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Modeling the Vulnerability of an Urban Groundwater System due to the Combined Impacts of Climate Change and Management Scenarios

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ABSTRACT: Climate change impact on a groundwater-dependent small urban town has been investigated in the semiarid hard rock aquifer in southern

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India. A distributed groundwater model was used to simulate the groundwater levels in the study region for the projected future rainfall (2012–32) obtained from a general circulation model (GCM) to estimate the impacts of climate change and management practices on groundwater system. Management practices were based on the human-induced changes on the urban infrastructure such as reduced recharge from the lakes, reduced recharge from water and wastewater utility due to an operational and functioning underground drainage system, and additional water extracted by the water utility for domestic purposes. An assessment of impacts on the groundwater levels was carried out by calibrating a groundwater model using comprehensive data gathered during the period 2008–11 and then simulating the future groundwater level changes using rainfall from six GCMs [Institute of Numerical Mathematics Coupled Model, version 3.0 (INM-CM.3.0); L'Institut Pierre-Simon Laplace Coupled Model, version 4 (IPSL-CM4); Model for Interdisciplinary Research on Climate, version 3.2 (MIROC3.2); ECHAM and the global Hamburg Ocean Primitive Equation (ECHO-G); Hadley Centre Coupled Model, version 3 (HadCM3); and Hadley Centre Global Environment Model, version 1 (HadGEM1)] that were found to show good correlation to the historical rainfall in the study area. The model results for the present condition indicate that the annual average discharge (sum of pumping and natural groundwater outflow) was marginally or moderately higher at various locations than the recharge and further the recharge is aided from the recharge from the lakes. Model simulations showed that groundwater levels were vulnerable to the GCM rainfall and a scenario of moderate reduction in recharge from lakes. Hence, it is important to sustain the induced recharge from lakes by ensuring that sufficient runoff water flows to these lakes.

KEYWORDS: Climate impacts; Urban groundwater; Management scenarios; Numerical modeling; PORFLOW

1. Introduction

Groundwater acts as a decentralized source to provide ‘‘safe drinking water’’ for millions in rural and urban areas. It accounts for nearly 85% of rural domestic water needs and 50% of urban water needs (Kumar and Shah 2006). Accelerated population growth, increasing per capita water use, and poor reliability of imported surface water from distant sources are resulting in increasing dependence on groundwater for water supply in urban towns and cities (Foster et al. 2010; Eckstein and Eckstein 2003). Urbanization often modifies the groundwater cycle, and induced changes to the groundwater system may be a sharp decline or rise of groundwater levels, reduced well yields, and deterioration in quality of groundwater (Tellam et al. 2006; Kim et al. 2001). Few investigations were made to analyze the groundwater system in urban areas (Drangert and Cronin 2004; Israfilov 2006; Ongen and Tinmaz 2006; Wolf et al. 2006; Srinivasan et al. 2010; Rao et al. 2012).

Even though climate models project with greater certainty, the rise in temperature in various parts of the globe, the projections of rainfall are still are uncertain (Earman and Dettinger 2011). During the last decade, an extensive amount of research has been published on how climate change might influence different aspects of the hydrological cycle with focus on surface water impacts (Adger et al. 2007). Even though in recent years groundwater impacts of climate change are receiving attention (Zekster and Loaiciga 1993; Allen et al. 2004; Green et al. 2007;

Scibek et al. 2007), most of these are limited to impacts on recharge and discharge conditions in moderate/large size catchments. Hansen and Dettinger (Hansen and Dettinger 2005) performed a study focusing on linkage between global-scale climate variations and local groundwater response for a coastal aquifer basin of Southern California. Simulations using multiple ensembles of the ECHAM-3.6 were explored by incorporating the applicable sea surface temperature (SST) variations as boundary conditions in the GCM in order to address the uncertainties in the climate trends. Detailed reviews were made addressing the gaps (Dragoni and Sukhija 2008; Earman and Dettinger 2011), but the climate change impacts on urban groundwater systems have not received the desired attention. Furthermore, there is yet limited information on addressing impacts from a combination of climate change and management scenarios (Risbey et al. 2007; Candela et al. 2009).

Since most of the semiarid southern India is already water stressed because the monsoon rainfall concentrates over a few months in a year with relatively higher variability across years, climate change impacts, if any, would exacerbate the water stress and hence the impacts of climate change need to be evaluated. Because of the excessive pumping of groundwater in the semiarid areas in recent years in countries such as India, there are concerns of future availability of groundwater resource for meeting irrigation (van der Gun 2012) and more so of water resource needs of urban/rural water utilities. Furthermore, in certain situations the impact of human activities (e.g., land-use/land-cover changes, urbanization) are found to be much stronger than the climate variability (Scanlon et al. 2007) itself, and hence there is a need to characterize the coupled effects of human activities and climate change on the groundwater system for developing sustainable groundwater resource programs.

The objective of the present paper was first to investigate behavior of the groundwater system in a small urban town in a semiarid hard rock aquifer in southern India, wherein the water utility solely depends on groundwater for drinking and other uses. Second, we aimed to analyze the impact of combined climate and management scenarios on the hydrogeological system, in particular on the future groundwater declines and vulnerability of the municipal pumping well network. The first aim was addressed by analyzing the comprehensive data gathered at a proper spatial scale for the urban groundwater system during the period 2008–11 using lumped and distributed groundwater models and characterizing the processes operating in such a system. The second objective was addressed by modeling the groundwater flow and linking the changes in the groundwater declines to the GCM rainfall and, furthermore, evaluating the system sensitivity to different management scenarios. The novelty of the study was to use an ensemble of GCMs that showed good correlation to the historical rainfall and predict the groundwater levels in the study region.

The paper is organized as follows: In the next section, we present the system details of the case study site along with the field investigations and monitoring carried out for 3 years (June 2008–June 2011) in order to perform the model calibration and discuss the dynamics of the groundwater system. We then present the future simulations of impact of climate change using appropriate GCM rainfall and the management scenarios. Finally, we discuss the simulated insights obtained under these scenarios and provide inputs, which could be used into policy formulation of water supply for the town.

2. Details of the study site

The town of Mulbagal is situated at 13°8′–13°10′N, 78°21′–78°25′E at a distance of 95 km from Bangalore and has an average elevation of 827 m in the Kolar district in the Karnataka state of southern India. The town is in a semiarid climatic setting and experiences temperature variation between 18° and 35°C (during the winter and summer seasons) and receives an average annual rainfall of 818 mm (based on the last 30 years of data record) with 72 rainy days in a year. It has a geographical area of 8.5 km^2 with a population of about 60 000 and the water needs of the town are mainly met by groundwater (Rao et al. 2012). They depend on groundwater for its water requirements through about 105 bore wells installed by local civic authorities. There are five pumping stations (PS), which are located outside the town, and each station has a cluster of bore wells that are pumped to distribute water to the town. Most of these clusters of wells are located very close to the manmade lakes to benefit the wells from additional recharge both during and after the rainy season.

The lakes have been built along the stream drainages and are common in southern India and often have runoff water stored in them during the rainy (monsoon) season. In the study area, a similar configuration is observed as well with about 18 larger lakes (>10 ha) and a large number of small lakes. The total area of large and small lakes was estimated as 510 ha. In the main town area, there are six major lakes. The lakes fill up during monsoon (June–October), and some of the lakes store water during the remaining dry season (November–May). The seepage from the lakes, being in the valley, maintains streamflows in the drainage network. However, in recent years with excessive groundwater pumping the groundwater levels in the vicinity of the lakes, the groundwater levels have declined. In these circumstances, the water stored in the lakes during the nonmonsoon provides recharge to the groundwater system. Moreover, it is becoming a common practice by the water utilities to drill bore wells in the vicinity of the lakes to benefit from induced recharge conditions from the water stored in the lakes. Since water is stored in the lakes for significant period of the summer season, the bore wells in the vicinity of the lakes have shown higher recharge. In addition, the well yield of these wells was found to be more reliable.

The lakes have been built along the stream drainages and are common in southern India and often have runoff water stored in them during the rainy (monsoon) season and often dry up in the months of February–May. A total of 51 bore wells exist in these five pumping stations. The rest of the 54 municipal wells are located within the town premises. In addition, there are a large numbers of private wells (~200) that are also within the town premises. The water pumped from all these wells is approximately 6.5×10^6 L day^{-1}, which varies during the various months of the year because of the yield from the wells and also because of the number of hours of electricity availability. Typically, about 5×10^6 L day^{-1} of water is pumped from all the pumping stations located outside the town to centralized municipal supply system where pumped water is collected in sumps, and then water from the sumps are pumped to service reservoirs, which then supply water through piped network to individual households or community taps at street levels (Rao et al. 2012). About 0.75×10^6 L day^{-1} is pumped from the municipal wells located within the town, which directly feeds into a separate localized pipe

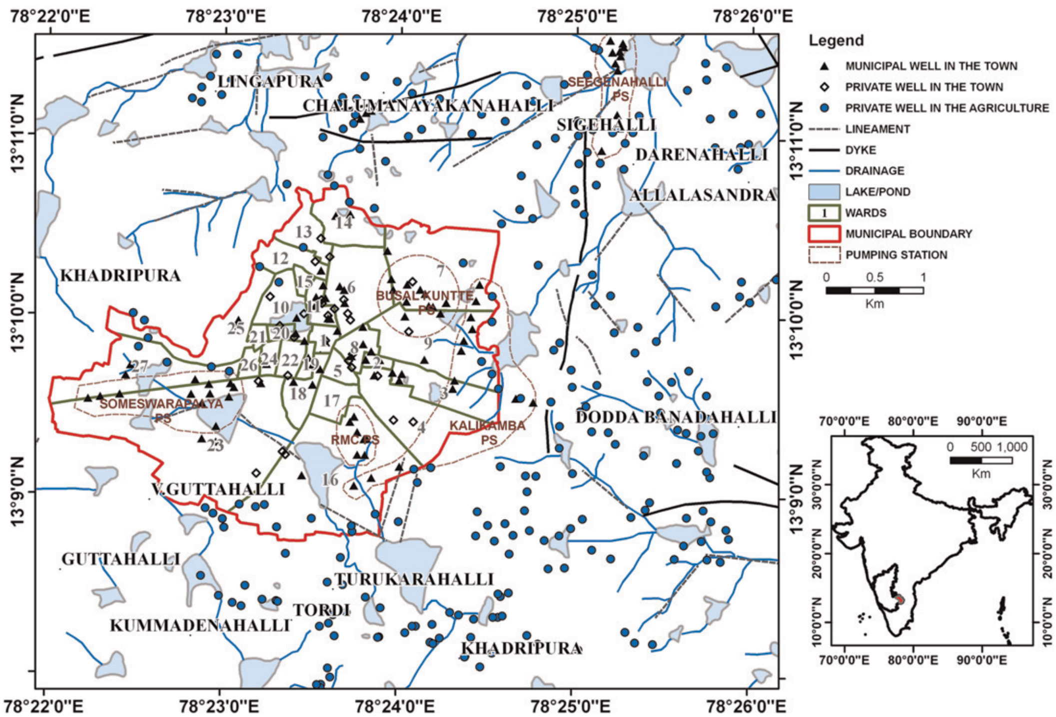

Figure 1. Groundwater-level monitoring stations in the town and outside the town.

network that provides water to the individual households/community taps/small water tanks, and another $0.75 \times 10^6\,\mathrm{L\,day^{-1}}$ is pumped from the private wells, which are installed by private users for domestic needs. Even though the number of wells of the municipal water utility are fewer than the private wells, the pumping from the municipal wells is much higher (PS wells receive about 10–12 h of electricity, which is much higher than what the other private and agricultural wells receive), with the private wells accounting to just 10% of the total pumping for urban water needs. Since the utility provided piped water supply is not adequate, consumers depend from a combination of utility-piped supply (from municipal bore wells), private bore wells (self-supply), tankers, and untreated water bodies, which are common practices in many urban towns in India (Srinivasan et al. 2010; Misra and Goldar 2008). The geology of the region is gneissic rock system composed of composite gneisses, migmatites, granites, and quartz veins. The weathered zone in the crystalline formation ranges from 1 to 20 m in thickness where larger thicknesses of weathered zones often are encountered in valley portions over gneiss deposits (DMG and CGWB 2005). The fracture/fissure system developed along joints and faults traversing the rock facilitates groundwater circulation and holds moderate quantities of water (Jal Nirmal Project Report 2004). The transmissivity of the formation ranges from 2 to $50\,\mathrm{m^2\,day^{-1}}$. The average yield of the wells vary from 0.8 to $5\,\mathrm{L\,s^{-1}}$ (DMG and CGWB 2005).

Figure 1 shows the geographical setting of the town of Mulbagal with the first-order drainages that are originating in all directions away from the town, the lakes

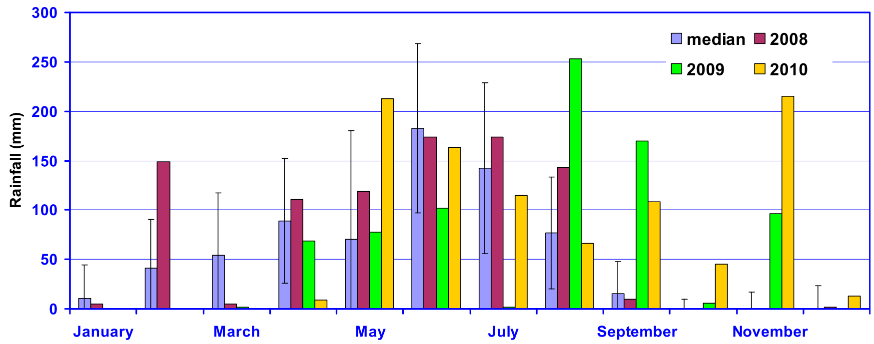

Figure 2. Monthly rainfall patterns in the town of Mulbagal during 2008–10.

that are present in these stream drainages along with the municipal bore wells, and the surrounding rural agricultural wells outside the town limits. The groundwater being the only source of potable water has been developed extensively since the mid-1980s, and its use has grown rapidly with extensive dependence since the mid-1990s. The region and the Kolar district as a whole has been assessed as a groundwater stressed district because of overutilization of groundwater for irrigation and drinking water needs during the last two decades in comparison to the resulting recharge from rainfall (Planning Commission 2007). Even though there is a national framework for groundwater development and assessment (GEC 1997), this assessment is limited mainly to agricultural regions/watersheds with a minimum scale of about 500 km^2 with little emphasis for urban towns. Hence, water utilities of small and medium urban towns like Mulbagal have to develop a sustainable water management plan by themselves toward the future needs and to efficiently manage the groundwater resources aided by groundwater studies using models and groundwater database developed at the relevant spatial scale.

3. Field investigations and database

The daily rainfall data were collected from the station monitored by the Karnataka State Natural Disaster Monitoring Cell for the period 2008–10. A plot of monthly rainfall patterns for the three years is shown in the Figure 2. The median rainfall of 1978–97 is also shown as a comparison. The annual (January–December) rainfall was 890, 681, and 947 mm for the years 2008, 2009, and 2010, respectively. The median rainfall (1978–97) was 680 mm with a standard deviation of 209.5 mm and a coefficient of variation of 25%. Among the three years, 2009 had a lower rainfall, which was comparable to the median rainfall, whereas during the other two years the rainfall was higher than the median. Also, the monthly distribution was different in each of the years, signifying the behavior of the monsoon rainfall.

The groundwater table mapping was carried out between 2008 and 2011, which corresponded to the three monsoon and nonmonsoon years of 2008/09, 2009/10, and 2010/11. The data collection helped in assessing the baseline and spatiotemporal variability through extensive field investigations. There was no prior detailed

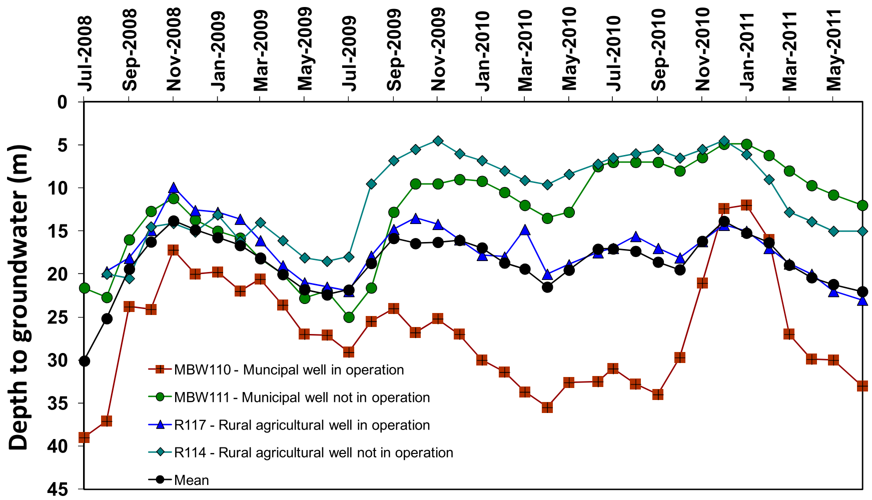

Figure 3. Groundwater levels at Seegenhalli PS.

observation well network of any government agency in the town in the past except monitoring performed at one monitoring well by the state groundwater agency. Therefore, the first step was to create a comprehensive database for the town. The groundwater level (GWL) measurements were performed using a monitoring network of 272 wells (98 municipal wells, 37 private wells, and 137 agricultural wells) in an area of approximately 50 km^2 with stations located within the town as well as outside the town in the agricultural region (Figure 1). This was performed by a novel approach in which the existing wells (both the municipal and the private wells) were used as piezometers and groundwater levels measured using a Heron skinny dipper when there was no pumping in these wells for extended hours of time. Moreover, the static state of the groundwater levels were ensured by allowing the water levels to recover for about 6–10 h after pumping from the concerned wells was stopped. This recuperation period was arrived at by monitoring groundwater levels of the wells in the postpumping stage during preliminary field trials. The measurements were performed for each month during the above period with the frequency chosen to be the same as that adopted for monitoring of groundwater levels in the state of Karnataka. Monitoring the groundwater levels both in the town and outside the town region helped in developing a reliable groundwater contour and flow map for the smaller region encompassing the town. Moreover, measurements in agricultural wells and the municipal wells helped in comparing the patterns of groundwater levels based on the respective uses and their controls on the groundwater system. Figure 3 shows a typical time series of the groundwater levels during July 2008 and July 2011. The plot indicates that groundwater levels declined during the nonmonsoon months (January–May) and again were raised during the monsoon period (July–November) and were mostly stable over the 3-yr period. Figure 3 shows the comparison between the temporal patterns in the groundwater level for a sample municipal well and an agricultural well, indicating that the municipal well experienced higher intrayear and interyear dynamics.

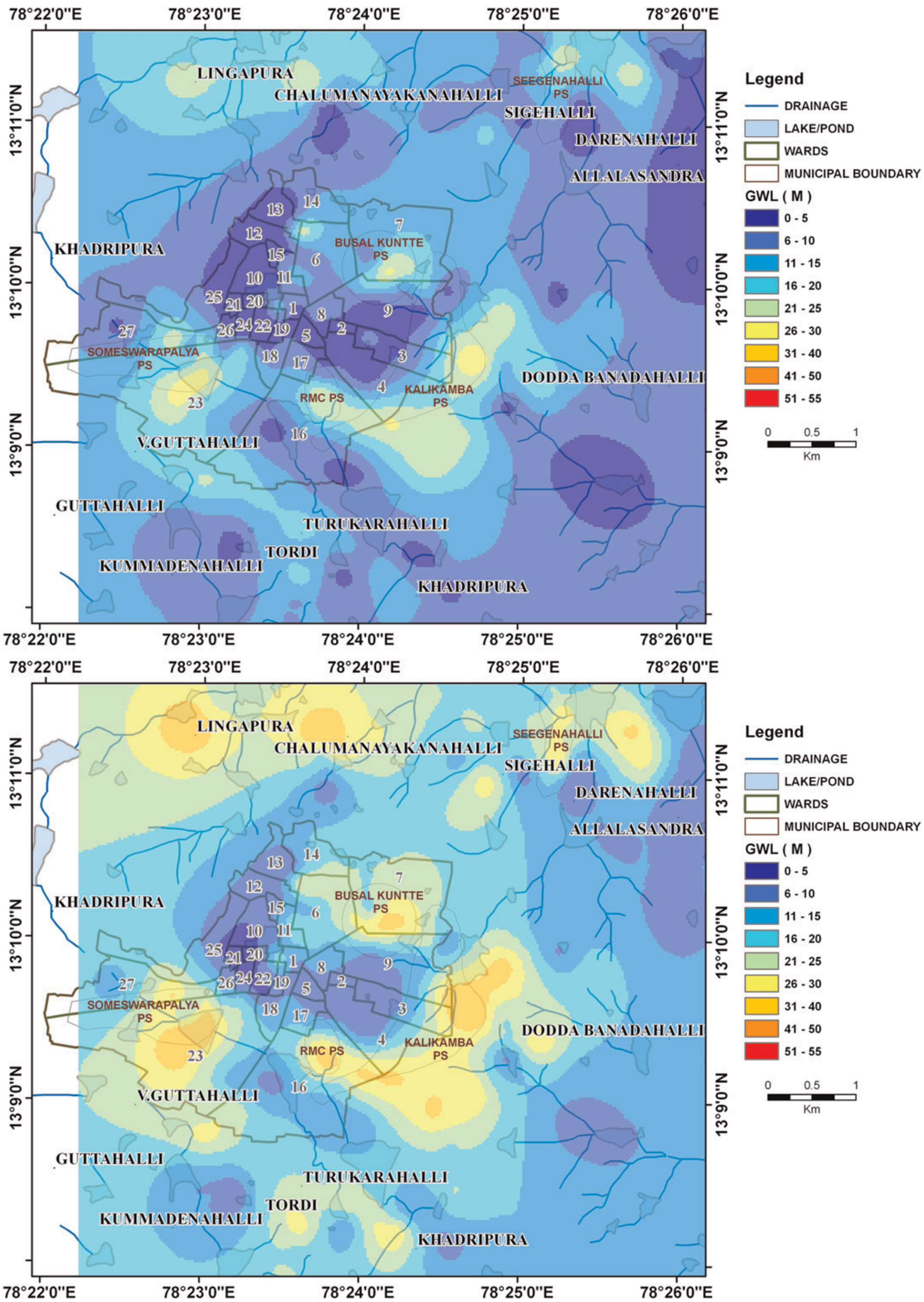

Figure 4. Groundwater-level contours for December 2010 and June 2011.

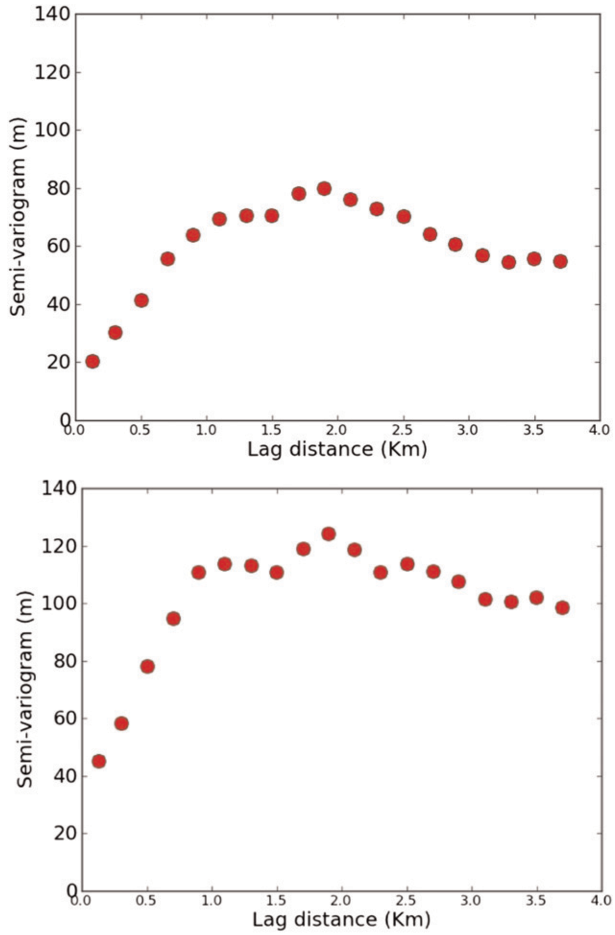

Figure 5. Semivariogram plot of groundwater levels for December 2010 and June 2011.

Figure 4 presents the contour maps of groundwater levels obtained using classical kriging analysis (Kitanidis 1997; Theodossiou and Latinopoulos 2006) for the months of December 2010 (postmonsoon) and June 2011 (summer). Figure 5 presents the semivariograms for these months, which show high nugget effect, indicating that the variability at very short distances for which no pairs of observations are available. Moreover, the sill value of the semivariogram, which indicates the prediction variance, was higher for the summer months in comparison to the postmonsoon period. Figure 5 shows a sudden jump in the variogram from the 0-lag distance to the average minimum distance among observations is called the nugget. The nugget explains the variability present in the data below the average minimum distance among observations. The observed variograms for December 2010 (postmonsoon) and June 2011 (summer) show a significant nugget. The possible reason for the nugget could be the presence of spatial random pumping and recharge to groundwater. This suggests that, while analyzing the groundwater table for the future, suitable scenarios (management scenarios) are required that capture the effects of urban groundwater catchments adequately. The sill is the value of variogram at large lag distance. The observed sill was higher for the summer months in comparison to the postmonsoon period, suggesting the presence of a higher spatially random pumping in the summer. However, studies performed in agricultural catchments with groundwater irrigation in similar lithology (granitic aquifer in southern India), climatic context, and scale (Kumar and Ahmed 2003) did not show the nugget effect. Hence, this brings out the subgrid variability effects controlled by human influences in urban catchments.

Groundwater levels in Figure 4 showed systematic rises due to the recharge from the rainfall during the monsoon season. Significant spatial variability in the rises was also observed. Spatial patterns of groundwater levels in and around Mulbagal indicated that within the core parts of the town the water levels were shallow during both summer and winter and this behavior was found to be stationary during all the three years. The shallow groundwater levels in urban cities were linked to relatively higher recharge than the natural drainage, with the higher recharge resulting because of the leakages from water and wastewater systems than the normal recharge from rainfall (Foster et al. 2010; Kim et al. 2001). The wastewater system in the town of Mulbagal is managed by a pit-toilet system and there was no underground drainage system, which resulted in infiltration of the used water brought from outside the town. Because of this, the groundwater quality was found to be poor and positively correlated in areas with shallow groundwater levels (Rao et al. 2012). Furthermore, the groundwater levels in the vicinity of the lakes were observed to be benefitted by the water present in the lakes, especially during the monsoon. The time series plots of groundwater levels at various pumping station wells in 2009–10 (relatively lower rainfall year) showed a higher decline relative to the other two years but then were able to regain the earlier levels because of the good rainfall in the subsequent year (2010–11). This suggested that the recharge from the median rainfall was not sufficient to sustain the groundwater levels in the pumping station wells unless there is higher than normal rainfall in the preceding or following years, meaning the groundwater use through pumping in the pumping station wells could be sustained only through recharge higher than that of a normal rainfall year.

4. Modeling of the groundwater system

4.1. Recharge estimation

The groundwater levels were periodically (once in 3 months) monitored at a station located outside the town boundary during the period 1978–97 by the state groundwater agency. The groundwater level time series at this station provided an opportunity to estimate recharge from rainfall. Moreover, since this station was away from the town and the data belonged to earlier periods when groundwater use was significantly lower in this region, it was assessed to be relatively less affected by pumping effects. Based on this hypothesis, the dataset was modeled using a simplified lumped groundwater model based on the cumulative rainfall departure (CRD) method (Xu and van Tonder 2001; Xu and Beekman 2003). A model based on this approach was found to be applicable for modeling the groundwater in low storage hard rock aquifers in the state of Karnataka (Sekhar et al. 2011). The model

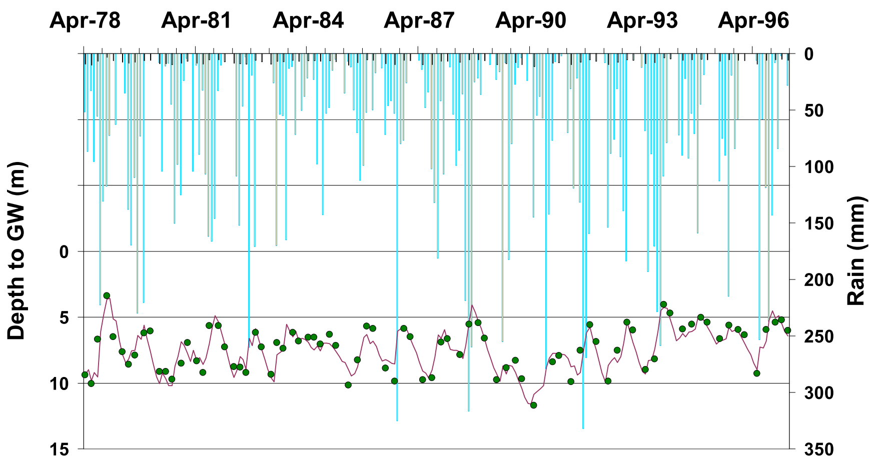

Figure 6. Comparison of observed and simulated groundwater levels monitored at a station during 1978–97. The line represents simulated and circle represents observations.

fit is presented in Figure 6 and shows that the model could capture the groundwater level dynamics at this station reasonably well. The figure also shows the monthly rainfall recorded at a station in the town of Mulbagal during this period. The specific yield in granitic-gneissic hard rock aquifers of southern India varies in the range 0.005–0.01. A value of 0.005 is found to be applicable when groundwater levels are relatively deeper (Sekhar et al. 1992; Marechal et al. 2006). Using an assumed specific yield of 0.005, the mean annual recharge for the period 1978–96 was estimated to be 68 mm for a mean annual rainfall of 790 mm (a rainfall recharge factor of 8.6%). The recharge and discharge values averaged over a long period were found to be nearly same as the groundwater levels were in equilibrium over this period. Interestingly, the coefficient of variation of annual rainfall for this period was 0.27, whereas the CV of annual recharge was 0.45, indicating that the annual recharge has a higher standard deviation and nearly twice that of rainfall.

4.2. Groundwater budget at the pumping station wells

To analyze the recharge and groundwater discharge components at the municipal wells near the PS, a simplified analysis was developed. The methodology is very similar to the recharge estimation methodology in operation in the country (GEC 1997; Marechal et al. 2006) except in the present case, instead of combined estimation of recharge and specific yield, recharge and total discharge (sum of natural discharge and pumping) were estimated assuming specific yield. A two-step approach was used for the monsoon and the nonmonsoon seasons with the assumption that there was no recharge during the nonmonsoon season, and the fall in the groundwater level was assumed to have occurred due to groundwater pumping and natural discharge or net outflow. This assumption was reasonable as the wells near the pumping stations were located away from the town and may have minimal

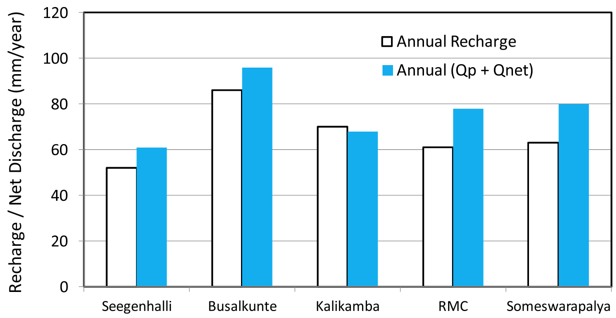

Figure 7. Mean annual recharge *R* and total discharge (sum of Q_{net} and Q_p) for pumping station wells.

effects of recharge resulting from leakage of water and wastewater utilities inside the town limits. The equations for the lumped groundwater system can be given as

$$\frac{\Delta h}{\Delta t} S_y = R - (Q_{\mathrm{net}} + Q_p), \tag{1}$$

where

$$Q_{\mathrm{net}} = (Q_{\mathrm{out}} - Q_{\mathrm{in}}). \tag{2}$$

Here, R is the recharge per time step from all sources (LT^{-1}), Q_{in} is the total groundwater inflow per time step (LT^{-1}), Q_{out} is the total groundwater outflow per time step (LT^{-1}), and Q_p is the pumping per time step (LT^{-1}). Using the two-step approach, the groundwater balance equation could be expressed for the monsoon and nonmonsoon as follows:
the monsoon is

$$(\Delta h) S_y = (R - Q_{\mathrm{net}} - Q_p)(\Delta t) \tag{3}$$

and the nonmonsoon is

$$(\Delta h) S_y = -(Q_{\mathrm{net}} + Q_p)(\Delta t). \tag{4}$$

In Equations (3) and (4), Δh indicates the rise or fall in groundwater level for respective season, with corresponding time periods Δt. Furthermore, in these equations, there are three unknowns: recharge R in the monsoon, the sum of net groundwater discharge and pumping ($Q_{\mathrm{net}} + Q_p$), and the specific yield S_y. By assuming suitable specific yield applicable to this region, the number of unknowns reduces to two and, in which case, it is feasible to estimate the R and ($Q_{\mathrm{net}} + Q_p$).

Figure 7 presents the spatiotemporal mean annual recharge R and total discharge (sum of Q_{net} and Q_p) based on the estimates over the three years for various pumping station locations. The figure shows that in all the locations, the total annual discharge was higher than the annual recharge. For Seegenhalli PS and Busalkunte PS this difference was marginal, whereas for RMC PS and Someswarapalya PS the difference was moderate. In the case of Kalikamba PS, the difference was insignificant, which means that the annual recharge was sufficient to replenish the aquifer depletion in the above cases. It may be noted that the rainfall in the town of Mulbagal in 2008–09 and 2010–11 was relatively higher than the long-term mean. This implies that in spite of higher recharge associated with a higher rainfall, the 3-yr average recharge was lower than the sum of natural discharge and pumping even though marginally. However, if the rainfall in the future is lower for a few years, this may result in larger deviation between recharge and discharge and could result in depletion of groundwater storage at the pumping station wells.

To assess the behavior at a well that is underpumping throughout the period and influenced by additional recharge from lakes, a municipal well (MBW; MBW105) at the Seegenhalli PS station was considered. The groundwater dynamics observed in this well for the 3-yr period were modeled using the CRD-based groundwater model. The model was modified by introducing pumping and additional recharge resulting from the lakes in order to fit the measured and simulated groundwater levels. The recharge from rainfall was estimated as 65, 50, and 70 mm for the three years 2008–09, 2009–10, and 2010–11, respectively. The additional recharge was found to be 75 mm, which is the recharge quantity from the lake system in the vicinity of this well. This implies that a considerable portion of the pumping was balanced by the recharge from the lake. Since several pumping station wells are located near or in the vicinity of lakes, the recharge from the lakes forms a significant quantity of additional recharge in the pumping wells. This is an important conclusion indicating that, even though the wells in the various pumping stations are affected by depletion of groundwater storage due to pumping, the additional recharge from the lakes is mitigating this aspect. Hence, it was critical that the lakes should have stored water each year for a sustainable groundwater conditions in these locations.

4.3. Modeling with a distributed groundwater model

Groundwater simulations were made using the 2D distributed groundwater model of PORFLOW version 5.5 for the study site. PORFLOW is a finite volume–based commercial software package developed by Analytic & Computational Research, Inc. (ACRi; http://www.acricfd.com/) and is a comprehensive mathematical model for simulation of multiphase fluid flow, heat transfer, and mass transport processes in variably saturated porous and fractured media, which has been applied for wide ranging applications (Flach 2004; Zhan and Park 2002). Cartesian grid structure was adopted to discretize the study region with a grid size of 36 m $\times$ 30 m using the initial condition of peizometric heads of December 2008. Since the model uses piezometric heads, these were generated by subtracting the kriged groundwater levels of the study region from the topographic levels. The topographic levels were generated using the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) digital elevation model (DEM) with the bias corrected using the field survey levels available from a total station survey with the municipal water utility. The boundary of the computational grid was chosen to be quite large with respect to the region of interest, which was feasible because of the presence of groundwater-level monitoring network beyond the study region with good granularity as shown in Figure 1. Constant head boundary condition was adopted using the groundwater levels of June 2009 as it was the lowest groundwater level and would result in more realistic groundwater flux condition close to the urban–periurban region. Sensitivity analysis was also performed to analyze the effect of the chosen boundary condition on the shape of the groundwater contours in the region of interest of the study, and it was observed that the effects, if any, were limited very close to boundary of the computational grid. Transmissivity was chosen as spatially homogeneous as the numerous pump tests conducted in the study region were found to vary in a narrow range of 10–25 $m^2 day^{-1}$. Specific yield was also assumed to be spatially homogeneous and a value of 0.005 was adopted based on the values reported for the granitic-gneiss lithology in this region (Sekhar et al. 1992). The groundwater pumping (source term in the model) was estimated by conducting field surveys of well yield at most of the wells, which are under operation during different seasons through extensive data collection. The yields were found to vary between 1 and 3 $L s^{-1}$. Data of the number of hours of electricity supplied each day to the municipal and agricultural wells were gathered from the local electricity agency, and combining these with the well yield survey data resulted in the estimates of groundwater pumping.

The numerical model was run with a half-day time step and the model was calibrated first during the nonmonsoon season of January–May 2009. The spatial variations of pumping adopted based on the estimates in MBWs and rural agricultural wells (RBW) were quite reasonable and provided good results for simulating the spatial variation of decline of groundwater levels in most locations during the nonmonsoon season. However, the decline in groundwater level simulated in the interior areas of the town was relatively higher than the observed. As discussed earlier, the interior areas of the town are affected by leakage of water and wastewater, which was as if there was recharge during this period even though the analysis was performed during the nonrainy season. By modifying and reducing the pumping values of municipal wells belonging to the interior areas of the town by 50%, the simulated groundwater declines were found to match well with the observed levels. Hence, through this argument the recharge due to leakage of wastewater system was assessed and it was found to be 50% of the water pumped from the wells in the interior town region. The plot of observed and simulated groundwater levels for April 2009 pertaining to the calibration phase is shown in Figure 8. As validation, simulations were performed for the monsoon of June–November 2009 using the calibrated parameters with an estimated rainfall recharge factor obtained using the lumped model discussed earlier. The spatial variations of simulated groundwater rise during the monsoon were captured well when compared with the observed levels. Figure 8 shows the plot of observed and simulated groundwater levels for January 2010 at the end of the monsoon of 2009.

5. Modeling the impacts of climate change and management scenarios

An increase of 0.4°–0.6°C has occurred over the past 100 years in India (Bhattacharya 2007) and was attributed to the climate change. Increases in extreme rains during the summer monsoon in northwestern India and a lower number of rainy days along the eastern coast were observed in recent decades (Cruz et al.

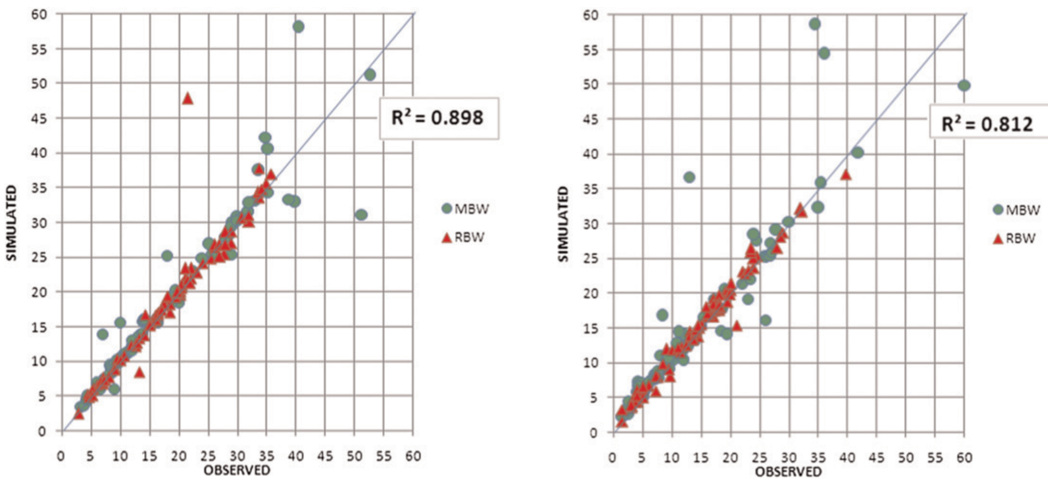

Figure 8. Groundwater levels (m) calibrated for April 2009 and validated for January 2010, respectively, at MBW and RBW locations using the PORFLOW model.

2007). A recent regional fine-grained climate model (Ashfaq et al. 2009) confirmed that monsoon patterns would change both in the timing of the advent of rains and in the amount of precipitation. Because of the uncertainties in projected trends of monsoon rainfall, it is not clear if the impacts of climate changes in India on water resources will be positive or negative (Paeth et al. 2008), and further it is hypothesized that each region may have a specific trend.

In general predictions are made using coupled atmosphere–ocean general circulation models (GCMs) after suitably downscaling them (Anandhi et al. 2009; Ghosh and Mujumdar 2008; Wilks 1992) and applying them at hydrologically relevant catchment scales. Several GCMs outputs of large-scale atmospheric variables are available at particular grid resolutions for the entire globe providing simulations for A1B scenario of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4; Solomon et al. 2007). Even though various studies have examined the most applicable GCM or GCMs for simulating the monsoon rainfall in India based on the historical ground observations and GCM model simulations, no single GCM is found to be well suited uniformly across India for simulating monsoon rainfall for a specific hydrological application. Hence, in the present study 18 GCMs were examined (details of the GCMs can be found at http://www.ipcc-data.org/) to find relevant GCM for simulating precipitation of the study region. Figure 9 shows the comparison of the CDF of monthly cumulative rainfall for the measured (1978–96) at a single station and 18 GCMs for the same period. As seen in the figure all the GCMs are significantly underestimating the measured rainfall. The underestimation could be due to the incomplete knowledge about the process and the assumptions made in the GCMs. This difference is called bias and needs to be removed before utilizing the data for hydrological applications. Li et al. (Li et al. 2010) proposed a quantile-mapping-based approach to remove the bias from GCM rainfall. The approach involves matching the quantile (or CDF) of the measured and GCM rainfall. A detailed

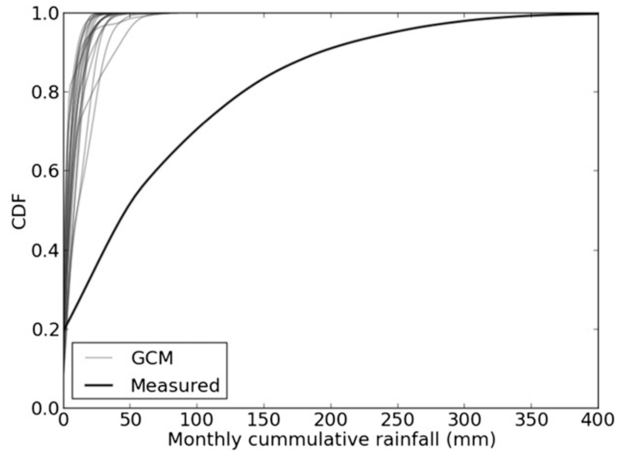

Figure 9. Comparison of the CDF of monthly cumulative rainfall for the measured and the additional 18 GCMs.

description of the methodology is given in Li et al. (Li et al. 2010). After the bias correction, the corrected monthly rainfalls from all GCMs were compared with measured monthly rainfall and root-mean-square error (RMSE), mean absolute error (MAE), and correlation were computed. Figure 10a shows the RMSE, MAE, and correlation for the all the GCMs. Based on the figure, the GCMs can be classified into two categories: showing relatively better and poor behavior with the measured rainfall. Worldwide, the skill of GCMs at forecasting time- and space-averaged rainfall, like all-India seasonal precipitation, is quite poor and the skill decreases as the spatial scale is reduced to single station. Thus, GCM simulations with high precipitation correlations are nonexistent. We have used an acceptable benchmark of correlation coefficient (CC) of 0.5 (Figure 10a) when the GCMs are correlated with monthly rainfall during 1978–97, which is significant at 95% or higher for the degrees of freedom involved. The relatively better performing six GCMs selected were as follows: Institute of Numerical Mathematics Coupled Model, version 3.0 (INM-CM.3.0); L'Institut Pierre-Simon Laplace Coupled Model, version 4 (IPSL-CM4); Model for Interdisciplinary Research on Climate, version 3.2 (MIROC3.2); ECHAM and the global Hamburg Ocean Primitive Equation (ECHO-G); Hadley Centre Coupled Model, version 3 (HadCM3); and Hadley Centre Global Environment Model, version 1 (HadGEM1). The approximate RMSE, MAE, and correlation for this group were 80 mm, 58 mm, and 0.47, respectively. Further, the Figure 10b presents the correlation between GCMs and mean monthly rainfall from the gauging station for the period 1978–97. A higher correlation of any GCM indicates that it captures the intra-annual pattern. The six GCMs mentioned above were found to have a correlation coefficient greater than 0.85, whereas some of the other GCMs perform poorly. Among the six GCMs, HadCM3 was chosen with the bias-corrected rainfall for future projections of rainfall at the study site as it was found to be one of the best from these metrics. Figure 11 shows the mean and standard deviation of precipitation for the above six GCMs for the period 2012–32.

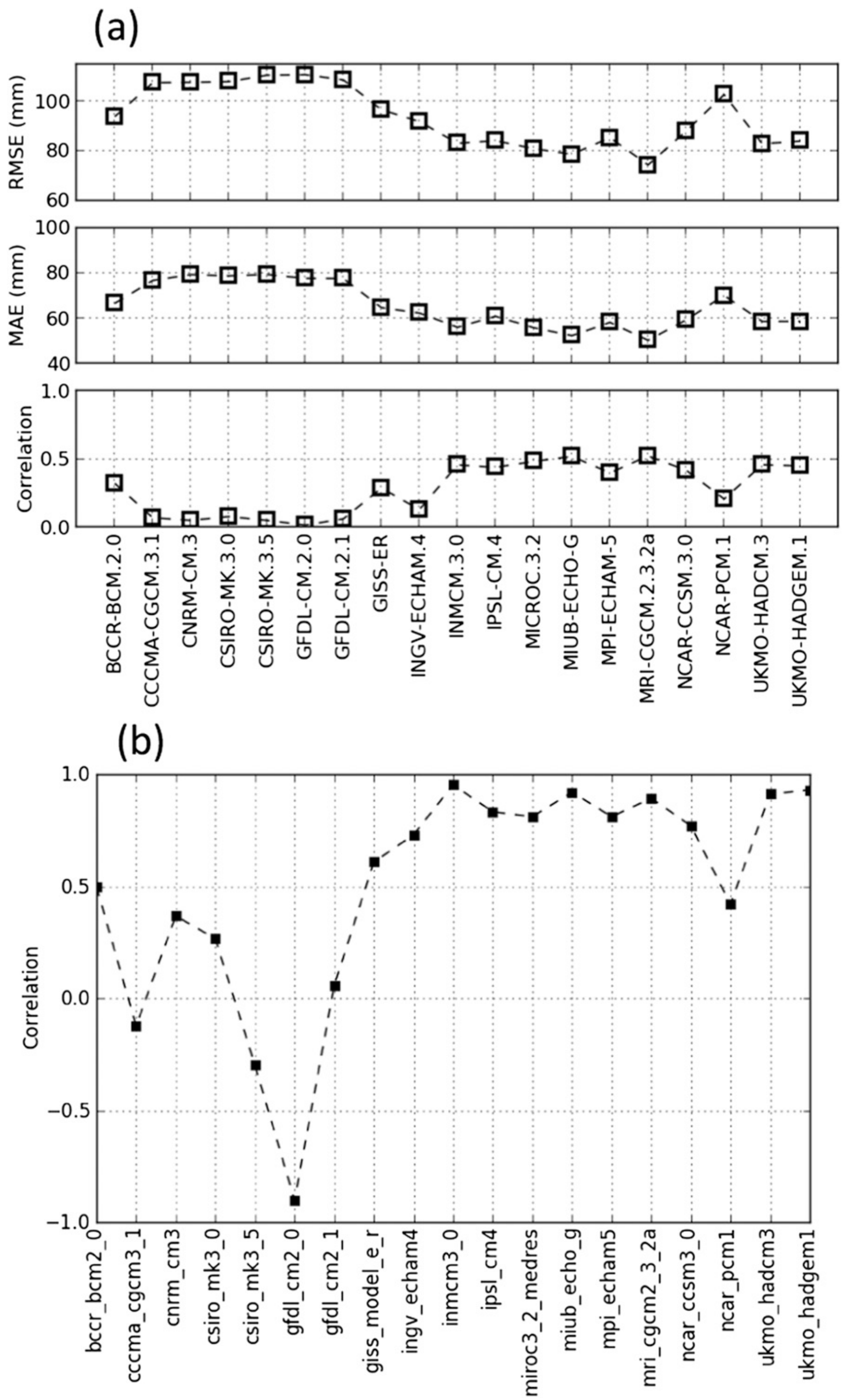

Figure 10. (a) The RMSE, MAE, and correlation between the 18 GCMs and measured monthly cumulative rainfall. (b) Correlation between the GCMs and measured mean monthly rainfall during 1978–97.

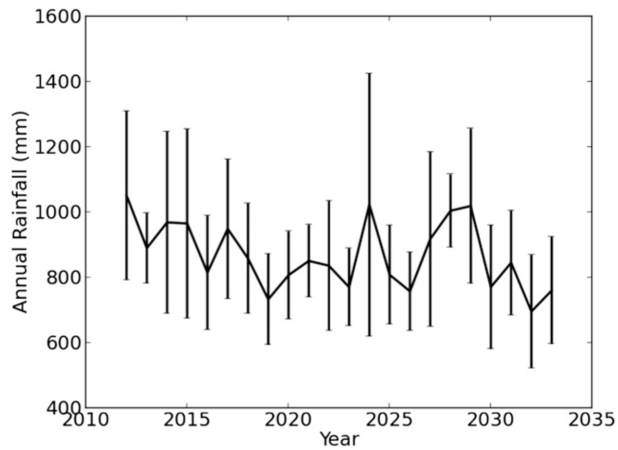

Figure 11. The mean and standard deviation of precipitation for the six GCMs (INM-CM.3.0, IPSL-CM4, MIROC3.2, ECHO-G, HadCM3, and HadGEM1).

In addition to a baseline case (scenario A), five other scenarios were analyzed, which were referred to as the management scenarios and are described below. These scenarios utilize the GCM rainfall (scenario A):

- Scenario A: The distributed groundwater model was used to simulate the groundwater levels in the study region for the projected future rainfall obtained from HadCM3.
- Scenario B: Currently, it is observed that the lakes are augmenting the recharge for the cluster of wells in the vicinity of the pumping stations (PS). This scenario corresponds to the case of lakes not filling adequately to their capacity and hence reduced recharge to the groundwater system.
- Scenario C: Municipal water utility decides to augment the town's water supply by adding additional wells at the pumping stations, increasing the hours of pumping, or using higher capacity pumps. The additional municipal wells that were considered in the study for this scenario were 175. This was arrived at by doubling current operating municipal wells outside the town (pumping station wells) and increasing the municipal wells inside the town by 33%. The water utility pumps each day about $5 \times 10^6\,\mathrm{L\,day^{-1}}$ from the pumping station wells and about $0.75 \times 10^6\,\mathrm{L\,day^{-1}}$ from within the town. Presently, the average water supply by the water utility is approximately 75–80 L per capita per day. The increase in the wells under this scenario is expected to generate $11 \times 10^6\,\mathrm{L\,day^{-1}}$ from the municipal network and the water utility could increase the supply to approximately 135 L per capita per day. Since the water utility is drawing plans to augment the supply in this manner, these additional wells were considered in the study in the computational domain.
- Scenario D: This scenario shows the impact of lowering groundwater levels because of a functioning and operational underground sewerage system. Currently, shallower groundwater levels inside the town are attributed to

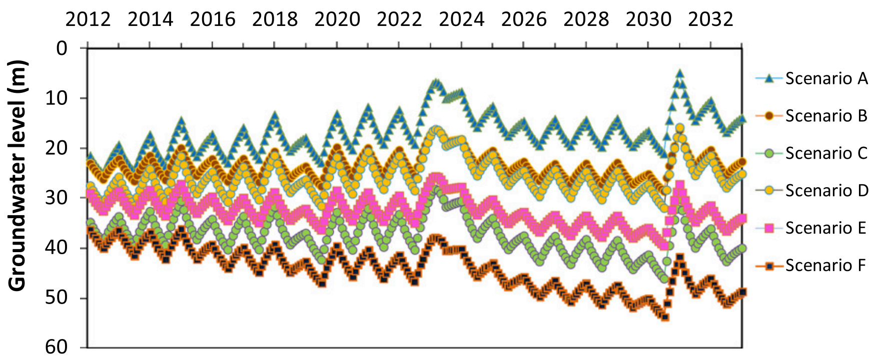

Figure 12. Simulated groundwater levels at RMC pumping station for scenarios A–F.

leakage of wastewater from septic tanks and pit toilets in the absence of operational underground drainage system. Water utility recently began and built the underground drainage network, which is connected to the septic tanks/pit toilets from households to this system

- Scenario E: This scenario is a combination of scenarios B and D: that is, reduction in recharge from lakes due to nonfilling of them along with an operational and functioning underground sewerage system.
- Scenario F: This scenario is a combination of scenarios B, C, and D. This could be a realistic scenario operating in the town in the near future.

Simulated groundwater levels for various scenarios near the RMC pumping station are shown in Figure 12. Since the groundwater imbalance was relatively higher (Figure 7), this case was selected for presenting the results. Figure 13 presents the groundwater contours in May 2030 for scenario F. The simulations revealed that the groundwater levels inside the town were reduced significantly for the scenarios B, D, and F when compared with that of the current levels of May 2011. Scenario F showed the deepest groundwater levels inside the town among the cases. Scenario D showed higher decline in the levels inside the town than for scenario B. Scenario D corresponds to reduced leakage of wastewater, which mainly affects the levels inside the town, while scenario B was of reduced recharge from lakes and mainly affects the levels outside the town in the PS locations. Scenario E behavior inside the town was very similar to scenario D as expected, though the levels in the PS areas show higher decline because of lower recharge from lakes plus the reduced flow from inside the town. The groundwater levels inside the town are least affected by scenario B as this corresponds to reduced recharge in lakes and hence the effect is only observed in PS regions while there was no effect in the groundwater levels inside the town.

Since the six GCMs (INM-CM.3.0, IPSL-CM4, MIROC3.2, ECHO-G, HadCM3, and HadGEM1) were found to show good correlation, the predictions were performed with these six GCMs for the period 2012–32. Figure 14 shows the mean groundwater level for scenario F based on these six GCMs for two pumping stations, Busalkunte and RMC. The groundwater level patterns observed were similar when these GCMs were used. It was observed that the standard deviation of

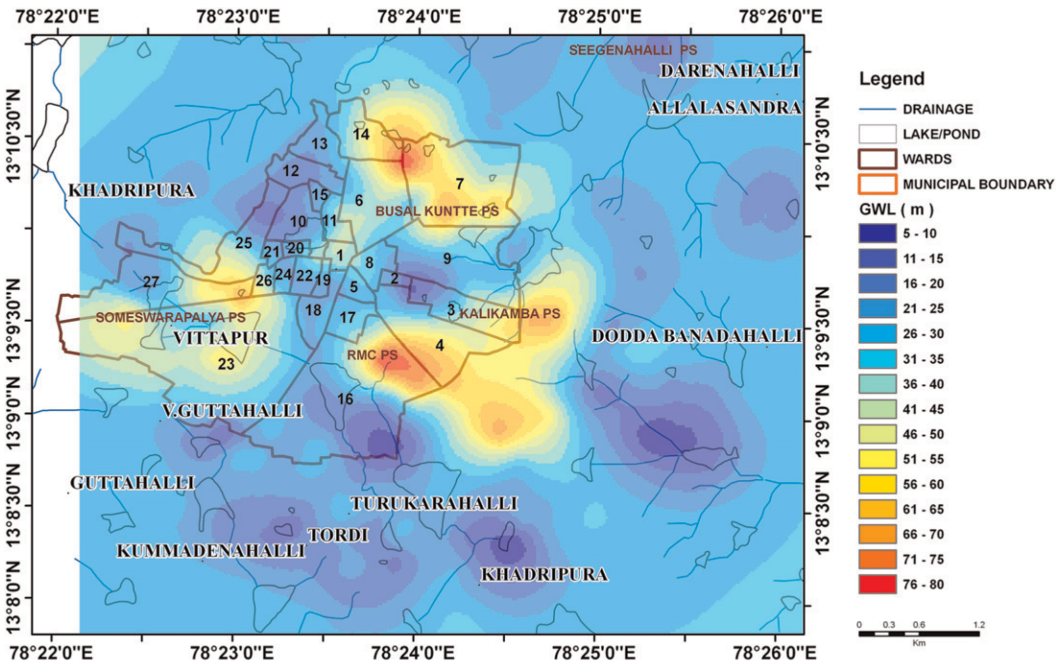

Figure 13. Simulated groundwater contours for scenario F for May 2030.

groundwater levels simulated using these GCMs was found to be small (2–3 m) until 2018 and thereafter it was relatively higher with approximately 6–8 m.

To study the sensitivity to the specific yield, simulations of groundwater levels were made for scenario F for the two specific yield values 0.005 and 0.01 using HadCM3 GCM rainfall. The mean difference between the groundwater levels for these two specific yields for the simulated period (2012–30) was obtained. Figure 15 shows the difference in the mean groundwater level at the various pumping station locations in the study area. It was observed that the mean difference in groundwater level in the domain due to these specific yield values was 1–4 m with a standard deviation of 1 m.

6. Summary and conclusions

The study found that the groundwater levels are quite stable across the three years of the study period at various locations in the town. The groundwater level fluctuation between wet and dry months for the wells inside the town is relatively small when compared to the pumping station (PS) wells. The recharge due to leakage of wastewater was estimated to be 50% of the pumping value from the municipal wells. The study showed higher than average pumping in the PS wells, less for the municipal wells inside the town, and average pumping in the rural agricultural area. On average, estimated pumping in the PS wells varied between 4.5 and 5.5×10^6 L day^{-1} and in the municipal wells in the town varied between 0.5 and 0.75×10^6 L day^{-1}. The groundwater level inside the town, which is at a higher topographic level, is shallow. Outside the town, toward the valleys, the

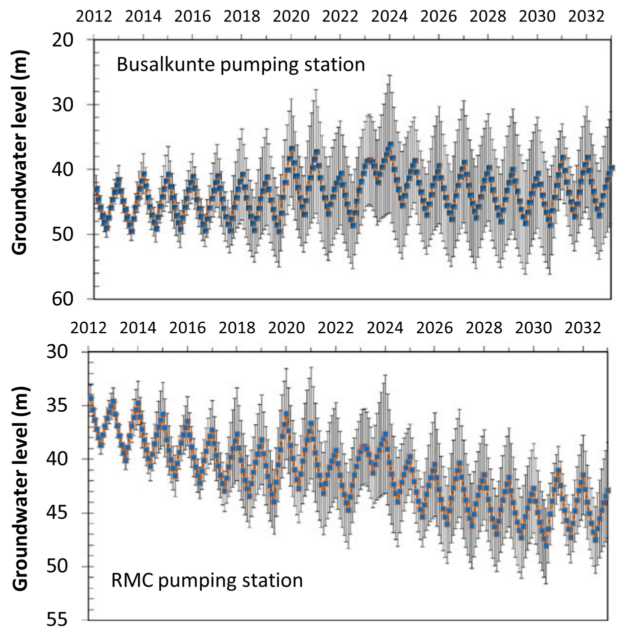

Figure 14. Simulated mean groundwater levels using rainfall from the six GCMs (INM-CM.3.0, IPSL-CM4, MIROC3.2, ECHO-G, HadCM3, and HadGEM1) at Busalkunte and RMC pumping stations for scenario F. The error bars show the standard deviation of the groundwater levels based on these six GCMs.

groundwater level is relatively deeper. This is a nonclassical hydrological behavior and may have resulted from the higher pumping in the shallow topographical regions outside the town, bringing this pumped water to the town, and causing a daily recharge by the generated wastewater within the town and leakages from the

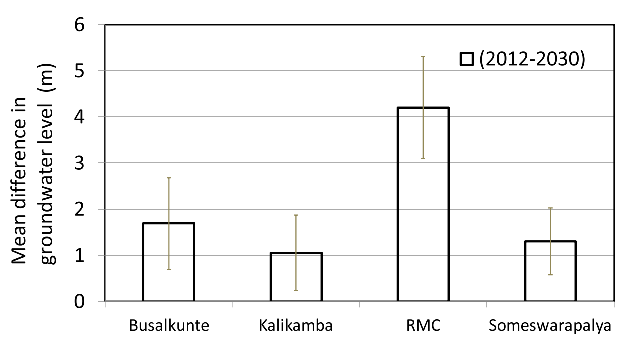

Figure 15. Mean goundwater-level difference during 2012–30 obtained for two specific yield values (0.005 and 0.01) using rainfall from the HADCM.3 GCM at the various pumping stations. Error bars show the standard deviation of groundwater-level difference over the above period.

water supply system. The pumping station wells also showed higher recharge, whereas there was average recharge over the town and rural areas. The higher daily extraction at the pumping station areas lead to higher decline of groundwater levels, which in turn facilitated better recharge.

Based on the results of the wells in the various pumping stations it appears that in all these locations groundwater use was much higher. At most of the pumping stations, the annual average discharge (sum of pumping and natural groundwater outflow) was marginally or moderately higher than the recharge. The study period of 3 years had two good rainfall years and hence the recharge was quite good. If in the future the rainfall is lower than the average, then there is likelihood of sharp depletion of groundwater levels at the pumping station wells for those years. It was also observed that the groundwater recharge near these pumping stations was enhanced because of the presence of lakes filled with water for some months. Hence, it is important to sustain the recharge process and ensure that sufficient runoff water flows to these lakes.

The combined impact of climate change and management scenarios were analyzed on the groundwater levels using the calibrated and validated distributed groundwater model. Impact of climate change was studied using the projected rainfall obtained from the six bias-corrected, better-performing GCMs INM-CM.3.0, IPSL-CM4, MIROC3.2, ECHO-G, HadCM3, and HadGEM1 for the study region. Five management scenarios were identified and were combined with the GCM-projected rainfall, and simulations were performed for the next 20 years (i.e., 2012–32). Cases such as reduced recharge from the lakes near the PS wells, reduced recharge from water and wastewater utility due to an operational and functioning underground drainage system, and water utility adding additional municipal wells near the pumping stations were analyzed independently and together as the scenarios to assess the groundwater levels at the PS wells and inside the town. It was found that, for the combined scenario, which may be realistic, the groundwater levels decline by about 20 m in the next 20 years: that is, $1\,\mathrm{m\,yr^{-1}}$ of groundwater level or $5\,\mathrm{mm\,yr^{-1}}$ of groundwater storage near the PS wells. In addition, the groundwater levels in the inside town show moderate decline from the current very shallow levels. The groundwater levels predicted using an ensemble of GCMs show similar patterns for the simulations performed until 2030. Moreover, it was observed that the standard deviation of groundwater levels simulated using the GCMs was found to be small (2–3 m) until 2018 and thereafter it was relatively higher with approximately 6–8 m. It was observed that the groundwater levels are monotonically declining at RMC pumping station for scenario F, and this behavior was observed for all the GCMs. This suggests that the infrastructure developed at this pumping station may not be sustainable in the future. Further, if the investment has to be secured, then it would be desired to develop alternate infrastructure projects such as managed aquifer recharge project in the vicinity of this pumping station.

On the policy aspect, the groundwater level survey performed in the town of Mulbagal during 2008–11 brings out the value of making such surveys in a town, which mainly depends for its water requirements on groundwater. The groundwater-level regime cannot be captured with few wells in a town, hence it is needed to capture the spatial variation of this information. In the present study, stationary shallow groundwater levels in the inside regions of the town are a cause of worry from the water quality point of view and also loss of potential recharge to the aquifer. Hence, even one-time quick mapping of the groundwater level along with the groundwater use in a town would bring out the spatial variations of the groundwater levels and would help in categorizing a town for suitable interventions. Modeling as demonstrated in the present study are useful in evaluating the extensive infrastructure (both public and private) developed for groundwater resource extraction and subsequent water supply distribution. Often pumping wells become obsolete in an urban region due to reduction of water yields, which are linked to the depletion of groundwater levels in such a region. Hence, it is required to assess the future aquifer stresses in different parts of an urban system and quantify them.

A sizable fraction of water supply in several towns and cities in developing countries comes from groundwater resources. Before embarking on further development of these resources, it is required that the sustainability of this resource for a variety of future likely conditions needs to be ascertained. The study performed here demonstrates an approach of simulating various management scenarios combining GCMs to address the effect of climate change. The methodology developed using a case study in an urban town is generic and is applicable for other urban groundwater settings.

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