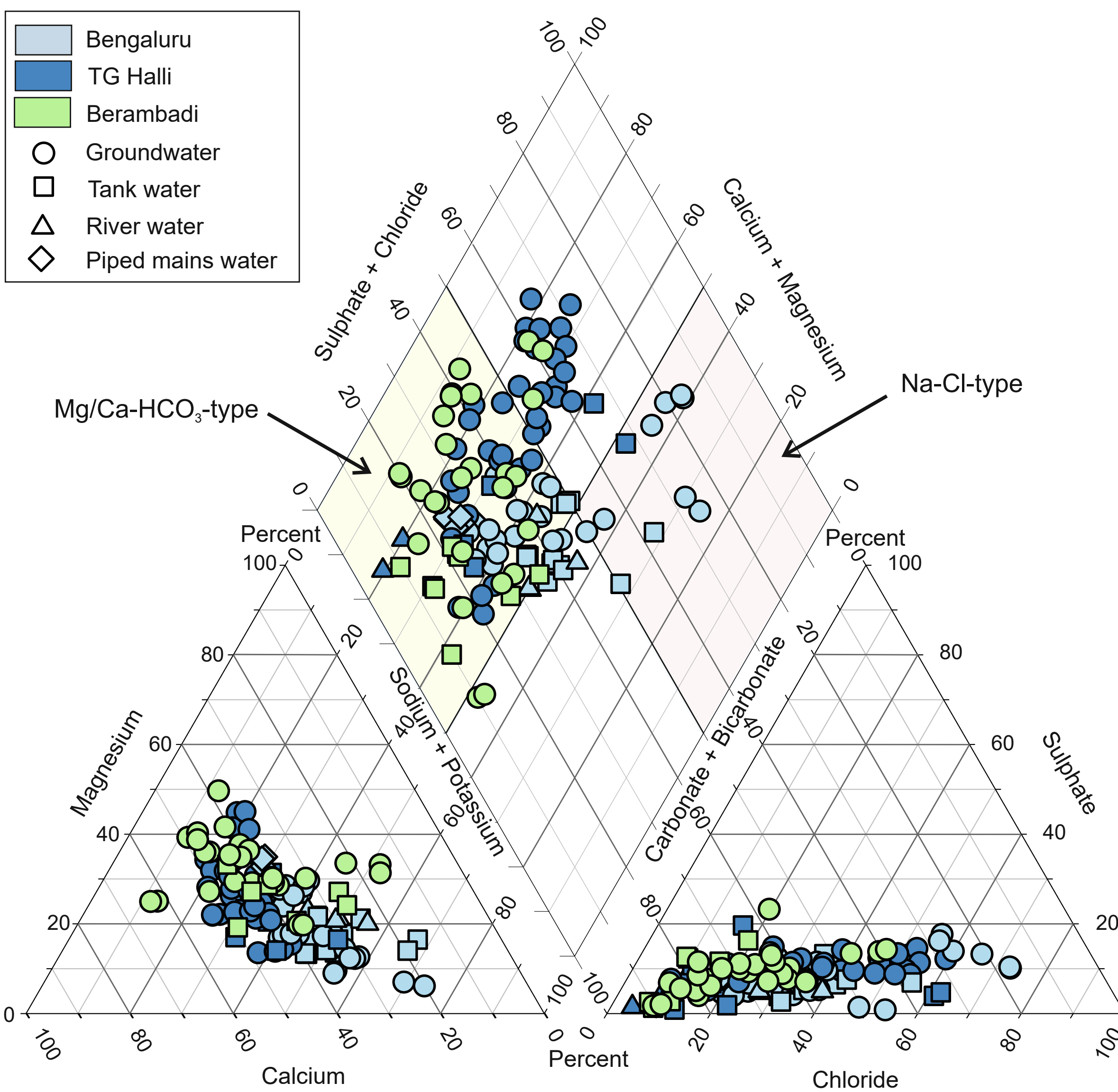

Fig. 5. Piper plot of water samples (groundwaters and surface water) from both sampling rounds grouped by study areas. Colours indicate the study area, and symbols reflect the water type.

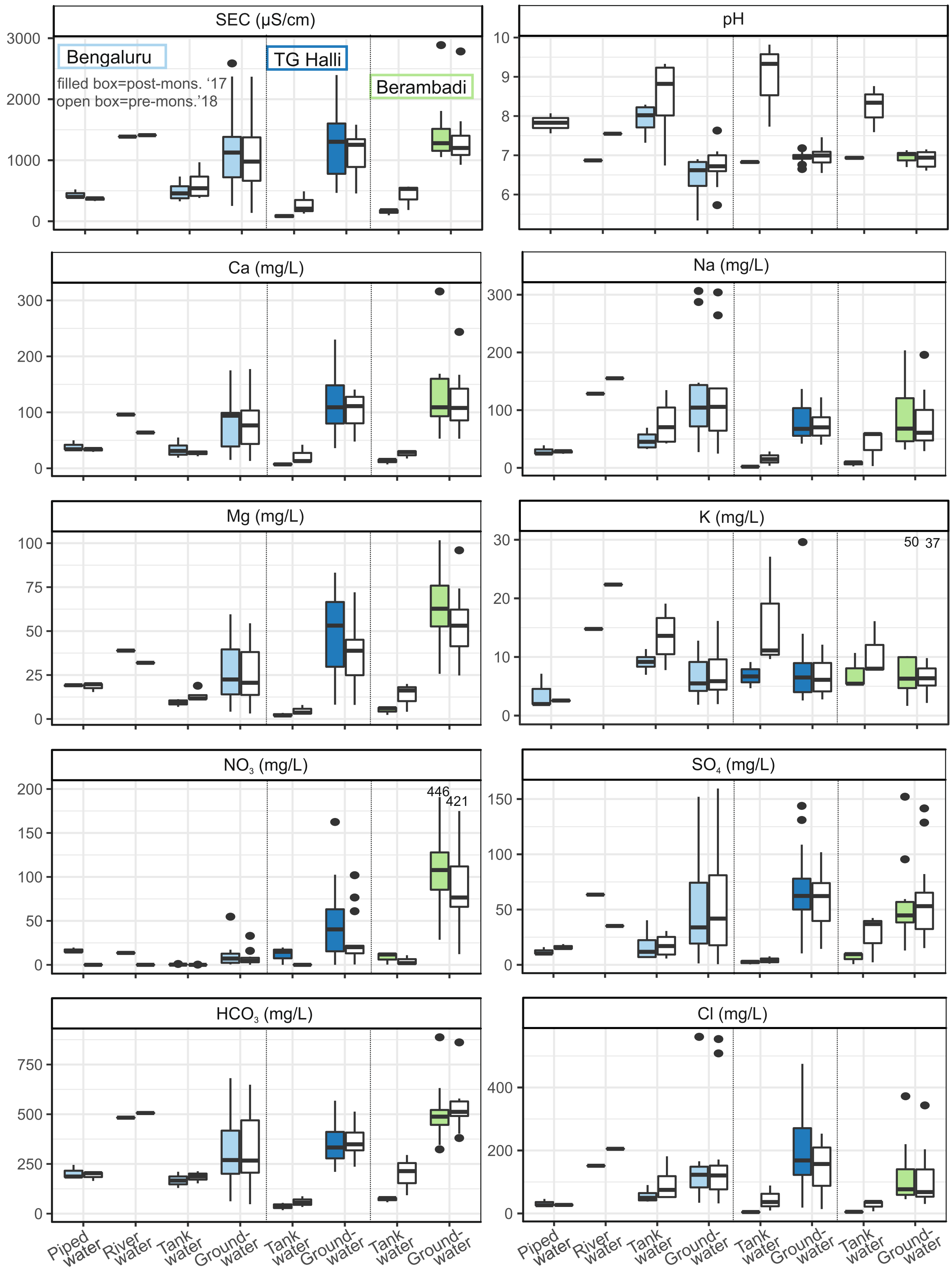

Fig. 6. Boxplot showing post-monsoon (Oct'17) and pre-monsoon (Mar-May'18) concentrations of selected major ions and field parameters for surface waters and groundwaters grouped by study area. Note that values exceeding the y-scale of the respective plot are included as values above the box. Lower and upper box hinges correspond to 25th and 75th percentiles and whiskers indicate 1.5 × Interquartile Range (IQR).

respectively. SEC and pH in tank waters are higher in the pre-monsoon, with generally larger increases in the rural catchments than in Bengaluru (Fig. 6).

3.2.3. Groundwater major ion chemistry and field parameters

Groundwaters in all three study areas have a relatively constant major ion composition over time (changes by < 25%) except for distinct decreases in NO_3 (by 27–41% in all study areas) and Mg (by 27% in TG Halli) in the pre-monsoon season. Ca, Mg, and NO_3 concentrations in the rural catchments are significantly higher than in Bengaluru, while the reverse holds true for pH (Wilcoxon rank sum test < 0.5). Mg, NO_3, HCO_3, and SEC all follow a distribution of Berambadi > TG Halli > Bengaluru. Median K concentrations in groundwaters are without significant differences across study areas and in time, and range 5.5 to 6.8 mg/L. Median Cl concentrations followed the order TG Halli > Bengaluru > Berambadi (highest/lowest median of 168.4 and 67.9 mg/L), and were slightly lower in the pre-monsoon sampling (decrease by 1–12%). Cl concentrations > 100 mg/L were measured in Bengaluru groundwater near Kaikondrahalli, Lalbagh and Vrishabhavathi River (highest measured concentration 560.9 mg/L; near Kaikondrahalli), and in TG Halli in almost all samples from the Aralamallige southern subcatchment (maximum concentration 475.1 mg/L) but none of the

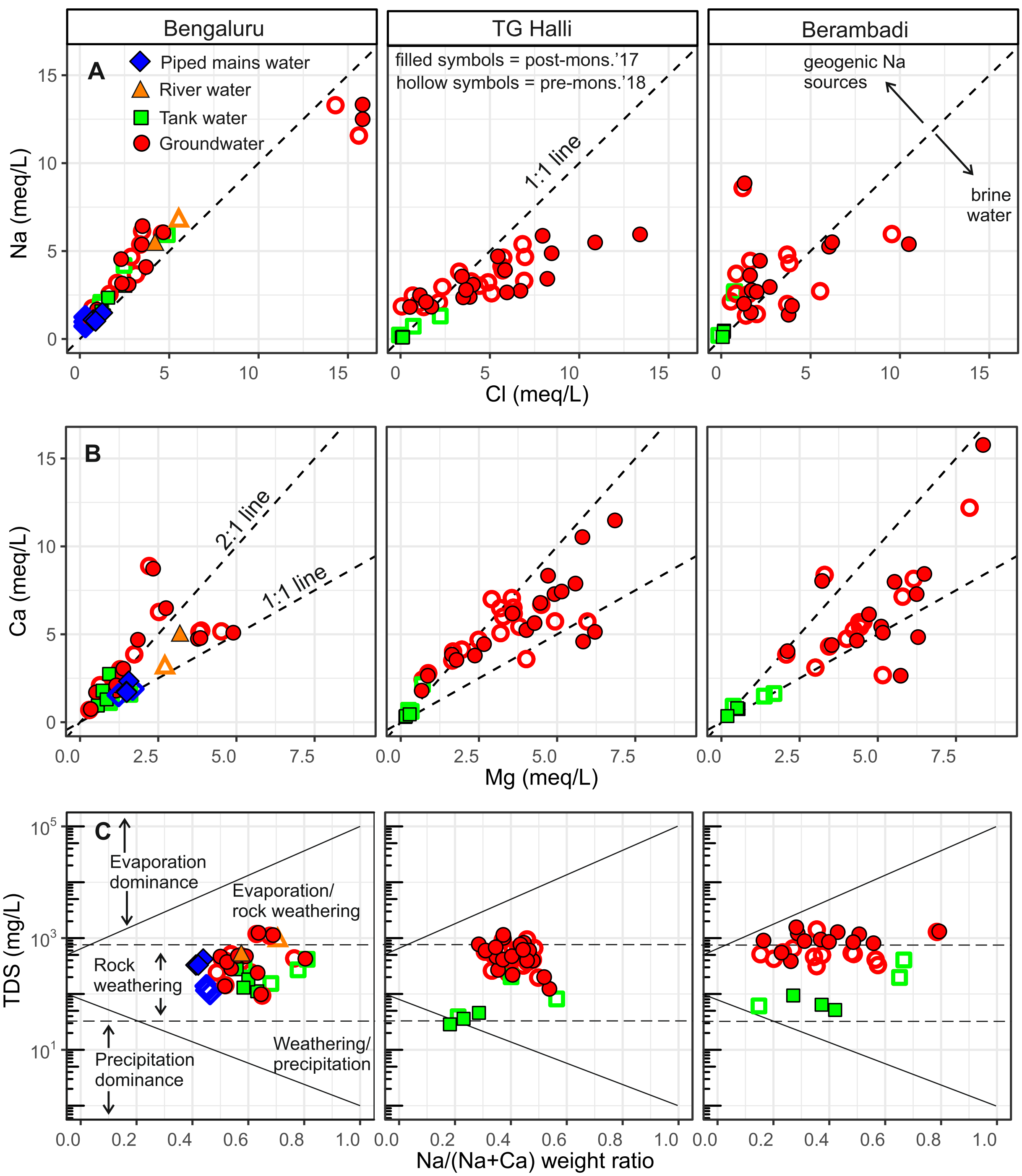

Fig. 7. Covariant plots of (A) Na versus Cl (meq/L) with indicated 1:1 line, (B) Ca versus Mg (meq/L) with indicated 2:1 line and 1:1 line. (C) Gibbs plot indicating main evolution processes (evaporation / rock weathering / precipitation) of waters. Sample type is indicated by symbol and colour, and sampling round (post-monsoon 2017/pre-monsoon 2018) by filled/hollow symbols.

samples from the second sub-catchment Hadonahalli (maximum concentration 61.3 mg/L). In Berambadi, a slight trend of increasing Cl concentrations from west (mostly $<$ 100 mg/L) to east (most concentrations $>$ 100 mg/L) was observed. High concentrations of NO_3 exceeding the Indian drinking water limit (DWL) of the Bureau of Indian Standards (BIS) of 45 mg/L NO_3 (BIS, 2012) were primarily detected in Berambadi (85% of all samples, maximum 446.3 mg/L NO_3) and TG Halli (33%, maximum 162.5 mg/L NO_3), and only at one site in Bengaluru (54.8 mg/L near Lalbagh tank; post-monsoon). It is noteworthy that, except for a weak significant correlation for TG Halli, NO_3 did not show significant trends with the drilled depth of the sampled boreholes (Fig. 3). For a full list of percent of samples exceeding DWLs by study area, see Supplementary Material Table S3.

3.2.4. Chemical ratios, trends with distance to surface water and estimated impact of tanks

The covariant plot of Na versus Cl (Fig. 7A) demonstrates that Na:Cl ratios in Bengaluru (with the exception of the Cl-rich samples from near Kaikondrahalli) closely follow the 1:1 ratio for halite sources or anthropogenic NaCl inputs, while there is excess Cl (or a depletion in Na) observed in TG Halli and Berambadi, especially in the post-monsoon season. In the covariant plot of Ca versus Mg (Fig. 7B), most groundwater samples in all study areas fall between the 2:1 line and 1:1 line, though there is generally a stronger ion concentration and higher proportion of Mg in the rural catchments compared to Bengaluru. This could be indicative either of local differences in geological setting, or be an impact of agricultural inputs, e.g. application of $CaNO_3$-type fertilizer, indicated by a weak to strong correlation between Ca and NO_3 in rural groundwaters ($R = 0.53$ and $R = 0.74$ for TG Halli and Berambadi, respectively, with $p < 0.0005$). Fig. 7C shows the Gibbs plot for TDS versus Na/(Na + Ca) weight ratio, which can give information about the dominant evolution processes of waters (Gibbs, 1970). The results indicate that neither study area exhibits strong evaporation nor precipitation dominance, and there is a stronger clustering of waters from all source types in Bengaluru, while in the rural catchments, most tank waters are separated out from the groundwater samples.

Fig. 8A shows the Cl/Br mass ratio versus Cl (mg/L) for each study area by source type. Ratios between Cl and Br in waters from different

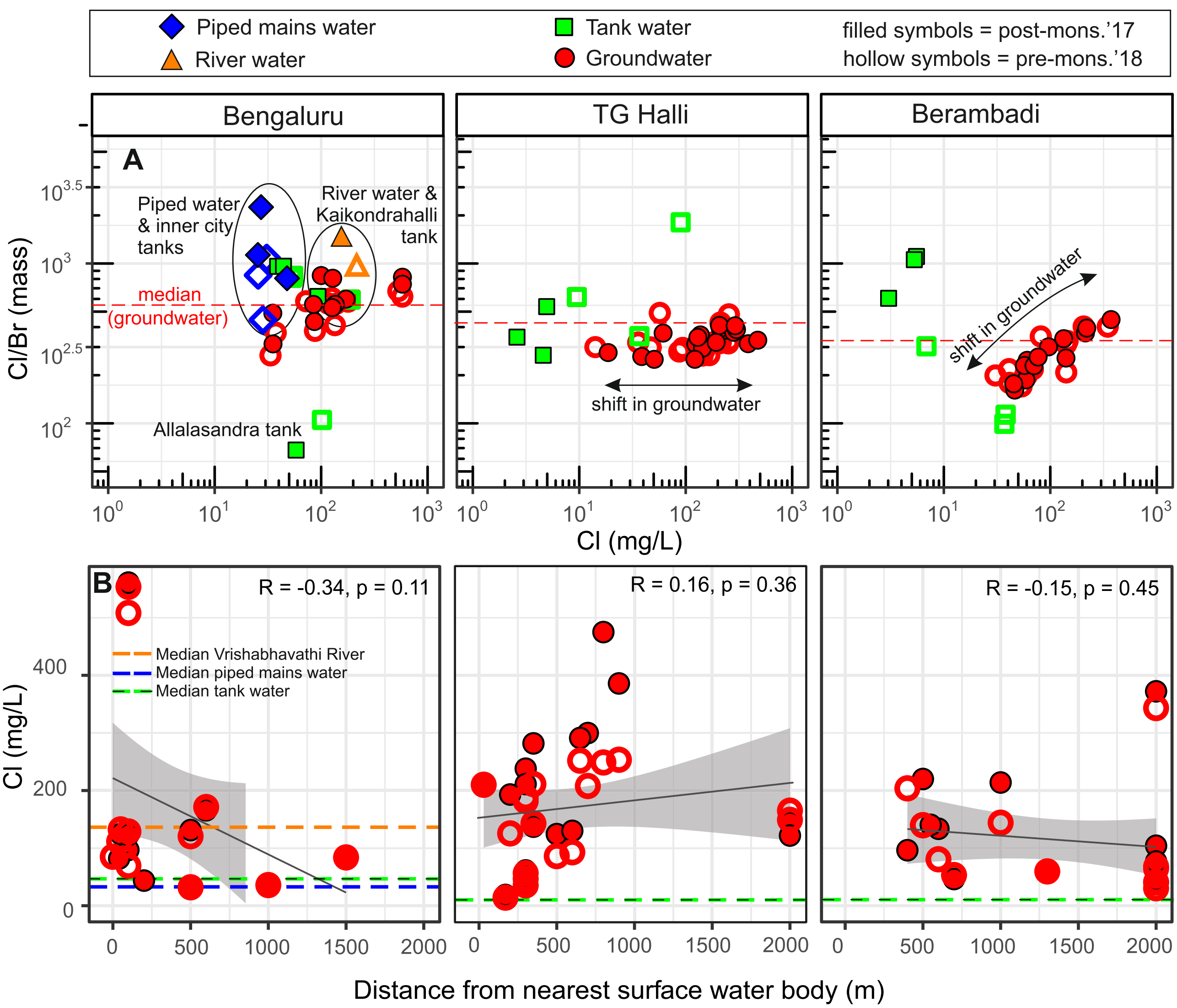

Fig. 8. (A) Cl/Br mass ratio versus Cl (mg/L) per study area for all water sources that were sampled in both sampling rounds. The median Cl/Br mass ratio for groundwater is indicated by the red dashed line. Arrows indicate the direction of potential groundwater mixing for rural groundwaters, which suggests endmembers in TG Halli with similar Cl/Br ratio, but higher/lower Cl, and in Berambadi with stable Br and higher/lower Cl concentration. (B) Correlation plot of Cl concentration (mg/L) in groundwater versus distance of the sample location from the nearest surface water, with Pearson correlation coefficients indicated on the top right. Dashed coloured lines indicate the median Cl concentrations over both sampling campaigns for Vrishabhavathi (Bengaluru), piped mains water (Bengaluru), and tank water (for each catchment). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

sources usually have a typical range, and due to these distinct ratios, the Cl/Br ratio can give information on mixing processes (Alcalá and Custodio, 2008) and be used to identify recharge to groundwater. Whilst Cl is usually detected at concentrations well above the detection limit, it should be noted though that low Br concentrations close to detection limits may cause some uncertainty in Cl/Br ratios. In our study, 4 of the tank water samples had Br concentration < 1.5 times the detection limit (2 in TG Halli and 2 in Berambadi, concentrations of around 0.015 mg/L). We have no repeat analysis of these samples, but a presumed uncertainty of +/- 10% would shift the Br/Cl mass ratio at the same percentage, so interpretation of these data will focus on the combination of Br/Cl mass ratio and Cl concentration, without too much emphasis on the Br/Cl mass ratios alone.

The Cl/Br plots show a distinct pattern for each study area. In Bengaluru, groundwaters have a median Cl/Br mass ratio of 552 (indicated by the dashed line, Fig. 8A). Surface water Cl/Br ratios mostly lay within 442–2222. One location, Allalasandra tank, has a markedly low ratio of 66 (post-monsoon) and 104 (pre-monsoon). This is caused by unusually high Br concentrations of up to 1 mg/L (versus the overall median of 0.1 mg/L). Other tank waters in the inner-city of Bengaluru plot similarly to most of the piped water (Fig. 8A). As indicated in the previous chapter, piped water and inner-city tanks in Bengaluru generally have lower Cl than river water samples and samples from Kaikondrahalli tank, which also creates a distinction in the Cl/Br plot. The groundwater samples mostly cluster according to their specific location, and no clear trend can be observed.

In TG Halli, groundwater has a relatively uniform Cl/Br ratio with a median of 239 (Fig. 8A), but with a large range in Cl concentrations (from 14–475 mg/L). Tank waters seem similar in Cl/Br ratio, but with some spread in Cl concentrations (3–89 mg/L). The shift in groundwater composition is dominated by a shift along the x-axis which may indicate mixing with either lower or higher Cl water (but with similar Cl/Br ratio). This could indicate a dilution of Cl-rich groundwater by the lower-Cl tank waters. However, a correlation analysis (Person correlation) between the proximity of the borehole location to tanks does not show significantly lower Cl concentration near tanks (Fig. 8B).

Berambadi groundwater samples show a very pronounced pattern indicative of a mixing line that could be produced by waters with constant Br concentration, but higher/lower Cl. Potentially, this is an indication of recharge by return flow from groundwater irrigation, as one may suspect similar Br, but increased Cl due to evaporation processes (mixing of this type will result in a right shift due to the increased Cl, and upward shift due to the change in Cl/Br ratio). Some of the higher Cl concentrated-tank waters seen on Fig. 8A could be a potential endmember (in this case of lower chloride concentration than the groundwaters, thus diluting their Cl concentration). However, the lack of correlation between a borehole's Cl concentration and its borehole proximity to tanks does not seem indicative of this ($R = -0.15$, $p = 0.45$; Fig. 8B), so that the mixing of the groundwater with higher Cl concentrations seem more likely.

Aside from Cl, water isotopes are usually considered a conservative tracer, as they are commonly detected in groundwater with the same isotopic composition as the recharging water, e.g. rainfall recharge (e.g. Darling and Bath, 1988). Table 3 shows the mean d-excess for amount weighted rainfall, tank water and groundwater (mean over both sampling periods) in the three study catchments. It should be noted that the Berambadi rainfall is missing the analysis of one sample, and that a longer-term (several years) amount weighted rainfall would be considered more reliable. Hence, we are only using TG Halli here as example for a 2-endmember mixing. Because there is no significant correlation between d-excess and distance of the boreholes to the nearest tank (Supplementary Material, Figure S2; this is in good correspondence with the lack of significant trends in Fig. 8B), the mean of all groundwater samples is considered. Assuming the fraction of tank water times tank water d-excess plus the fraction of amount weighted rainfall times rainfall d-excess to be equal to the groundwater composition, this would result in a fraction of 2.6% (TG Halli) for tank recharge, which is very low and indicates that the effective recharge of deeper groundwater within the fractured bedrock seems to be negligible compared to other recharge sources. A more specifically designed monitoring network with site-specific installation of deeper monitoring boreholes of varying distance from tanks could provide further details on whether significant trends of conservative tracers might be detectable on smaller scales.

Table 3
Mean d-excess (‰ VSMOW) for rainfall (amount weighted rainfall), tank water and groundwater (mean over both sampling periods). It should be noted that the Berambadi rainfall is missing the analysis of one sample, and that a longer-term (several years) amount weighted rainfall would be considered more reliable. Hence, these values are here only being used to exemplify that — considering rainfall and tank water to be two end-members — tank water seems to play a minor contribution in annual groundwater recharge.

Catchment	Mean d-excess (‰ VSMOW)		
	Amount weighted rainfall	Tank water	Groundwater
Bengaluru	5.83	−0.42	5.83
TG Halli	5.83	−9.85	5.67
Berambadi	9.88	−3.73	6.38

3.3. Groundwater level observations

Fig. 9 shows the high-frequency (15-min interval and daily maximum) monitored groundwater level observations from September 2017 to September 2018 for Bengaluru and (only until April 2018) one site in Berambadi, and monthly to bi-monthly dipped data for TG Halli and Berambadi. The monitored boreholes are typically cased in the weathered zone and are open bores in the fresh rock, with depth of 50–163 m bgl in Bengaluru, 218–296 m bgl in TG Halli, and 61–98 m bgl in Berambadi. Borehole head elevations in Bengaluru were at elevations of 889–926 m above sea level (asl; except Bangalore University at 831 m asl) and 874–888 m asl in TG Halli. Borehole head elevations in Berambadi ranged 831–897 m asl (Supplementary Material Table S1). Most monitored sites show a decreasing trend in water level between November and April when precipitation is low.

In Bengaluru, groundwater levels are shallow (average daily maximum level ranging 1–9 m bgl) at the three sites closest to the city centre, and deeper (19–34 m bgl) at sites towards the outskirts (Fig. 9B). Daily groundwater level fluctuations are highly variable across sites, but can be categorized into Group A: sites that experience high and rapid fluctuations (IISC, Yelahanka, Nimhans), and Group B: sites that show little daily fluctuations (Cubbon Park, Lalbagh Park, Bangalore University). Because rapid changes in groundwater level are most commonly caused by nearby groundwater abstractions, it can be assumed that Group A is more directly influenced by anthropogenic head changes, while Group B reflects a more undisturbed condition. The extremely rapid drawdown in some of the boreholes (level decrease of up to 3.5 m in 15 min) is indicative of a high fracture connectivity and low storage in this part of the aquifer. The maximum daily water level in Bengaluru decreased by 1–5 m in the dry season, and showed no strong overall trends, but possibly some downward tendency at two sites (IISc and Lalbagh).

Groundwater levels in TG Halli (Fig. 9B) were only monitored from September 2017 to end of March 2018, which coincides with the pre-monsoon water sampling. Water levels are much deeper than those in Bengaluru with averages ranging 79 to 148 m bgl. These levels may have dropped somewhat lower in the summer months that are not included in this dataset. The strong variation in groundwater levels between sites corresponds well to previous studies (Ballukraya and Srinivasan, 2019). Three of the five monitored sites (indicated by the black lines Fig. 9B) show much more rapid level increases after strong rainfalls in September to November 2017 (Fig. 9A), which is indicative of rapid fracture flow into these boreholes.

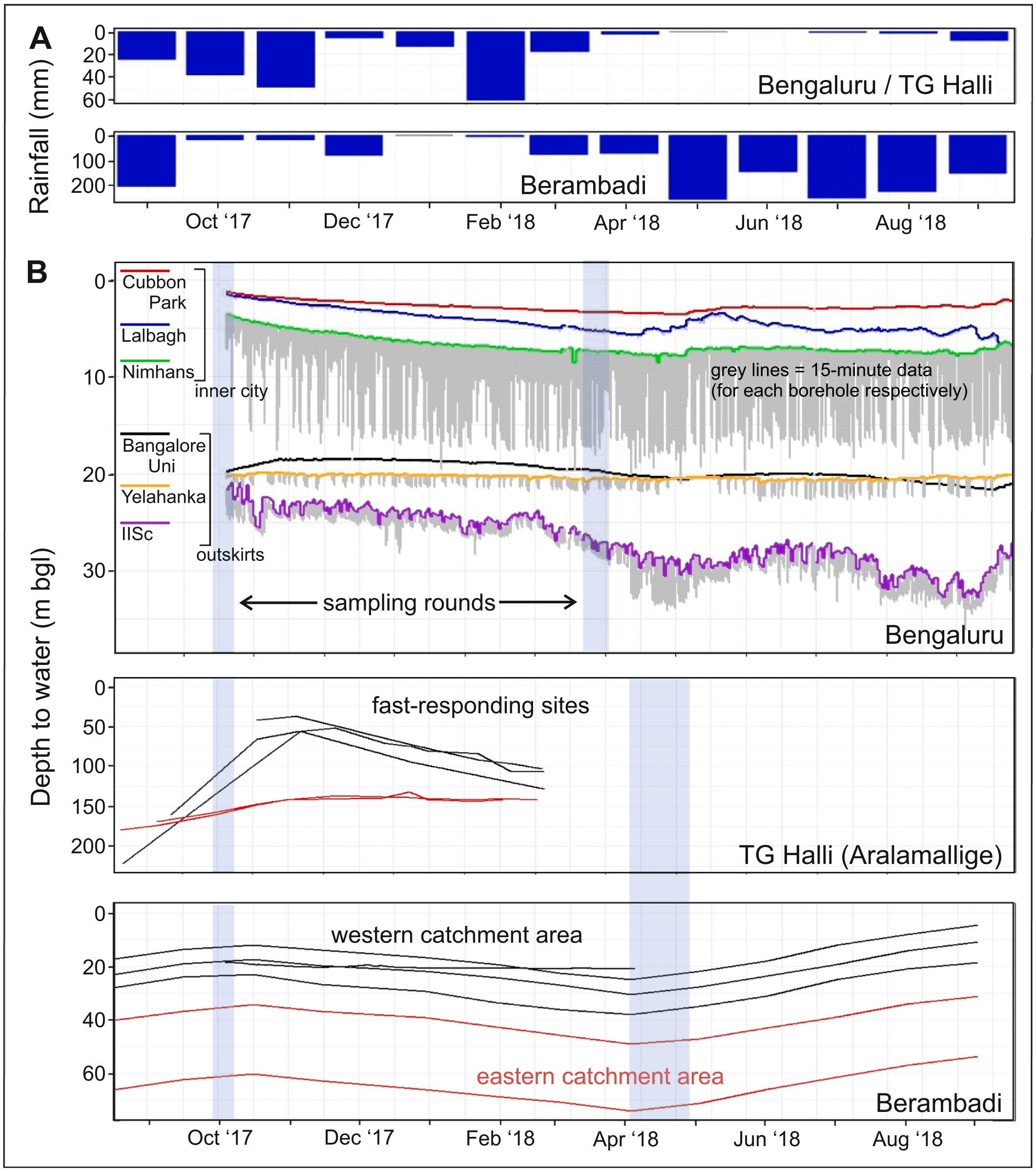

Fig. 9. (A) Precipitation data for Bengaluru/TG Halli and Berambadi from September 2017 to October 2018, and (B) depth to water in metres below ground level (m bgl) for all three study areas. Observations in Bengaluru are shown as daily maximum groundwater level (coloured lines) and corresponding high-frequency measurements (15-minute interval; grey lines below the coloured lines for each location), and for TG Halli (data only from Sep 2017 to end Mar 2018) and Berambadi as monthly dipped data. Shaded vertical bars indicate times of groundwater sampling. Note the different scale of the y-axes.

In Berambadi, groundwater levels show a distinct regional gradient with the shallowest average groundwater level (14 m bgl) at the westernmost site, and deepest average level (62 m bgl) at the easternmost location, which corresponds to observations from previous studies (e.g. Buvaneshwari et al., 2017; Collins et al., 2020; Sharma et al., 2018). The monitored sites exhibit a temporal trend with post-monsoon peak levels in November 2017 and a gradual decline until the onset of the new recharge in May 2018. Compared to Bengaluru and TG Halli, the seasonal groundwater level declines are more pronounced with a drop of 13–15 m from the peak level in November 2017 to the lowest recorded level in April 2018.

4. Discussion

4.1. Evidence of connectivity of the deeper basement aquifer to modern recharge processes

The observed lack of strong correlations between isotopic ratios or NO_3 concentrations with borehole depth in all study areas (Fig. 3) is indicative of a well-mixed system, and the detection of typical anthropogenic pollutants, such as NO_3, in high concentrations even at greater depth indicates that recharge is modern. These findings are in accordance with a parallel study by Collins et al. (2020) who demonstrated by means of a range of hydrogeochemical techniques, including the residence time tracer CFC, a high degree of lateral and vertical connectivity in the Berambadi catchment. For example, a homogenously high concentration of CFCs in both shallow and deep monitoring boreholes in this study was found indicative of recent recharge and of a well-mixed groundwater system without clear vertical stratification. However, depending on the number and position of intercepted fractures (borehole casings in the study area are usually cased down to the base of the weathered zone, which likely ranges between 15 and 60 m bgl, and open bores from thereon), a water sample may represent an integrated sample with contributions from shallower fractures in the upper part of the fresh rock potentially overlaying chemical signatures from deeper fractures. It can be concluded that the deeper basement aquifer has a component of modern recharge in all investigated catchments with either fractures or the boreholes acting as preferential pathways.

4.2. Comparison of relative contribution of tank recharge to other sources

The variability of isotopic ratios in the groundwater samples from Bengaluru (Fig. 2 and Supplementary Material Table S2), indicates that groundwater recharge in the urban setting is influenced by multiple sources including mains leakage, urban runoff and drainage, and infiltration from rainfall and surface waters (conceptualized in Fig. 10).

As expected for the complex urban setting, hydraulic heads in the monitored boreholes demonstrated distinct patterns, ranging from sites with little daily fluctuations (Cubbon Park, Lalbagh Park, Bangalore University) to sites with high and rapid fluctuations (IISC, Yelahanka, Nimhans) (Fig. 9). From a monitoring perspective, these strong head changes at Bengaluru highlight that manual monitoring in low-storage fractured aquifers is best undertaken by taking a series of measurements over time to ensure that a representative water level is recorded. Monitored boreholes in areas with a higher density of the piped water supply system that delivers mainly water from the Cauvery River as potable water supply generally exhibited shallow groundwater levels, typically about 1 m bgl (Lalbagh and Cubbon Park). The shallower groundwater level is likely caused by substantial recharge from the piped mains water network. This is in accordance with other recent studies (Sekhar et al., 2018; Tomer et al., 2021). The similar isotopic signature (Fig. 4) and Cl/Br ratios in inner-city tanks, piped water and groundwater (Fig. 8) also point to a strong connection between these waters - with tanks possibly being recharged by the shallow groundwater in the post-monsoon season. Pre-monsoon, most groundwater levels were below the assumed average tank depth, and tanks would be expected to lose water through infiltration and potentially recharge groundwater (Fig. 10A). However, assumed flow is not based on precise monitoring of the tank water level, and a more detailed study would be necessary to clearly identify the predominant flow direction. In either case however, connections and exchange of tank, piped and groundwater in the inner-city area is of high likelihood. In the outskirts, tank water is mainly fed by direct rainfall and runoff, as well as treated and partially untreated sewage collected in drainage canals (indicated by a higher pollutant load of these sites, e.g. Cl), and to a lesser extent by the sparser mains system (Fig. 10B). This conceptualization is supported by strong post-monsoonal similarity between tank water and the amount weighted average rainfall composition in the outskirts, and conversely the stronger post-monsoonal similarity of isotopic composition in tank waters with piped water and groundwater in the inner-city areas (Fig. 4).

In the rural catchments (TG Halli and Berambadi), recharge pathways differ from the urban city in regards to a lack of water mains and the additional recharge from irrigation return flow (Fig. 11). The rural groundwaters show higher spatial similarity in isotopic compositions (e.g. lower standard deviations across the sample groups, see Supplementary Material, Table S2) than groundwaters in Bengaluru, and very similar isotopic composition to the amount weighted average rainfall (Fig. 2). This could indicate that the majority of groundwater recharge in the rural catchments is constituted either by rainfall or — considering that most of this area is highly irrigated — also by (usually slightly more evaporated) return flow from irrigated agriculture. The latter is indicated by the higher evaporative change in rural groundwaters (significant increase in d-excess in the pre-monsoon) compared to Bengaluru (no significant change, Wilcoxon rank sum test; Supplementary Material Figure S1). The analysis of the Cl/Br ratios showed groundwater samples with relatively constant Cl/Br ratio, but with a high range of Cl concentrations, indicative for mixing of low Cl 'pristine' groundwater with a high Cl endmember, for TG Halli (Fig. 8). In Berambadi, a typical mixing line of groundwater with an endmember with higher Cl and higher Cl/Br could be observed. This mixing with Cl-rich water is a good indication that irrigation return flows, which typically have increased Cl from agrochemical inputs, could be the dominant recharge source. High NO^3 concentrations further corroborate this conclusion. Even though potential recharge from Berambadi tanks is somewhat spatially distributed because nearby farms may supply water from the tank to fields via drainage channels (Collins et al., 2020), this neither creates an isotopic signal in the groundwaters nor is there indication from the Cl/Br analysis that much mixing of tank water and groundwater is taking place (tank waters mostly had higher Cl/Br, but lower Cl, and no mixing line with tanks as endmember could be identified). Thus, this indicates that much of the infiltrated water from tanks is lost within the unsaturated zone, for example by lateral flow processes and evapotranspiration (Scanlon and Cook, 2002), and is therefore not significantly adding to groundwater recharge.

This finding is in contrast to those from investigations using recharge estimations based on water level fluctuation methods (Kumar et al., 2017), and studies relating tank density to groundwater levels (Chowdhury and Behera, 2018) which observed higher groundwater levels near tanks. However, in both of these studies, it is not clear if the higher water levels can be attributed to groundwater recharge by tanks,

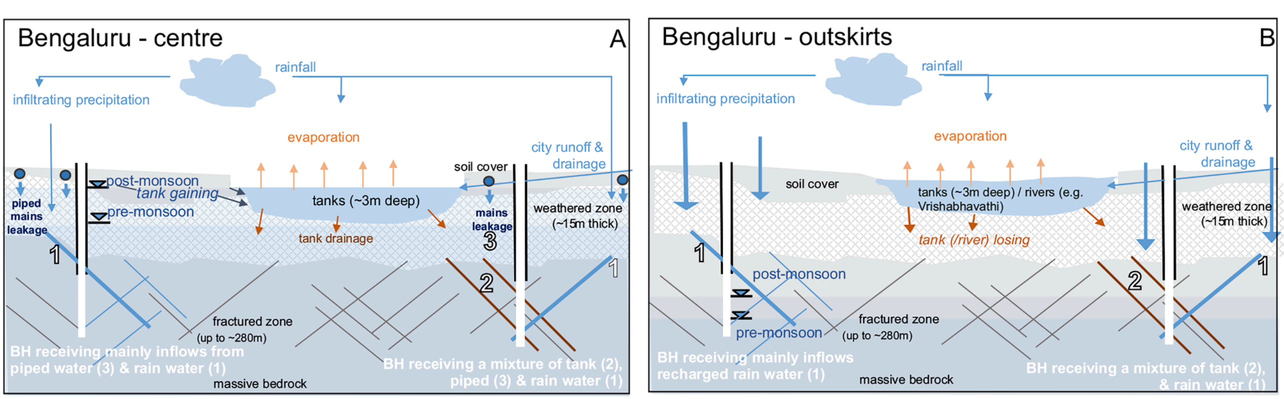

Fig. 10. Conceptual model of recharge sources and patterns (A) in the centre and (B) the outskirts of Bengaluru. Water levels are indicated for post-monsoon and pre-monsoon. Different colours are used for source differentiation (e.g. brownish colour for tank water, lighter blue for rainwater). Arrows indicate recharge pathways, with thickness of arrows corresponding to dominant recharge sources. (Drawings are not to scale.) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

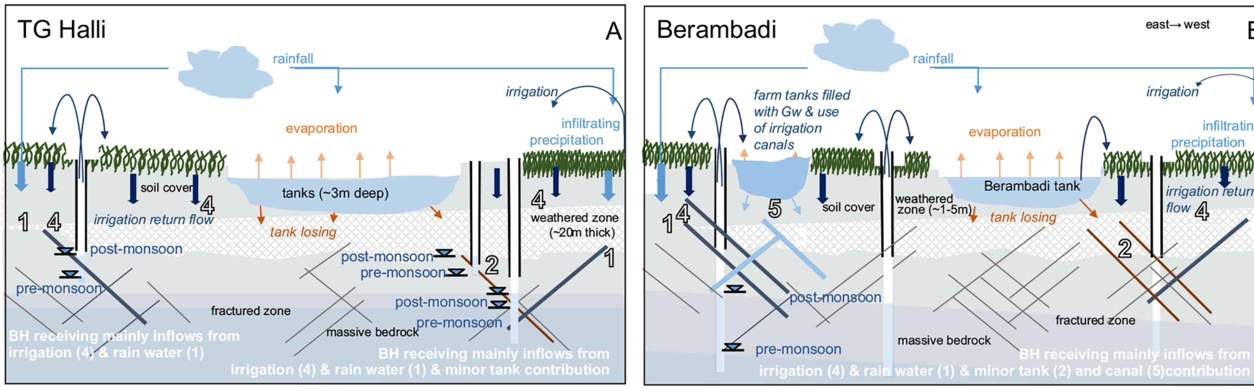

Fig. 11. Conceptual model of recharge sources and patterns in TG Halli (A) and Berambadi (B). Water levels are indicated for post-monsoon and pre-monsoon. Different colours are used for source differentiation (e.g. brownish colour for tank water, lighter blue for rainwater, darker blue for irrigation returns). Arrows indicate recharge pathways, with thickness of arrows corresponding to dominant recharge sources. (Drawings are not to scale.) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

or to other factors, such as decreased groundwater abstractions in areas with higher surface water availability (i.e. tanks), or higher water storage from tanks in the vadose zone (i.e. less need for irrigation).

Previous studies have calculated percolation efficiencies of tanks, defined as the percolated fraction of tank water depletion over a given time period, of 35–68% (Boisson et al. 2014; Massuel et al., 2014; Metha and Jain, 1997; Perrin et al., 2012; Singh et al., 2004; Sukhija et al., 1997). However, little is known about how much of the infiltrated water actually recharges groundwater, as not all water lost through the base of a tank can be expected to reach the groundwater table, but may be stored in the vadose zone or taken up by evapotranspiration (Boisson et al., 2014; De Vries and Simmers, 2002). A rare study using water level data in combination with water isotopes and chemical data to estimate recharge sources concluded that rainfall was the main source of recharge with only marginal recharge from a nearby tank (Saha et al., 2013). Thus, a revised approach to directly estimate water fluxes below tanks may be beneficial, for example by more local-scale studies using environmental tracers as suggested by (Boisson et al., 2014) combined with water level observations. Regardless of the recharge rate beneath individual tanks, in the context of the landscape as a whole, tanks cover small areas, especially in urban setting where they are encroached on for development, and hence their overall contribution to recharge may always be limited, but yet, it will be a useful endeavour to quantify better the unit area impacts of tanks. For example, we did not see significant trends of conservative tracers (stable isotopes and Cl, Pearson correlation) in groundwater with distance from tanks, and we estimated a recharge contribution only 2.6% from tank waters in TG Halli (based on a two-end-member mixing for d-excess). Because of constraints on the regional data availability (for example, only a one-year amount weighted rainfall average was obtained for this study, and data on variations in tank surface areas and tank levels/storage for the three regions are not available) there is some uncertainty in these results, and it may go beyond this study to define a per-unit-area value of tank recharge. However, a more specifically designed monitoring network with site-specific installation of deeper monitoring boreholes of varying distance from tanks could provide further details on whether significant trends of conservative tracers might be detectable on smaller scales. We therefore propose that studies following a hydrochemical approach as presented here combined with more site-specific monitoring networks as for example outlined in Knappett et al. (2012) and (Stahl et al., 2014) could be informative for the future.

4.3. *Contamination risks posed by tanks and other sources to groundwater*

Distinct hydrochemical patterns were observed in Bengaluru (e.g. Mg and Cl 'hotspots' near Kaikondrahalli tank and Vrishabhavathi River, and higher concentrations of NO_3 near Lalbagh tank), while contamination in the rural catchments seemed more widespread.

In Bengaluru, increased concentrations of Cl were present in tank water and groundwaters, and the dominating 1:1 molar ratio of Na/Cl (Fig. 7A) and very high Cl/Br ratio (Fig. 8A) indicates that Cl contamination is related to anthropogenic sources, such as effluent from households and industry (Alcalá and Custodio, 2008). Increased levels of Cl were found in particular in the western outskirts of Bengaluru, around Kaikondrahalli tank, and our conceptualized model indicates that the lower groundwater levels and lower density of mains network (i.e. lower dilution of infiltrated tank water by mains leakage) will increase the risks to surface water quality. This holds true for tanks, but in particular also for larger perennial drainage systems, such as the Vrishabhavathi River, which was found to have high concentrations of K, SO_4, Cl and HCO_3 – also indicative of anthropogenic pollution. In the city centre, water levels were extremely shallow in the wetter part of the year, and recharge/mixing of tank water with mains leakage will substantially reduce the impact of tanks on groundwater recharge. However, it should be noted that post-monsoon samples from the piped water showed high NO_3 concentrations (up to 19.7 mg/L NO_3 with a median of 15.2 mg/L). Considering that most of the piped water is imported from the Cauvery River, which flows through agricultural areas, it needs to be considered if the imported piped water might be introducing agricultural pollutants into the groundwater system.

Similar to Bengaluru, high Cl concentrations were detected in TG Halli groundwaters (seasonal median up to 168.4 mg/L) and Berambadi (seasonal median up to 76.8). For comparison, Buvaneshwari et al. (2020) only detected Cl concentration of mostly $<$ 10 mg/L in a neighbouring, more pristine area in similar geological setting and at a close distance to the Berambadi catchment. Therefore, the higher concentrations in Berambadi compared to its neighbouring area are unlikely to be of natural origin. The most likely cause of this are applied fertilizers (e.g. $Mg(NO_3)_2$, $Ca(NO_3)_2$, KCl, or $MgCl_2$), from which NO_3 and Cl are leached into the groundwater during the monsoon season (Buvaneshwari et al., 2020). This could also explain the higher concentrations of Mg in the rural catchments, especially post-monsoon in Berambadi. NO_3 concentrations exceeding the BIS DWL (drinking water limit) of 45 mg/L were detected most frequently (85% of all groundwater samples) in Berambadi, with a peak concentration of 446 mg/L (Table S5, Supplementary Material). This is slightly higher than observed in the same catchment by Buvaneshwari et al. (2017), who detected peak concentrations of 360 mg/L, and average concentrations of 77 mg/L in September 2012, and 75 mg/L in June 2013. Average concentrations in this study were somewhat higher with 133 mg/L (post-monsoon, October 2017) and 113 mg/L (pre-monsoon, April 2018), which shows an upward trend in nitrate pollution in recent years and re-iterates that better nutrient (and irrigation) management is crucial to prevent further deterioration of the region's groundwater quality (Sharma et al., 2018).

5. Conclusions

A suite of chemical analyses (stable isotopes, water chemistry) of samples from piped water (sourced mainly from the Cauvery River), surface waters (tank water and river water) and groundwater in three catchments set in the crystalline basement of the Cauvery Basin, Karnataka, India, was undertaken to investigate recharge patterns and pathways. The three catchments comprised the urban area of Bengaluru City (the state capital), and rural areas with higher levels of agricultural activity north of Bengaluru (TG Halli) and the Berambadi catchment in southern Karnataka. The focus of this study was to use hydrochemical tracers to see if significant groundwater recharge from 'tank water' (water from artificial lakes) could be identified within the groundwater system.

The distinct isotopic ratios and hydrochemistry between tank water and groundwaters at most sites — and especially in the rural catchments — observed in this study suggest that these are suitable tracers of tank water recharge. The groundwater chemistry results indicate that tank recharge is of limited importance to regional groundwater recharge and quality in rural areas, where recharge from precipitation and groundwater recycling from irrigation dominate the recharge signal. In the urban setting (Bengaluru), impermeable surfaces increased the relative effect of recharge from point sources such as tanks and rivers, but where present, pipe leakage from public-water-supply accounted for the majority of recharge. Location-specific differences could be observed, e.g. between the city centre, where shallow groundwater levels are predominant and groundwater (as well as mains water leakage) is likely to interact and possibly recharge tanks, and the outskirts of Bengaluru. This means that to sensibly estimate recharge by tank water, site-specific information, especially on water level fluctuations and alternative recharge sources needs to also be considered. Additional studies to quantify tank recharge and revisions to the current guidelines for national groundwater recharge estimations, using a less generalised approach, are recommended to avoid over-estimating the role tanks play in groundwater recharge.

Groundwater contamination in Bengaluru from different sources was observed with distinct regional patterns, e.g. Cl and Mg 'hotspots' near Kaikondrahalli tank and Vrishabhavathi River, and higher concentrations of NO_3 near Lalbagh tank. Due to the shallow water levels in Bengaluru's inner-city, and slight indication of recharge from tank water in the outskirts, tanks in Bengaluru could be a possible source of contamination due to vertical infiltration to groundwater in the dry season. In the rural catchments, especially Berambadi, contamination was more ubiquitous, particularly regarding agricultural pollutants. The exceedance of DWLs by NO_3 in the rural catchments is likely the impact of diffuse recharge under fertilized areas, with tanks posing a negligible risk to groundwater quality compared to other agricultural activities on the land surface.

CRediT authorship contribution statement

Bentje Brauns: Methodology, Investigation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Somsubhra Chattopadhyay:** Methodology, Investigation, Writing – review & editing, Resources. **Dan J. Lapworth:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition. **Sian E. Loveless:** Methodology, Investigation, Formal analysis, Writing – review & editing. **Alan M. MacDonald:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition. **Andrew A. McKenzie:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition. **Muddu Sekhar:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition, Resources. **Siva Naga Venkat Nara:** Methodology, Investigation, Writing – review & editing. **Veena Srinivasan:** Conceptualization, Methodology, Writing – review & editing, Resources, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The research underlying this paper was carried out under the UPSCAPE project of the Newton-Bhabha programme "Sustaining Water Resources for Food, Energy and Ecosystem Services", funded by the UK Natural Environment Research Council (NERC-UKRI) [NE/N016270/1], and the Indian Ministry of Earth Sciences (MoES) [MoES/NERC/IA-SWR/P1/08/2016-PC-II (i), (ii)]. Interpretation and write up were funded by the British Geological Survey NC-ODA Grant Geoscience for Sustainable Futures [NE/R000069/1].

The authors would like to thank Carole Arrowsmith and Melanie Leng in NIGL, BGS Keyworth for stable isotope analysis, and Michael Watts, Simon Chenery, Tom Barlow, Elliott Hamilton and Andy Marriott at BGS are thanked for providing the chemical analysis. The Central Groundwater Board (CGWB) in Bengaluru is thanked for access to and information on selected monitoring boreholes in the city and their support of field visits. P.R. Giriraja is thanked for collecting groundwater levels in Berambadi, and G. Manjunatha and C. Aradhya for field support in TG Halli catchment. Amritha Thankachan, Renuka Prasad and Subhash Chandra are thanked for local guidance in Bengaluru, their valuable advice, and field support. The Kabini Critical Zone Observatory is managed by the Indo–French Cell for Water Sciences. It is part of the Service National d'Observation (SNO) M-TROPICS, funded by the University of Toulouse, IRD and CNRS-INSU, and belongs to the French network of Critical Zone Observatories: Research and Application. We further acknowledge GIS support and provision of rainfall data by ATREE ecoinformatics lab and from Amit Kumar Sharma, and assistance in spatial analysis by K.N. Sanjeeva Murthy at IISc. Lastly, we would like to thank three anonymous reviewers whose critical reading and comments/suggestions helped improve and clarify this manuscript. B. Brauns, D.J. Lapworth, A.M. MacDonald and A.A. McKenzie publish with the permission of the Director of the British Geological Survey (UKRI).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.hydroa.2022.100121.

References

Alcalá, F.J., Custodio, E., 2008. Using the Cl/Br ratio as a tracer to identify the origin of salinity in aquifers in Spain and Portugal. J. Hydrol. 359 (1–2), 189–207. https://doi.org/10.1016/j.jhydrol.2008.06.028.

Ambast, S., Tyagi, N., Raul, S., 2006. Management of declining groundwater in the Trans Indo-Gangetic Plain (India): some options. Agric. Water Manag. 82 (3), 279–296. https://doi.org/10.1016/j.agwat.2005.06.005.

Ballukraya, P.N., Srinivasan, V., 2019. Sharp variations in groundwater levels at the same location: a case study from a heavily overexploited, fractured rock aquifer system near Bengaluru. South India. Curr. Sci. 117 (1), 130–138.

Banks, E.W., Simmons, C.T., Love, A.J., Cranswick, R., Werner, A.D., Bestland, E.A., Wood, M., Wilson, T., 2009. Fractured bedrock and saprolite hydrogeologic controls on groundwater/surface-water interaction: a conceptual model (Australia). Hydrogeol. J. 17 (8), 1969–1989. https://doi.org/10.1007/s10040-009-0490-7.

Bhanja, S.N., Mukherjee, A., Rangarajan, R., Scanlon, B.R., Malakar, P., Verma, S., 2019. Long-term groundwater recharge rates across India by in situ measurements. Hydrol. Earth Syst. Sci. 23 (2), 711–722. https://doi.org/10.5194/hess-23-711-201910.5194/hess-23-711-2019-supplement.

BIS, 2012. Indian standard drinking water–specification (second revision). Bureau of Indian Standards (BIS), New Delhi.

Boisson, A., Baïsset, M., Alazard, M., Perrin, J., Villesseche, D., Dewandel, B., Kloppmann, W., Chandra, S., Picot-Colbeaux, G., Sarah, S., Ahmed, S., Maréchal, J. C., 2014. Comparison of surface and groundwater balance approaches in the evaluation of managed aquifer recharge structures: Case of a percolation tank in a crystalline aquifer in India. J. Hydrol. 519, 1620–1633. https://doi.org/10.1016/j.jhydrol.2014.09.022.

Buvaneshwari, S., Riotte, J., Sekhar, M., Mohan Kumar, M.S., Sharma, A.K., Duprey, J.L., Audry, S., Giriraja, P.R., Praveenkumarreddy, Y., Moger, H., Durand, P., Braun, J.-J., Ruiz, L., 2017. Groundwater resource vulnerability and spatial variability of nitrate contamination: insights from high density tubewell monitoring in a hard rock aquifer. Sci. Total Environ. 579, 838–847. https://doi.org/10.1016/j.scitotenv.2016.11.017.

Buvaneshwari, S., Riotte, J., Sekhar, M., Sharma, A.K., Helliwell, R., Kumar, M.S.M., Braun, J.J., Ruiz, L., 2020. Potash fertilizer promotes incipient salinization in groundwater irrigated semi-arid agriculture. Sci. Rep. 10 (1) https://doi.org/10.1038/s41598-020-60365-z.

CGWB, 2007. Manual on Artificial Recharge of Ground Water. Government of India, New Delhi, India.

CGWB, 2012. Aquifer Systems of India. Government of India, New Delhi, India.

CGWB, 2013. Master Plan for Artificial Recharge to Ground Water in India. Government of India, New Delhi, India.

CGWB, 2019a. Ground water year book – India 2017-18, Ministry of Water Resources, River Development and Ganga Rejuvenation, Government of India, Faridabad, India.

CGWB, 2019b. National Compilation on Dynamic Ground Water Resources of India, 2017. Government of India, Faridabad, India.

Chowdhury, K., Behera, B., 2018. Is declining groundwater levels linked with the discontinuity of traditional water harvesting systems (tank irrigation)? Empirical evidence from West Bengal. India. Groundw. Sustain. Dev. 7, 185–194. https://doi.org/10.1016/j.gsd.2018.05.007.

Collins, S.L., Loveless, S.E., Muddu, S., Buvaneshwari, S., Palamakumbura, R.N., Krabbendam, M., Lapworth, D.J., Jackson, C.R., Gooddy, D.C., Nara, S.N.V., Chattopadhyay, S., MacDonald, A.M., 2020. Groundwater connectivity of a sheared gneiss aquifer in the Cauvery River basin, India. Hydrogeol. J. 28 (4), 1371–1388. https://doi.org/10.1007/s10040-020-02140-y.

D'Souza, R., Nagendra, H., 2011. Changes in public commons as a consequence of urbanization: The Agara Lake in Bangalore. India. Environ. Manage. 47 (5), 840–850. https://doi.org/10.1007/s00267-011-9658-8.

Dansgaard, W., 1964. Stable isotopes in precipitation. Tellus 16 (4), 436–468. https://doi.org/10.3402/tellusa.v16i4.8993.

Darling, W.G., Bath, A.H., 1988. A stable isotope study of recharge processes in the English Chalk. J. Hydrol. 101 (1–4), 31–46. https://doi.org/10.1016/0022-1694(88)90026-1.

De Vries, J.J., Simmers, I., 2002. Groundwater recharge: an overview of processes and challenges. Hydrogeol. J. 10 (1), 5–17. https://doi.org/10.1007/s10040-001-0171-7.

Dixit, G., Kupaswamy, G., Mohan, S., 1993. Tank Irrigation in Karnataka-Historical survey. Gandhi Sahitya Sanga, Malleswaram, Bangalore, Karnataka.

EMPRI 2015. Final report on: Comprehensive assessment of Thippagondanahalli Reservoir catchment area and its preservation zone. Volume-I.

EMPRI, 2018. Inventorisation of Water Bodies in Bengaluru Metropolitan Area (BMA), Technical Document, Centre for Lake Conservation (CLC), EMPRI, Bengaluru, India.

Esha, S., 2008. Telling otherwise: a historical anthropology of tank irrigation technology in South India. Technol. Cult. 49 (3), 652–674. https://doi.org/10.1353/tech.0.0054.

GEC, 1997. Ground Water Estimation Methodology–1997. Government of India, New Delhi, India.

GEC, 2017. Report of the Ground Water Resource Estimation Commitee (GEC-2015) – Methodology, Ministry of Water Resources. River Development & Ganga Rejuvenation, Government of India, New Delhi, India.

Gibbs, R.J., 1970. Mechanisms controlling world water chemistry. Science 170 (3962), 1088–1090. https://doi.org/10.1126/science.170.3962.1088.

GoI, 2012a. Census of India 2011: House Listing and Housing Census. Government of India, Government of India (GoI), New Delhi, India.

GoI, 2012b. National Water Policy, Government of India (GoI). New Delhi, India.

GoI, 2015. All India report on Agricultural Census 2010–11, Government of India (GoI). New Delhi, India.

Guihéneuf, N., Boisson, A., Bour, O., Dewandel, B., Perrin, J., Dausse, A., Viossanges, M., Chandra, S., Ahmed, S., Maréchal, J.C., 2014. Groundwater flows in weathered crystalline rocks: impact of piezometric variations and depth-dependent fracture connectivity. J. Hydrol. 511, 320–334. https://doi.org/10.1016/j.jhydrol.2014.01.061.

Hedge, G.V., Chandra, K.C.S., 2012. Resource availability for water supply to Bangalore City, Karnataka. India. Curr. Sci. 102 (8).

Hedge, G.V., Subhash Chandra, K.C., 2014. Piezometric water-level condition in Bangalore city, Karnataka, India. Curr. Sci. 106 (2), 156–159.

IAEA/GNIP, 2014. International Atomic Energy Agency/Global Network of Isotopes in Precipitation: precipitation sampling guide. Available under: http://www-naweb.iaea.org/napc/ih/documents/other/gnip_manual_v2.02_en_hq.pdf, Date of last access 05/09/2021.

Knappett, P.S.K., McKay, L.D., Layton, A., Williams, D.E., Alam, M.J., Huq, M.R., Mey, J., Feighery, J.E., Culligan, P.J., Mailloux, B.J., Zhuang, J., Escamilla, V., Emch, M., Perfect, E., Sayler, G.S., Ahmed, K.M., van Geen, A., 2012. Implications of fecal bacteria input from latrine-polluted ponds for wells in sandy aquifers. Environmental science & technology 46 (3), 1361–1370. https://doi.org/10.1021/es202773w.

Kottek, M., Grieser, J., Beck, C., Rudolf, B., Rubel, F., 2006. World map of the Köppen-Geiger climate classification updated. Meteorol. Z. 15 (3), 259–263. https://doi.org/10.1127/0941-2948/2006/0130.

Kulkarni, H., Shah, M., Vijay Shankar, P.S., 2015. Shaping the contours of groundwater governance in India. J. Hydrol. Reg. Stud. 4, 172–192. https://doi.org/10.1016/j.ejrh.2014.11.004.

Kumar, B., Rai, S.P., Kumar, U.S., Verma, S.K., Garg, P., Kumar, S.V.V., Jaiswal, R., Purendra, B.K., Kumar, S.R., Pande, N.G., 2010. Isotopic characteristics of Indian precipitation. Water Resour. Res. 46 (12) https://doi.org/10.1029/2009WR008532.

Kumar, S., Bhadra, B.K., Paliwal, R., 2017. Evaluating the impact of artificial groundwater recharge structures using geo-spatial techniques in the hard-rock terrain of Rajasthan, India. Environ. Earth Sci. 76 (17) https://doi.org/10.1007/s12665-017-6953-6.

MacDonald, A.M., Bonsor, H.C., Ahmed, K.M., Burgess, W.G., Basharat, M., Calow, R.C., Dixit, A., Foster, S.S.D., Gopal, K., Lapworth, D.J., Lark, R.M., Moench, M., Mukherjee, A., Rao, M.S., Shamsudduha, M., Smith, L., Taylor, R.G., Tucker, J., van Steenbergen, F., Yadav, S.K., 2016. Groundwater quality and depletion in the Indo-Gangetic Basin mapped from in situ observations. Nat. Geosci. 9 (10), 762–766. https://doi.org/10.1038/ngeo2791.

Massuel, S., Perrin, J., Mascre, C., Mohamed, W., Boisson, A., Ahmed, S., 2014. Managed aquifer recharge in South India: what to expect from small percolation tanks in hard rock? J. Hydrol. 512, 157–167. https://doi.org/10.1016/j.jhydrol.2014.02.062.

Metha, M., Jain, S., 1997. Efficiency of artificial recharge from percolation tanks. Recharge of phreatic aquifers in (semi-) arid areas. IAH Int. Contrib. Hydrogeol 19, 271–277.

Nagendra, H., Ostrom, E., 2014. Applying the social-ecological system framework to the diagnosis of urban lake commons in Bangalore. India. Ecol. Soc. 19 (2), 18. https://doi.org/10.5751/es-06582-190267.

Ofterdinger, U., MacDonald, A.M., Comte, J.C., Young, M.E., 2019. Groundwater in fractured bedrock environments: managing catchment and subsurface resources – an introduction. Geological Society, London, Special Publications, 479(1): 1.1-9. doi: 10.1144/sp479-2018-170.

Pahuja, S., Tovey, C., Foster, S.S.D., H., G., 2010. Deep wells and prudence: towards pragmatic action for addressing groundwater overexploitation in India, The World Bank, Washington, USA.

Palanisami, K., Meinzen-Dick, R., Giordano, M., 2010. Climate change and water supplies: options for sustaining tank irrigation potential in India. Econ. Polit. Wkly. 183–190.

Pant, N., Verma, R., 2010. Tanks in Eastern India: a study in exploration. Hyderabad, India: International Water Management Institute, IWMI-TATA Water Policy Research Program; Lucknow, Uttar Pradesh, India: Centre for Development Studies., 232 pp. doi: 10.5337/2010.228.

Patil, N.K., 2011. Preservation of Lakes in the City of Bangalore: Report of the committee constituted by the Honorable High Court of Karnataka, Bangalore, Honorable High Court of Karnataka, Bangalore.

Perrin, J., Ferrant, S., Massuel, S., Dewandel, B., Maréchal, J.C., Aulong, S., Ahmed, S., 2012. Assessing water availability in a semi-arid watershed of southern India using a semi-distributed model. J. Hydrol. 460-461, 143–155. https://doi.org/10.1016/j.jhydrol.2012.07.002.

Rahul, P., Ghosh, P., Bhattacharya, S.K., Yoshimura, K., 2016. Controlling factors of rainwater and water vapor isotopes at Bangalore, India: Constraints from observations in 2013 Indian monsoon. J. Geophys. Res. Atmos. 121 (23), 13936–13952. https://doi.org/10.1002/2016jd025352.

Reddy, P.R., 2015. An over view of Irrigation Tanks Rehabilitation in semi arid hard rock terrain. J. Indian Geophys. Union 19 (4), 481–487.

Reddy, V.R., Behera, B., 2009. The economic and ecological impacts of tank restoration in South India. Eur. J. Dev. Res. 21 (1), 112–136. https://doi.org/10.1057/ejdr.2008.12.

Richard-Ferroudji, A., Raghunath, T., Venkatasubramanian, G., 2018. Managed aquifer recharge in India: consensual policy but controversial implementation. Water Altern. 11 (3), 749–769.

Robert, M., Thomas, A., Sekhar, M., Badiger, S., Ruiz, L., Willaume, M., Leenhardt, D., Bergez, J.-E., 2017. Farm typology in the Berambadi Watershed (India): Farming systems are determined by farm size and access to groundwater. Water 9 (1), 51. https://doi.org/10.3390/w9010051.

Rodell, M., Velicogna, I., Famiglietti, J.S., 2009. Satellite-based estimates of groundwater depletion in India. Nature 460 (7258), 999–1002. https://doi.org/10.1038/nature08238.

Saha, D., Dwivedi, S.N., Roy, G.K., Reddy, D.V., 2013. Isotope-based investigation on the groundwater flow and recharge mechanism in a hard-rock aquifer system: the case of Ranchi urban area, India. Hydrogeol. J. 21 (5), 1101–1115. https://doi.org/10.1007/s10040-013-0974-3.

Scanlon, B.R., Cook, P.G., 2002. Theme issue on groundwater recharge. Hydrogeol. J. 10 (1), 3–4. https://doi.org/10.1007/s10040-001-0175-3.

Sekhar, M., Riotte, J., Ruiz, L., Jouquet, J., Braun, J.J., 2016. Influences of Climate and Agriculture on Water and Biogeochemical Cycles: Kabini Critical Zone Observatory. Proc. Indian National Sci. Acad. 82 (3) https://doi.org/10.16943/ptinsa/2016/48488.

Sekhar, M., Tomer, S., Thiyaku, S., Giriraj, P., Murthy, S., Mehta, V., 2018. Groundwater Level Dynamics in Bengaluru City. India. Sustainability 10 (2), 26. https://doi.org/10.3390/su10010026.

Shah, T., Roy, A.D., Qureshi, A.S., Wang, J., 2003. Sustaining Asia's groundwater boom: an overview of issues and evidence. Nat. Resour. Forum. Wiley Online Library 27 (2), 130–141. https://doi.org/10.1111/1477-8947.00048.

Sharda, V., Kurothe, R., Sena, D., Pande, V., Tiwari, S., 2006. Estimation of groundwater recharge from water storage structures in a semi-arid climate of India. J. Hydrol. 329 (1–2), 224–243. https://doi.org/10.1016/j.jhydrol.2006.02.015.

Sharma, A., 2003. Rethinking tanks: Opportunities for revitalizing irrigation tanks. Empiricalfindings from Ananthapur district, Andhra Pradesh, India, Working Paper 62. International Water Management Institute, Colombo, Sri Lanka, Available under: http://www.iwmi.cgiar.org/Publications/Working_Papers/working/WOR62.pdf, Date of last access: 09/05/2021.

Sharma, A., Hubert-Moy, L., Buvaneshwari, S., Sekhar, M., Ruiz, L., Bandyopadhyay, S., Corgne, S., 2018. Irrigation history estimation using multitemporal landsat satellite images: application to an intensive groundwater irrigated agricultural watershed in India. Remote Sens. 10 (6), 893. https://doi.org/10.3390/rs10060893.

Singh, J., Awasthi, M., Sharma, R., 2004. Quantification of percolation from percolation tank. J. Soil Water Conserv. 3 (3), 128–132.

Singhal, B.B.S., Gupta, R.P., 2010. Applied hydrogeology of fractured rocks. Springer Science & Business Media, The Netherlands. doi: 10.1007/978-90-481-8799-7.

Srinivasan, V., Thompson, S., Madhyastha, K., Penny, G., Jeremiah, K., Lele, S., 2015. Why is the Arkavathy River drying? A multiple-hypothesis approach in a data-scarce region. Hydrol. Earth Syst. Sci. 19 (4), 1905–1917. https://doi.org/10.5194/hess-19-1905-2015.

Stahl, M.O., Tarek, M.H., Yeo, D.C.J., Badruzzaman, A.B.M., Harvey, C.F., 2014. Crab burrows as conduits for groundwater-surface water exchange in Bangladesh. Geophysical Research Letters 41 (23), 8342–8347. https://doi.org/10.1002/2014GL061626.

Sukhija, B.S., Reddy, D.V., Nandakumar, M.V., 1997. A method for evaluation of artificial recharge through percolation tanks using environmental chloride. Ground water 35 (1), 161–165. https://doi.org/10.1111/j.1745-6584.1997.tb00071.x.

Tomer, S.K., Sekhar, M., Balakrishnan, K., Malghan, D., Thiyaku, S., Gautam, M., Mehta, V.K., 2021. A model-based estimate of the groundwater budget and associated uncertainties in Bengaluru, India. Urban Water J. 18 (1), 1–11.