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Impact of land use changes and management practices on groundwater resources in Kolar district, Southern India

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A R T I C L E I N F O

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Water balance
Groundwater recharge
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A B S T R A C T

Study region: This study analyzes the impact of land use changes on the hydrology of Kolar district in the state of Karnataka, India. Kolar receives on average 565 mm ($\sigma = 130$) rainfall during June to October and has a wide gap between its water supply and demand.
Study focus: This research identifies the reasons and causes of the gap. A water balance model was successfully calibrated and validated against measurements of groundwater level, recharge and surface runoff.
New hydrological insights for the region: The study revealed that between 1972 and 2011, there was a major shift from grass and rainfed crop lands to eucalyptus plantation and irrigated cultivation. About 17.7 % and 18 % of the district area converted into eucalyptus plantation and irrigated lands during this period, respectively. Eucalyptus plantations tended to cause large losses by ET leading to increase in soil moisture deficit and reduction in the recharge to groundwater and in surface runoff (approx. 30 %). The irrigation demand of the district increased from 57 mm (1972) to 140 mm (2011) which resulted in increased groundwater abstraction by 145 %. The expansion of the irrigated area is the major contributing factor for widening the demand-supply gap (62 %) of the freshwater availability. Results could help various stakeholders, including district and national authorities to develop the most suitable water management strategies in order to close the gap between water supply and demand.

1. Introduction

Globally, freshwater availability is declining, coupled with increasing population pressure, land use change, industrial growth and urbanization (Vörösmarty et al., 2000; Gordon et al., 2005; Gerten et al., 2011, 2013; Haddeland et al., 2014). There is increasing concern among different sectors/stakeholders for their water share at local, regional and national scale (Punjabi and Johnson, 2016; Stefano et al., 2017; Avellán et al., 2017; Atef et al., 2019; Veise et al., 2020). Globally, agriculture consumes about 80 % of fresh water resources and more than 570 million farm families are dependent on the agriculture sector (Lowder et al., 2016) and are vulnerable to increasing water scarcity (Recanati et al., 2017). Climate change has worsened the situation further with uncertainty in freshwater availability and its sustainability (Wada et al., 2011; Feng et al., 2013; Elmeddahi et al., 2016; Mousivand and Arsanjani, 2018; Rodell

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et al., 2018; Huang et al., 2019). This also has become critical to meet food security and poverty eradication according to the United

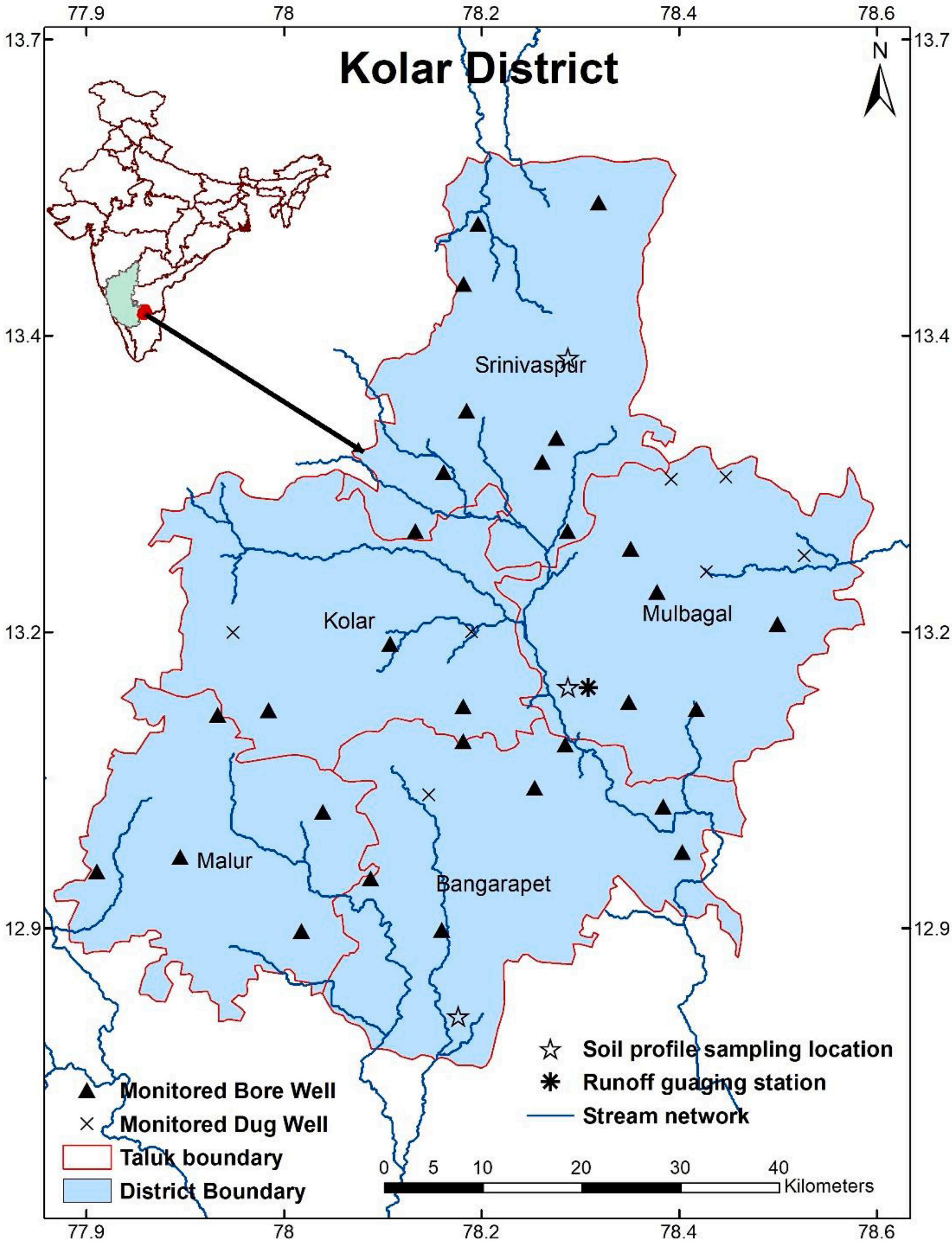

Fig. 1. Location of different borehole wells and dug wells monitored for long-term data collection in Kolar district, Karnataka, India.

Nations Agenda 2030 (Schleicher et al., 2018; Zhou et al., 2019).

Globally, about 480 million ha of land was brought under crop and grazing land use since 1960 to feed an increasing population with changing food habits (Gibbs et al., 2010; Lambin and Meyfroidt, 2010). The change in land use has affected hydrological cycle at regional scale and has crossed the critical level of safe operation (Rockström et al., 2009; Dearing et al. 2014; Cole et al., 2014; Hossain et al., 2017; Steffen et al., 2015). With increasing crop land, pressure on water resource, especially groundwater has increased. Globally, about 982 Billion Cubic Meter (BCM) groundwater is abstracted annually and out of which 70 % is used for agriculture (Siebert et al., 2010; Gleeson et al., 2016). The crop land under irrigation is about 301 million ha, of which 38 % is dependent on groundwater sources (Siebert et al., 2010; Gleeson et al. 2016). India ranks number one in groundwater use for meeting its demand from domestic, industrial and agricultural sectors. Groundwater extraction in India has accelerated from 25 BCM in the 1960 to 250 BCM by 2015 (Gleeson et al., 2016; GoI, 2019). The increase in water utilization was linked to the need to ensure the food security of the country. However, it resulted in depletion of groundwater resources, especially in dry regions (Reddy, 2005; Palanisami et al., 2008; Anantha, 2013). In addition, groundwater assessment in India showed that annual groundwater recharge has decreased from 447 BCM to 432 BCM due to multiple factors (e.g., urbanization, crop intensification, etc.) (GoI, 2019). About 17 % of the India has been categorized as overexploited, indicating groundwater extraction exceeds the annual replenishable groundwater recharge and 5% are critical where the state of groundwater extraction is equal to annual replenishable groundwater recharge (GoI, 2019). This situation raises serious concerns about the future of the groundwater resources pertaining to water availability, food and livelihood security and sustainability of the dependent ecosystems (Rodríguez-Suárez et al., 2011).

Southern Indian states are rapidly growing in terms of economic development including agriculture (Akram and Rath, 2020). To sustain this growth, this region is exploiting available resources which lead to overexploitation of certain resources such as groundwater. In this context, there is a need to understand the changing pattern of resource utilization and its impact on hydrological processes. Kolar district in the state of Karnataka has undergone substantial change in terms of land use due to number of anthropogenic activities and one of the water stressed district in southern India (Srinivasan et al., 2015; Penny et al., 2018). There are no comprehensive studies that attempted to understand the changes in hydrological processes.

Given that, this district has a gap between its water supply and demand (Srinivasan et al., 2015), this research aims to identify reasons and causes of the gap with the following objectives: (i) analyze changes in water balance components of the Kolar district since 1970; and (ii) assess the causes of groundwater and surface water depletion.

2. Material and methods

2.1. Study area

Karnataka is the eighth largest state in India, accounting for 5.13 % of country's total population (GoK, 2011). Karnataka has variable rainfall, diverse soil types and cropping patterns (Wani et al., 2017). Based on this diversity, the state has been divided into ten agro-climatic zones (GoK, 2018a). Among these agro-climatic zones, the southern dry zone is vulnerable in terms of climate change (Mujumdar, 2013; Rao et al., 2013), changes in land use and declining available natural resources (Ramachandra et al., 2004). Kolar district is located (13.135745°N, 78.132561°E) in the southeast of Karnataka state and has a total geographical area of 4012 km^2 and a population of 1.54 million (GoI, 2011). Agriculture and associated activities are the major livelihood source in the district. Nearly 30 % of the geographical area in the district is covered by pasture, trees and shrubland which was largely planted with eucalyptus in the last two to three decades; and 66 % of the area is under agriculture (Nagaraj et al., 2003; Reddy, 2005). Out of 2651 km^2 agriculture land, 59 % of the area is rainfed in which millet and cereal are the dominant crops (GoK, 2018b). The remaining 41 % of the area is irrigated fruits, vegetables and mulberry which require year-round irrigation (GoK, 2018b).

Kolar district (Fig. 1) was known for its ancient surface water reservoirs, commonly known as tanks. The tanks were excavated by ancient dynasties in order to address water scarcity of the dryland areas. With nearly 3000 such reservoirs, Kolar district had the highest number of 'tanks' in the state (GoK, 1975). The tanks had multiple uses, such as domestic, livestock, agriculture and groundwater recharge. They were located in villages across the district and were designed in topographical sequence, such that generated runoff was harvested from upstream to downstream reservoirs in a cascading manner. Some of the tanks had a connecting infrastructure of canal networks that have been established by various development agencies (Lars Engberg-Pedersen, 2011).

The submergence area (water spread area) for most of the tanks is 5−10 ha but a few have a submergence area as large as 100 ha or more (Reddy et al., 2018) at its full capacity. Historically, the major part of the irrigated area was next to these tanks.

The district is currently operates the highest number of wells (around 30,000 borehole wells in 2012) for irrigation purpose (CGWB, 2012). The major portion of the aquifer is made up of fractured rocks of granites, gneisses and schists that are characterized by a low-storage (0.005 to 0.03 %) capacity/poor storability (CGWB, 2012). The occurrence and movement of groundwater is controlled by the weathered zone fractures and fissures that exist in hard rocks. In the district, groundwater occurs in phreatic and semi-confined to confined conditions (CGWB, 2012; GoK, 2018b). The weathered thickness varies from 6 to 18 m in most of the area. The depth of irrigation borehole wells ranges from 100 m to 300 m below the surface. The yield of borehole wells in hard rock areas varies generally from 15 to 200 m^3/day (CGWB, 2009). The Kolar district has also witnessed declining groundwater levels since 1990 (Nagaraj et al., 2003; Reddy, 2005). The cropping system has changed from low water requiring crops (e.g. finger millet) to high water requiring and water-intensive crops (vegetables, mulberry, etc.).

2.2. Data and analysis

Fig. 2 shows a flow diagram of the adopted methodology. Steps to quantify the water balance components at district level are described in the following sections: i) Section 2.2.1 describes the collection of primary and secondary data of soil physical properties, observation wells, storage capacity and submerged area of a few selected tanks; ii) groundwater trend analysis and estimation of groundwater recharge using difference in water table levels as described in Section 2.2.2; iii) land use change analysis using remote sensing (Section 2.2.3). All these data were used as input into one-dimensional water balance model to parameterize the hydrological processes, validate the results and compute water balance components at district scale for two different periods (Section 2.2.4).

2.2.1. Data collection

Data of 35 monitored wells distributed across the Kolar district was collected from the Department of Mines and Geology, Government of Karnataka (Fig. 1). The data included monthly observation of groundwater levels between 1973 and 2013 (40 years). A one-degree resolution gridded dataset of daily rainfall and maximum and minimum temperature was obtained from the India Meteorological Department (IMD), Pune for the period 1971−2007. Reference crop evapotranspiration (ET_o) was computed on a daily basis using the Hargreaves-Samani method (Hargreaves and Samani, 1985). Land use-land cover (LULC), cropping pattern and source of irrigation details (tank, borehole and dug well irrigated area) were collected for the period of 1970–2007 from the Directorate of Economics and Statistics.

ICRISAT has collected surface runoff at a micro watershed of 300 ha in Huthur village in the Kolar district over a three-year period during 2006−08 under World Bank supported Sujala watershed program (Sreedevi et al., 2008; World Bank, 2009). An automatic runoff recorder measured surface runoff at every 30 min intervals. In addition, soil samples were collected from 3 micro watersheds (profile samples up to 120 cm depth at 2 locations in each watershed) under Sujala program and analysed for soil-physical properties (soil texture, water retention). Location of these three watersheds are shown in Fig. 1. Moreover, a detailed survey of four selected tank locations for storage capacity and submergence area was undertaken to analyze the depth of water harvesting.

2.2.2. Groundwater historic trends in Kolar

Studying the historic groundwater trend is important to understand the changes in recharge pattern, extraction, and the current availability, as well as to predict the future groundwater availability (Nune et al., 2014). TREND, a statistical tool developed by the Cooperative Research Centre for Catchment Hydrology (CRCCH) was used to facilitate both parametric and non-parametric tests for detecting the trend, change and randomness in hydrological and other time series data (Kundzewicz and Robson, 2000; Grayson et al., 1996). Trends in groundwater levels (hydraulic head) and annual rainfall were analyzed using Mann-Kendall, Spearman's Rho test and Linear regression.

The water table fluctuation (WTF) method is a well-accepted technique for estimating groundwater recharge in hard rock regions (Sharda et al., 2006; Dewandel et al., 2010; Glendenning and Vervoort, 2010; Pavelic et al., 2012; Garg and Wani, 2013, Tilahun et al., 2020). However, there are difficulties in defining and evaluating the specific yield which may vary with depth (Healy and Cook, 2002).

The water balance equation can be presented as follows:

$$R = (\Delta h^{*}S)/100 + W \tag{1}$$

where R is the net groundwater recharge (mm), Δh is the change in hydraulic head before and after the monsoon period (m), S is the specific yield (%), W is the water withdrawal during the monsoon period (mm).

The hydraulic head in open wells over time was obtained from water level data. Based on previous studies, the value of storability (specific yield) for a shallow and weathered zone is considered as 0.03 (σ = 0.01) and 0.005 (σ = 0.004) for deep aquifers for peninsular India (Dewandel et al., 2010; Garg and Wani, 2013; Maréchal et al., 2006; Massuel et al., 2006, ; Subrahmanyam and Khan, 2008; Pavelic et al., 2012). The amount of water pumped and used for agriculture is calculated for each year under different cropping

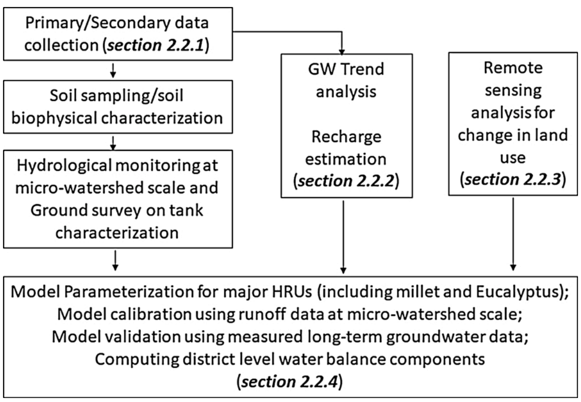

Fig. 2. Flow diagram of adopted methodology.

systems using a simulation model. The one dimensional water balance model, WIC, described below, was used. The auto-irrigation module is built-in in the model to provide supplemental irrigation whenever the soil moisture levels drop below the defined threshold in respective seasons/cropping systems. This model was validated in field scale studies in different cropping systems and soil types in semi-arid regions (Garg et al., 2016).

2.2.3. Land use change using remote sensing technique

Time series satellite data for the years 1972, 1992 and 2011 were used to analyse the land use change in the study area. Landsat images were downloaded from Earth Explorer for respective years (Geological Survey & EROS Data Center, 1900). The digital numbers were converted to reflectance values to normalize the multi-date effect (Thenkabail et al., 2004). The images were converted into top of atmosphere (TOA) reflectance using a reflectance model built in ERDAS Imagine (Thenkabail et al., 2004; Velpuri et al., 2009; Gumma et al., 2011b). The normalization was based on the meta data available in the header files. We used unsupervised classification due to many unknown classes and limited data. Unsupervised ISOCLASS cluster K-means classification was used to capture the range of variability in phenology in the image. As discussed by Thenkabail et al. (2004) and Gumma et al. (2011a), various datasets such as bi-spectral plots, ground data, Google high resolution imagery and Landsat time series NDVI signatures were used for class identification and labeling. Bi-spectral plots were prepared based on spectral properties of red and NIR bands extracted from unsupervised classification. The diagonal line in bi-spectral plots represents the soil line, differentiating the vegetation classes. Water bodies and shrub lands/trees have large variation in vegetation and were easily identified and labeled. Further, to verify major classes ground truthing data were collected and accuracy analysis (producer accuracy) was carried out which showed less than 10 % of uncertainty in classification.

2.2.4. District scale water balance components

2.2.4.1. Description of water impact calculator. This study uses a one-dimensional water balance model 'Water Impact Calculator' (WIC) developed by ICRISAT to analyze the water balance components (Garg et al., 2016). The WIC is a generic decision-making tool which could be applied to any land use and cropping system by providing minimum sets of biophysical details and management inputs (Garg et al., 2014, 2016). WIC requires soil (water retention properties and soil layer thickness), weather (Reference evapotranspiration, ET_o and rainfall), crop growth (biomass, crop coefficient, k_c and root growth function), topography (land slope, landform conditions) and crop management (crop sowing and harvesting dates & irrigation method) details as an input. The model calculates the daily water balance as:

$$R + I = RO + \Delta D + ET + \Delta S \quad (2)$$

where R is rainfall (mm), I is irrigation (mm), RO is surface runoff generated by the rainfall (mm), ΔD is the change in groundwater storage due to recharge and deep percolation (mm), ET is evapotranspiration (mm) and ΔS is the change in soil moisture storage (mm).

In WIC, runoff is estimated based on curve number technique. The Soil Conservation Service Curve Number (SCS-CN) is a simple but popular method for predicting surface runoff and is widely used in many hydrological applications, such as flood estimation and water balance models (Abon et al., 2011; Steenhuis et al., 1995; van Dijk, 2010). It is sensitive to changes in values of curve number parameter, CN, and the antecedent moisture conditions (Hawkins, 1993; McCuen, 2002; Michel et al., 2005; Ponce and Hawkins, 1996; Soulis and Valiantzas, 2012).

In WIC, the amount of water in excess of infiltration, after satisfying the soil moisture deficit, is considered deep percolation (Garg

Table 1
Hydrological response units (HRUs) in Kolar district[a].

LULC[b]	Description	LULC in 1972 (km^2)	LULC in 2011 (km^2)	Modelled as	Season	HRU
	Geographical area	4012	4012			
1	Forest	256	256	Eucalyptus	Perennial	1
2	Plantation (eucalyptus)	64	776	Eucalyptus	Perennial	1
3	Shrub lands/grasslands	1039	160	Grasses/millets	Kharif	2
4	Agricultural land	2440	2651			
	Rainfed land	2074	1562			
	Cereals (millets)	1087	669	Finger millet	*Kharif*	2
4a	Pulses	58	164	Pigeonpea	*Kharif*	3
	Oil seed	75	128	Groundnut	*Kharif*	4
	Others	354	601	Maize	*Kharif*	5
	Irrigated land	366	1089			
	Mulberry and orchards	173	424	Mulberry	Perennial	6
4b	Vegetable	142	284	Tomato	*Kharif*	7
	Cereals	51	381	Maize	*Kharif*	5
	Vegetable	142	284	Tomato	*Rabi*	7
5	Water bodies	195	132	–		
6	Settlements	17	38	–		

[a] Crop coefficients obtained from National Water Development Agency (NWDA, 2019).
[b] Land use/land cover.

et al., 2016). Evaporation and transpiration values are estimated based on the surface boundary conditions and moisture accessibility between surface soil layer and the root zone. Water available in the top 10 cm layer is considered the main layer that is satisfying the bare soil evaporative demand, whereas moisture available within the root zone is used to meet crop water uptake/transpiration demand. The crop water requirement (CWR) for a given day is calculated as:

$$CWR = K_c * ET_o \tag{3}$$

where K_c is the crop coefficient and ET_o *(mm/day)* is the reference crop evapotranspiration.

The root zone depth is a dynamic variable and is controlled by crop growth stage (days after sowing) as defined by Allen et al. (1998). Usually, evaporation from soil surface is inversely proportional to vegetative growth stage. Thus, after achieving full vegetative crop growth ($K_c \geq 1.0$), evaporation from the bare soil surface becomes insignificant. If moisture in the root zone was not sufficient to meet CWR, then WIC declares that the crop is under water stress condition. A detailed description of WIC, model development, testing and validation procedure is given by Garg et al. (2016).

2.2.4.2. Model parameterization. The data collected from Huthur micro watershed on surface runoff was used to calibrate the Curve Number and same CN values were used for district scale analysis. Subsequently, WIC was used to estimate the district level water balance. The entire district is divided into four major land use classes: (1) forest and eucalyptus, (2) shrub land or grassland, (3) rainfed, and (4) irrigated agriculture, and further divided into seven hydrological response units (HRUs) as per land use classification and cropping system (Table 1). HRUs are the areas with similar biophysical (topography, soils and land use) characteristics and therefore their hydrological response is expected to be similar as defined by Arnold and Fohrer (2005). The HRU concept is widely used in water balance studies, catchment/regional scale modeling, and in soil and water assessment studies (Arnold and Fohrer, 2005; Flugel, 1995; Li et al., 2009; Garg et al., 2012a, 2012b; Abbaspour et al., 2015).

In the current study, WIC was run for each HRU by providing historic weather data and crop management details using 37 years of rainfall data. Table 2a & Table 2b showed the model parameters used in WIC for different HRUs. Root depth of eucalyptus measured from 10 years old plantation at ICRISAT heritage experiments was used as an input into the model. Similarly, effective root zone depth for other crops such as millets were also retrieved from literature (ICRISAT, 1990).

Keeping the land use unchanged for 1972 and 2011, respectively, the water balance components were derived for these two periods (Table 1). HRU results were analysed to assess i) total freshwater availability (harvested surface water in tanks and groundwater); ii) total irrigation demand, for the respective land use scenario.

2.2.4.3. Uncertainties of the model results. Landscape hydrology is highly complex as is driven by various biophysical (topography and soil types) and land management factors. In the current study, the model simulation was based on major selected HRUs that have soil hydraulic and moisture retention data (Table 2a). Auto-irrigation was considered for tomato, mulberry and maize crops; however, farmers commonly follow a range of irrigation practices which usually lead to under or over irrigation compared to the actual requirement. Moreover, the model calibration was restricted to the micro scale catchment and it was validated using the groundwater system due to unavailability of runoff data at catchment scale for this study.

Table 2a
Layer wise soil physical properties measured in Kolar district.

Location name	Latitude	Longitude	Depth	Sand %	Fine sand %	Silt %	Clay %	FC* (cm^3 cm^{-3})	PWP ** (cm^3 cm^{-3})
Huthur, Kolar taluk	13.1 N	78.3 E	0–15	43	33	12	12	0.10	0.03
			15–30	36	33	12	18	0.14	0.05
			30–60	32	23	14	31	0.18	0.07
			60–90	27	23	17	33	0.26	0.09
			90–120	27	25	20	28	0.28	0.10
Chikkakalvanchi, Bangarapet taluk	12.8 N	78.2 E	0–15	34	28	17	21	0.15	0.05
			15–30	31	23	14	32	0.18	0.06
			30–60	40	21	12	27	0.14	0.05
			60–90	26	16	13	44	0.20	0.08
			90–120	30	14	14	42	0.20	0.08
Gudibanda, Srinivaspur taluk	13.4 N	78.3 E	0–15	35	43	10	12	0.10	0.03
			15–30	33	30	14	23	0.18	0.05
			30–60	23	28	18	31	0.25	0.08
			60–90	28	26	16	30	0.25	0.08
			90–120	46	30	16	8	0.15	0.05

Note: Profile at two locations were excavated in each of the micro-watersheds.
[*] Soil moisture at field capacity.
[**] Soil moisture at permanent wilting point.

Table 2b
Crop parametrization of major HRUs provided to WIC.

Parameter	Value	Unit	Source
Crop Coefficient: K_c			
Millets (110 days)	0.2–0.9	(-)	NWDA, 2019
Groundnut (110 days)	0.2–1.0	(-)	NWDA, 2019
Tomato (110 days)	0.4–1.2	(-)	NWDA, 2019
Maize (120 days)	0.3–1.1	(-)	NWDA, 2019
Pigeon pea (180 days)	0.3–1.1	(-)	NWDA, 2019
Mulberry (Perennial)	0.4–1.1	(-)	NWDA, 2019
Eucalyptus (Perennial)	0.85–1.1	(-)	Al-Jamal et al., 2002; Alves et al., 2013
Effective rooting depth			
Millet, Groundnut, Maize, Tomato	0.50–0.60	meter	ICRISAT Annual report 1974; Gregory and Reddy 1982
Pigeon pea, Mulberry	0.8–1.0	meter	ICRISAT Annual report 1990
Eucalyptus	2.0	meter	ICRISAT experiment
Landscape topography			
Average land slope	2	Per cent	DEM data
Initial curve number (-) calibrated using micro watershed scale surface runoff data between 2006–08	75	(-)	Based on micro-scale runoff measurement in Huthur village

3. Results

3.1. Groundwater trend in Kolar

Fig. 3 shows the yearly variation in hydraulic head (mean with standard deviation) in borehole wells and dug wells between 1972 and 2013. A total of 28 borehole wells and 7 dug wells were monitored. Hydraulic head in borehole wells during 1970 and 1980 ranged from 15 m to 60 m depending on borehole well depth and its location in the topo-sequence. The hydraulic head in all the borehole wells has declined as the hydraulic head in 2013 was below 20 m in all the observation wells. Similarly, the hydraulic head in dug wells has also declined to below 2 m by 2013.

Trend analysis indicated that there is no change in total rainfall during the study period (Table 3, 1973–2013). However, groundwater levels during pre-monsoon (May) and post-monsoon (November) seasons showed a decreasing trend (Table 3). The month of May had the least groundwater head in respective wells. Whereas November which falls immediately after the monsoon period generally had the highest groundwater head. Therefore, the trend analysis was shown for these two months. Trends ($a \leq 0.01$, z-statistic $> \pm 2.5$, see footnote below Table 3 for definition) showed that hydraulic head in open wells dropped down drastically after 1995 and most of the open wells in the Kolar district became out of use in the past 10–15 years. Similarly, the water table in borehole wells also dropped down drastically ($a \leq 0.01$, z-statistic $> - 2.5$) from 1980 onwards (Fig. 3).

The average rainfall received during the monsoon period over the past four decades was similar, i.e., 533, 556, 566, 570 mm, respectively. Though there is no significant difference in monsoon rainfall amount, a slight increasing trend was observed in total annual rainfall amount received during the study period (1973–2013). Fig. 4 shows a decadal rate of change in water level in different observation wells. The figure also indicates location of observation wells along with stream network within the district. The rate of change in water levels during the first (1974–83) and second (1984–1993) decades does not show any trend. Whereas out of total 35 observation wells, 11 (31 % of total) showed a drop of more than one meter per year during the third (1994–2003) decade. Further, 17 wells out of 35 (47 %) have shown a drop of more than one meter during the fourth (2004–2013) decade. In addition, the number of wells with more than two-meter drop has doubled during fourth decade compared to third decade. One also should note that few of the wells between 1994–2003 and 2004–2013 do not indicate any declining pattern which might be due to their location near the tanks.

3.2. Change in land use

The population of Kolar district increased from 0.83 million in 1972 to 1.54 million in 2011 indicating 86 % growth in four decades (Table 4). There was a significant change in land use in the district between 1972 and 2011. Remote sensing analysis showed that area under plantation crops (i.e., eucalyptus) increased from 64 km^2 to 775 km^2 (converted 17.7 % of total district area) and the irrigated cropland increased from 366 km^2 to 1089 km^2 (converted 18 % of total district area) during the same period. On the other hand, shrub/grasslands were reduced from 1022 km^2 to 160 km^2 (i.e., reduced by 21.5 % of total district area). Further, the analysis revealed that 30 % of water bodies have disappeared (their area reduced from 195 km^2 to 132 km^2) (Fig. 5 and Table 4).

The data on the source of irrigation indicated that major irrigation sources during 1970 and 1980 were the open wells and minor irrigation tanks (GoK (Government of Karnataka, 2011). Fig. 6 shows that minor irrigation tanks and open wells were the predominant source of irrigation water until 1985. With diminishing outflows from irrigation tanks and depleted groundwater in open wells, farmers started extracting groundwater from deeper aquifers to irrigate their lands. The irrigation in the district predominantly depends on borehole wells since 2000 (Nagaraj et al., 2009, 2011).

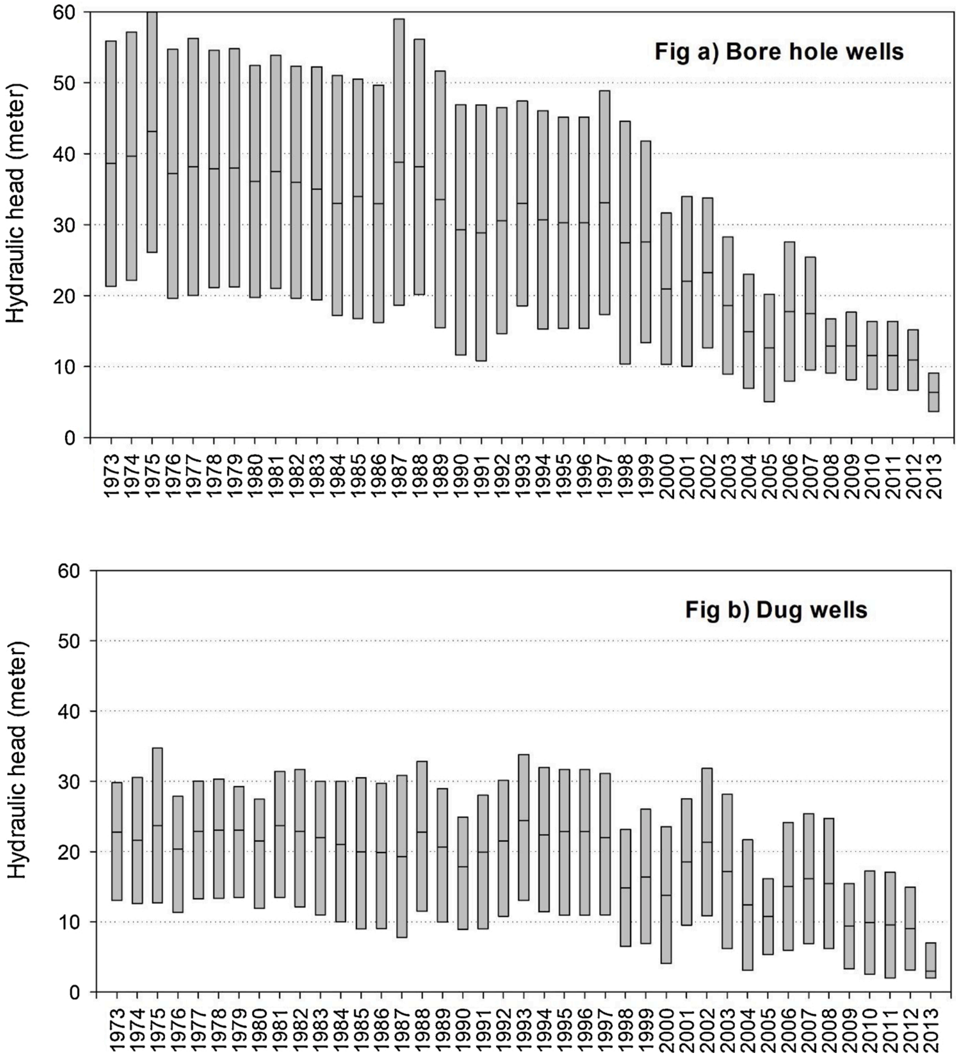

Fig. 3. Average hydraulic head in a) borehole wells and b) dug wells trend in Kolar district on yearly time scale (no of total observation wells = 35) between 1973 and 2013; bar indicates standard deviation around the mean.

Table 3
Trends in total rainfall and hydraulic head measured in open and borehole wells at Kolar (between 1973 and 2013). In which "a" indicates level of significance and "z" indicates its test statistic value.

Parameters	Test	Rho	Total S score	SD	Z-statistic	p-value	Test results
Rainfall (mm)	Mann-Kendall		−278	387	−0.71	0.238	No trend (a = 0.10)
	Spearman's rho	−0.077			−0.80	0.212	
Open wells (m)	Mann-Kendall		−66100	3554	−18.59		Decreasing trend (a <0.01)
	Spearman's rho	−0.73			−16.25		
Borehole wells (m)	Mann-Kendall		−97831	3554	−27.52		Decreasing trend (a <0.01)
	Spearman's rho	−0.961			−21.12		

Note: For 90 % level of confidence (a = 0.10), z value in between −1.29 and 1.29 indicates no trend; For 99 % level of confidence (a = 0.01), z value in between −.2.5 and +2.5 indicates no significant trend; z > 2.5 indicates increasing trend; and z< −2.5 indicates decreasing trend.

3.3. Model calibration and validation

Rainfall received in Huthur micro watershed during 2006, 2007 and 2008 was 547 mm, 370 mm and 882 mm respectively. Measured surface runoff from the micro watershed of 300 ha was 22 mm, 18 mm, and 52 mm, respectively (Table 5). The land use in this watershed was agriculture (60 %) and eucalyptus (40 %). The total available water [(FC-PWP) * depth] for this soil is 125 mm m^{-1}.

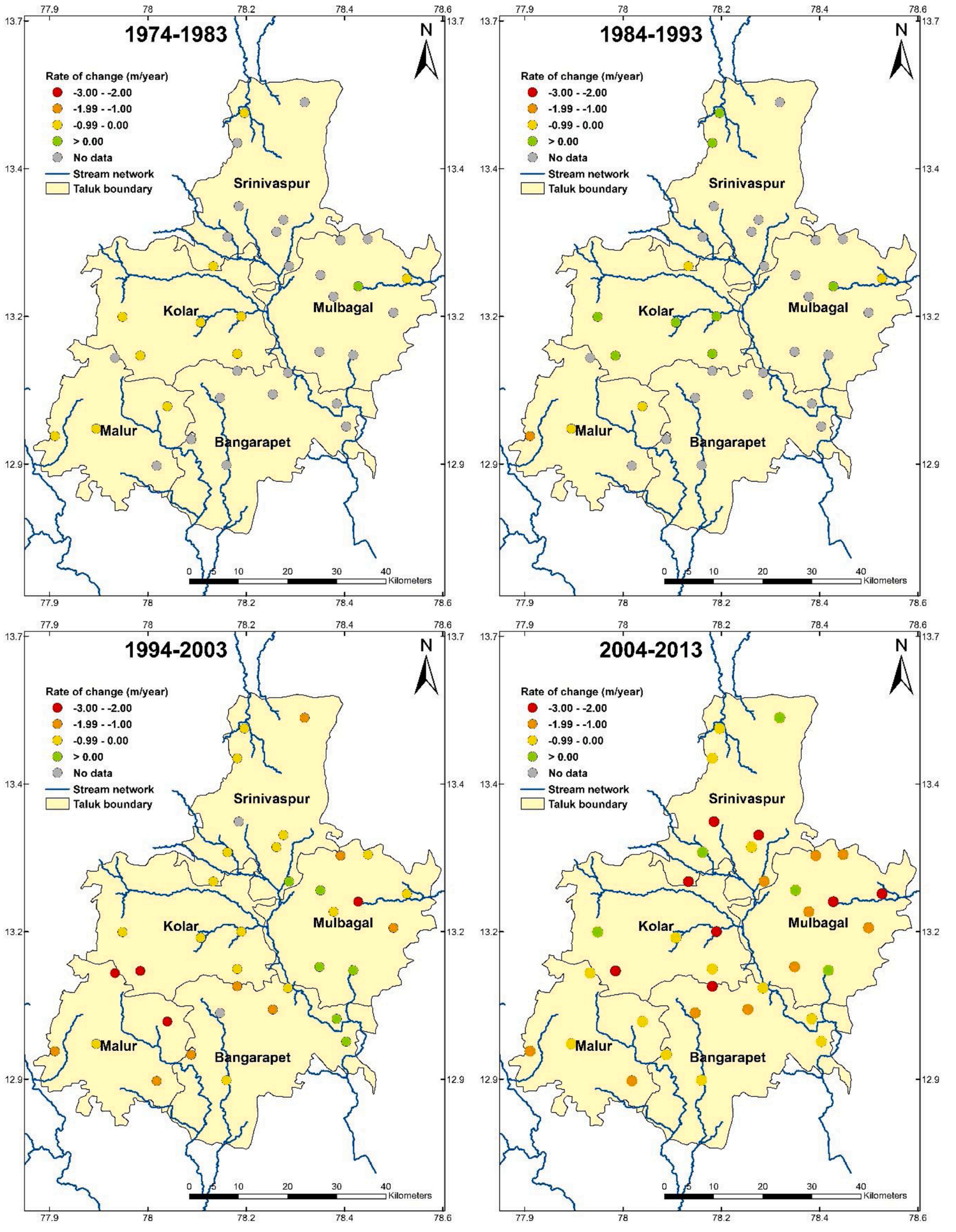

Fig. 4. Rate of change in water table from 1974 to 2013 (decadal wise) in different observation wells in Kolar district, Karnataka state.

Table 4
Change in land use from 1972 to 2011 in Kolar district.

LULC	Area (km^2)			Change equivalent to per cent total district area between 1972 and 2011
	1972	1992	2011	
Forests	256	256	256	0.0 %
Plantations (*e.g.*, eucalyptus)	64	571	775	17.7 %
Shrub lands/grasslands	1022	560	160	−21.5 %
Rainfed croplands	2092	1829	1562	−13.2 %
Irrigated croplands	366	628	1089	18.0%
Water bodies	195	133	132	−1.6 %
Settlements	17	35	38	0.5 %
Population (in million)*	0.83	1.21	1.54	

*Source: Kolar district at a Glance, various years.

WIC simulated surface runoff was 38 mm, 15 mm and 43 mm for 2006, 2007 and 2008 respectively. The Curve Number was modified to fit modeled value with observed value. Fig. 7 highlight that, on a daily time scale, WIC simulated runoff is comparable with measured values (Table 5).

However, there was no basin scale observed runoff data for district scale comparison. The model was validated using the simulated

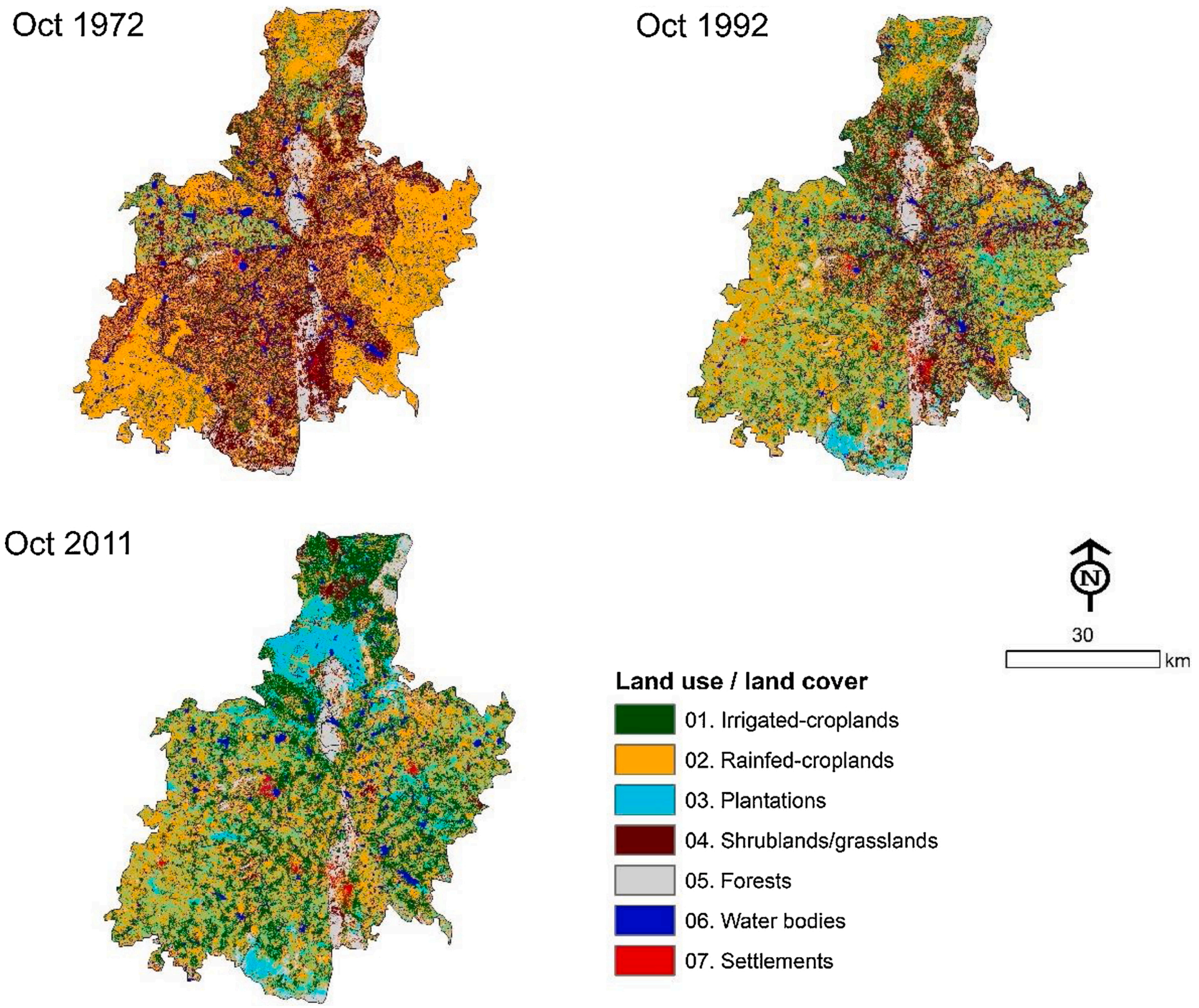

Fig. 5. Change in land use and land cover between 1972 and 2011 in Kolar district.

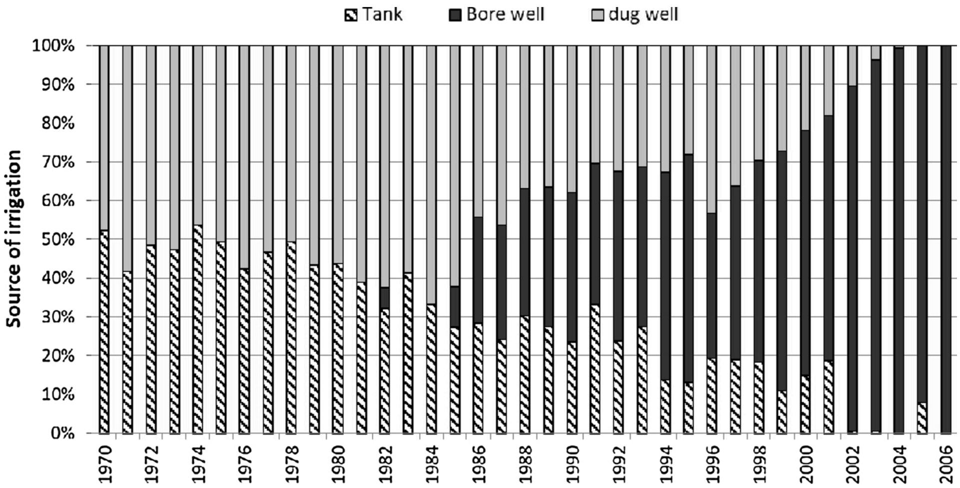

Fig. 6. Change in source of irrigation water in Kolar district. Source: Directorate of economics and statistics, Government of Karnataka, 2010.

Table 5
Measured and simulated surface runoff from micro-watershed of 300 ha at Huthur during 2006-2008.

Year	Annual Rainfall (mm)	Measured runoff (mm)	Simulated runoff (mm)
2006	547	22	38
2007	370	18	15
2008	882	52	43

groundwater recharge and compared with observed water table level data. The Observed head differences between June and October were converted into depth unit (mm) by multiplying them with specific yield as shown in Eq. (4). The groundwater withdrawal for agriculture during this period was considered negligible as irrigation in the rainy season (except during dry spells/dry years). Due to hard rock geology, water moves between fissures and fractures. In addition to soil strata, the district also has evidence of quick recharge during the wet season (Sekhar et al., 2013, 2018). Therefore, we consider that the amount of recharge within the region contributes eventually to the deeper aquifers during the monsoon season.

Simulated groundwater recharge was compared with the difference in measured groundwater head between pre-monsoon and post-monsoon seasons both for dug wells (Fig. 8a) and borehole wells (Fig. 8b). These variables represent the groundwater status but in different units and, therefore, each variable is shown on the primary and secondary Y axis. Comparison shows that both variables follow a similar trend, indicating that the model is capturing the groundwater recharge trend reasonably well (*Pearson Correlations*, r = 0.80).

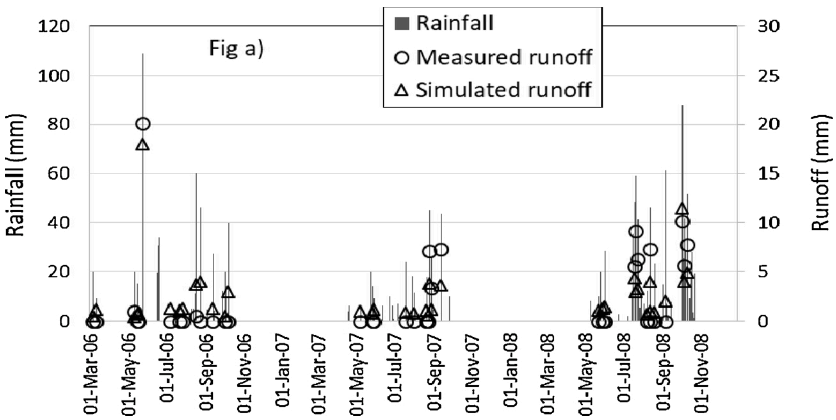

Fig. 7. Comparison between measured (circle) and simulated (tringle) runoff on daily time scale along with rainfall (vertical line) during 2006–08.

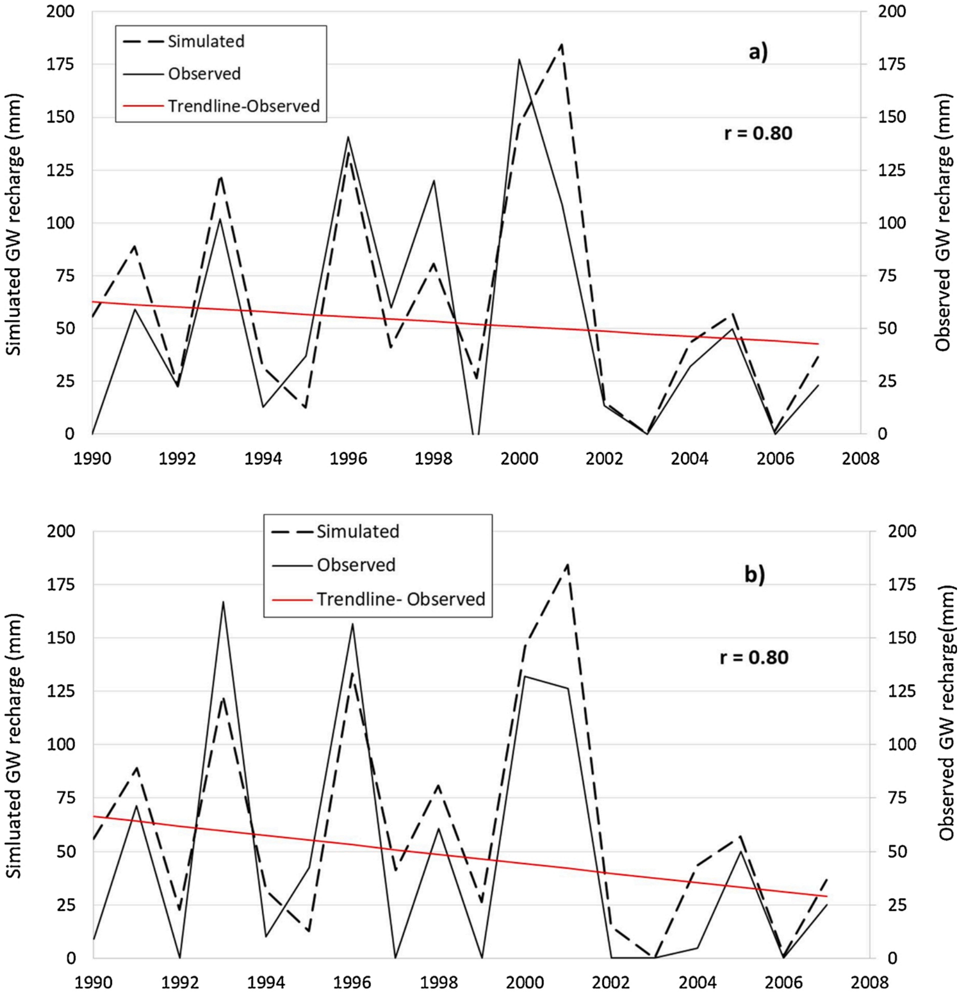

Fig. 8. Comparison between observed and simulated groundwater (GW) recharge of a) dug wells and b) borehole wells between pre- and post-monsoon periods; The trend line is related to the observed values.

3.4. *Water balance components of Grass-Crop Land (GCL) and Eucalyptus*

3.4.1. *Rainfall versus water balance components*

Fig. 9 compares the simulated hydrological relationships (rainfall versus water balance components in different years) for GCL and eucalyptus fields. Surface runoff increased with increasing rainfall. The generated runoff from GCL was 20 % higher than from eucalyptus. The largest hydrological impact (simulated) of land use change from GCL to eucalyptus was noticed on groundwater recharge (represented as deep percolation). There was no predicted deep percolation for rainfall up to 500 mm in eucalyptus fields. Deep percolation in eucalyptus fields for about 800 mm rainfall was just 50 mm compared to 200−250 mm in GCL. Evapotranspiration, ET, increased linearly with increasing rainfall in eucalyptus fields in different years. The ET in GCL increased up to 600 mm but for high rainfall years ET remained nearly the same.

3.4.2. *Monthly variation*

The predicted monthly water balance of GCL and eucalyptus fields is presented for a selected normal year (between −20 % and +20 % of long term average rainfall) (Fig. 10). About 72 % of the rainfall (565 mm) occurred during monsoon season (June to October). ET was generally high during the monsoon season; groundwater recharge occurred predominantly in September and October, and runoff occurred largely in August and September. In the simulation, the rainfall received in June and July was utilized completely by the crop (as water uptake and then transpiration). Once the soil water storage reached its maximum capacity, the rainfall generates blue water (runoff and deep percolation) which occurred after August. Rainfall during the non-monsoon period (November to May) was nearly 28 % (212 mm) of total rainfall. The non-monsoonal rainfall, is largely partitioned between the soil moisture store and the deep percolation (Fig. 10a).

On the other hand, more than 90 % of the received rainfall during the monsoonal and post-monsoonal period in eucalyptus field

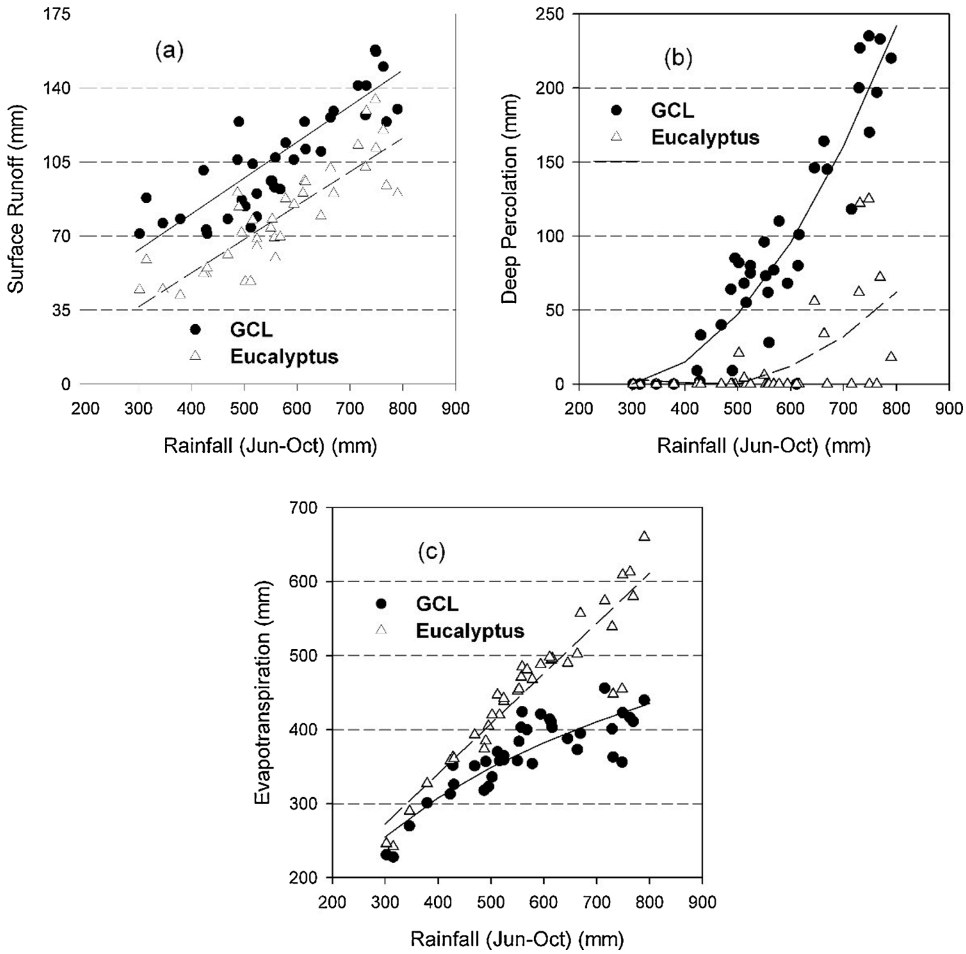

Fig. 9. Comparison of simulated hydrological response of grass and cropland (GCL) and eucalyptus. Rainfall vs. (a) surface runoff, (b) deep percolation and (c) evapotranspiration (Each dot represents relationship between monsoonal rainfall and various water balance components for respective years between 1971 and 2007).

appears to be used up by the tree crops (ET) and some of the rainfall (high intensity rainfall) was converted into surface runoff especially during August and September. Comparison of water balance components of GCL with eucalyptus clearly showed that the fraction of water, which was simulated as deep percolation in GCL was utilized by eucalyptus (Fig. 10b). Due to the deep rooting system (~2 m effective root zone as validated through field monitoring at ICRISAT micro-watershed) and high water demand, the root zone of eucalyptus frequently reached low soil moisture content despite the good amount of the received rain. Under such conditions, percolation was low.

3.4.3. Variation in water balance among dry, normal and wet years

The water partitioning differs for dry (rainfall less than 20 % of the long-term average), normal (rainfall between −20 % and +20 % of the long-term average) and wet years (rainfall greater than 20 % of long-term average) (Fig. 11). In wet years, in GCL, nearly 55 % (410 mm) of the total rainfall is lost by ET; the remaining amount was partitioned into deep percolation (26 %) and surface runoff (18 %). On the other hand, 77 % of the total rainfall in normal years was lost by eucalyptus ET and the remaining amount was partitioned into surface runoff (16 %) and deep percolation (6 %). In dry years, predicted ET of eucalyptus amounted to nearly 92 % of total monsoonal rainfall and left very little for surface runoff (9 %) and there was no deep percolation below the root zone. It is worth noting that even in normal years, estimated deep percolation is almost nil under the eucalyptus, whereas about 80 mm (14 %) was estimated to be available for deep percolation under GCL.

3.4.4. Irrigation demand of different crops during dry, normal and wet years

Table 6 summarizes simulated irrigation demand for different irrigated crops. Irrigation demand of Maize, Vegetables and Mulberry was 65−190 mm, 230−550 mm and 730−1050 mm, respectively. Two to three irrigation was suggested by the model for Maize crops which was cultivated during kharif season if the available soil moisture was lower than the crop water requirement. Thus, irrigation demand was found dependent on rainfall variability (its distribution and amount) from year to year. Irrigation demand for

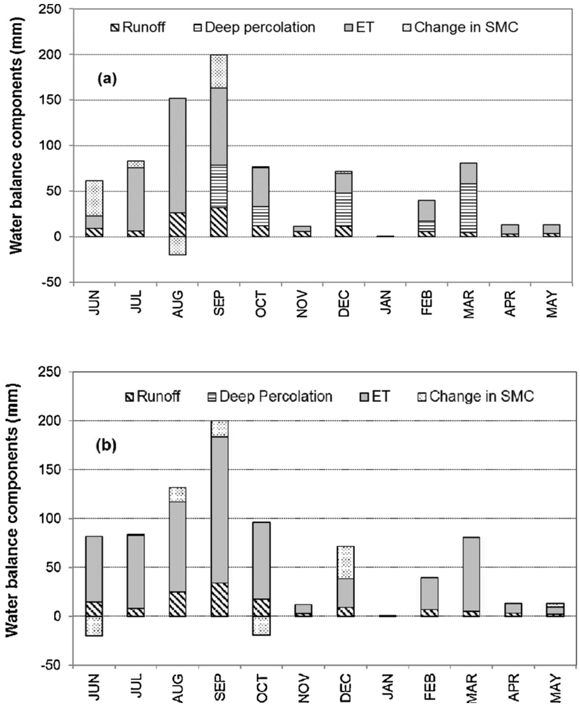

Fig. 10. Comparison of monthly water balance components [rainfall = runoff + Deep percolation + Evapotranspiration + Change in Soil moisture content (SMC)] of (a) GCL and (b) eucalyptus field in selected (rainfall in 1983 = 783) normal year in Kolar district.

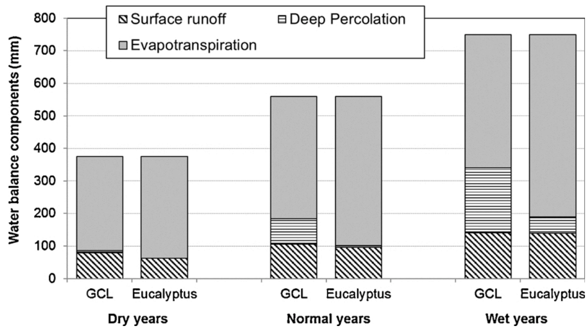

Fig. 11. Comparison of the simulated water balance components of grass and cropland (GCL) and eucalyptus in dry, normal and wet years.

Table 6
Simulated irrigation demand of different crops in dry, normal and wet years.

Crop	Season	Irrigation demand, mm Dry year	Irrigation demand, mm Normal year	Irrigation demand, mm Wet year
Maize	Kharif	190	130	65
Vegetables	Kharif and Rabi	550	400	230
Mulberry	Perennial	1050	875	730

vegetables and Mulberry was significantly higher as crop duration of these crops extends up to the dry periods and frequent irrigation was essential for crop survival and production.

3.5. Impact of land use change on water availability at district scale

3.5.1. Change in fresh water availability between 1972 and 2011

Water balance components of Kolar district for 1972–2011 period are summarized in Tables 7a–7d. These results are based on 37

Table 7a

Water balance components of Kolar district considering land use of 1972 and estimated groundwater (GW) utilization in different seasons (results based on 37 years of model run); Figures in parentheses indicate standard deviation.

Type of year	Number of year	Monsoonal water balance				Total blue water availability (GW + Harvested water in tanks) (mm)	Rainfall (Nov-May) (mm)	GW withdrawal/ blue water utilization (mm)				Net water deficit (mm/ yr)
		Rainfall (Jun-Oct) (mm)	ET (mm)	Surface runoff (mm)	Groundwater, GW recharge (mm)			*Kharif*	*Rabi*	Summer	Total	
Dry	7	375 (55)	289 (45)	77 (10)	8 (13)	8 + 71 = 79	194 (20)	29 (4)	20 (4)	24 (2)	72 (10)	−7
Normal	22	560 (59)	379 (32)	105 (26)	74 (39)	74 + 71 = 145	224 (22)	20 (5)	16 (4)	22 (2)	57 (5)	−88
Wet	8	750 (24)	416 (39)	141 (14)	192 (40)	192 + 71 = 263	195 (24)	9 (9)	11 (9)	23 (2)	43 (3)	−220
Average	37	565 (131)	370 (55)	108 (29)	87 (71)	87 + 71 = 158	212 (22)	19 (8)	15 (6)	23 (2)	57 (10)	−101

Table 7b
Water balance components of Kolar district considering land use in 2011 and estimated groundwater (GW) utilization in different seasons (results based on 37 years of model run). Figures in parentheses indicate standard deviation.

Type of year	No of years	Monsoonal water balance				Total blue water availability (GW + Harvested water in tanks) (mm)	Rainfall (Nov-May) in mm	GW withdrawal/blue water utilization (mm)				Net water deficit (mm y^{-1})
		Rainfall (June-Oct) in mm	ET (mm)	Surface runoff (mm)	Groundwater,GW recharge (mm)			Kharif	Rabi	Summer	Total	
Dry	7	375 (55)	318 (47)	51 (7)	6 (8)	6 + 48 = 54	194 (20)	77 (9)	44 (10)	58 (4)	179 (21)	125
Normal	22	560 (59)	441 (36)	72 (21)	47 (28)	47 + 48 = 95	224 (22)	52 (11)	35 (10)	54 (5)	141 (11)	46
Wet	8	750 (24)	476 (54)	140 (16)	134 (44)	134 + 48 = 182	195 (24)	24 (20)	24 (20)	57 (5)	105 (7)	−77
AVG	37	565 (131)	435 (71)	72 (29)	58 (52)	58 + 48 = 106	212 (22)	51 (18)	34 (14)	55 (5)	140 (23)	34

Table 7c
Total storage capacity of tanks during the years of 1972 and 2011.

Year	Tanks water spread area (km^2)	Average Tank depth (m)	Tank storage capacity (MCM)	Tanks storage capacity (mm)
1972	195	1.5	293	71
2011	132	1.5	198	48

Table 7d
Partitioning demand-supply gap due to change in land use (reduced freshwater) and increased irrigation demands.

Year	Average GW Recharge (mm)	Average Surface Runoff (mm)	Average Blue water availability in district (mm)	Irrigation Water demand (mm)	Demand-Supply Gap
1972	87	109	158	57	(-) 101
2011	58	72	106	140	(+) 34
Difference (mm)	(-29)	(-37)	(-) 52	(+) 83	(+) 135

years of model simulation. Out of 37 years, 7 years were dry, 22 years were normal, and 8 years were wet. Due to differences in land use, there is a significant change in the hydrological processes at district level. ET for 1972 scenario was 370 mm which increased to 435 mm during the 2011; whereas runoff reduced from 108 mm to 72 mm and groundwater recharge reduced from 87 mm to 58 mm. The surface runoff during dry years was reduced by 34 % (from 77 mm to 51 mm). Further, the groundwater recharge reduced by 30 % even in wet years (from 192 mm to 134 mm).

Table 7c further describes the change in storage capacity of the available tanks during 1972 and 2011. Considering an average height of 1.5 m storage capacity (based on ground truth data), the tank volume in 1972 at full capacity was estimated to be 293 MCM which was reduced to 198 MCM during 2011, this amount is equivalent to 71 mm and 48 mm (water depth) harvesting capacity at the district scale, respectively.

3.5.2. Demand-supply gap

The estimated groundwater withdrawal of the entire district for 1972 and 2011 is presented in Tables 7a and 7b. This estimation is based on weighted average of different HRUs which includes soil and groundwater variation within the HRUs. The results are based on model simulation. In 1972, the total pumping [kharif, rabi and summer] for agricultural use was 57 mm and groundwater recharge was 87 mm. Total irrigation requirements, even in dry years, were met with available groundwater resources and water from the tank storage system. Generated runoff from fields was harvested in nearby tanks. Harvested water in tanks was source of freshwater in addition to groundwater. Average annual groundwater recharge in dry years under the natural condition was estimated to be 8 mm; however, harvested runoff in tanks was 71 mm which largely met the irrigation requirements of 1972's cropping system. It is to be noted that, varietal change of simulated crops over the period was not considered in this analysis. Surplus availability of freshwater during normal /average and wet years were keeping tanks and shallow dug wells in functioning condition during 1972.

On the other hand, during 2011, the simulated groundwater extraction (140 mm) was higher than the total blue water availability (106 mm) which resulted into an annual net water deficit of 34 mm. Water balance analysis showed that there was a negative water balance (deficit status) both for dry and normal years. However, the water balance during wet years was found to be positive. Total blue water availability in wet years was estimated to be 182 mm compared to 105 mm of water use, leaving a 77 mm surplus.

As there was no difference in rainfall pattern from 1973 to 2013 (described in section 3.1), groundwater depletion could be from two major factors: (i) change in land use (GCL to eucalyptus, leading to reduced recharge) and (ii) higher pumping rate due to increased irrigated area. The contributing factors to the groundwater depletion at district level are summarized in Table 7d. The negative demand-supply gap (i.e., - 101 mm) of 1972 indicated that there was sustainable ecosystem with surplus blue water resource availability; whereas this difference was estimated to be positive (i.e., 34 mm) during 2011. Table 7b shows the simulated annual average reduction of surface runoff and groundwater. The blue water availability was estimated to be reduced by 52 mm in 2011 compared to 1972. Whereas ET losses, mainly from irrigation application, increased from 57 mm to 140 mm (net increase by 145 %) from 1972 to 2011. Out of this, 38 % estimated to be a reduction in blue water availability (which is due to change in land use from GCL to Eucalyptus) and 62 % is estimated to be due to increased irrigation requirements.

4. Discussion

District scale freshwater demand and supply analysis revealed that on the one hand district has reduced water availability due to increased area under eucalyptus; and on the other hand, gross irrigated area has increased multiple folds, widening the demand-supply gap. Increased irrigation water demand with change in land use and crop intensification was largely driven by population pressure. The freshwater demand increased by 150 % but blue water availability reduced by 30 % in 2011 compared to 1972. There was expansion of commercial crops such as mulberry (about 40 % of irrigated land, Table 1) which is a perennial shrub requires frequent irrigation. It is also to be noted that out of total blue water consumption, 30–50 % is required only in summer (Mar-May) to support mulberry growth.

Millets are resilient to the extreme climatic and soil conditions prevalent under the rainfed dryland system. Other cereals such as maize requires two to three supplemental irrigations (of total 50−200 mm) depending on rainfall amount and its distribution. Cultivating long duration- crops require significant amount of irrigation support as the potential evaporative demand of the region is relatively high (~1800 mm annually). Crop intensification, however, is inevitable with increasing population pressure but following the water balance approach could help to decide permissible threshold on freshwater use.

The study showed that change in land use and irrigation management both are important factors impacting sustainable water management. Similar observations were made by Srinivasan et al. (2015) for Arkavathy catchment (1440 km^2) near to the study area. The study revealed that groundwater pumping and expansion of eucalyptus plantation was the main driving factor for declined surface flow to the downstream water bodies. Further, they found that the variation in the temperature and rainfall did not influence catchment hydrology (Srinivasan et al., 2015).

Mass-scale land use conversion from GCL to eucalyptus in Kolar is suggested to have led to a depletion of groundwater and reduced surface runoff. The model results indicated that a large quantity of monsoonal and post-monsoonal rainfall on eucalyptus fields was largely converted into increased soil moisture and subsequently utilized by the trees; and only a limited quantity was left for deep percolation, recharge and surface runoff. GCL used the green water (rainwater) effectively within the 0.6 m soil depth (ICRISAT, 1974, 1990) during its growth season from July to October. Soil moisture of GCL reached field capacity level rapidly and the excess rainfall was partitioned into surface runoff and deep percolation. After saturating the root zone, the excess rainfall was partitioned into runoff and GW recharge; whereas soil moisture was consistently being utilized by vegetation (crop or plantation).

Plantations such as eucalyptus trees can develop roots more than 2 m deep. As these are perennial-ever green tree species, the modeled water demand is relatively high based on the crop coefficient K_c (ratio of crop ET to reference ET) ranging from 0.85 to 1.1 (Al-Jamal et al., 2002; Alves et al., 2013). However, the increased eucalyptus area in Kolar, explain only part of the changes in surface runoff and deep percolation which would have affected groundwater recharge and tank inflow. Water harvested in tanks helps to enhance local recharge especially during monsoon (Palanisami et al., 2012); and improved groundwater availability supports baseflow during the post-monsoon season (Kumar et al., 2016).

When the groundwater table had depleted much below the tank elevation, the groundwater driven baseflow declined (Kumar et al., 2016; Srinivasan et al., 2015). Fig. 4 highlights farmers had become dependent on borehole well irrigation after 1985. The source of irrigation in Kolar during 1970−85 was largely from dug wells and tanks which depleted significantly after 1985 and are out of use since 2000 (Rao et al., 2006). This has various socio-economic implication and sustainability issues of the number of ecosystem services. For example, increasing groundwater depletion resulted in high rate of well failure and capital investment by farmers (Anantha, 2013). Cost of cultivation including energy requirement was also increased (Sidhu et al., 2020).

With the increasing depletion of groundwater resource, equity and management aspects are of greater importance to build the resource resilience (Chandrakanth and Nagraj, 1997; Chaitra and Chandrakanth, 2005). In this situation, small and marginal farmers who cannot afford to invest on deepening borehole wells are bearing the brunt of declining water table (Anantha, 2013). There are only less than 30 % of farmers who are able to invest on groundwater extraction from deep aquifers (Chaitra and Chandrakanth, 2005). This has led to inequality in resource accessibility (Anantha, 2013). To sustain the groundwater resources, water policies should aim at integrating all water sources in the regional context rather than treating them in isolation. Demand management is equally important especially in the context of resource scarcity situation, as the supplies are limited. It helps in efficient and sustainable use of the resources when compared to supply side regulations.

5. Conclusions

This paper analyzes water balance components and change in hydrological processes due to land use change between 1972 and 2011 in Kolar district of Karnataka. This district has a gap between its water supply and demand. Change in land use from grass-cropped land, GCL to eucalyptus and high extraction of groundwater resources in Kolar was found to be the main reason for the depleting groundwater resource. Nearly 75 % of the total rainfall received during the monsoon period (i.e. 560 mm) was partitioned into evapotranspiration, ET, surface runoff and groundwater recharge. Conversion of GCL to plantations (mainly eucalyptus) reduces groundwater recharge by 33 % (from 87 mm to 58 mm) while the expansion of the irrigated area increased net groundwater withdrawal/abstraction by 145 % (from 57 mm to 140 mm). This has altered hydrological processes of the district and might explain why dug wells and tank systems have gone out of use from 2000 onwards. The main factors contributing to widening the demand-supply gap in Kolar were land use change (38 %) and over-pumping (62 %). These results will eventually help the various stakeholders including district and national authorities to revisit the land allocation for different land uses and to decide on the optimum allocation of land uses to close the gap between water supply and demand.

Author statement

Below are contribution by different authors in this study:
Kaushal K Garg: Conceptualization, data analysis and manuscript writing.
KH Anantha: Conceptualization, and manuscript writing.
Rajesh Nune: conceptualization.
Venkata Radha Akuraju: data analysis.
Pushpraj Singh: data collection.

G Murali Krishna: Remote sensing analysis.
Sreenath Dixit: reviewing and editing.
Ragab Ragab: Conceptualization, reviewing and editing.

Declaration of Competing Interest

The authors report no declarations of interest.

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