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Agricultural groundwater management in the Upper Bhima Basin, India: current status and future scenarios

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Abstract

The basaltic aquifers of the Upper Bhima River Basin in Southern India are heavily utilized for small-scale agriculture but face increasing demand-related pressures along with uncertainty associated with climate change impacts. To evaluate likely groundwater resource impacts over the coming decades, a regional groundwater flow model for the basin was developed. Model predictions of different climate change and abstraction scenarios indicate continuation of current rates of abstraction would lead to significant groundwater overdraft, with groundwater elevations predicted to fall by −6 m over the next three decades. Groundwater elevations can however be stabilized, but would require 20–30 % of the mean surface water discharge from the basin to be recharged to groundwater, along with reductions in pumping (5–10 %) brought about by improved water efficiency practices and/or shifts towards lower-water use crops. Modest reductions in pumping alone cannot stabilize groundwater levels; targeted conjunctive use and improved water use efficiency are also needed.

1 Introduction

Hardrock crystalline aquifers cover approximately two-thirds of India, providing a vital yet finite groundwater resource that greatly supports India's food and livelihood security (World Bank, 2010). The contribution from groundwater to India's GDP has been estimated at about 9 % (Mall et al., 2006), with the demand from the non-agricultural sectors rising (Shah, 2009a). Since 1960, the area irrigated with groundwater has increased 5-fold (Garduño and Foster, 2010) and groundwater is presently the source for over 60 % of the irrigated areas. This growth has been supported by increasing availability in supply of drilling equipment, mechanical pumps and rubber pipes, combined with conducive government policies (Foster et al., 2007; Shah, 2009a). With the steadily rising food demand brought about by population pressures, there is concern that in many regions of India, the limit of groundwater development expansion will soon be reached. When this is considered along with the uncertainties associated with future climate patterns, achieving development targets and, at the same time, managing the resource sustainably becomes increasingly challenging.

The impacts of climate change are expected to be most severe across low-latitudes and the developing world in particular, including India, because of the lower capacity to adapt (Gosain et al., 2006). Aquifer systems have greater buffering capacity against droughts and climate fluctuations compared to surface water sources (Dragoni and Sukhija, 2008; Shah, 2009b). However, hard rock aquifers, such as those of India are vulnerable as these have low groundwater storage and yields tend to decrease rapidly with depth as the weathering-related permeability is reduced, thereby making the deepening of wells in response to falling water tables less viable. However the fracturing and jointing below the weathered zone supports fairly an additional extraction of groundwater from further depths in some parts.

The focus for this study is the Upper Bhima Basin, an area of 46 000 km^2 in Southern India (Fig. 1) where the groundwater provided by the basaltic aquifers helps to sustain the lives of 15 million people; 9 million of which are in rural areas (2001 Census figures). The groundwater resources of the basin are extensively utilized, with around 70 % of the average annual recharge withdrawn for consumptive uses, and many sub-areas having groundwater development greater than safe level for exploitation according to Government of India protocols (Chaterjee and Purohit, 2009). Shallow dug wells are prone to drying-out in areas where the weathered profile is thin and underlain by hard compact basalt that tends to limit recharge during the wet season (Kharif). Average residence time of the shallow, accessible groundwater are less than four years and therefore two or more consecutive years of drought can seriously threaten the livelihoods of smallholder farming communities (Pavelic et al., 2012). Despite this, the sub-basin is a major surface water-exporter which also creates opportunities for enhancing groundwater recharge and for effective conjunctive use of water resources (Venot, 2009; Garg et al., 2012a).

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Unresolved issues remain concerning future sustainability of the groundwater resources in response to the effects of climate and demand-related pressures. The objective of this study is to address these issues through the use of numerical groundwater modeling techniques to simulate groundwater flows and availability within the Upper Bhima Basin under a range of future scenarios in order to identify viable policy options.

2 Hydrology, agriculture and climate

The Krishna River basin is the fifth largest river system in India, with a discharge of 69.8 $\text{km}^3\,\text{yr}^{-1}$, draining an area of nearly 260 000 km^2. The Bhima River is one of two major tributaries of the Krishna and the Upper Bhima sub-basin, situated almost entirely within the Indian state of Maharashtra, is one of twelve sub-basins of the Krishna River basin (Biggs et al., 2007). The headwaters of the three major rivers in the Upper Bhima sub-basin (the Sina, Bhima, and Nira), originate in the dense forests on the eastern side of the Western Ghats range. These rivers flow to the southeast, over the plains of the Deccan Plateau, a fertile agricultural area with densely populated riverbanks. Natural river flows are ephemeral, having been steadily influenced by many irrigation canal structures and dams, with the Ujjani dam is the largest (Biggs et al., 2007).

Agriculture is the largest consumer of water in the Bhima Basin, with about 70 % of total land area under agriculture. The soils are predominantly vertisols, typical for the geology and climate. These soils have a high content of the expansive clay montmorillonite, which makes them almost impermeable when saturated, and therefore suitable for rice production. The natural vegetation is grassland, savanna or grassy woodland. The major crops grown in this basin are sugarcane, sorghum, wheat, corn, millet, groundnut, fodder grass and a variety of other horticultural crops. Irrigated crops such as sugarcane and sorghum account for 25 % of the total geographical area in the Kharif and Rabi seasons (Garg et al., 2012a).

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The climate of the Upper Bhima is highly variable, both spatially and temporally. Most of the rainfall falls on the eastern side of the Western Ghats ($> 4000\,\text{mm}\,\text{yr}^{-1}$), whilst the plains of the Deccan Plateau receive $< 500\,\text{mm}\,\text{yr}^{-1}$. Of the annual rainfall, 80–90 % falls intermittently during the monsoon period from June to October.

3 Hydrogeology

The Upper Bhima sub-basin is situated in the Deccan Plateau, a large igneous province composed of Deccan Trap basalts. These erupted at the end of the Cretaceous era and cover an area of approximately $500\,000\,\text{km}^2$ (Deolankar, 1980). The Deccan Trap basalt shows a high degree of heterogeneity by virtue of its weathering, jointing and fracturing properties and is composed of vesicular amygdaloidal basalt and compact basalt layered horizons. A red tuffaceous layer, sometimes referred to as red bole, often caps the vesicular amygdaloidal basalt and represents the glassy top of a lava flow. Each lava flow ranges in thickness from only a few meters to approximately 100 m. The maximum thickness of all flows is approximately 1.5 km (Saha and Agrawal, 2006).

Groundwater is present under shallow unconfined or semi-confined conditions in the mantle of local alluvium, laterite and weathered upper portion of the Deccan Trap basalts. The basalts possess little or no primary porosity; the groundwater resource potential is controlled by the degree of weathering, geomorphological and geological features, such as the size and distribution of vesicles, and the frequency and interconnection of joints and fractures (Kulkarni et al., 2000). The aggregate porosity for fractured-jointed basalt ranges up to 15 % (Deolankar, 1980). The horizontal layering of the basalt lava flows and the high clay content of the red bole horizons impart a degree of transverse isotropy that restricts vertical flow of groundwater. The basalt aquifers are also anisotropic, due to fractures and dykes, which channel, or block the flow of groundwater, dividing the system into smaller hydrogeological units. The maximum depth of useful quantities of groundwater is usually limited to about 100 m (Limaye, 2010). Water level trends from observation wells and piezometers from the study area reveal that short-term rainfall only improves soil moisture and serve farmers, but only adequate rainfall over long duration can replenish groundwater.

4 Groundwater use

Groundwater in the basalts is generally fresh and potable, although some areas have been polluted due to the use of chemical fertilizers, pesticides and unregulated discharge of industrial and municipal wastes (Limaye, 2010). Groundwater is generally extracted from large diameter dug wells or dug-cum-bored wells screened in the weathered portion of the basalt. These wells are generally 3 to 8 m wide and 8 to 15 m deep. Typical yields are in the range of 1–100 $m^3\,day^{-1}$, supporting an average land holding per farming family of around 2 ha (Limaye, 2010). With depth, the basalt becomes more compacted, unaltered, and the widths of the fracture decrease and well yields reduce significantly. Therefore, deepening wells to chase falling water levels is often ineffectual (Foster et al., 2007). Groundwater elevation responds quickly to recharge, due to the low storage characteristics of the basalts. The groundwater elevations generally vary between 2 to 10 m below ground level (bgl) depending on the time of year, and the total depth of wells varies between 3.8 to 36.1 m with a mean depth of 10.8 m.

Data from 135 pumping tests from dug and bore wells across the Upper Bhima Basin and adjacent areas supplied by the Groundwater Surveys and Development Agency (GSDA) were interpreted using the Jacob and Theis equations (with typical assumptions). Specific yield (S_y) 5th percentile, median, and 95th percentile values were calculated as 0.01, 0.03 and 0.08 respectively. Corresponding transmissivity values are 5 $m^2\,day^{-1}$, 45 $m^2\,day^{-1}$ and 200 $m^2\,day^{-1}$. S_y values range between 0.01 and 0.025 for basaltic rocks (Chatterjee and Purohit, 2009) and the GEC (Groundwater Resource Estimation Committee) recommend 0.02 for weathered or vesicular, jointed basaltic terrains (Government of India, 1997). The slightly higher than typical value used here can be attributed to testing predominantly shallow dug wells that bias the uppermost (weathered) part of the aquifer, which will also have greater permeability than deeper portions. It also represents the most active depth at which the replenishable water (every monsoon) exists and discharged throughout the single hydrological cycle. The interconnection between the vesicles and the degree of deposition of zeolites in the vesicles determines the aquifer parameters. Cooling joints and sheet joints within thick lobes are the other loci where water is stored (Kulkarni and Deolankar, 1995). Transmissivity values for weathered basalts, vesicular basalts and fracture-jointed basalts of the Deccan Traps range from 90 to 200 $\mathrm{m^2\,day^{-1}}$, 50 to 100 $\mathrm{m^2\,day^{-1}}$ and 20 to 40 $\mathrm{m^2\,day^{-1}}$ respectively (Deolankar, 1980).

5 Methodology

5.1 Model conceptualization

In general terms, the Deccan Volcanic province can be distinguished into three subunits; a weathered upper zone with sub-horizontal sheet joints; a middle zone comprising compact basalt with decreased jointing and a lower zone associated with subhorizontal and vertical joints. Figure 2 presents a conceptual model of the hydrogeological system extending longitudinally across the study area based on previous studies carried out for groundwater exploration and hydrogeological mapping in the area (Deolankar, 1980; Kulakarni, 1987, 2005; Phadnis, 2005; Vadagbalkar, 2011; Maurya and Vittal, 2011). This model suggests that the weathered and horizontal joints portion is limited to the upper 50 m of the profile followed by compacted basaltic flows whilst the lower part is associated with vertical joints and occasional horizontal discontinued joints. The upper 50 m the aquifer is most sensitive to recharge and discharge due to the prevailing hydrogeological properties. The vertical joints act as conduits to recharge the deeper aquifers. The specific yield of Deccan Basaltic aquifers in the upper Bhima vary laterally and vertically. Higher specific yields arise in weathered and dissected sheet joints units whereas the massive basalt unit, has a lower specific yield (Saha and Agrawal, 2006). However, the variation in the specific yield within the top 50 m portion was not significant with depth. Groundwater flow was simulated for only upper active weathered zone associated with sheet joints with a uniform thickness of 50 m and uniform S_y within the range specified in the above section over the entire modeled domain. The hydrogeologic properties of the bottom portion are highly heterogeneous in nature and were not included in the model. The grid cells were uniformly fixed at 1 km × 1 km. The ground surface elevations were input using downloaded data from Shuttle Radar Topography Mission (SRTM) website (http://www2.jpl.nasa.gov/srtm/). The original data has a resolution of 90 m, which was downscaled to a point data grid spacing of 1 km to match the grid cell size in the model.

A quasi 3-D dimensional finite-difference groundwater flow model was constructed using Visual MODLFOW Version 4.3 (Waterloo Hydrogeologic, 2002). This finite-difference block-centered 3-D modeling package can simulate transient groundwater flows for different hydrogeological systems (McDonald and Harbaugh, 1988). The conceptual model of the Upper Bhima hydrological system was based on hydrological and subsurface geological data available in the literature. The sub-basin was modeled as an Equivalent Porous Medium (EPM). The EPM method requires the cell-size of the groundwater model be sufficiently large, so that flow within an irregular medium behaves as if in a regular, porous medium when modeled on a sufficiently large scale (Singhal and Gupta, 1999).

5.2 Model and boundary conditions

Hydrogeological input parameters were selected from the ranges stated above, and subject to calibration. The vertical hydraulic conductivity was set at 10 % of the horizontal hydraulic conductivity to reflect the layered composition of the basalt flows. The low hydraulic conductivities in the basin, ranging from 0.01 to 1.5 m day^{-1}, help to retard the groundwater outflow and made available to store water in the aquifer (Limaye, 2010). The average hydraulic conductivity was applied to the entire modeled area within in the range of these values varying from 0.05 to 0.86 m day^{-1} to calibrate the model. The upland regions occupy less than 30 % of the present study area and are associated with limited permeability and storage. Whilst these areas were not specifically described in the model, they are still taken into account through relationships developed between rainfall and groundwater levels that were developed throughout the basin as a whole (described below). The surface watercourses in the sub-basin have complex discharge patterns, and have undergone large anthropogenic changes at a range of scales (Biggs et al., 2007). Data for the characteristics of these courses (such as river widths, stage heights, stream bed thickness and conductivity) were unavailable and therefore it was not possible to directly include surface water features in the model. However, natural discharge is accounted for in the groundwater budget calculations and exchange fluxes between groundwater and surface water, so it was considered acceptable to not directly include surface water in the model. Recharge and discharge was applied to the model based on empirical equations derived between groundwater levels and rainfall by Pavelic et al. (2012). A constant head boundary was placed along the southeast edge of the model domain 5.5 m below the ground level, coinciding with mean groundwater elevation as outflow boundary which allows groundwater outflow from the basin.

6 Recharge inputs

Across the sub-basin recharge rates are known to be highly spatially variable, and related to topography, storm duration and soil thickness. Spatially varying recharge based on the known spatial rainfall distribution was attempted but found to not improve the model results. Therefore a spatially uniform (basin aggregated) and temporally varying distribution of recharge (and discharge) was applied across the basin. Since most rain falls during the four monsoon months of each year, all rainfall (and thus recharge – see below) was modeled to fall in the monsoon (Kharif) season, and all pumping during the non-monsoon (Rabi) season. This broad averaging method does not distinguish between canal irrigation and rainfed areas, which will have different demands for water.

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Based on an analysis of the observed water levels pre- and post- monsoon for over 300 observation wells across the basin and rainfall data from 1997 to 2007 (Pavelic et al., 2012), the following empirical relationships were derived and used to calculate the recharge and pumping inputs as a function of annual rainfall.

$$\text{recharge (mm)} = 0.1133 \times \text{rainfall (mm)} - 5 \times 10^{-13}$$

$$\text{pumping (mm)} = -0.0737 \times \text{rainfall (mm)} + 130$$

The calculated recharge coefficient of ~11 % is in agreement with other reported values for basaltic terrain such as the Groundwater Resource Estimation Committee methodology (commonly known as GEC-1997) (Chaterjee and Purohit, 2009) and within the 3 % and 13 % stated by Limaye (2010).

7 Model calibration

The model was calibrated using data from 313 observation wells (Fig. 3) using the root mean square (RMS) and normalized root mean square (NRMS) error as the goodness-of-fit measure. Initially the model was run under steady-state conditions and simulated heads were assessed against observed heads. The resultant errors and sensitivity to the hydraulic conductivity (K_{xy}) and specific yield (S_y) were tested with K_{xy} ranges from 0.05 m day^{-1} to 0.86 m day^{-1} and specific yield from 0.01 to 0.03. The quantitative results of model calibration are show in Table 1. The model shows good calibration using $K_{xy} = 0.86$ and $S_\text{y} = 0.03$ with a root means square error of 4.5 m, normalized error 1.023 and exhibits reasonable agreement between simulated and observed head data over the 11 yr period. Therefore for the prediction stage, these properties were selected, and the model run in transient mode with 27 stress periods for each of the forecast scenarios described below.

Due to the broad averaging of input parameters, the quality of calibration varies from one observation well to another, as indicated by the hydrographs for three representative observation wells given in Fig. 4. However, the calibrated model was considered to be sufficiently robust to enable predictive modeling of major trends within the basin, but not necessarily of high accuracy at the local scale.

8 Future rainfall projections

Future climate scenarios were modeled from the end of the calibration period record (2007) until 2040 (thirty years is the classic forecast period, as defined by the World Meteorological Organisation; Government of India, 2008). Global climate modeling studies suggest that precipitation may increase or decrease by as much as 15 % under the scenario of a doubling of atmospheric CO_2, depending on latitude and other factors (Government of India, 2008). Examination of historical trends suggests little change in rainfall at India-level, but evidence of both increases and decreases in rainfall at specific locations (Mall et al., 2006). Many parts of peninsular India, especially the Western Ghats, are likely to experience a 5 % to 10 % increase in total precipitation (Shah, 2009). Increases in extremely large rainfall events, but a reduction in rainfall days, will exacerbate floods and droughts. According to Rupa Kumar et al. (2006) a 20 % percent rise in summer monsoon rainfall is forecast across the sub-continent, whereas Gosain et al. (2006) suggests that in the Krishna basin, a 20 % decline in precipitation and corresponding 30–50 % decrease in runoff can be expected.

The projected rainfall patterns for the Upper Bhima over the coming decades is not clear. Published regional climate models (RCMS) do not give basin-scale scenarios and as an alternative to the downscaling of the IPCC RCM data sets the control prediction (no change in rainfall variation, scenario A) simply replicated the historical record (1970 to 2009) through to 2040. A modeled increase in rainfall (scenario B) for this study area of a gradual increase (relative to scenario A) up to +10 % by 2040, and gradual reduction in rainfall to −10 % by 2040 (scenario C) offer possible end-member scenarios, as shown in Fig. 5. Although the proportion of rainfall that contributes to recharge could also change as factors such as rainfall duration and intensity, soil moisture content and land use respond to climate change (Dragoni and Sukhija, 2008), this was not varied in the model since it was accounted for indirectly to some degree, by the large rainfall variation between scenario's B and C.

9 Groundwater recharge and development projections

Watershed development (WSD) activities have been actively promoted for decades as a means of increasing groundwater (and soil-water) availability and thereby boosting crop productivity and rural livelihoods (Calder et al., 2008). Major WSD programs are undertaken to counter groundwater over-exploitation (as well as soil erosion) across the drier rainfed areas of India, including within the Upper Bhima (Garg et al., 2012b). Modeling the anticipated expansion in WSD first requires an estimate of the sub-basin's excess surface water that is available for harvesting. To estimate the available discharge (pre-WSD), the mean annual rainfall data in the sub-basin with river discharges measured at the most downstream gauging stations of the sub-basin (Takli and Wadakbal), using data from 1970–1995 (National Water Development Agency, 2003). There is a reasonable correlation between discharges recorded at these downstream locations and rainfall (Fig. 6). Much of the scatter in the trend is likely to be due to growth in WSD, irrigation canals and the development of large-scale dam projects over this period. The average combined surface water discharges measured at these locations for the period 1970–1995 is 7258 $\text{Mm}^3\,\text{yr}^{-1}$, corresponding to a basin-average rate of 158 $\text{mm}\,\text{yr}^{-1}$. Whilst it is recognized that much of this water supports agricultural and urban development in downstream, it provides an absolute upper limit of the maximum potential resource available for capture using WSD. More recently, Garg et al. (2012a) reported average discharge of 2270 Mm^3 for the sub-basin (7 % of average annual rainfall) for the period from 1999–2004, however this covered is relatively short and covers the exceptionally dry years from 2001–2003 and hence this figure was not considered representative of the longer term water availability.

Projected growth in WSD was assumed to be uniformly distribution across the basin and to steadily increase (linearly) over the prediction period. Peak values of 20 to 30 %

of the 7258 $\text{Mm}^3\,\text{yr}^{-1}$ (158 $\text{mm}\,\text{yr}^{-1}$) of surface water potentially available for capture were used. A maximum recharge contribution of +20 % from WSD was added incrementally to the annual recharge of scenario C (decreasing rainfall) to generate scenario D, and maximum recharge contributions of +20 % and +30 % added to scenario B (increasing rainfall) to generate scenarios E and F.

Four additional pumping regimes were also assessed (scenario's 2–5). Two growth rates (+5 % and +10 %) and two negative growth rates (–5 % and –10 %) were modeled, based against the control rate (scenario 1). These were included to assess changes in groundwater demand. The alpha-numeric input matrix of rainfall, WSD and pumping inputs for all 30 (6 × 5) scenarios that were modeled is shown in Table 2.

10 Results

Basin-aggregated groundwater recharge in the control scenario (A1) varies from 4097 $\text{MCM}\,\text{yr}^{-1}$ to 3896 $\text{MCM}\,\text{yr}^{-1}$; groundwater draft varies from 2899 $\text{MCM}\,\text{yr}^{-1}$ to 3621 $\text{MCM}\,\text{yr}^{-1}$; and groundwater storage varies from 1199 $\text{MCM}\,\text{yr}^{-1}$ to 277 $\text{MCM}\,\text{yr}^{-1}$ between the years 2008 to 2040. Groundwater outflows are only 0.02 $\text{MCM}\,\text{yr}^{-1}$ in the year 2008 and decline to zero after the year 2030 because of over utilization of groundwater resources. Groundwater outflows are very negligible in all scenarios and declines to zero after the year 2030. In the worst-case scenarios (C3 and D3) groundwater storage varies from 1199 to 681 $\text{MCM}\,\text{yr}^{-1}$ (C3) and 832 to 735 $\text{MCM}\,\text{yr}^{-1}$ (D3); recharge varies from 4098 to 3511 $\text{MCM}\,\text{yr}^{-1}$ (C3) and 4144 $\text{MCM}\,\text{yr}^{-1}$ to 4945 (D3); and groundwater draft varies from 2899 to 4195 $\text{MCM}\,\text{yr}^{-1}$ (C3) and 3313 to 4213 $\text{MCM}\,\text{yr}^{-1}$ (D3). In the best-case scenario (E5) recharge varies from 4144 $\text{MCM}\,\text{yr}^{-1}$ to 5144 $\text{MCM}\,\text{yr}^{-1}$; groundwater draft varies from 2899 $\text{MCM}\,\text{yr}^{-1}$ to 3904 $\text{MCM}\,\text{yr}^{-1}$; and groundwater storage varies from 1246 $\text{MCM}\,\text{yr}^{-1}$ to 1242 $\text{MCM}\,\text{yr}^{-1}$. Groundwater recharge varies from 2899 $\text{MCM}\,\text{yr}^{-1}$ to 5607 $\text{MCM}\,\text{yr}^{-1}$ with 30 % WSD (F1) and groundwater storage varies from 1246 $\text{MCM}\,\text{yr}^{-1}$ to 1977 $\text{MCM}\,\text{yr}^{-1}$.

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Groundwater elevations for three representative observation wells: BM-20 (upper basin), BM80 (middle basin) and BM-110 (lower basin) were selected for presentation of the results for 6 selected scenarios, including the control (A1), best-case (B1), worst-case (C3), and three intermediate-cases (D3, E5 and F1), as shown in Fig. 7. The results for all 30 scenarios are given in Table 3, expressed in terms of the average groundwater level change measured in all (non-dry) observation wells across the basin for three intervals throughout the simulation period. The major groundwater elevation trends strongly reflect the rainfall conditions associated with each scenario. Relative changes between scenario's tend to be less significant prior to 2020 due to the incremental modeled change in recharge and pumping. The control simulation (A1) suggests that groundwater in the basin is being overexploited, as shown by a long-term steady decline in groundwater elevations even though the control rainfall projection (A) has a stable trend (Fig. 7). Under declining precipitation scenarios and highest pumping scenarios (C1–3), groundwater is predicted to fall across the basin by up to 18 m from the 2007 groundwater levels and by more than 34 m at some locations along the eastern margins. In this situation groundwater elevations may fall below the critical aquifer depth limit (most permeable weathered portion of the basalt) by approximately 2034. This is also the case under scenario A3, in which the increase in pumping has reduced groundwater levels to 50 m bgl. Under scenario B3, the gradual increase in rainfall only begins to outweigh the over-abstraction caused by current pumping rates by about 2027. Under scenarios A4 and A5, groundwater depletion can be shown to be reversed with a reduction in pumping of 5 % and 10 %. Figure 7 also shows that WSD is able to stabilize, and in some cases (such as scenario F1), reverse groundwater declines.

11 Discussion

The results from all scenarios without WSD indicate that groundwater elevations may fall by approximately 5 to 6 m by the year 2020. Given that the majority of pumping

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takes place from dug wells that are less than 20 m and access the shallow groundwater layers, many would become perennially dry in the coming years. Deepening of wells will not provide a realistic response solution, since well yields decline with depth, and pumping costs will increase greatly. Such a pessimistic forecast would cause much damage to the livelihoods of those dependant on groundwater in the basin. However, the simulations also reveal that the Upper Bhima's groundwater resources can be maintained and possibly enhanced in a sustainable manner for a long time under moderate reductions in pumping rates supplemented by WSD. Under best-case scenarios of increased rainfall and reduced abstraction and/or modest WSD (scenarios E5, F1 and F5) groundwater can be brought close to the 2007 groundwater elevations and even above.

Despite the assumptions inherent in the modeling of WSD in this study, these results indicate the potential to reverse a projected decline in basin-wide groundwater elevations under the current settings. The challenge is to deliver WSD in a way that is technically and economically effective, whilst taking into account of the water requirements of downstream areas. Garg et al. (2012b) reports that in the Kothapally micro-watershed of the Musi sub-basin, the surface water outflow reduced by more than 50 % after the implementation of the watershed development programme. When such treatments are applied in a widespread fashion, Garg et al. (2012b) demonstrated that this has significant implications on downstream flows to Osman Sagar reservoir that provides supplies to Hyderabad (the sixth biggest city in India).

Across the Upper Bhima sub-basin and the Krishna basin as a whole, more than half of the irrigation water is sourced from groundwater and therefore groundwater-based irrigation practices have a significant bearing on the water resources at the basin scale. Such considerations become even more critical in a case such as the Krishna where most of the available resources within the basin are utilized and there is limited outflow to the sea. This analysis highlights that the detention of up to 30 % of the surface water outflow from this upstream sub-basin comes at a price for the downstream areas that include the Lower Bhima and Lower Krisna sub-basins. Major irrigation projects such as Nagarjuna Sagar reservoir, power generation at Srisailam reservoir and provision of drinking supplies for Hyderabad are key examples of existing water users. A clearer indication of the significance of these flows comes by noting that the harvesting of 2260 $\mathrm{Mm}^3\,\mathrm{yr}^{-1}$ (the 30 % excess) is almost 5-fold greater than the total water demand for Hyderabad of 430 $\mathrm{Mm}^3\,\mathrm{yr}^{-1}$ (George et al., 2009). It is fitting to ask if the benefits in sustaining groundwater levels and therefore irrigated areas in the Upper Bhima justify the diminished socio-economic activity in downstream reaches associated with WSD.

Reducing the crop water demand and therefore the magnitude of groundwater pumping is an alternative strategy to keeping groundwater overexploitation in check. Implementation of water saving measures such as micro-irrigation or growing less high water use cash crops such as sugarcane may offer a plausible alternative, but would need to be undertaken on a sufficiently large scale. Community management of groundwater aimed at creating self-governing groundwater users organizations geared towards sustainable management of groundwater through collective monitoring of groundwater on the one hand, and limiting demand in accordance to groundwater availability on the other, have had widespread success across rainfed areas Andhra Pradesh (World Bank, 2010), and may offer a suitable model for other regions including Upper Bhima.

12 Conclusions

The Upper Bhima Basin is a sensitively balanced, finite groundwater resource, and is at risk of being overexploited in the coming decades. A regional groundwater flow model was developed to simulate the groundwater conditions and variability within this basin, based on simplifications and assumptions about hydrological processes and an averaging of parameters such as aquifer thickness, recharge and discharge. Nevertheless, the model was adequately calibrated, and considered indicative of the whole-of-basin trends. The results of the forecast scenarios suggest serious implications for groundwater availability in the sub-basin. Under the control scenario over the period from 2008 to 2040 (drawing from historical rainfall patterns with no change in pumping rates or WSD), the results suggest that the depth limit of exploitable groundwater will be reached within the next decade. Stabilization of groundwater levels can be achieved with 20 % of the harvestable surface water flows being recharged to groundwater via WSD combined with a 10 % reduction in pumping rates, or by 30 % WSD if pumping remains at current rates.

A challenging dilemma arises in that sustaining the livelihoods of farmers and groundwater baseflow to surface water bodies in the upstream sub-basin through WSD comes at the cost of the downstream users in major irrigation canal project areas and for urban consumers of water and energy. An answer to this multi-dimensional problem relies upon a hydro-socio-economic trade-off analysis that encompasses both upstream and downstream sub-basins to identify the best solution. Such an analysis should recognize the exchange and inter-dependence between surface and groundwater resources, along with the pre-existing constraints associated with surface water allocation agreements brokered between the three affected riparian states.

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Table 1. The quantitative results for the various calibration runs.

		Percent error		
K_{xy} (m day^{-1})	Calibration measure	$S_y = 0.01$	$S_y = 0.02$	$S_y = 0.03$
0.05	RMS	4.436	4.506	4.53
	NRMS	0.918	1.014	1.019
0.08	RMS	4.436	4.506	4.531
	NRMS	0.92	1.021	1.023
0.1	RMS	4.436	4.506	4.531
	NRMS	0.921	1.014	1.023
0.86	RMS	4.439	4.508	4.508
	NRMS	0.931	1.014	1.023

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Table 2. Matrix of forecast scenarios covering variations in rainfall (and hence recharge), pumping rates and watershed development (WSD).

Scenarios	A. Reproduction of historical rainfall	B. Increased rainfall to +10 %	C. Decreased rainfall to −10 %	D. (C) + WSD to 20 %	E. (B) + WSD to 20 %	F. (B) + WSD to 30 %
1. Control pumping	A1	B1	C1	D1	E1	F1
2. 5 % growth in pumping	A2	B2	C2	D2	E2	F2
3. 10 % growth in pumping	A3	B3	C3	D3	E3	F3
4. 5 % reduction in pumping	A4	B4	C4	D4	E4	F4
5. 10 % reduction in pumping	A5	B5	C5	D5	E5	F5

Table 3. Average groundwater level change relative to 2007 for all forecast scenarios for three different time periods.

Scenario	Year 2020 (m)	2030 (m)	2040 (m)
A1	5	9	11
A2	5.7	9.6	11.8
A3	5.8	10.4	14
A4	5	6	9
A5	4	5.7	7.5
B1	5.4	8.3	7.8
B2	5	8.6	8.9
B3	5.5	9.2	9.9
B4	5.2	7.1	6.3
B5	4	6.1	4.7
C1	6	10.8	15.8
C2	6.1	11.3	16.9
C3	6.1	11.7	18.1
C4	6.1	11	17.1
C5	5.5	10.1	15
D1	5.5	8.8	10.2
D2	5.5	8.1	11.3
D3	5.5	8.2	11.2
D4	5.1	7.8	8.9
D5	4.7	6.8	7.9
E1	5.1	5.4	2.8
E2	5.3	6.8	3.1
E3	5.7	7.1	4.9
E4	4.7	6	2
E5	4.3	4.1	0.8
F1	2.1	1.8	−0.4
F2	4.5	5.1	1.8
F3	5.1	6.9	3.8
F4	4.3	3.8	0.1
F5	3.1	1.1	−4.26

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Fig. 1. Location of the Upper Bhima sub-basin within the Krishna River Basin, South-Western India.

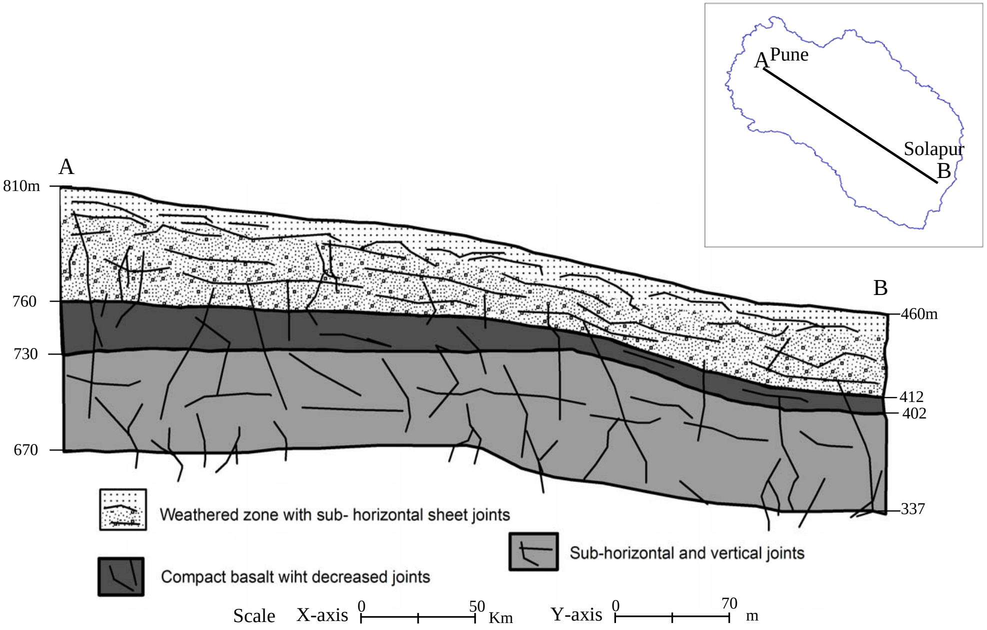

Fig. 2. Generalized geological cross section of Upper Bhima Basin (modified after Phadnis et al., 2005; Kulkarni, 2005; Saha and Agrawal, 2006; Maurya, 2011).

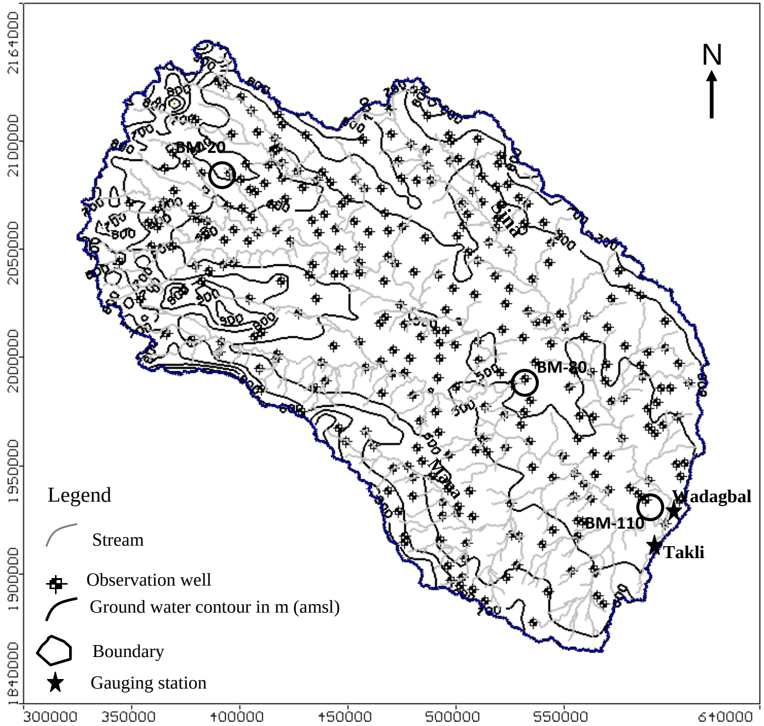

Fig. 3. Location of observation wells and groundwater contour in m (a.m.s.l.) – June 2008.

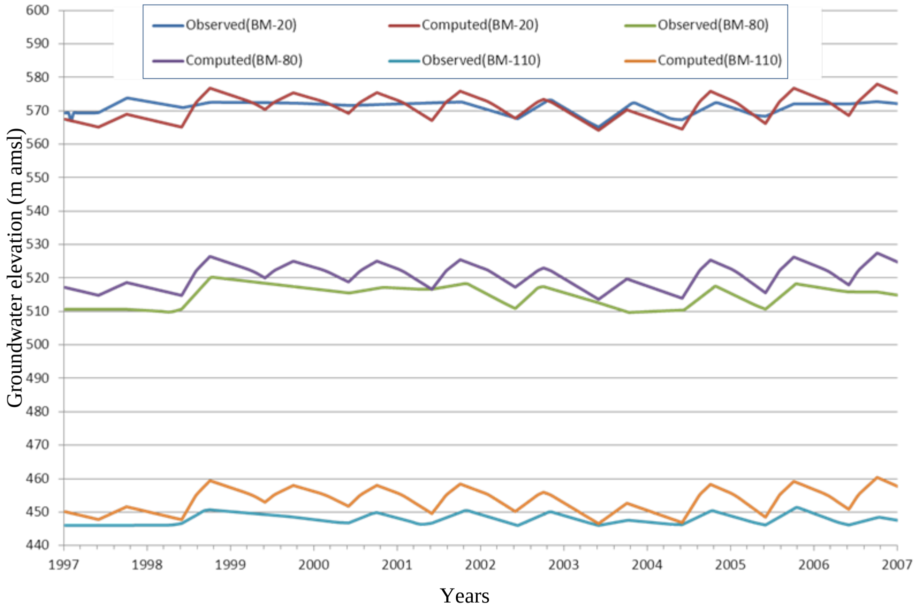

Fig. 4. Observed and simulated water levels during the calibration period for three representative observation wells.

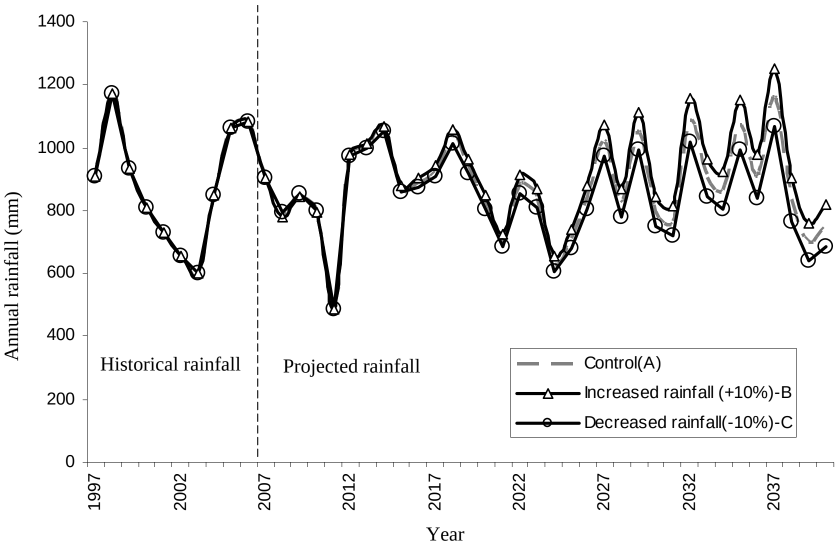

Fig. 5. Historical and projected rainfall sequence used for the predictive scenarios.

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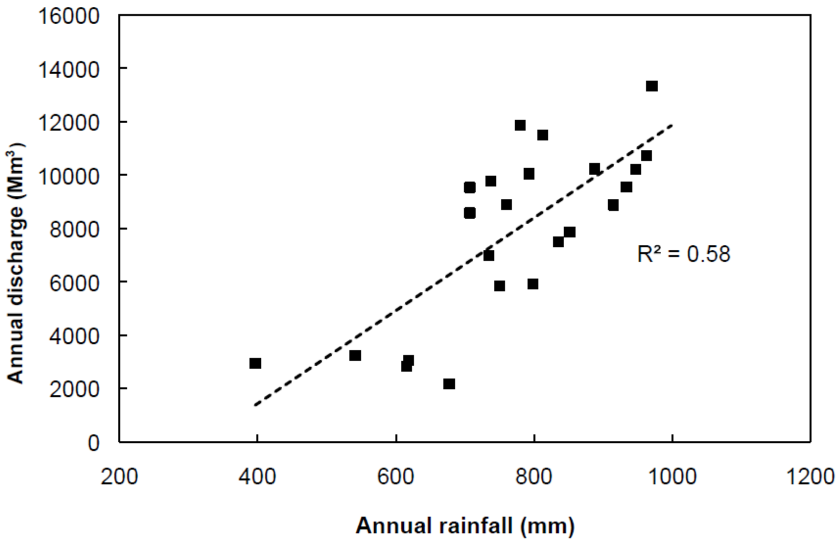

Fig. 6. Annual basin-wise rainfall versus cumulative discharge at Takli and Wadakbal gauging stations, 1970–1995 (source: NWDA, 2003).

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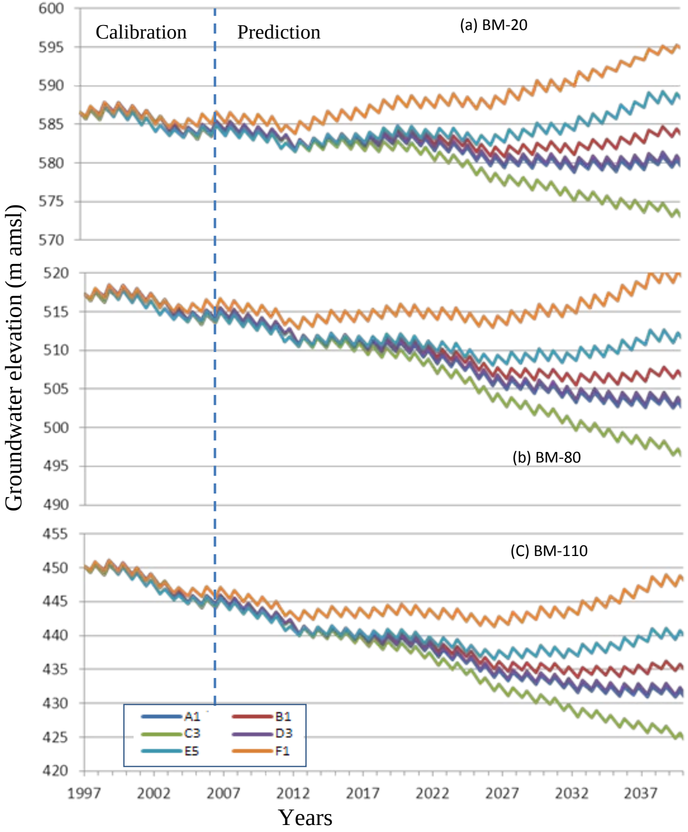

Fig. 7. Observed and simulated water levels for three observation wells between 1997 and 2040 for 6 scenarios (predictions commence in 2008). Note that the curves for scenarios A1 and D3 closely overlap.