Development of groundwater flow models and preparation of aquifer management plans

Report prepared for

Central Ground Water Board,
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1. Background and scope

To ensure the long term sustainability of aquifer systems in the country, Central groundwater Board (CGWB), Ministry of Water Resources, River Development and Ganga Rejuvenation, Government of India has initiated the National Aquifer Mapping Programme (NAQUIM). To bring scientific inputs in the policy making, CGWB signed Memorandum of Agreement (MoA) with Indian Institute of Science (IISc), Bangalore to perform the groundwater modelling and development of management plan over selected Taluks in the state of Karnataka covering an area of 48294 km^2. The objective of the study was, "**Development of groundwater flow models and preparation of aquifer management plans for the 45 taluks in the state of Karnataka.**"

The scope of work for the study is as following:

I. Preparation of datasets in GIS framework and data integration of various parameters required for groundwater modelling.
II. Development of a conceptual and numerical groundwater models.
III. Calibration and Validation of developed groundwater flow model.
IV. Evolving aquifer management plans considering existing issues and projected scenarios.
V. Suggest suitable strategies for implementation of aquifer management plans.
VI. Final report preparation by IISc, Bangalore.

2. Introduction

Several research studies in India have used distributed numerical models (e.g. MODFLOW and its variant) to understand the behaviour of groundwater (e.g. Prasad and Rastogi, 2001; Katpatal et al.,2014; Khare et al., 2006; Kushwaha et al., 2009; Majumdar et al., 2008; Sekhar et al., 2004; Senthilkumar and Elango, 2004). These models are grid based and require extensive information about the forcing (recharge and draft) and parameters (specific yield and transmissivity). These forcing and parameters are not available for large scale modeling and need to be estimated by inverse modelling coupled with the groundwater level observations. When the number of groundwater level observations are not sufficiently high compared to the number of variables being estimated, it causes equifinality, which results in the higher uncertainty. In order to minimize the uncertainty, hypotheses are made for the parameters and/or forcings, which may not hold true over large areas and long duration.

On the other hand, in India, operationally the estimation of groundwater resources (recharge and draft) is performed by using GEC (1997), which is based on lumped Water Table Fluctuation (WTF) approach. In the GEC methodology for the hard rock aquifers, the estimation is performed by taking seasonal groundwater level data while ignoring the groundwater lateral flows (i.e. the groundwater in the assessment unit/watershed/catchment is assumed to be closed). Since the groundwater well density of long term observation network is approximately 1 number per 100 km^2, the operational unit of assessment is taken as watersheds/catchements, usually having an area of about 600 to 1000 km^2. With some modifications, these approaches have been to estimate the specific yield and recharge (e.g. Maréchal et al., 2006; Sharda et al., 2006).

In order to take advantage of the spatial resolution and lateral connectivity of a distributed model, and robustness of the estimated parameters in the lumped approach, a predictor-corrector approach is required, wherein lumped model is used to estimate the parameters and prior forcings and then distributed model is used to utilize these parameters and correct the estimated forcings.

In the current study, groundwater modelling is performed using the suits of ambhas groundwater flow models developed at IISc. Ambhas-lumped model estimates the parameters such as specific yield (*Sy*) and annual rainfall-recharge factor and simulates the draft and lateral groundwater discharge. Then, these parameters are given as input to the ambhas-distributed groundwater flow model and the prior estimates of the draft and lateral groundwater discharge are updated. The groundwater flow modelling was performed in 45 taluks of the state of Karnataka, at taluka scale in lumped model and at a spatial resolution of 5 km using the distributed model. Description of the study area and data used along with the modelling strategies adopted is mentioned in section 3. Results are described in the section 3 followed by the conclusions in section 5.

3. Materials and methods

3.1 Study area

The Karnataka State, situated between 11° 31′00″ and 18° 45′00″ north latitudes and 74° 12′00″ and 78° 40′00″ east longitudes in the west-central part of peninsular India and has a total geographical area of 1,91,791 km^2, which is administratively divided into 30 districts and 176 taluks (Figure 1). The state is bounded by Maharashtra and Goa states in the north and north-west, Arabian sea in the west, Tamilnadu and Kerala states in the south and in the east it is bounded by Andhra Pradesh and Telangana states. The four main types of geological formations of the Karnataka state are the Archean complex made up of Dharwad schists and granitic gneisses, the Proterozoic non-fossiliferous sedimentary formations of the Kaladgi and Bhima series, the Deccan trappean and intertrappean deposits and the tertiary and recent laterites and alluvial deposits.

The total area covered by the 45 taluks (pertaining to this study) falling in the 16 districts of Karnataka is given in Table 1. The taluks under study covered a total area of 49433 km^2 of which the taluk under Chitradurga district covers a maximum area of 7695 km^2. The Spatial distribution of the average annual rainfall of the 45 taluks computed for the period of 1980 to 2017 (i.e. 4 decades) is shown in Figure 1. As can be observed from the figure, the mean annual rainfall in the taluks varies from 480 mm to 800 mm in which Yadgir, Kolar, Mulabagal, Srinivasapura, Malur, Devanahalli, Doddaballapur taluk receive a relatively higher rainfall ranging from 740 to 800 mm whereas Athni, Raybag, Ligsugur, Bagalkot, Ramdurg, Jagalur, Challakere, Chitradurga, Hiriyur and Chintamani taluk receive a relatively lower rainfall ranging from 480 to 545 mm of rainfall. The depth to groundwater table for the month of January, 2015 (a typical month of recent years) is shown in Figure 2. As can be observed from the figure, the groundwater levels are relativer deeper in the taluks of the districts in the south-east part of Karnataka (i.e. Bangalore rural, Chikballapur, Kolar, Tumkur, Davanagere) even through the mean annual rainfall is relatively higher in these districts suggesting a higher groundwater development.

3.2 Data

Following data were collected and prepared in GIS framework to perform the groundwater modelling:

(a) Groundwater level: The groundwater well observations were obtained from two sources: (i) CGWB, and (ii) Department of Mines and Geology (DMG). CGWB's data, was available four times in a year, i.e. during May, August, November and January during 1980-2017. DGM's data were available for each month during 1980-2017. The groundwater level data was converted into monthly time series of groundwater levels for each of the 45 taluks into two spatial resolutions - (i) taluk averaged by aggregating the well data in each taluk, and (ii) at a spatial grid of 5 km through interpolation. While combining the data from both the sources, deeper groundwater levels were given more weightage in this study. One time field measurements of groundwater levels through field survey during 2018-2019 were also made for three taluks: Chikkanayakanahalli taluk in Tumkur district, Chintamani taluk in Chikballapur district and Hiriyur taluk in Chitradurga district. About 75-150 villages were covered uniformly in each taluk for measuring the groundwater levels during these field surveys.

(b) Rainfall: The monthly rainfall data for all the 45 taluks were collected from KSNDMC for the period 1980-2017. The data available at the spatial granularity of a taluk were used.

(c) Drainage layers and location of minor irrigation tanks estimated using the satellite data.

(d) Geology of underlying rock.

(e) Number of wells for each village and the well density based on 5^{th} MI census.

(f) Area irrigated for each village by surface and groundwater based on 5^{th} MI census.

(g) Actual evapotranspiration at a spatial resolution of 5km based on the MODIS and MERRA-2 data (Eswar et al., 2017).

3.3 Groundwater flow modelling

In order to minimize the number of variables being estimated in the distributed groundwater model, a two step approach such as predictor-corrector method is implemented using the suite of models. A flow chart of the modelling strategy is presented in Figure 3. In the first step, ambhas groundwater model in lumped mode is used for simulations at monthly time step to estimate the S_y and rainfall-recharge factor, and forcings (annual draft and annual discharge) for the period 1980-2017 for each taluk. In the second step, the estimated parameters from the first step are used as input to the ambhas distributed flow model in two dimensions to simulate spatially distributed depth averaged groundwater levels for each taluk at a grid resolution of 5 Km and monthly time step. Since ambhas-lumped model accounts for the lateral flow, the fluxes estimated from the first step were used as a good prior estimate for the distributed model. Ambhas groundwater flow model has been used in lumped mode (e.g. Tomer et al, 2010; Tomer et al, 2011; Subash et al., 2017) and in distributed mode (Scheidegger et al., 2018) for Indian conditions.

For an unconfined, homogeneous and isotropic aquifer, the governing equation of groundwater flow in two dimensions can be written as (Todd and Mays 2005),

$$\frac{\partial}{\partial x}\left(h\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(h\frac{\partial h}{\partial y}\right)=\frac{S_y}{K}\frac{\partial h}{\partial t}+Q \qquad (1)$$

where, h is the hydraulic head [L], S_y is the specific yield [-], K is the hydraulic conductivity [L/T], Q is the source/sink term [-], x and y are the coordinates [L] , and t is time [T].

If the drawdown in the aquifer is very small compared to the saturated thickness, *h* can be replaced with an average thickness, *b* assumed to be constant over the aquifer, and the Eq. 1 can be re-written as,

$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}=\frac{S_y}{Kb}\frac{\partial h}{\partial t}+\frac{Q}{b} \qquad (2)$$

The term *Kb* is similar to the transmissivity (*T*) in the case of confined aquifer, re-writing Eq. 2 as,

$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}=\frac{S_y}{T}\frac{\partial h}{\partial t}+Q/b. \qquad (3)$$

Eq. 3 is solved in two parts. First equation is solved vertically for the source/sink term (*Q/b*), then in the second part, it is solved horizontally. When the vertical solution alone is used i.e. no spatial variability is assumed, the solution is similar to a lumped model and when both the parts (vertical and horizontal) are considered, the solution is similar to a distributed model. In the following text, first the lumped model is described and then the distributed model is described.

3.3.1 Lumped

The source/sink terms are the recharge to groundwater and groundwater abstraction for irrigation. The solution for the recharge/abstraction is done independently for each cell, and this can be expressed as,

$$\frac{dh}{dt} = \frac{1}{S_y}(-\lambda h + R - D_{net}) \quad (4)$$

where, R is the recharge to groundwater [LT^{-1}], D_{net} is the net groundwater draft [LT^{-1}], and λ is the base flow parameter. This equation is similar to the equation derived by (Park and Parker, 2008) except for one additional term for draft. The solution of equation (4) is described in Subash et al. (2017).

The lumped model relaxes the assumption of zero lateral flow which is made while applying GEC (1997) in hard rock aquifers. Since, ambhas-lumped is applied by considering the groundwater level dynamics over longer duration, the estimation of parameters is more robust. The lumped model also estimates the temporal variability in recharge and draft, which provides an opportunity to generate future scenarios which are described in the next subsection.

Since S_y was not known a priori, in the first step ambhas-gw lumped model was run for each of the taluks independently at a monthly time step. The model was run for a period of 38 years (1980-2017). There was a significant temporal variation in the groundwater levels and since this can illustrate variations in S_y as the depth to groundwater levels change, accordingly the modelling period was divided into the following four periods chosen based on the typical groundwater levels in these periods:

I. 1980-1987
II. 1988-1998

III. 1999-2006

IV. 2007-2017

In the model simulations, S_y was assumed to be constant for each time period, however, rainfall-recharge factor and the draft were assumed to be dynamic for each year. It should be noted that if T was negligible, the lumped model will provide the same simulated groundwater levels as provided by distributed model. Since T has a relatively lower value in hard rock aquifers, the parameters estimated from the lumped model can be used in the distributed modelling as a prior data.

3.3.2 Distributed

By dropping the vertical flux (Q/b), the groundwater flow equation can be re-written as,

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = \frac{S_y}{T}\frac{\partial h}{\partial t} \tag{5}$$

The boundary condition of Eq. (5) are assumed as variable head at each time step computed from the observed groundwater level data. This equation is solved using the explicit finite difference scheme in R programming language. The solution is similar to the MODFLOW when single layer and depth-averaged unconfined aquifer is used.

For the distributed groundwater modelling, T was assumed to be 100 m^2/day. Using the estimated S_y from the lumped model, distributed groundwater model was run at monthly time step. Since the taluks do not represent a hydrological boundary, the boundary conditions were taken as Dirichlet boundary condition by using the observed gridded groundwater level data. To run the distributed groundwater model, fluxes computed in the lumped model were taken as a prior fluxes, then the optimization was performed to match the simulated groundwater level data with gridded observed groundwater level data. These optimized fluxes were used to assess the sustainability of groundwater levels in a taluk.

3.4 Management scenarios

According to the Census 2011 the total population of Karnataka was 61 million and is expected to increase by 80 million by 2030. Total water consumption demand from urban and industrial sectors is expected to rise rapidly from 1982 MCM per year to about 4785 MCM in 2030 indicating an additional requirement of 2747 MCM to tackle the demand and supply gap. In order to address the sustainability of water resources in Karnataka, 2030 Water Resources Group (2030 WRG) was formed (https://www.2030wrg.org/karnataka/). The 2030 WRG aims to contribute to the United Nations Sustainable Development Goals by assisting at the request of the government in accomplishing water security by 2030. 2030 WRG is based on ACT (Analyze, Convene, and Transform). It raises awareness through further analysis on existing water resource information, convening initiatives by bringing together public, private, and civil society stakeholders to build workflow momentum, and enables transformation by providing solutions based on local scenarios.

The scenarios of future groundwater resources were generated till 2030 by taking the scenarios of future rainfall and draft projections for developing future management options for CGWB. It was felt that setting the modeling simulations up to 2030, is relevant and useful to 2030 WRG of Karnataka state with regard to groundwater security aspects.

3.4.1 Future rainfall-recharge scenario

The COordinated Regional Climate Downscaling EXperiment (CORDEX; Giorgi et al. 2009) provides a regionally dynamically downscaled climate for GCM projections driven by the fifth Coupled Model Intercomparison Project (CMIP5). CORDEX- South Asia domain experiment constitutes 11 different suites, with the combination of different RCMs using different GCMs' initial and boundary forcing. The CORDEX South Asia data is available at a spatial resolution 0.44° (~50 km) and monthly temporal resolution as well as daily for some experiments. To simulate the future groundwater levels, rainfall from the Coordinated Regional Climate Downscaling Experiment-South Asia (CORDEX-SA) project for representative concentration pathway (RCPs) of 4.5, which is a stabilization scenario is used. In RCP 4.5, the radiative forcing values in the year 2100 is 4.5 W/m^2, the emissions peak 2040 and then decline. Although some studies (Sekhar et al., 2013; Subash et al., 2017) have used several GCMs and their ensembles from CMIP-5 and RCMs, however in the present study we have considered only the outputs of The Rossby Centre Regional Atmospheric Model (RCA4) simulations of CORDEX experiment (SMHI RCA4 ICHEC-EC-EARTH (r12i1p1)) were specifically selected for the simulation owing to their better performance with the observed data. The RCM simulated rainfall may be biased for the local regions/ taluk, hence the bias correction was performed using the quantile mapping technique. The “qmap” package in R was used to do the quantile based bias correction (Hakala et al., 2018). Several studies have shown that it is important to evaluate the RCMs before they are used in hydrological climate change impact analysis. We have compared the observed rainfall with the RCM’s rainfall in the historical period (1980-2005). We found that there is bias in the rainfall from RCM with overestimation in the months of January, February, March and April. There are several bias-correction methods delta-factor (Lenderink et al., 2007); nonlinear correction factor (Leander and Buishand, 2007), distribution-based quantile mapping (Piani et al., 2010) distribution-free quantile mapping (e.g. empirical distribution, Wood et al., 2002, 2004; Ashfaqet al., 2010). The quantile based bias correction does not make an a-priori assumption about the distribution of precipitation data. We tested the delta factor, distribution-based quantile mapping and Empirical distribution correction method with the data split into calibration and validation periods i.e 70% of the data was used for calibration and the rest 30 percentage for validation and found that the Empirical distribution correction method is best among the three methods. The historical rainfall is available for the period (1951-2005) and the forecasted rainfall is available for 2006-2100.

An annual rainfall-recharge function was developed with the whole period split into three periods. ie. 1980-1987, 1988-1998 and 1999-2017. The developed rainfall recharge function was used to estimate the recharge for a given rainfall into the future.

3.4.2 Future draft scenarios

Following three scenarios are generated based on the estimated annual draft during 1980-2017:

Scenario I: In this scenario, draft is assumed to increase with time. The rate of increase is assumed to be the same as that estimated in the historical data (~say business as usual).

Scenario II: In this scenario, the draft is assumed to be stabilizing with time.

Scenario III: In this scenario, it is assumed that the draft has reached the maximum possible value and the same draft is assumed for the future years.

Scenario IV: This scenario is used for taluks whose stage is assessed as “safe”, wherein the historical data does not present an trend of increasing draft. Moreover, the current stage of development in these taluks is sustainable. Hence an increased draft starting from 2017 is tested to assess the sustainability for the future years with enhanced groundwater development.

The yearly trends of draft and the associated draft values for the future years starting from 2017 are presented for all the 45 taluks in the figures 146 to 188.

4. Results and Discussion

4.1 Estimation of parameters and prior draft — lumped model

The model was used to estimate the S_y for the four periods (1980-87, 1988-1997, 1998-2006, and 2007-2017) in addition to annual rainfall-recharge factor and annual draft. It should be noted that the draft estimated by the lumped model (termed as prior draft) is updated while calibrating the distributed model.

The estimates along with the time series of observed and simulated groundwater levels are shown in Figures 4 to 48 for all the 45 taluks. A good fit was observed between the simulated and observed groundwater levels with RMSE ranging from 0.57 m to 3.65 m over the 45 taluks. In the first time period, all the taluk showed relatively shallow groundwater level with a relatively deeper groundwater level observed in the fourth time period. In most of the taluks, relatively higher values of S_y and rainfall-recharge factor were observed in the first time period.

A comparison of the groundwater balance during the first and fourth time periods for all the 45 taluks is shown in Figures 49 to 93. A histogram of the ratio of discharge to recharge for all the 45 taluks during the first and fourth time periods are shown in Figure 94. As can be observed from the figure, during the first period, groundwater discharge (lateral flux from the taluk) forms the significant portions of the recharge in all the taluks, however, during the fourth period, in most of the taluks, the groundwater discharge component with respect to recharge has reduced significantly. Even in the fourth period (2007-2017), there is significant groundwater discharge component present in various taluks and hence it suggests that the taluks can not be modelled as a closed unit and the distributed modelling is required to understand the lateral flows. The results of the distributed groundwater flow modelling are presented in the next subsection.

To assess the sustainability of groundwater resources, the stage of groundwater development (a ratio of draft to rainfall-recharge) was computed for all the 45 taluks for all the four time periods. A histogram of the same is shown in Figure 95. The criteria used for classifying taluks is presented in Table 2 and the status of taluks for all the four periods is presented in Table 3. As can be seen from the figures and Table 3, in the first two periods, the stage of groundwater development is less than 70% for all the taluks. As the draft increased over time, in the third period, only 32 taluks are having the stage of groundwater development less than 70%, while 3 taluks showing higher than 100%. In the fourth period, approximately one-fourth (13 out of 45) are in the ‘safe’ category while 9 taluks are in the ‘over exploited’ category.

A histogram of the estimated S_y is presented in Figure 96. As can be seen from the figure, the S_y is decreasing over time, possibly due to the increase in the depth to groundwater table (histogram of which is presented in Figure 97).

4.2 Estimation of fluxes — distributed model

Since a significant fraction of groundwater discharge (lateral flow) was observed in the lumped model simulations, distributed modelling was performed for the connected clusters of taluks. Prior fluxes (lateral flow and draft) estimated in the lumped model were updated during the distributed model. The distributed groundwater modelling was performed during 2007-2017. The rainfall-recharge factor and Sy were taken the same as estimated by the lumped model to reduce the parameter uncertainty during the calibration. Comparison of the spatial distribution of simulated and observed groundwater levels along with the temporal distribution of taluk-averaged groundwater levels is shown in Figures 98 to 142 for all the 45 taluks. The observed and simulated groundwater levels showed a significant spatial variability in most of the taluks. This implies the necessity of using a distributed groundwater model. The distributed groundwater flow model showed a good fit with RMSE ranging from 0.92 m to 6.38 m. The RMSE for the lumped model simulation ranges from 0.5 m to 2.86 m. The higher value of RMSE from the distributed model could be due to the higher degrees of freedom in the parameters.

The components of groundwater balance computed using the distributed groundwater flow model are shown in Table 4. When the distributed model is used the draft component and net laterflow from the taluk will be separately estimated with improved reliability than those initially estimated using the AMBHAS-1D model as first approximation. Even though this model has a laterflow component built into it, the estimates of laterflow become more reliable in AMBHAS-2D due to the boundary conditions posed in the distributed model. The stage of development will present variations when combining both draft and laterflow vis-a-vis just using laterflow alone in the numerator with recharge as the denominator. This is shown clearly in Table 2 in separate columns (Column F and Column H in Table 2). When both draft and laterflow together are combined (Column H in Table 2) as often used in a model without laterflow component such as the operational approach used as per GEC methodology, then the numerator is greater and hence a higher value is obtained when computing the norms of stage of development. The re-classification of stage of development is presented based on these criteria in Table 2 based on the updated fluxes obtained in the distributed groundwater flow model. When using draft alone (Column F in Table 2), the number of taluks pertaining to the 'safe', 'semi-critical', 'critical' and 'over exploited' categories based on the components estimated using the distributed model are 10, 14, 10, and 11, respectively. However, when both draft and laterflow are combined together (Column H in Table 2), 41 taluks are in the category of Over Exploited while 4 are in Critical category. Further it is emphasised here that the assessment of stage of development in the modeling studies are made using the period 2007-2017 and hence it represents the mean condition for the 10 year period in this time window.

The ratio of computed lateral flow to the recharge was computed and the spatial distribution is presented in Figure 143 and histogram is presented in Figure 144. The lateral flow was found to be significant in several of the taluks.

Figure 145 shows the comparison of mean estimated draft over 2007-2017 with the density of wells based on the 5^{th} MI survey. As can be seen from the figure that a moderate linear relationship is observed between the estimated draft and number of density of wells. It should be noted that only the taluks having well density upto 0.1 wells per hectare were considered for the relationship. About ten taluks had higher well density than 0.1 wells per hectare and for these the relationship was poor so they were not used. In the taluks with higher well densities, there are potential effects of interference between pumping wells and in addition greater percent of wells not in use due to failures, all of these reasons possibly explain the reasons of poorer correlation between draft and well density.

4.3 Management scenarios

Management scenarios were developed for all the forty five taluks. For obtaining the rainfall for the future years, the empirical quantile mapping bias correction is used to correct the bias in the SMHI RCA4 ICHEC-EC-EARTH rainfall and this was used as input to the model to simulate the groundwater levels for the period 2018-2030. The estimated temporal draft scenarios (as discussed in Section 4.1 & Section 3.4.2) were used to project upto 2030. The estimated *Sy* (as discussed in the section 4.1) for the period 2007-2017 was utilized. Using the annual rainfall-recharge estimate (as discussed in Section 4.1), a relationship is developed between rainfall and recharge for the time period 2007-2017. Using the draft scenarios presented in Section 3.4.2, simulations were performed and the corresponding results are presented in Figures 146 to 188.

Figure 146 presents the scenario for the Kolar taluk in Kolar district. As can be seen from the figure, the groundwater table is unsustainable in all four pumping scenarios considered. An additional scenario was tried for this taluk, where the draft was taken equal to the draft of the year 2010. Even with the reduced draft of this scenario, the groundwater level was found to be unsustainable. To make the groundwater sustainable in Kolar taluk, significant reduction in the draft than that of 2010 levels is required. A similar behaviour was observed in the case of Chikkanayakanahalli taluk in Tumkur district (see Figure 147).

Figure 148 presents the scenario for the Koratagere taluk in Tumkur district. The groundwater table was found to be unsustainable for the three scenarios considered.

However, when the draft was limited to the level corresponding to that of 2010 year, the groundwater table resulted in sustainable levels. A similar case was observed for the Bangarpet taluk in Kolar district (see Figure 149), and Doddaballapur taluk in Bangalore rural district (see Figure 150). Figure 151 presents the scenario for the Jagalur taluk in Davanagere district. The groundwater level fluctuates between 20-30 m for all the scenarios during the 2018-2030. This taluk is sustainable for all the pumping scenarios.

Figure 152 shows the results for Chikballapur taluk in Chikballapur district. For this taluk, the groundwater levels are unsustainable for all the pumping scenarios including the draft limited to the level of 2010. Figure 153 shows the simulations for Chintamani taluk in Chikkaballapur district. The taluk appears to be unsustainable for all the three pumping scenarios, however, the taluk appears to be sustainable when draft is limited to that year 2010. Similarly, the taluks Sidlaghatta in Chikballapur district (Figure 154) and Hiriyur in Chitradurga district (Figure 155) are also sustainable only if the annual pumping is limited to that of the year 2010. Figure 156, 157 and 158 correspond to Srinivaspura, Mulabagal and Malur taluks in Kolar district respectively. The taluk appears to be unsustainable and to make them sustainable the draft is to be limited to that year 2010. Figure 159, 160 and 161 Madhugiri, Tiptur and Sira in Tumkur taluks which are unsustainable at the current pumping rate. To make these taluks sustainable the pumping needs to be reduced to that of 2010. Figure 162, is for the Bagepalli taluk in Chikkaballapura district where the pumping reduced to about 70 mm would make the taluk sustainable. Figure 163 shows the simulations for Ron in Gadag district. The taluk is sustainable for all two pumping scenarios (scenario #1 and #2). Figure 164 to 165 depicts future simulated groundwater levels for taluks Arasikere in Hassan, becoming sustainable if pumping is reduced to that of 2010, whereas Yelburga in Koppal district is unsustainable even with reduced pumping.

Devanahalli in Bengaluru Rural district (Figure 166) and Nargund in Gadag district (Figure 167) are sustainable for all the pumping scenarios. Figure 168 and 169 shows the simulations for Hagaribommanahalli in Bellary district and Gauribidanur in Chikkaballapura are sustainable with reduced pumping as that of the year 2010. Figure 170, 171 and 172 shows simulation for Athni, Hukeri and Raybag taluk of Belagavi district. Figure 173 and 174 shows simulation for Hadagali taluk of Bellary district and Holalkere taluk of Chitradurga district. Figure 175 and 176 shows simulation for Channagiri taluk and Davanagere taluk of Davangere district. Figure 177 and 178 shows simulation for Ranebennur taluk of Haveri district and Afzal taluk of Kalaburagi district.

Figures 179 to 188 show the simulations for the taluks (Yadgir, Harappanahalli, Hosadurga, Chitradurga, Challakere, Saundatti, Ramdurg, Bagalkot, Badami, Lingsugur, Afzalpur), whose draft is considerably lower and hence there is an opportunity to test a draft scenario with minor enhanced draft by future groundwater development in these taluks unlike in the rest of the 35 taluks, which had to be tested for reduced draft from a sustainability condition. For these taluks a pumping scenario of minor uniform linear increase each year to a total of about 25mm by 2030 was applied as an additional draft scenario and this additional draft was found to be acceptable within the sustainability condition for the year 2030. Table 4 presents the draft limit that needs to be imposed based on the management scenario or further recharge augmentation for certain cases for various taluks.

Table 5 presents the management plan option that is found to be the best among various scenarios tested for each of the 45 taluks for achieving acceptable groundwater conditions based on sustainability criterion by the year 2030. This was based on the multiple scenarios of draft conditions tested for the years between 2018-2030. Table 6 presents a summary of net lateral fluxes from each of the 45 taluks indicating the relative importance of groundwater transfer across boundaries of the administrative taluk boundaries with respect to groundwater use in each of the taluks.

5. Summary and Conclusions

As part of the scope of work, following GIS layers were developed and shared with CGWB:

- ❖ Drainage layer and location of minor irrigation tanks.
- ❖ Location of rain gauges and GW observation network
- ❖ Geology.
- ❖ Wells under use for each village and well density based on the 5th minor irrigation survey.
- ❖ Area irrigated by surface and groundwater based on the 5th minor irrigation survey.
- ❖ Actual evapotranspiration at a spatial resolution of 5km based on the MODIS and MERRA-2 data.

Ambhas-lumped groundwater flow model was used to estimate the S_y in each of the 45 taluks. The analysis was performed by dividing the modelling period (1980-2017) into four periods (1980-1987,1988-1999,1999-2006 and 2007-2017). The S_y was estimated for each taluk and for each period as it can vary depending upon the depth of groundwater table. For most of the taluks, it was observed that the S_y was decreasing with the increase in the depth to groundwater table and vice versa. The sustainability of the groundwater in each taluk was analyzed based on the estimated prior fluxes (by using the ambhas-lumped groundwater flow model) for the four periods. The specific yield estimated during different time periods (covering approximately four decades), results as a depth varying specific yield (due to the declines in groundwater levels in these four decades) in several taluks and hence provides an opportunity to be used or integrated with the the ongoing aquifer mapping studies (NAQUIM). The stage of development estimated using the lumped model suggested that 41 taluks are Over-exploited while 5 are in the critical category based on the operational norms. The categorisation is based on the analyses over a ten year period of 2007-2017.

Distributed groundwater flow modelling was performed by using the AMBHAS-distributed model over the period 2007-2017. The distributed model was able to separate the impact of lateral flow and draft on the groundwater table in each taluk. In several taluks the net lateral flow component is relatively higher and suggests the groundwater transfers across the administrative boundaries of the taluks. Using the stage of development based on the draft estimated for each of the taluks from the distributed model, presents an alternative set of categorisation for the 45 taluks. This is expected since the lateral flow component is relatively higher in several taluks and thereby using draft alone in the computation of stage of development will result in an underestimate of the stage. Accordingly, 10 taluks were found to be within the 'safe' category. However, it should be noted that some of these taluks are close to the threshold of 70% for the classification of 'safe' category and should be watched in the future for the exploitation/development of groundwater resources. Taluks falling in other categories i.e. 'semi-critical', 'critical' and 'over exploited' categories are 14, 10, and 11, respectively. This categorization is based on the model analyses over the period 2007-2017.

The distributed model applied over a cluster of taluks, provided an opportunity to assess the lateral groundwater flow between taluks. During the early period (1980-1987), all the taluks had significant lateral groundwater flow components ranging from 50 to 100% of recharge. However during the last simulation period (2007-2017), there was a significant reduction in the lateral groundwater flow component. The net lateral groundwater outflow was in the range of 0-25% in about 24 taluks, while 18 taluks had a net groundwater outflow in the range of 25-50%. Three taluks (e.g. Kolar taluk, Gauribidanur taluk) have a net groundwater inflow from the neighboring taluks.

For the management scenarios, we considered all 45 taluks. Based on the draft estimated in the period 2007-2017, the draft scenarios were developed to determine taluks that are sustainable for the future rainfall. Twenty out of twenty four taluks were found to be unsustainable for all the pumping scenarios considered in the study. However if the pumping is limited to the draft as on the year 2010, twenty out of twenty four taluks (Koratagere, Bangarapet, Doddaballapur, Jagalur, Chintamani, Sidlaghatta, Hiriyur, Srinivaspura, Mulabagal, Malur, Madhugiri, Tiptur, Sira, Bagepalli, Arasikere, Hagaribommanahalli, Gauribidanur, Ron, Devanahalli and Nargund) are found to attain sustainable groundwater levels. Four taluks (i.e. Kolar taluk, Chikballapur taluk and Chikkanayakanahalli taluk and Yelburga taluk), which do not show sustainable groundwater levels even with reduced draft as on 2010, the future management options for groundwater security would require extensive managed aquifer recharge (MAR) options in addition to the reduced draft to achieve the sustainability of groundwater levels. The draft pertaining to 2010 for these taluk is presented in Figures 4 to 48. The remaining taluks were tested with various draft scenarios and the draft that fits well with the sustainability conditions for 2030 were assessed. For arriving at a management plan for each taluk a mean rainfall recharge factor estimated based on annual recharge factor 2007-2017 was used. The taluks which are very close to the margin of safety need to be augmented with recharge where feasible. Summary Table (Tables 5) present the suggested viable management plan for each of the taluks. Summary Table (Table 6) presents the net lateral flux for the period 2007-2017 from each of the taluks.

6. Acknowledgement

The help provided by Subash Yeggina and Dr. Sat Kumar Tomer from Satyukt Analytics in data analysis & model simulations is duly acknowledged. P. Giriraja and Sanjeeva Murthy conducted the fieldwork and prepared maps in GIS, and their efforts are also acknowledged. The Regional Director, CGWB SWR and his team are acknowledged for sharing the groundwater level data and other relevant datasets and for constantly being in touch with the IISc team throughout this study. The DMG, Karnataka State is acknowledged for sharing the groundwater levels and other relevant data sets. The KSNDMC is acknowledged for sharing the rainfall data. The members of the monitoring committee are duly acknowledged for

providing their valuable inputs during the review meetings held in Bangalore, which immensely helped this study.

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Table 1: List of districts with taluks and the total area.

Number	District	Number of taluks	Total area (km^2)
1	Bagalkote	2	2319.13
2	Belagavi	5	6721.17
3	Bellary	2	1933.91
4	Bengaluru Rural	2	1251.86
5	Chikkaballapura	6	4244.57
6	Chitradurga	5	7694.67
7	Davanagere	4	4572.71
8	Gadag	3	2818.19
9	Hassan	1	1266.28
10	Haveri	1	901.18
11	Kalaburagi	1	1307.98
12	Kolar	5	3982.93
13	Koppal	1	1497.04
14	Raichur	1	1966.95
15	Tumkur	5	5229.75
16	Yadgir	1	1724.96
	Total	**45**	**49433.28**

Table 2: Categorisation based on the stage of groundwater development. (Adapted from GEC,1997)

S.N.	Stage of Groundwater Development (%)	Categorisation
1	<= 70	Safe
2	> 70 and <= 90	Semi-critical
3	> 90 and <= 100	Critical
4	> 100	Over-Exploited

Table 3: Status of the 45 taluks over the four periods based on the First Approximation i.e. prior fluxes estimated by the lumped groundwater model. (OE-Over Exploited)

SN	Taluk Name	1980-1987		1988-1998		1999-2006		2007-2017	
		%	Status	%	Status	%	Status	%	Status
1	Badami	6	Safe	26	Safe	53	Safe	53	Safe
2	Bagalkot	16	Safe	11	Safe	50	Safe	47	Safe
3	Athni	14	Safe	23	Safe	38	Safe	23	Safe
4	hukeri	9	Safe	13	Safe	7	Safe	7	Safe
5	Raybag	12	Safe	13	Safe	35	Safe	28	Safe
6	Saundatti	9	Safe	18	Safe	28	Safe	74	Semi-critical
7	Ramdurg	17	Safe	13	Safe	33	Safe	40	Safe
8	HagariBommanahalli	15	Safe	24	Safe	72	Semi-critical	72	Semi-critical
9	Hadagalli	9	Safe	23	Safe	61	Safe	11	Safe
10	Devanhalli	10	Safe	13	Safe	42	Safe	59	Safe
11	Doddaballapur	7	Safe	16	Safe	102	OE	84	Semi-critical
12	Bagepalli	7	Safe	18	Safe	73	Semi-critical	124	OE

13	chikballapur	7	Safe	15	Safe	80	Semi-critical	136	OE
14	chinthamani	10	Safe	29	Safe	82	Semi-critical	87	Semi-critical
15	Gauribidanur	41	Safe	16	Safe	65	Safe	67	Safe
16	Gudibanda	12	Safe	16	Safe	46	Safe	55	Safe
17	Sidlaghatta	7	Safe	16	Safe	49	Safe	104	OE
18	Challakere	30	Safe	10	Safe	11	Safe	37	Safe
19	Chitradurga	8	Safe	33	Safe	81	Semi-critical	65	Safe
20	Hiriyur	18	Safe	29	Safe	66	Safe	75	Semi-critical
21	Holalkere	7	Safe	12	Safe	39	Safe	52	Safe
22	Hosadurga	12	Safe	23	Safe	38	Safe	48	Safe
23	Channagiri	11	Safe	10	Safe	5	Safe	24	Safe
24	Davanagere	13	Safe	10	Safe	12	Safe	13	Safe
25	Harapanahalli	4	Safe	9	Safe	12	Safe	44	Safe
26	Jagalur	17	Safe	33	Safe	64	Safe	74	Semi-critical
27	Gadag	5	Safe	15	Safe	29	Safe	68	Safe
28	Ron	7	Safe	21	Safe	113	OE	94	Critical
29	Nargund	-	-	18	Safe	10	Safe	36	Safe
30	arasikere	12	Safe	16	Safe	59	Safe	104	OE
31	Ranibennur	9	Safe	13	Safe	39	Safe	7	Safe
32	Afzalpur	8	Safe	13	Safe	6	Safe	7	Safe
33	bangarpet	4	Safe	23	Safe	86	Semi-critical	144	OE
34	Kolar	5	Safe	16	Safe	93	Critical	210	OE
35	Malur	11	Safe	12	Safe	58	Safe	118	OE
36	Mulabagal	9	Safe	8	Safe	55	Safe	157	OE
37	srinivasapura	4	Safe	7	Safe	30	Safe	131	OE
38	Yelburga	10	Safe	22	Safe	114	OE	100	Critical

39	Lingsugur	13	Safe	5	Safe	8	Safe	34	Safe
40	chikkanayakanahalli	9	Safe	36	Safe	71	Semi-critical	85	Semi-critical
41	Koratagere	8	Safe	17	Safe	54	Safe	99	Critical
42	Madhugiri	8	Safe	36	Safe	80	Semi-critical	84	Semi-critical
43	Sira	15	Safe	27	Safe	39	Safe	74	Semi-critical
44	Tiptur	11	Safe	39	Safe	90	Critical	87	Semi-critical
45	Yadgir	10	Safe	15	Safe	67	Safe	60	Safe

Table 4: Computed fluxes and categorisation of stages for all 45 taluks using components estimated by the distributed groundwater flow model for 2007-2017

Taluk Name	Storage change mm/yr	Recharge mm/yr	Draft mm/yr	Lateral flux mm/yr	Stage of GW develo-pment (Draft/ Recharge) (%)	Category based on column F	Stage of GW develo-pment ([Draft + Lateral flux] / Recharge) (%)	Category based on column H
A	B	C	D	E	F	G	H	I
Afzalpur	2.1	66.8	37.5	-27.2	56	Safe	97	Critical
Athni	-0.7	50.5	35.1	-16.1	70	Safe	101	OE
Yadgir	0.8	64.3	52.5	-11.0	82	Semi-critical	99	Critical
Raybag	-1.7	51.1	32.0	-20.8	63	Safe	103	OE
Hukeri	-0.8	75.3	42.0	-34.1	56	Safe	101	OE

Lingsugur	-1.3	54.2	35.7	-19.8	66	Safe	102	OE
Bagalkot	-3.5	69.6	59.4	-13.6	85	Semi-critical	105	OE
Ramdurg	-5.0	54.3	39.2	-20.1	72	Semi-critical	109	OE
Saundatti	-5.9	59.7	53.5	-12.2	89	Semi-critical	110	OE
Badami	-7.4	60.9	47.6	-20.8	78	Semi-critical	112	OE
Nargund	-8.1	60.1	55.3	-12.9	92	Critical	113	OE
Ron	-3.6	56.6	59.4	-0.8	105	OE	106	OE
Yelbarga	1.0	65.9	65.7	0.8	100	Critical	98	Critical
Gadag	-1.0	54.7	43.4	-12.4	79	Semi-critical	102	OE
Hagaribomma nahalli	-2.2	55.7	51.4	-6.5	92	Critical	104	OE
Hadagalli	-1.7	63.4	36.9	-28.2	58	Safe	103	OE
Harapanahalli	-1.0	64.9	46.3	-19.6	71	Semi-critical	102	OE
Ranibennur	-0.4	86.9	51.3	-36.0	59	Safe	100	Critical
Jagalur	-0.4	59.3	52.2	-7.6	88	Semi-critical	101	OE
Challakere	-0.7	51.0	39.0	-12.7	77	Semi-critical	101	OE
Davanagere	-1.6	91.0	56.0	-36.6	62	Safe	102	OE
Chitradurga	-1.4	79.8	63.2	-18.0	79	Semi-critical	102	OE
Channagiri	-1.0	74.7	46.0	-29.7	62	Safe	101	OE

Holalkere	-1.2	71.7	49.1	-23.9	68	Safe	102	OE
Hiriyur	-1.7	56.9	56.3	-2.3	99	Critical	103	OE
Sira	-3.4	69.9	65.4	-8.0	93	Critical	105	OE
Hosadurga	-2.8	63.1	50.2	-15.7	80	Semi-critical	104	OE
Bagepalli	-16.9	49.8	59.9	-6.8	120	OE	134	OE
Madhugiri	-7.0	62.8	59.0	-10.9	94	Critical	111	OE
Gauribidanur	-5.8	68.5	77.9	3.6	114	OE	108	OE
Gudibanda	-11.7	60.5	45.4	-26.8	75	Semi-critical	119	OE
Chikkanayaka-nahalli	-3.4	70.0	69.9	-3.5	100	Critical	105	OE
Chinthamani	-16.6	65.0	65.8	-15.8	101	OE	126	OE
Sidlaghatta	-13.8	63.2	70.4	-6.6	111	OE	122	OE
Chikballapur	-10.0	48.0	42.1	-15.8	88	Semi-critical	121	OE
Koratagere	-7.2	61.6	60.2	-8.6	98	Critical	112	OE
Srinivasapura	-35.7	48.6	77.1	-7.1	159	OE	173	OE
Arasikere	-8.0	63.3	63.8	-7.5	101	OE	113	OE
Doddaballapur	-4.2	76.4	62.9	-17.7	82	Semi-critical	105	OE
Tiptur	-6.6	68.6	65.9	-9.2	96	Critical	109	OE
Devanhalli	-13.6	61.4	55.6	-19.3	91	Critical	122	OE
Mulabagal	-47.4	41.6	74.3	-14.8	178	OE	214	OE
Kolar	-50.7	41.0	93.8	2.1	229	OE	224	OE
Malur	-20.9	45.7	53.9	-12.8	118	OE	146	OE

Bangarpet	-26.2	46.2	72.1	-0.3	156	OE	157	OE

NOTE:

positive (+) lateral flux is inflow

negative (-) lateral flux is outflow

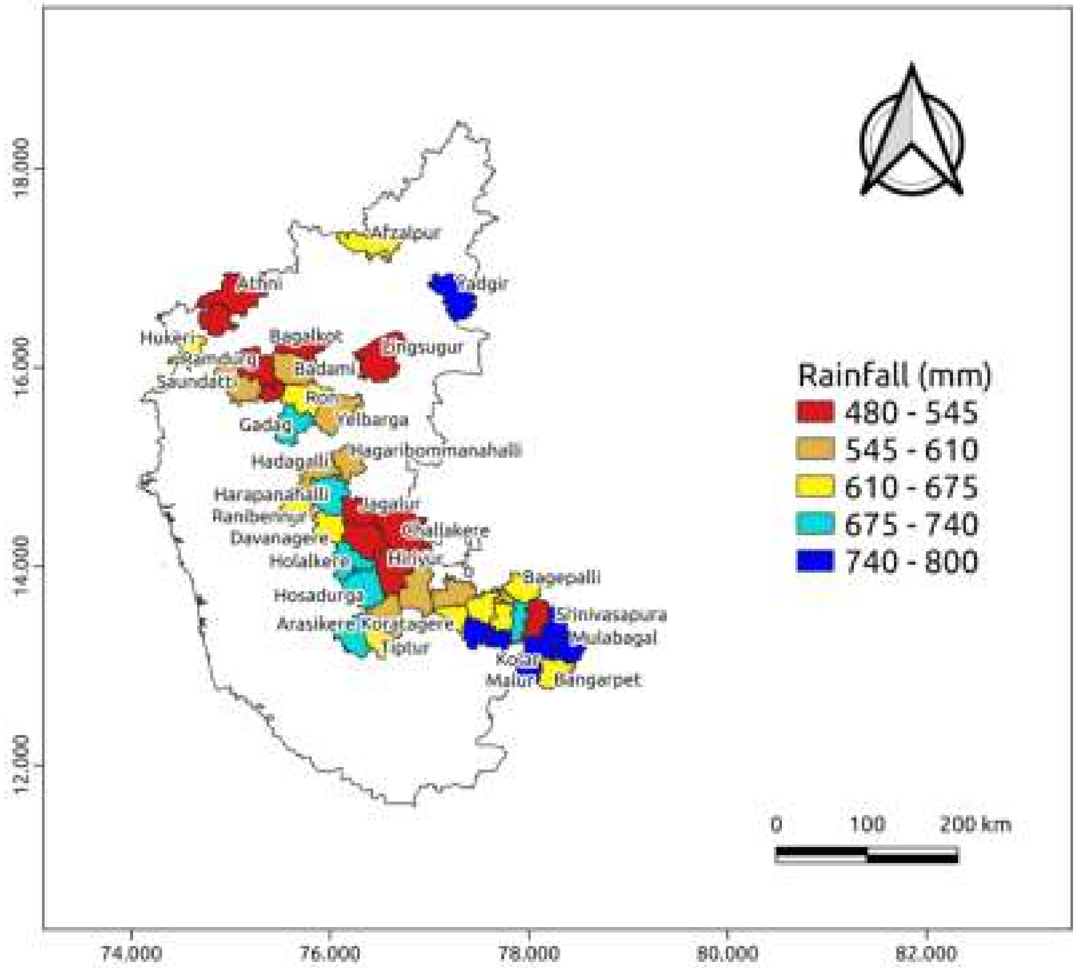

Figure 1: Spatial distribution of the average (computed over 1980-2017) annual rainfall of 45 taluks.

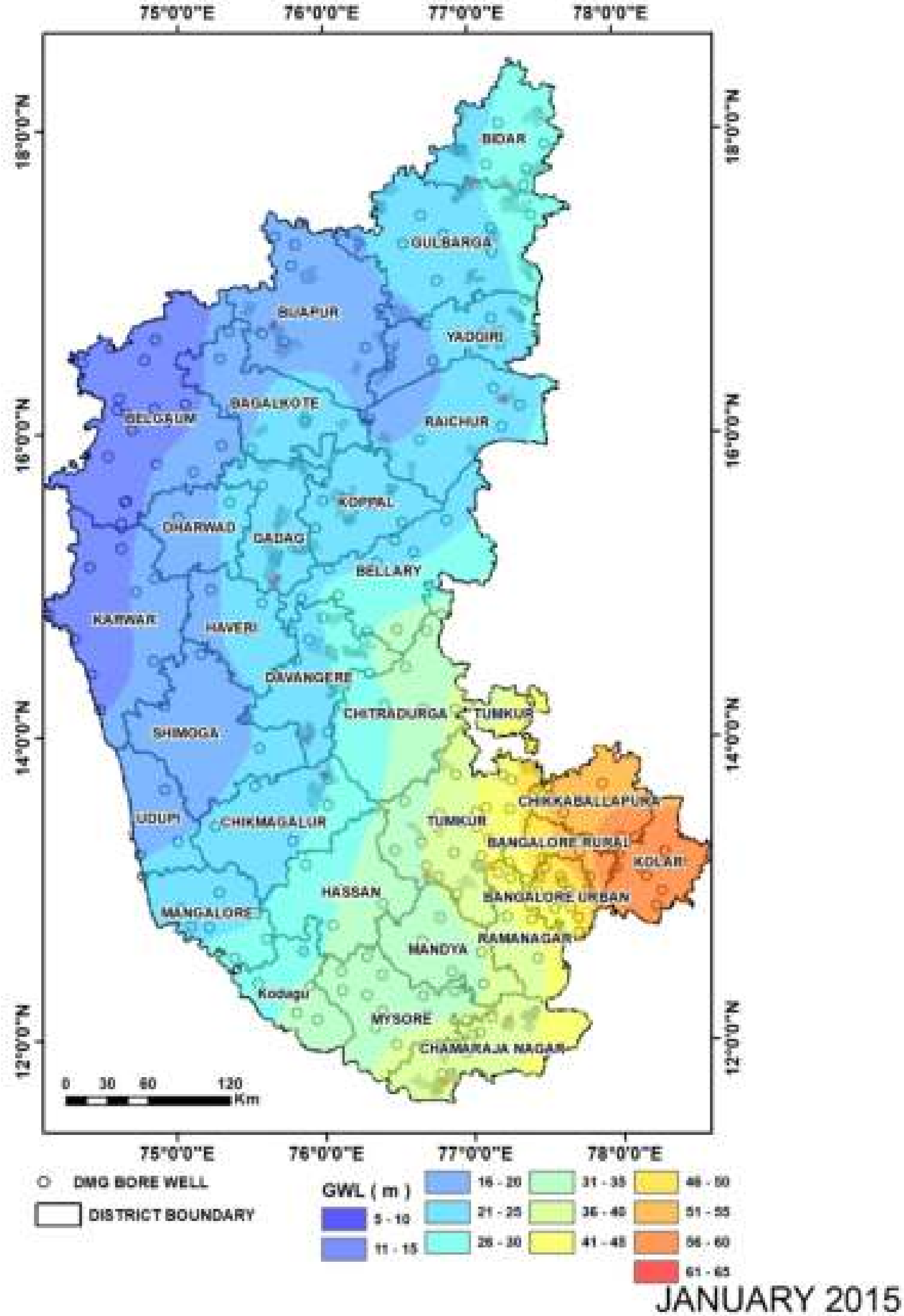

Figure 2: Spatial distribution of the depth to groundwater table during January, 2015 in the state of Karnataka.

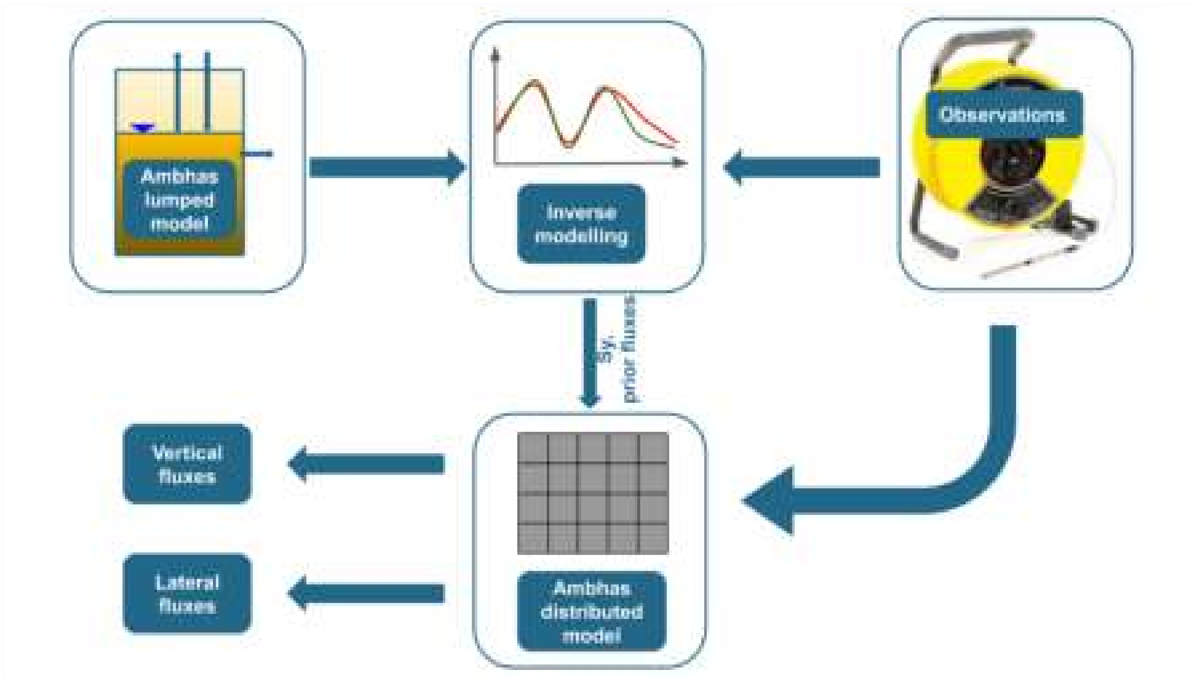

Figure 3: Flow chart of the modelling strategy.

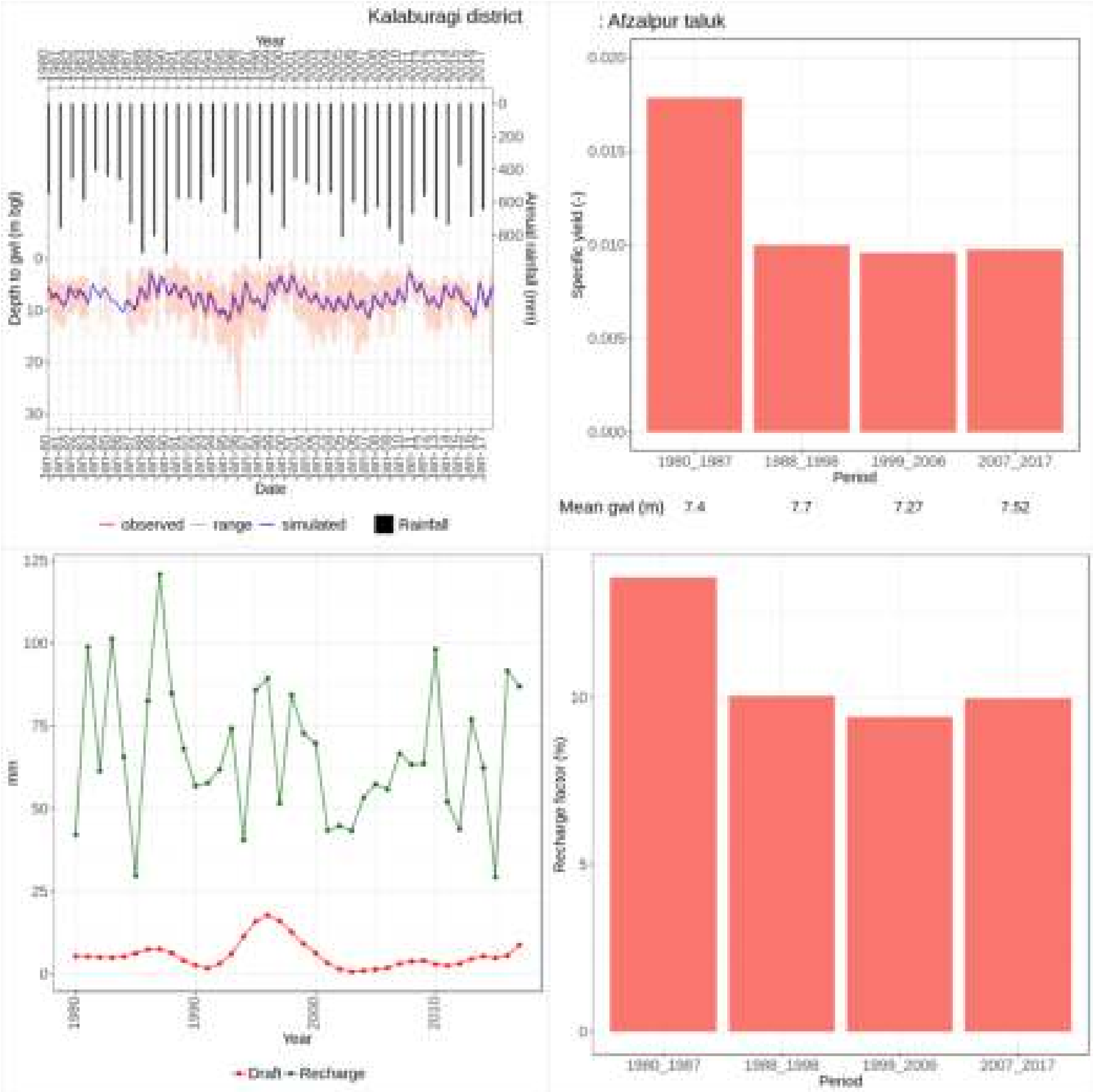

Figure 4 : Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Afzalpur taluk.

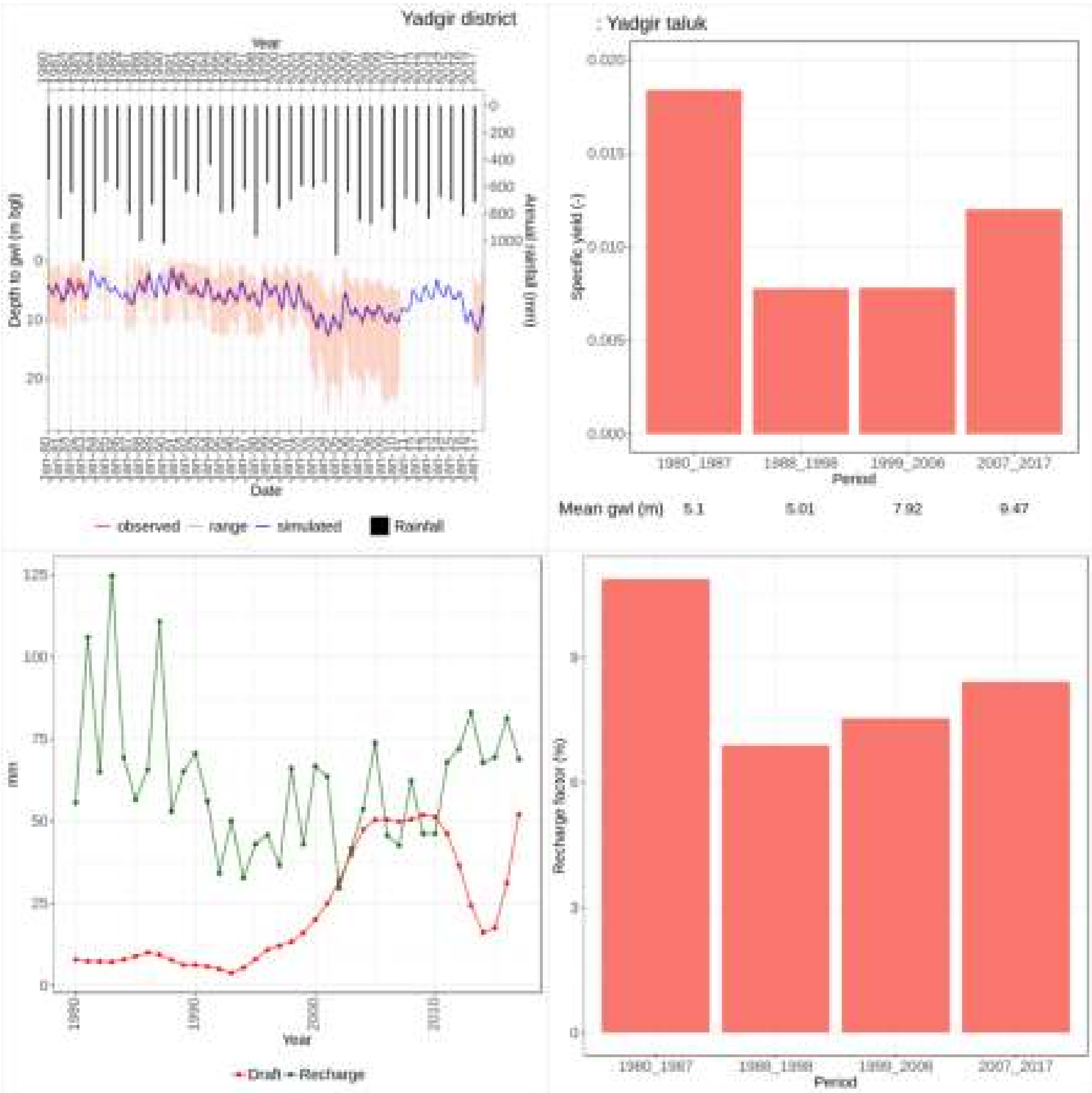

Figure 5 : Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Yadgir taluk.

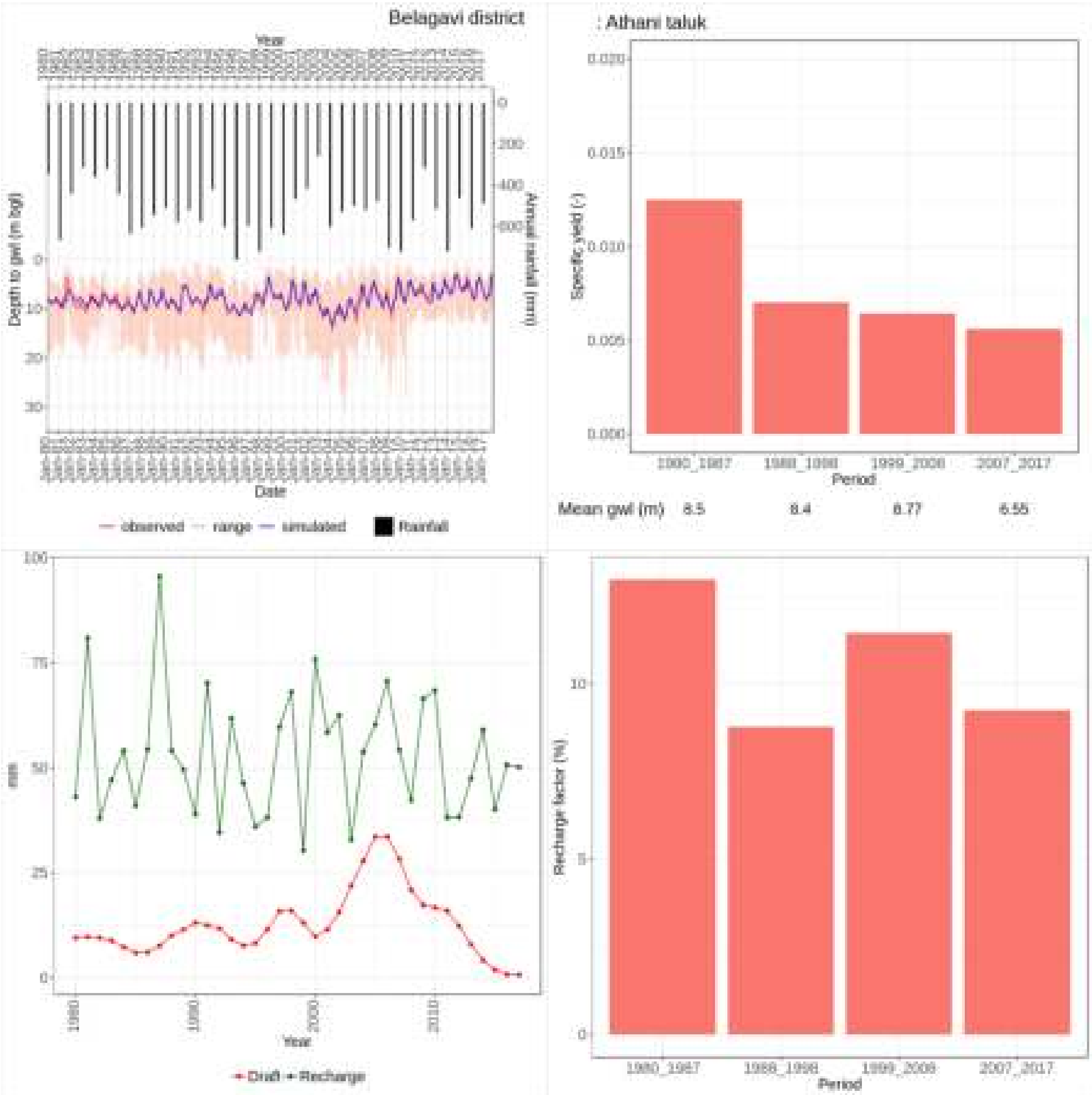

Figure 6 : Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Athani taluk.

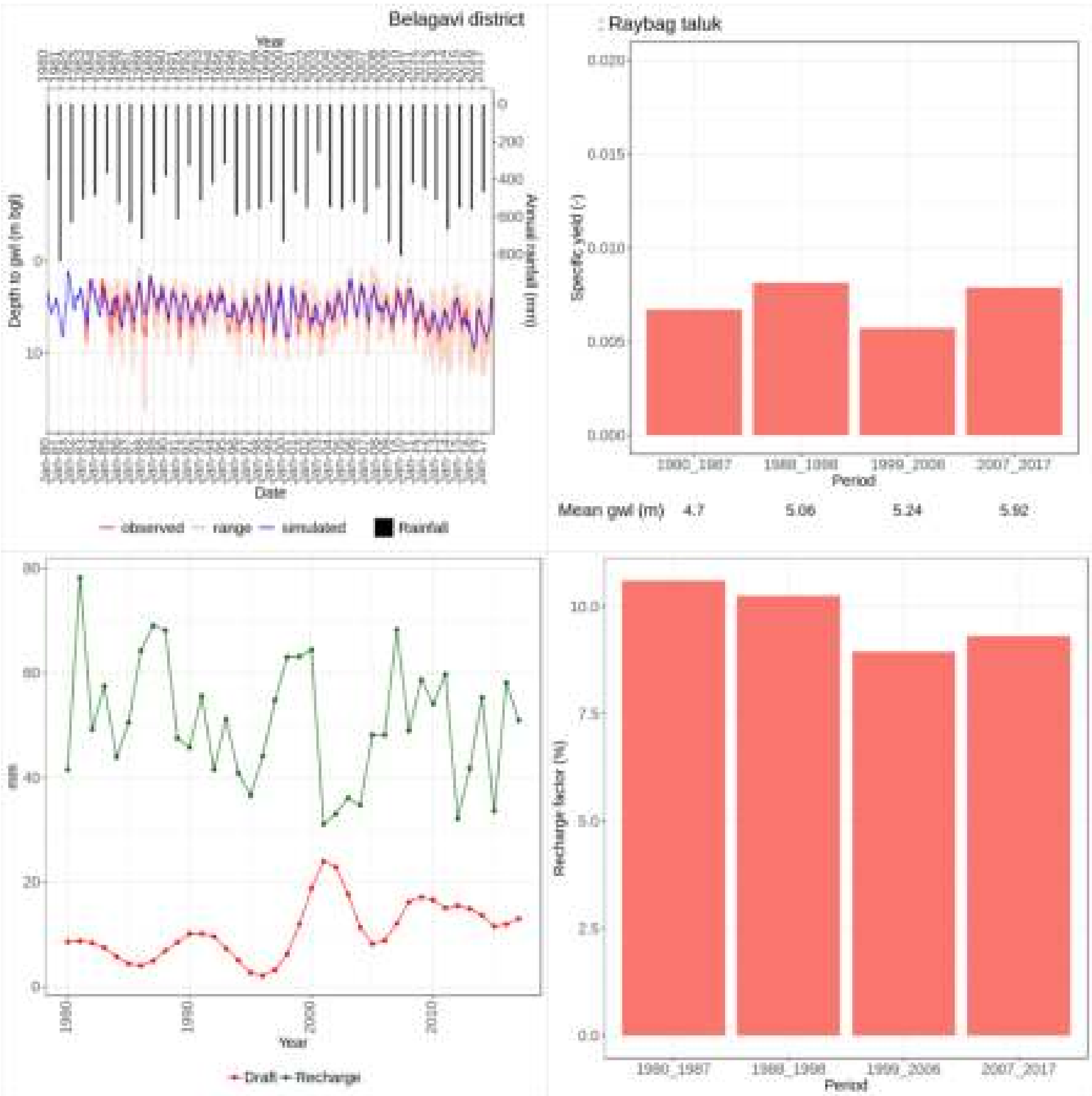

Figure 7 : Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Raybag taluk.

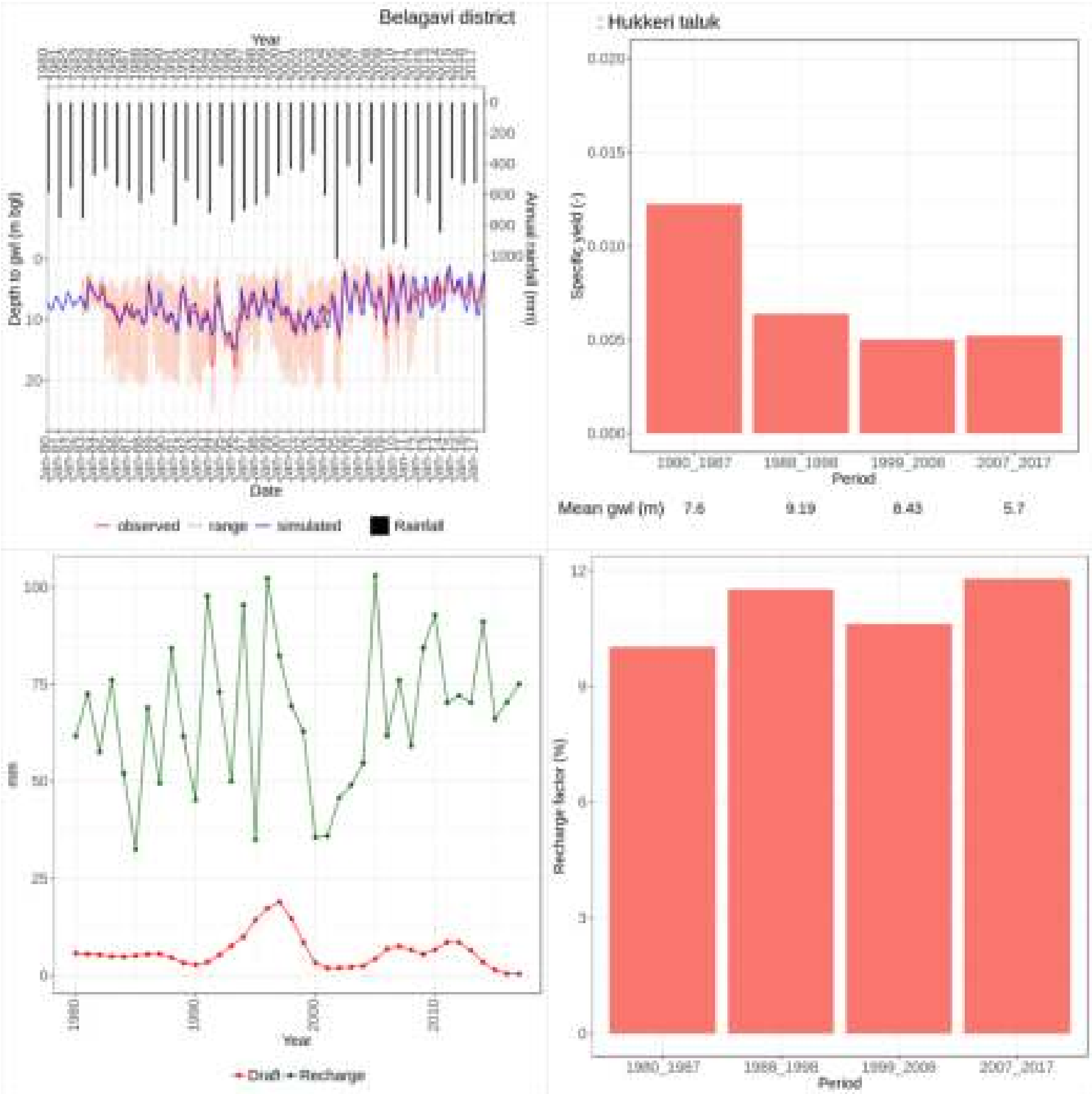

Figure 8 :Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Hukkeri taluk.

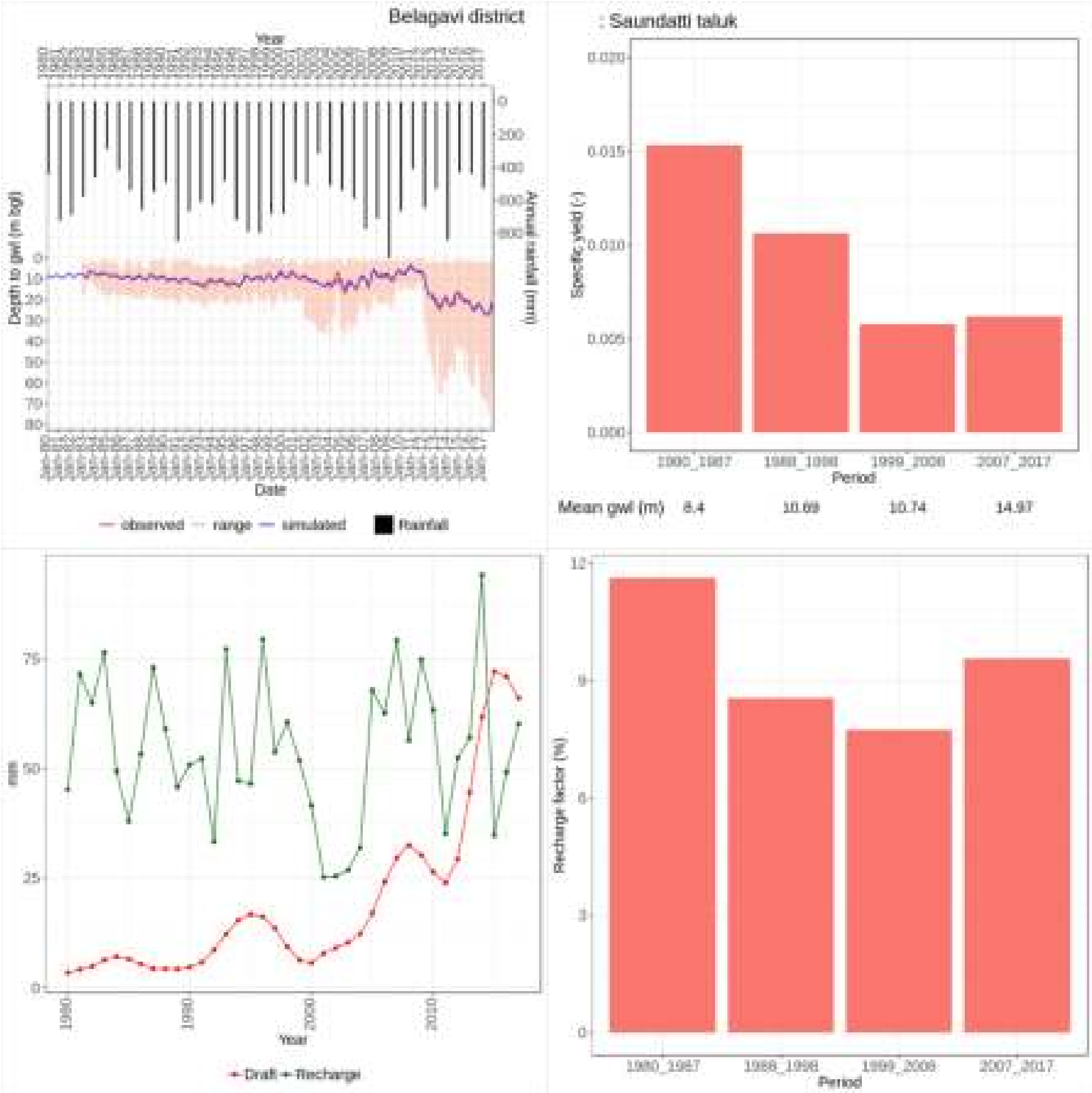

Figure 9 : Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Saundatti taluk.

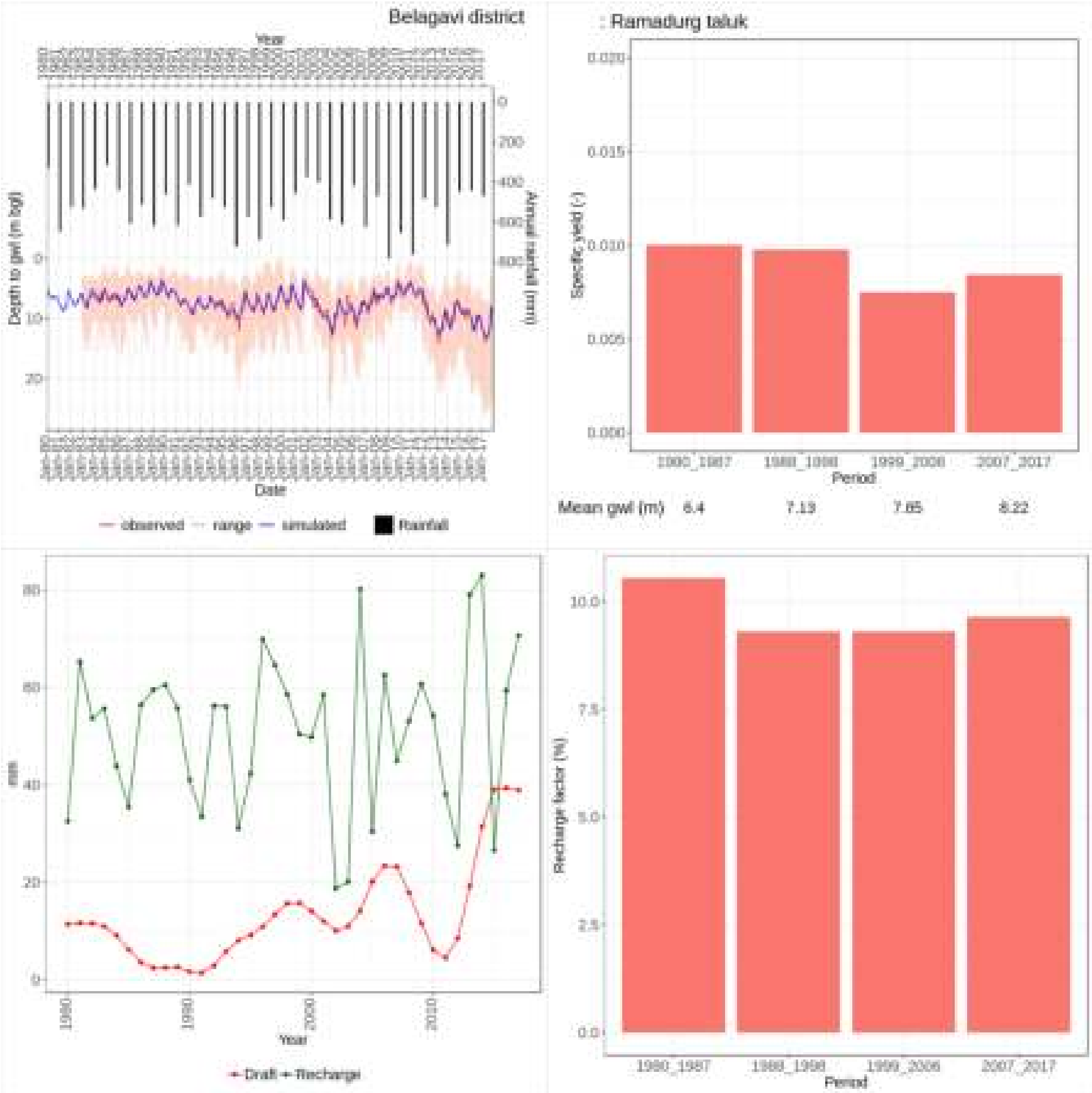

Figure 10: Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Ramadurg taluk.

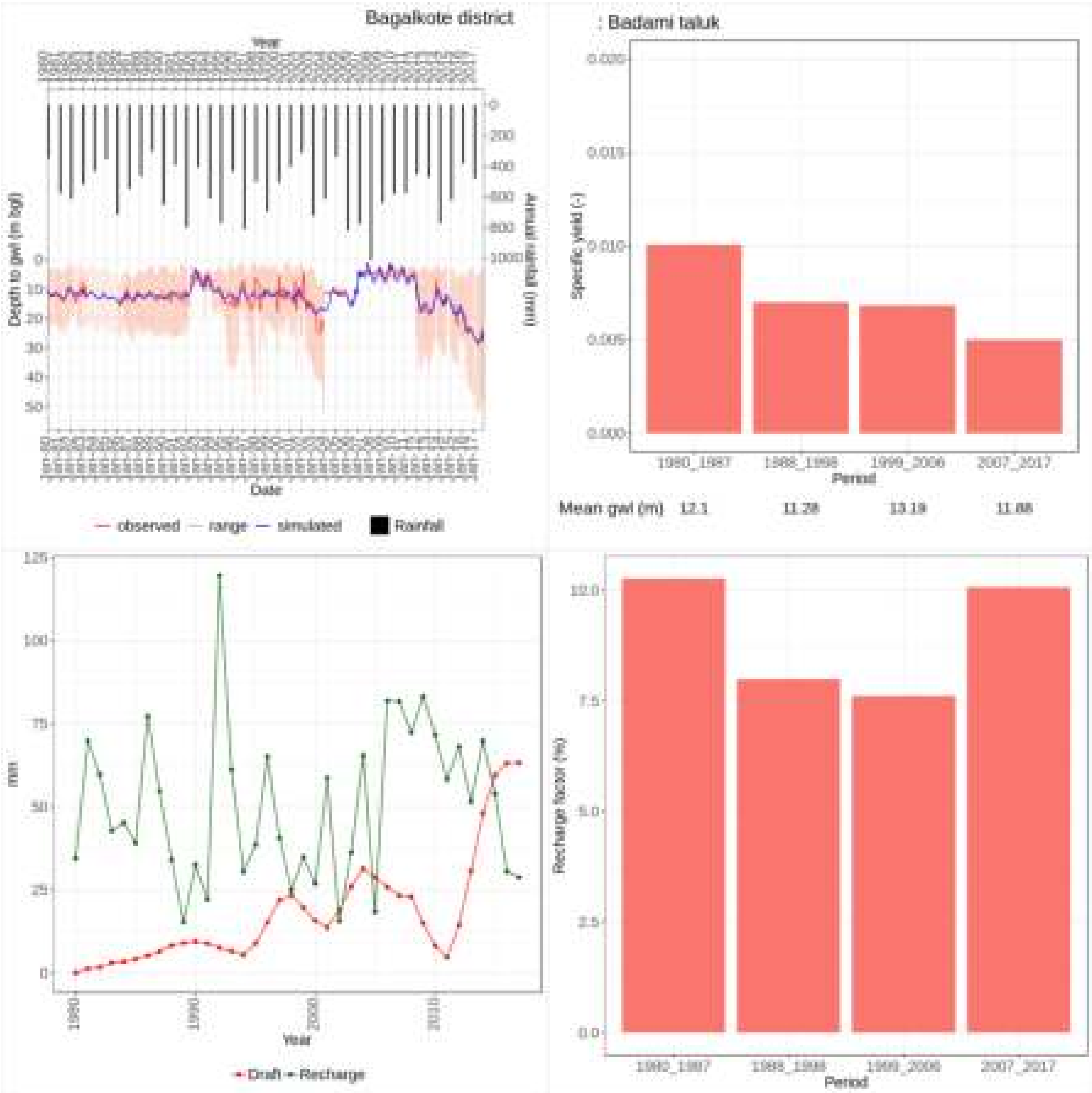

Figure 11 : Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Badami taluk.

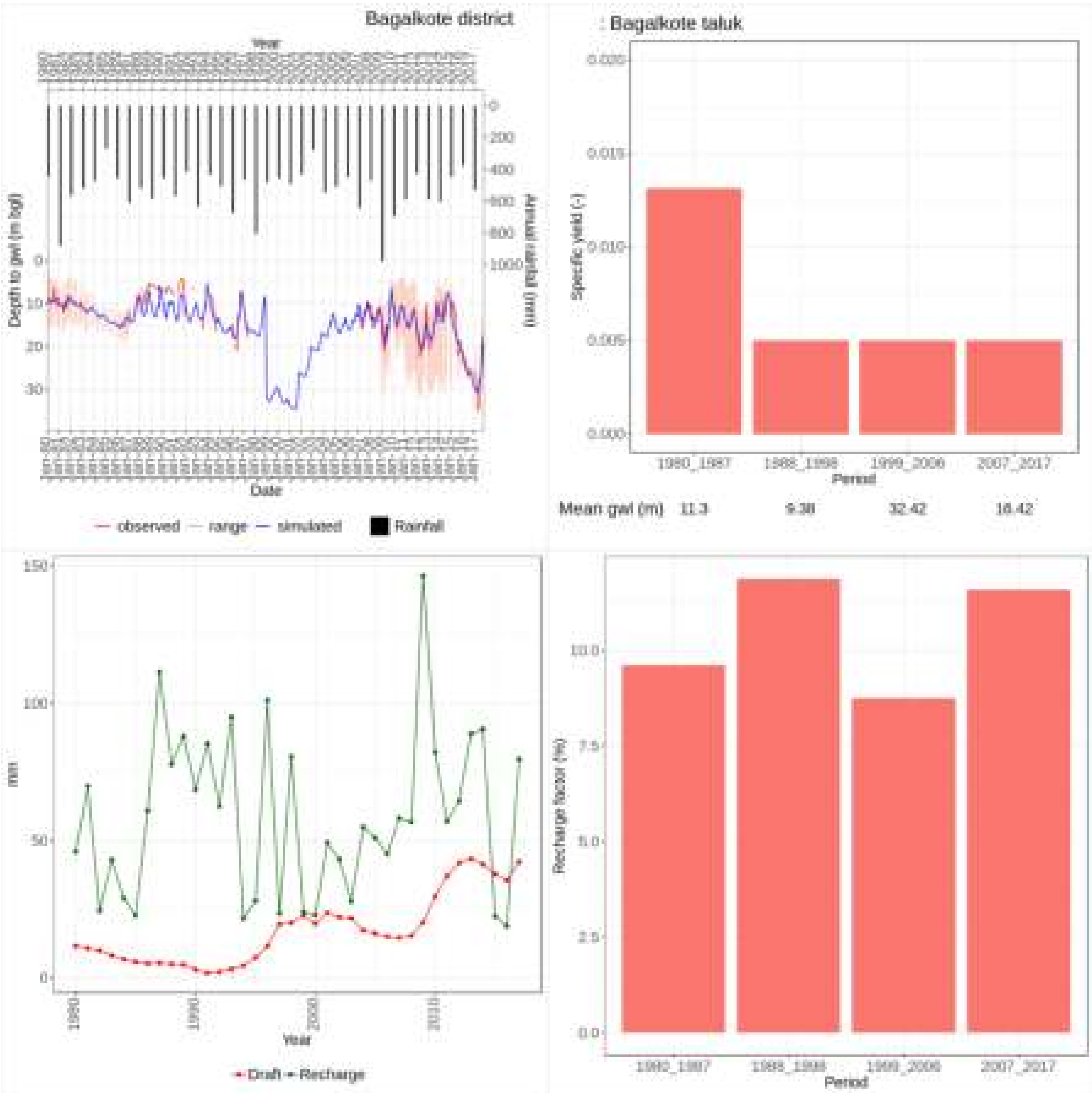

Figure 12 : Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Bagalkote taluk.

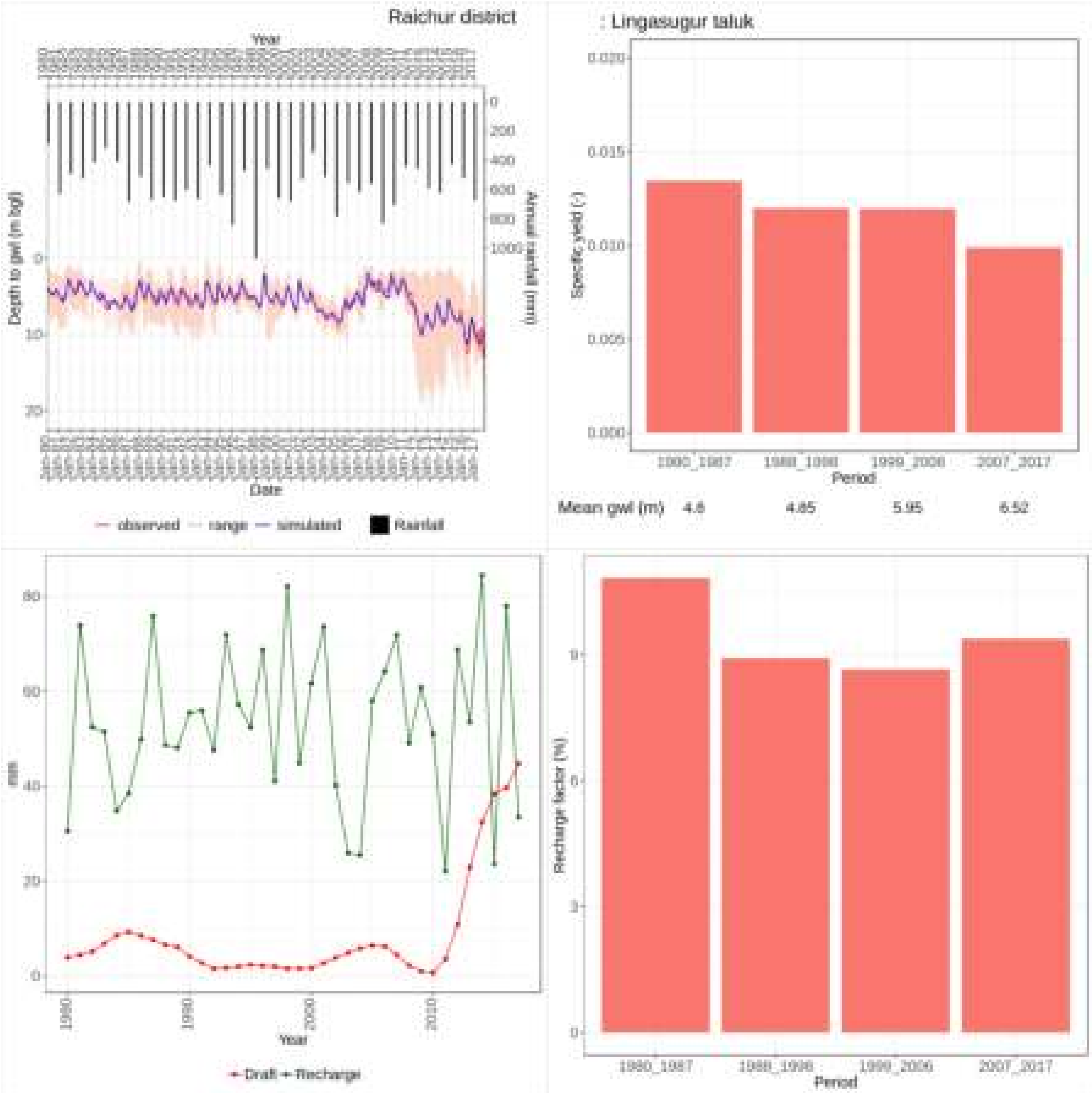

Figure 13 : Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Lingasugur taluk.

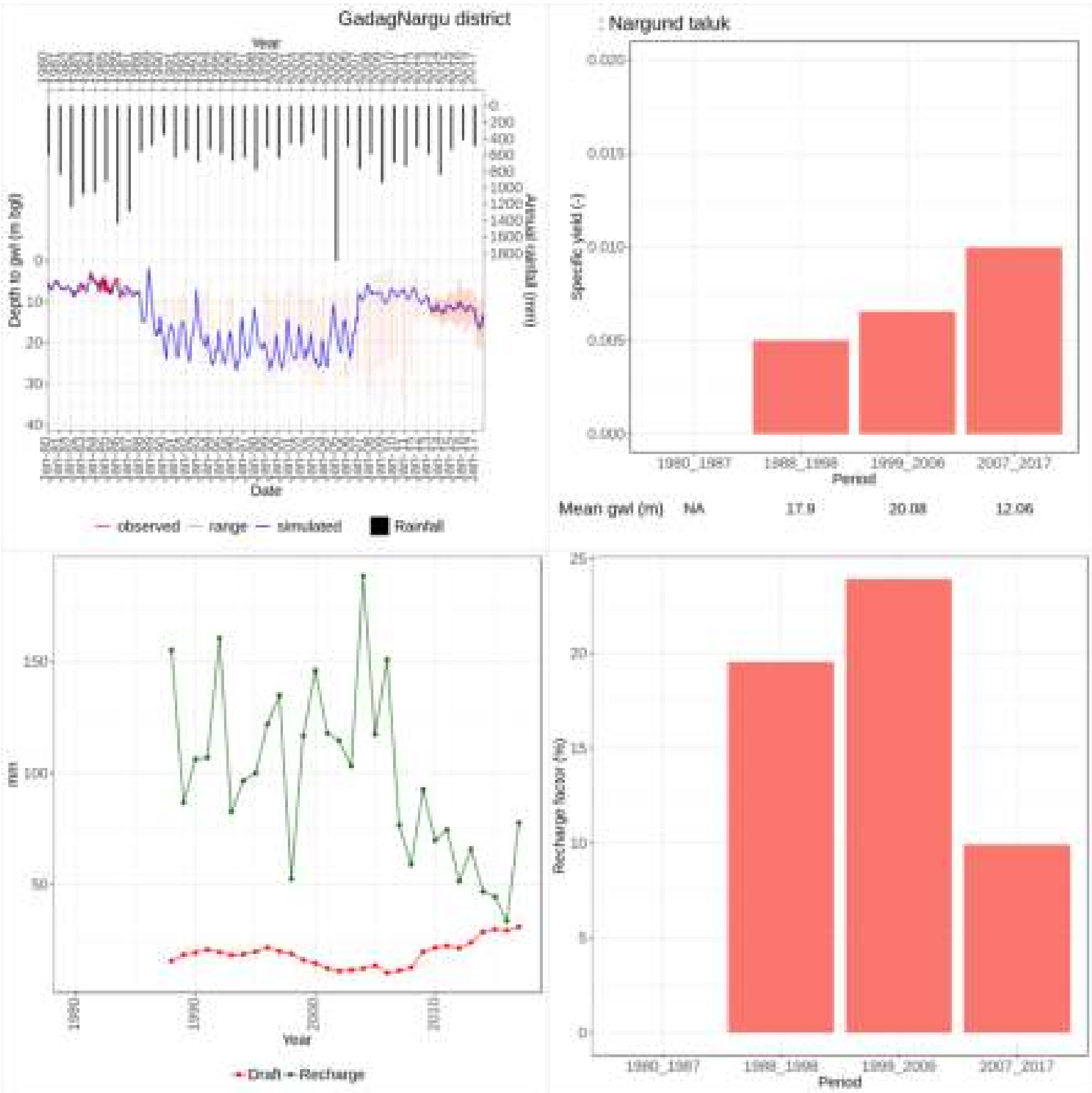

Figure 14 : Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Nargund taluk.

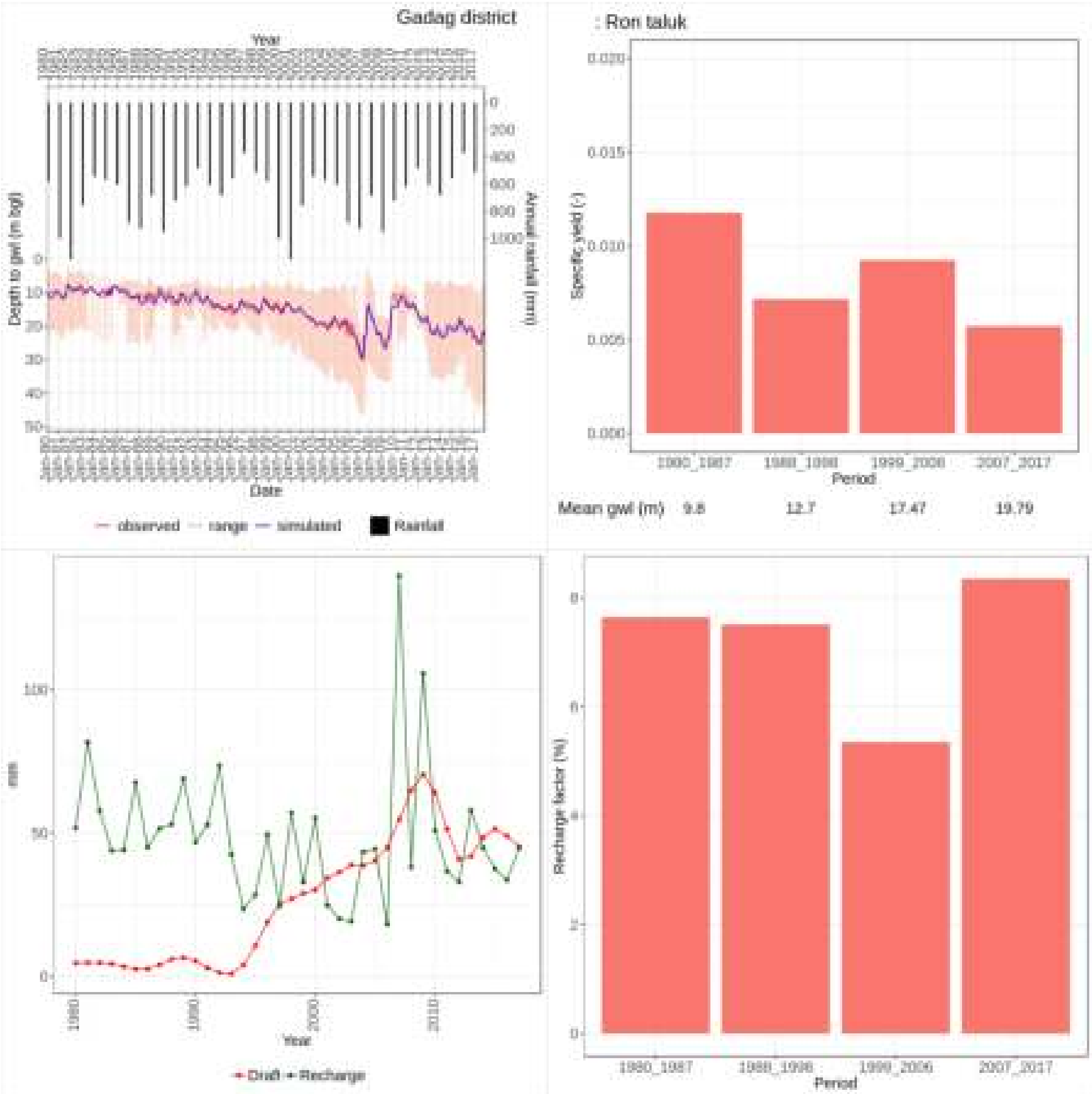

Figure 15 : Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Ron taluk.

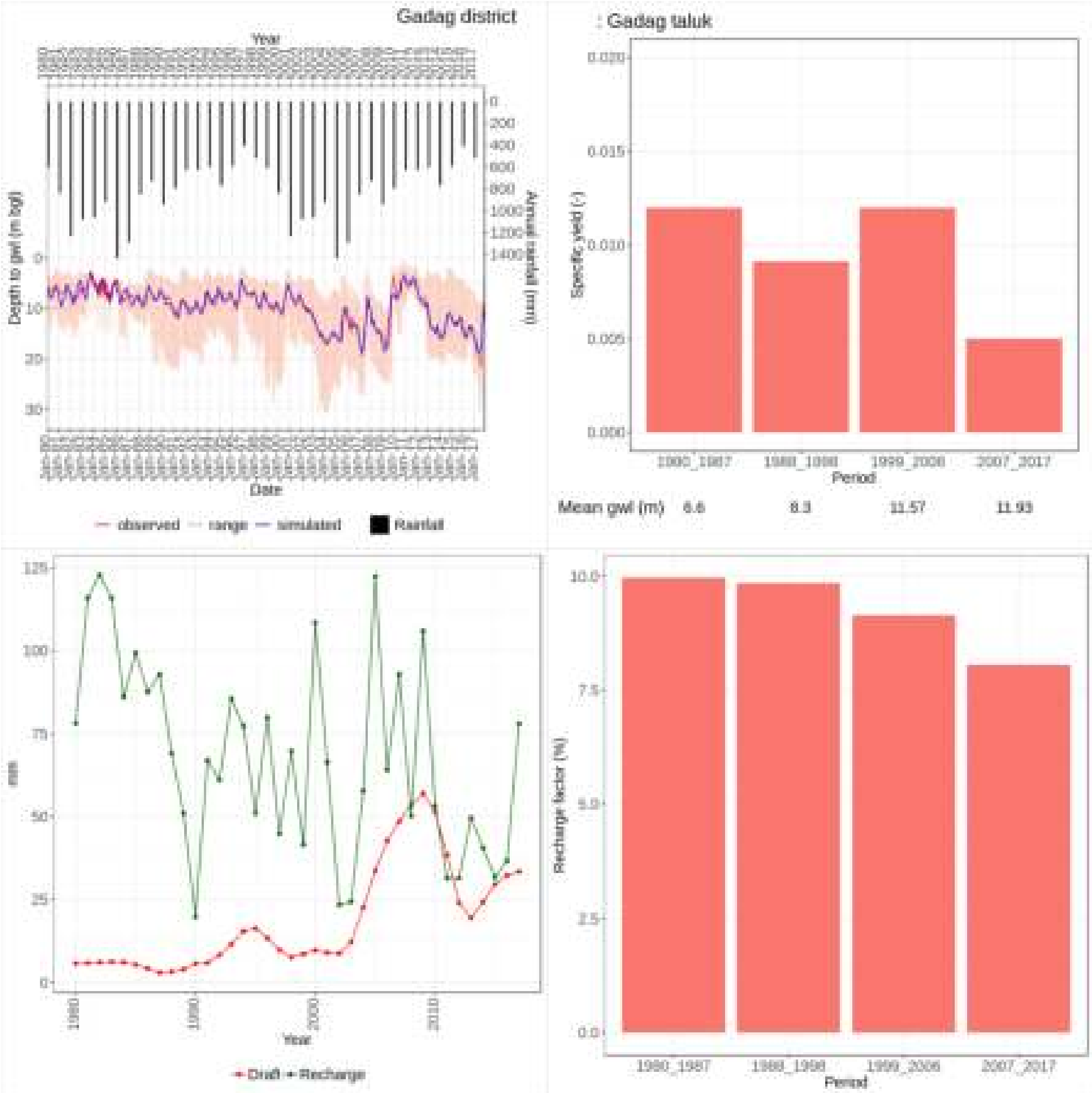

Figure 16 : Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Gadag taluk.

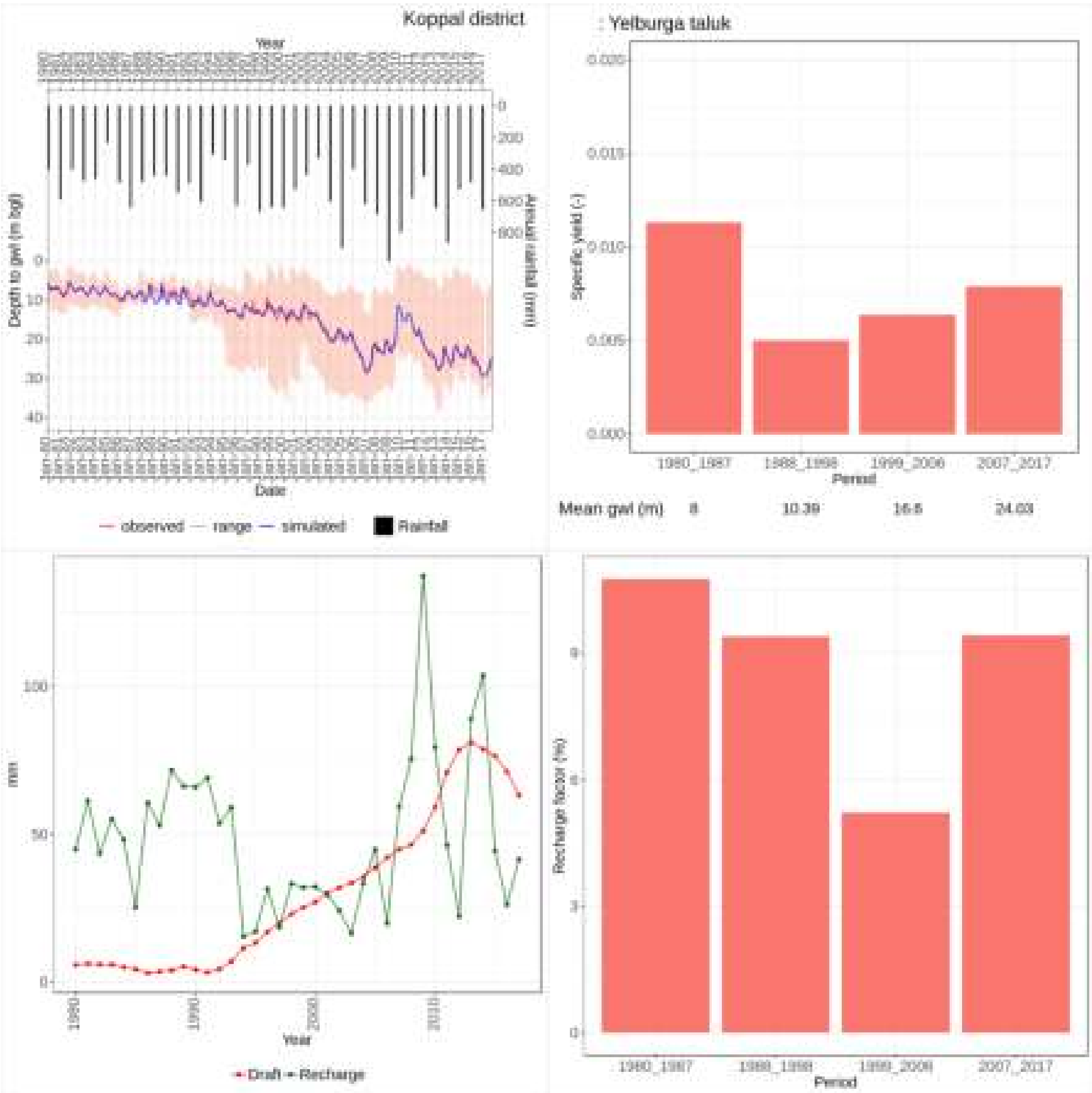

Figure 17 : Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Yelburga taluk.

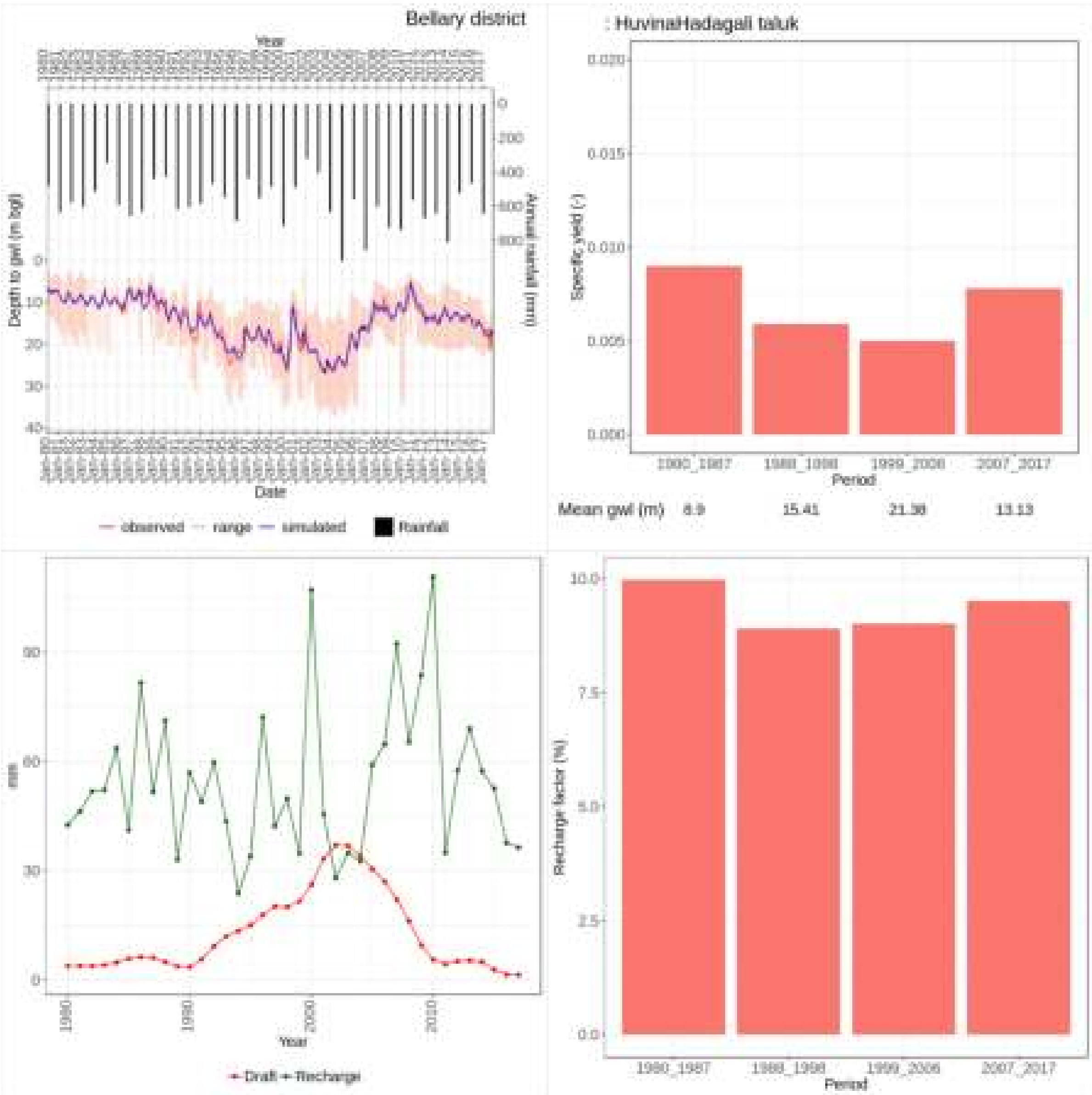

Figure 18 : Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for HuvinaHadagali taluk.

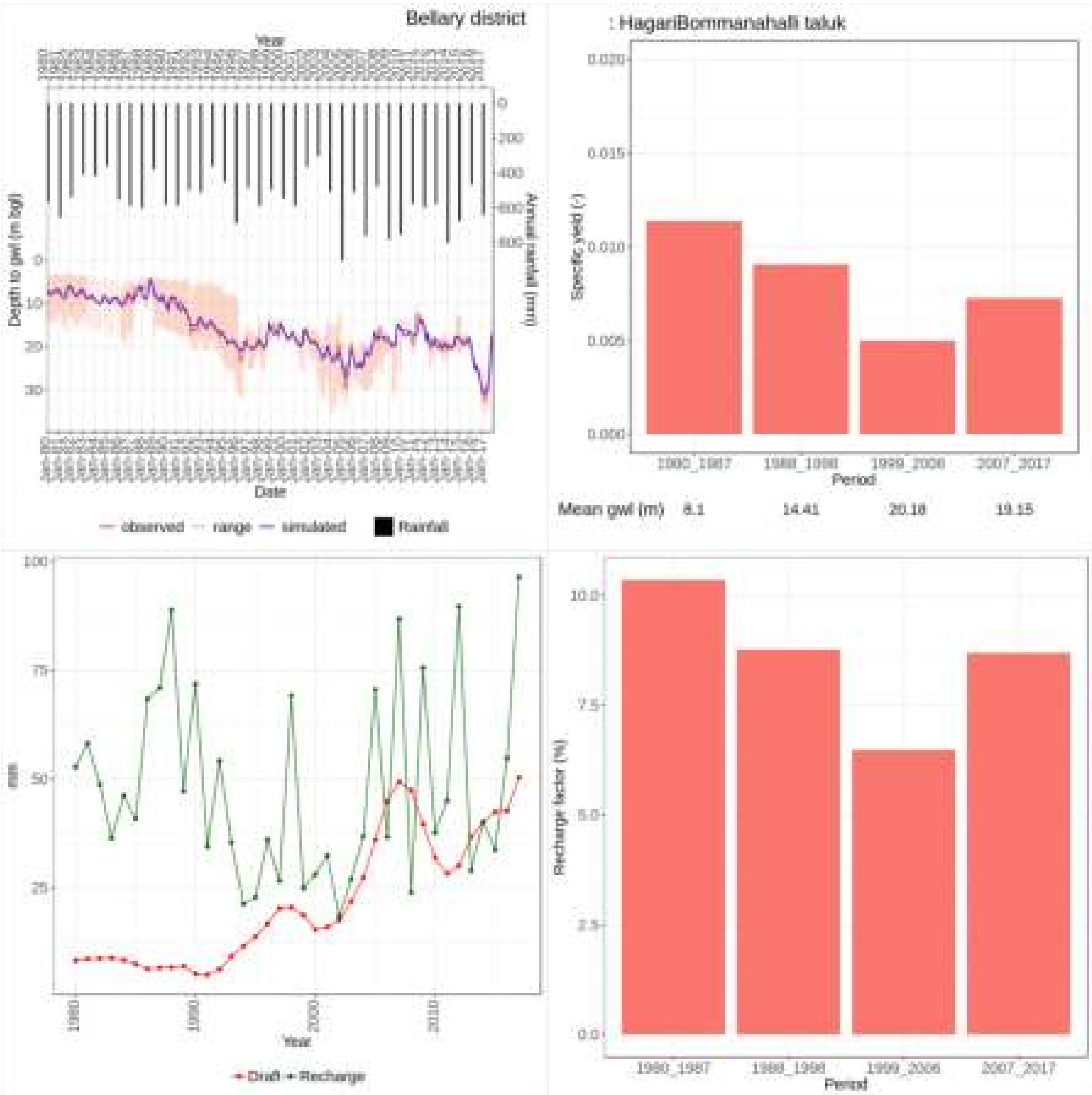

Figure 19 : Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for HagariBommanahalli taluk.

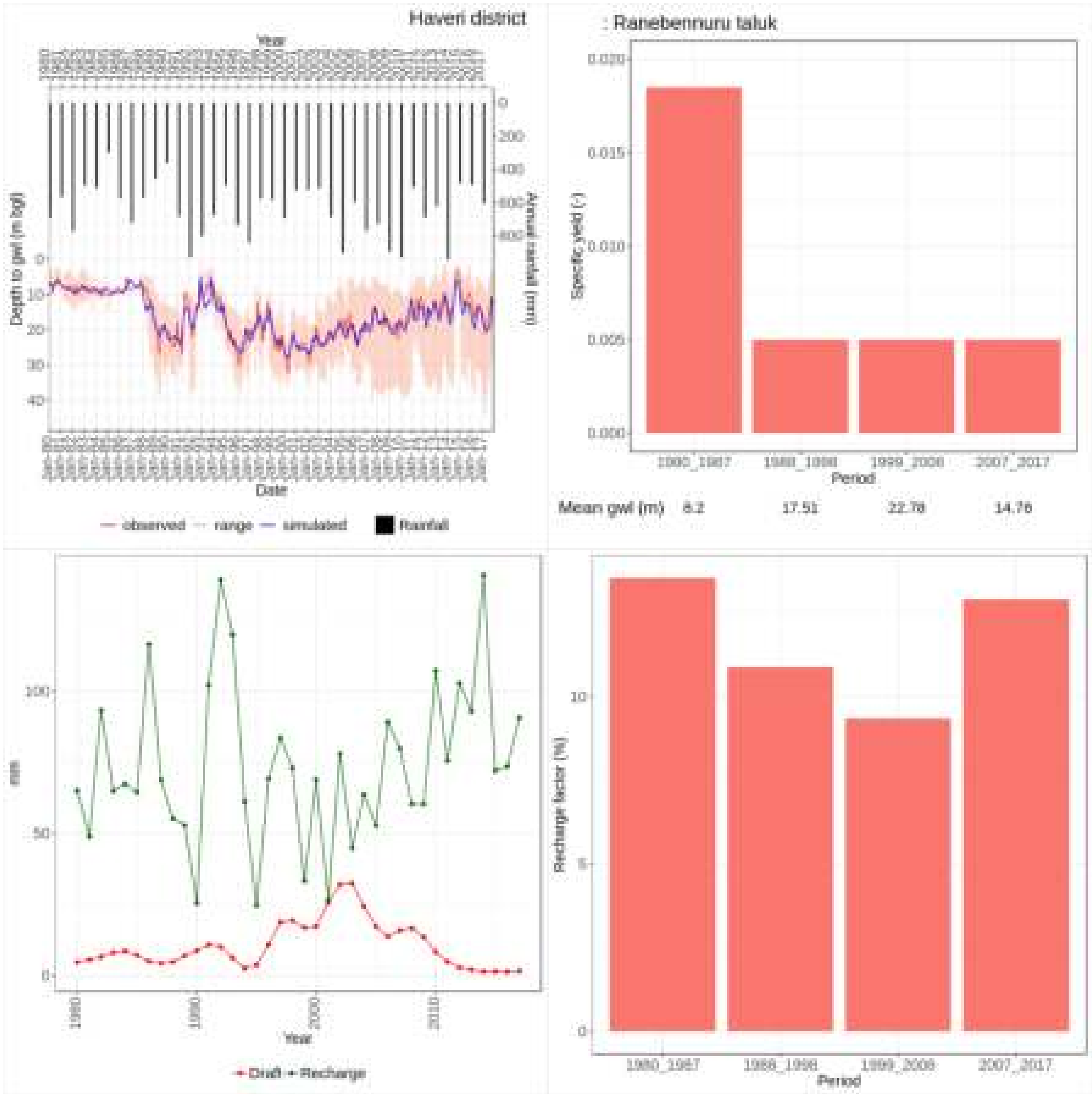

Figure 20 : Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Ranebennuru taluk.

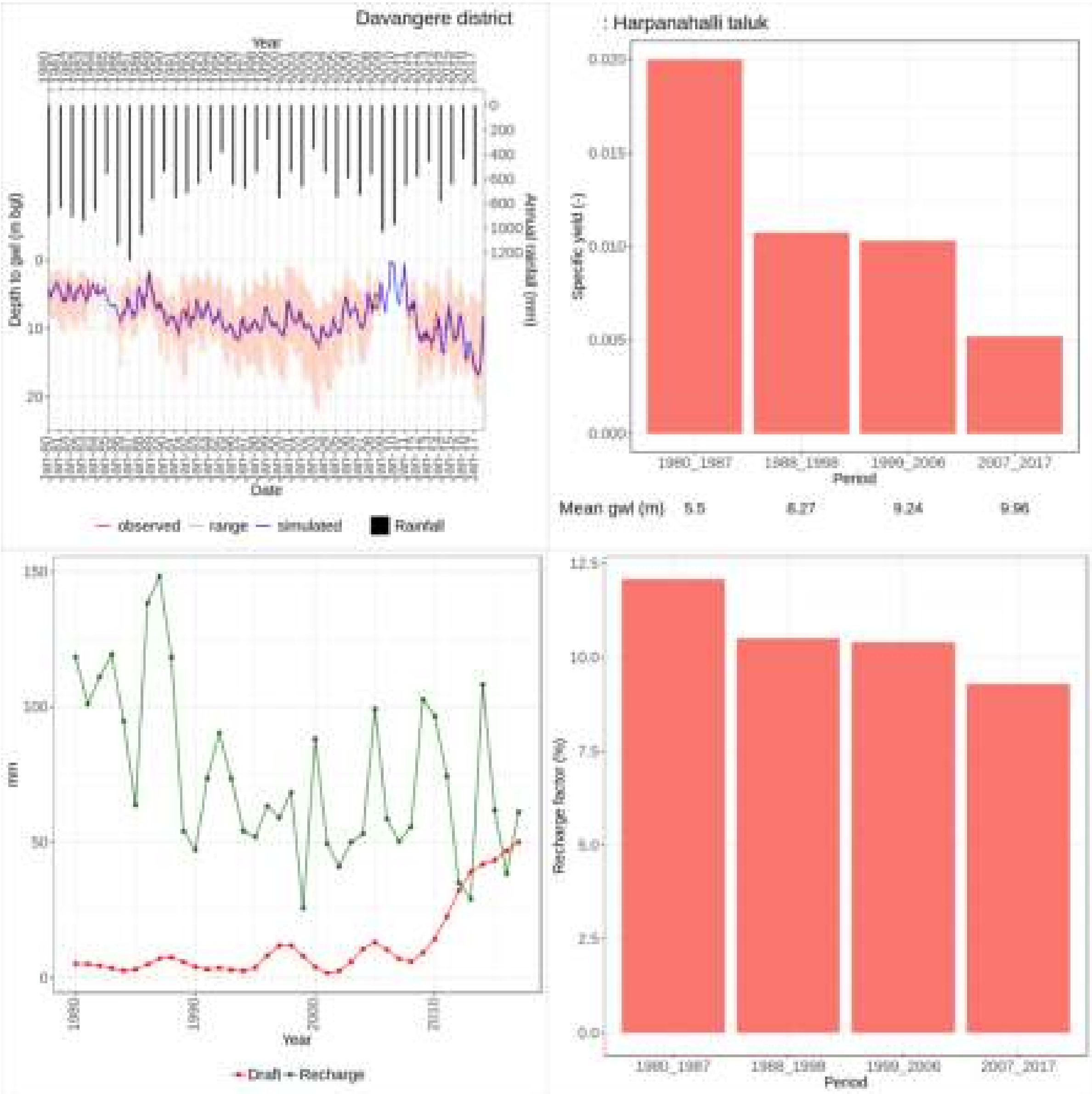

Figure 21: Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Harpanahalli taluk.

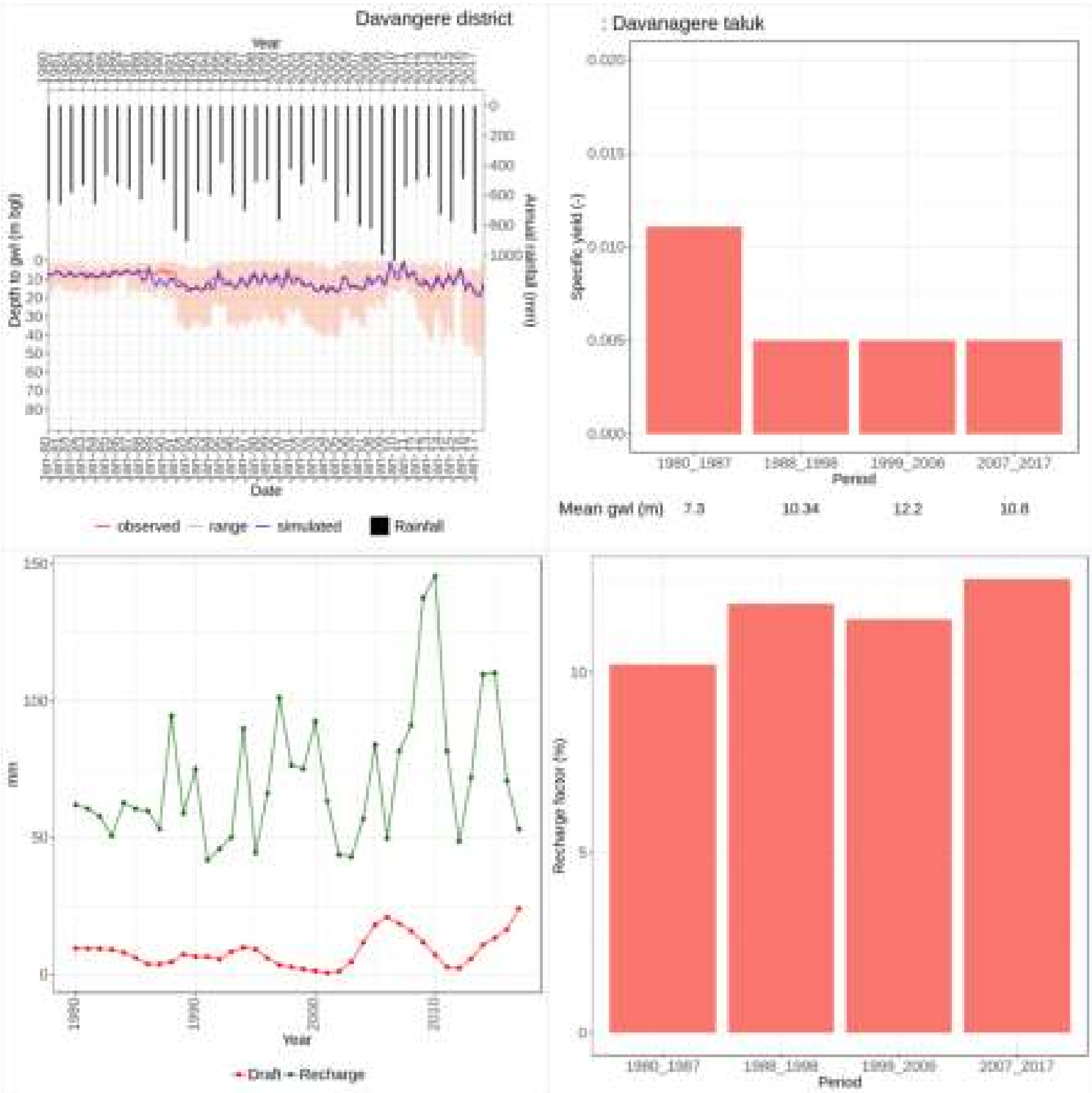

Figure 22 : Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Davanagere taluk.

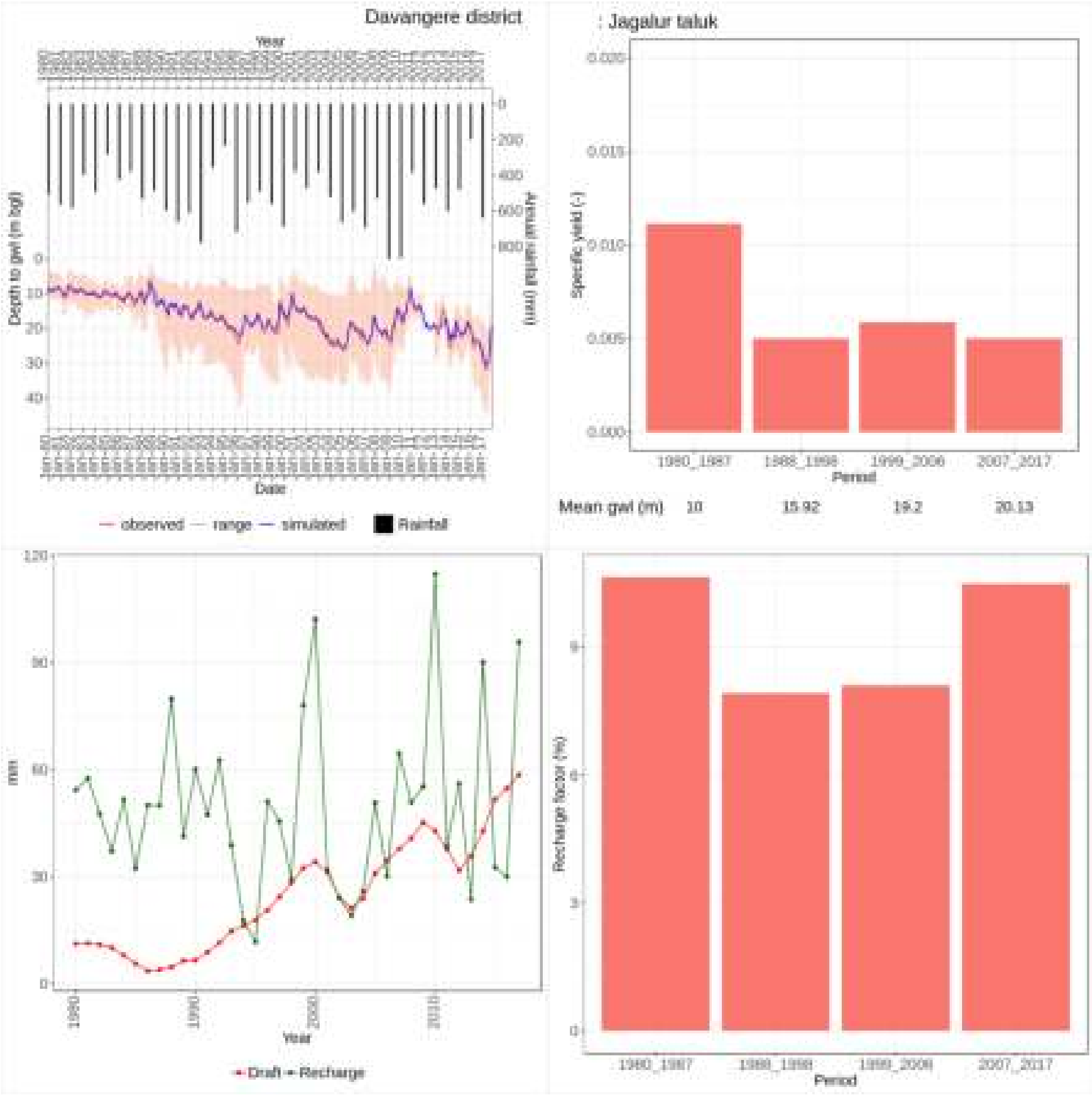

Figure 23 : Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Jagalur taluk.

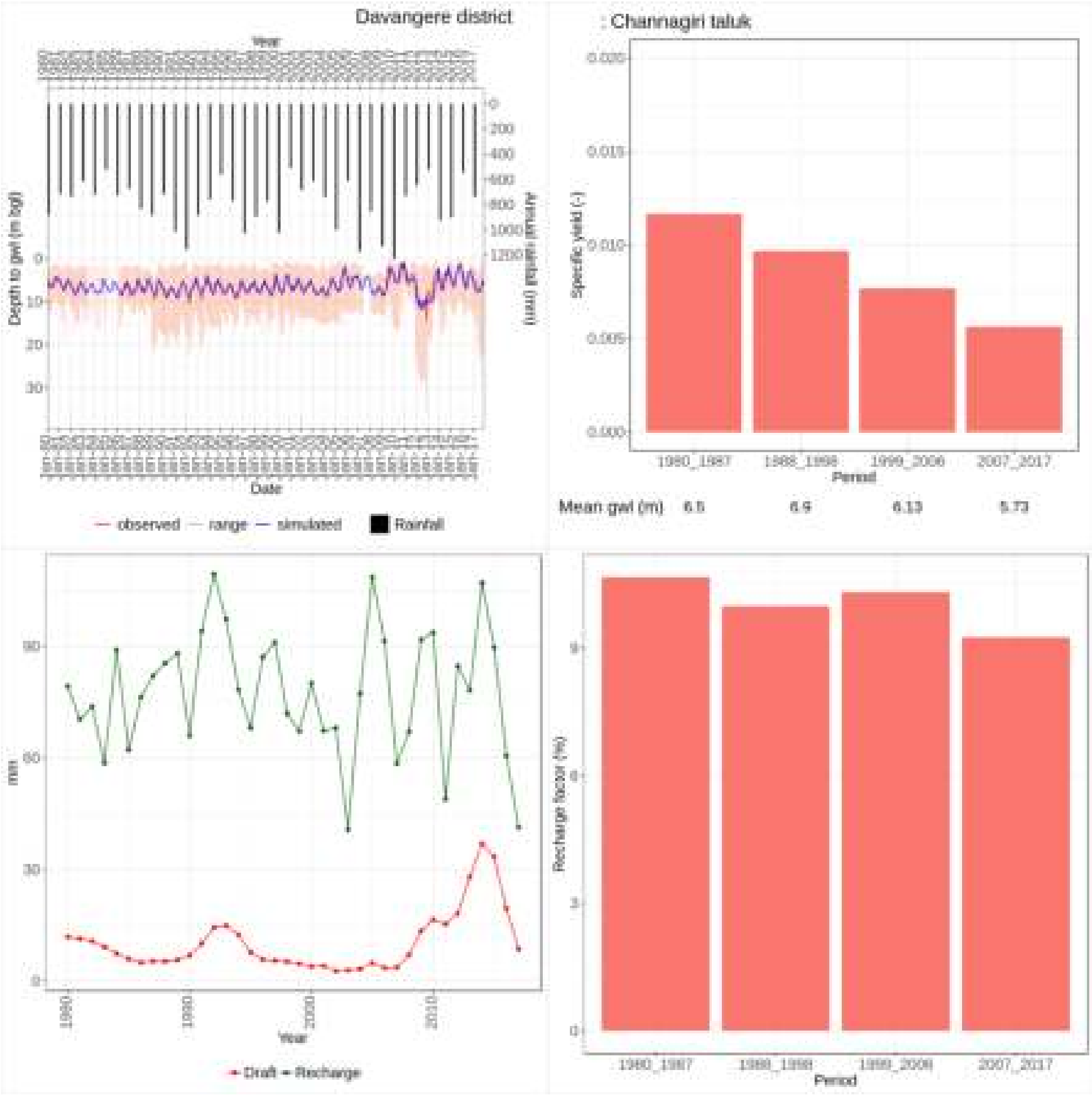

Figure 24 : Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Channagiri taluk.

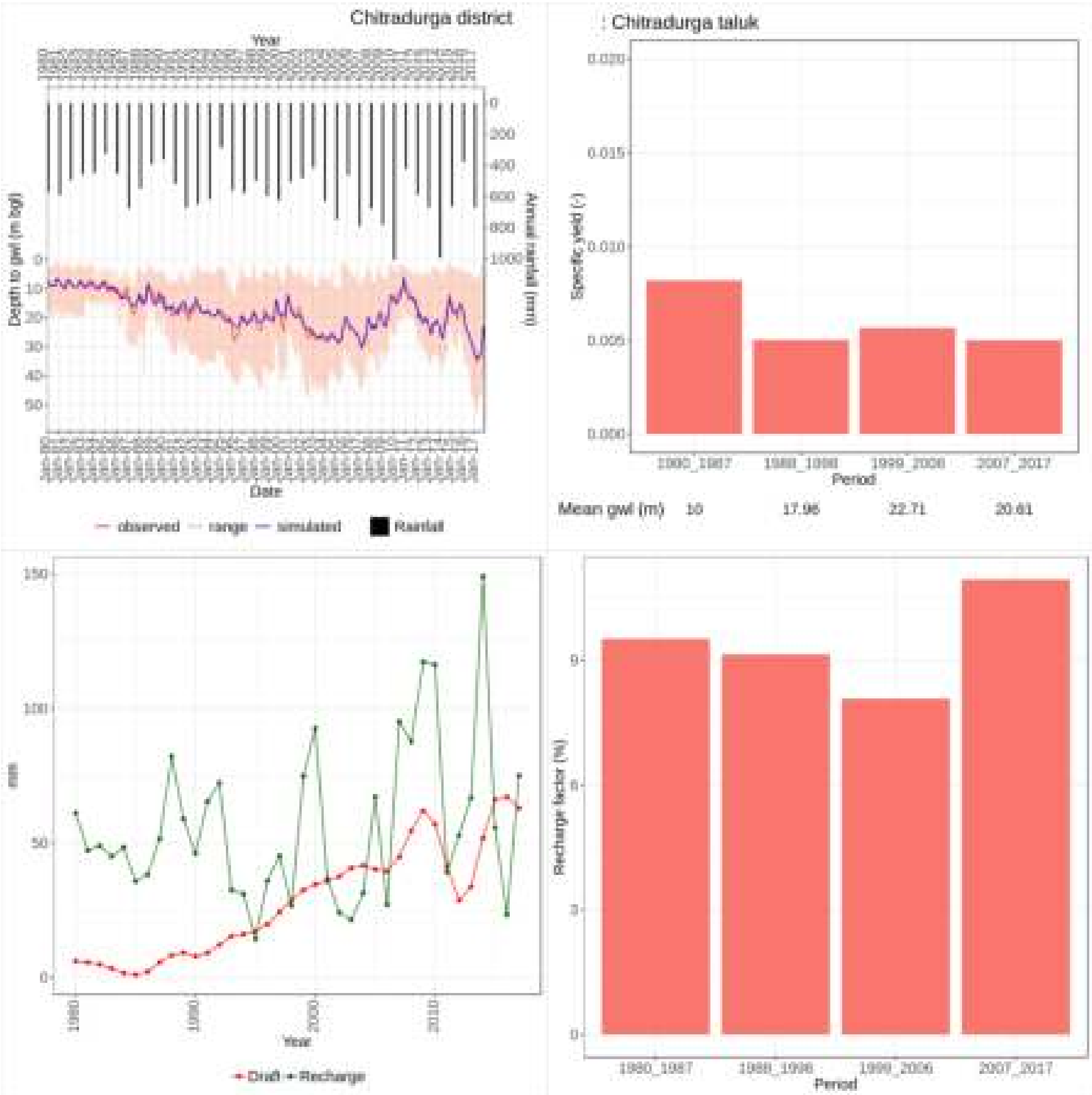

Figure 25 : Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Chitradurga taluk.

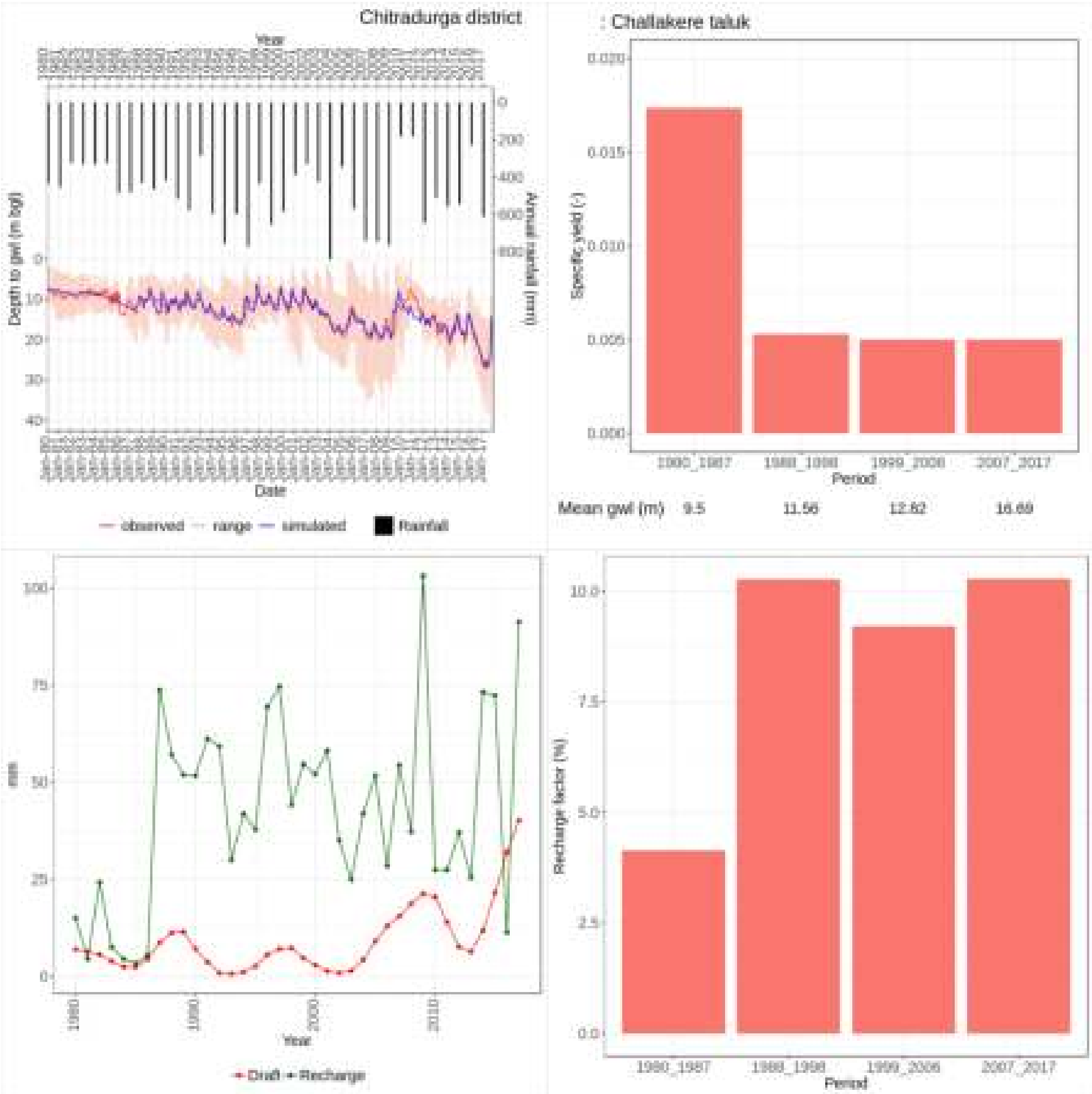

Figure 26 : Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Challakere taluk.

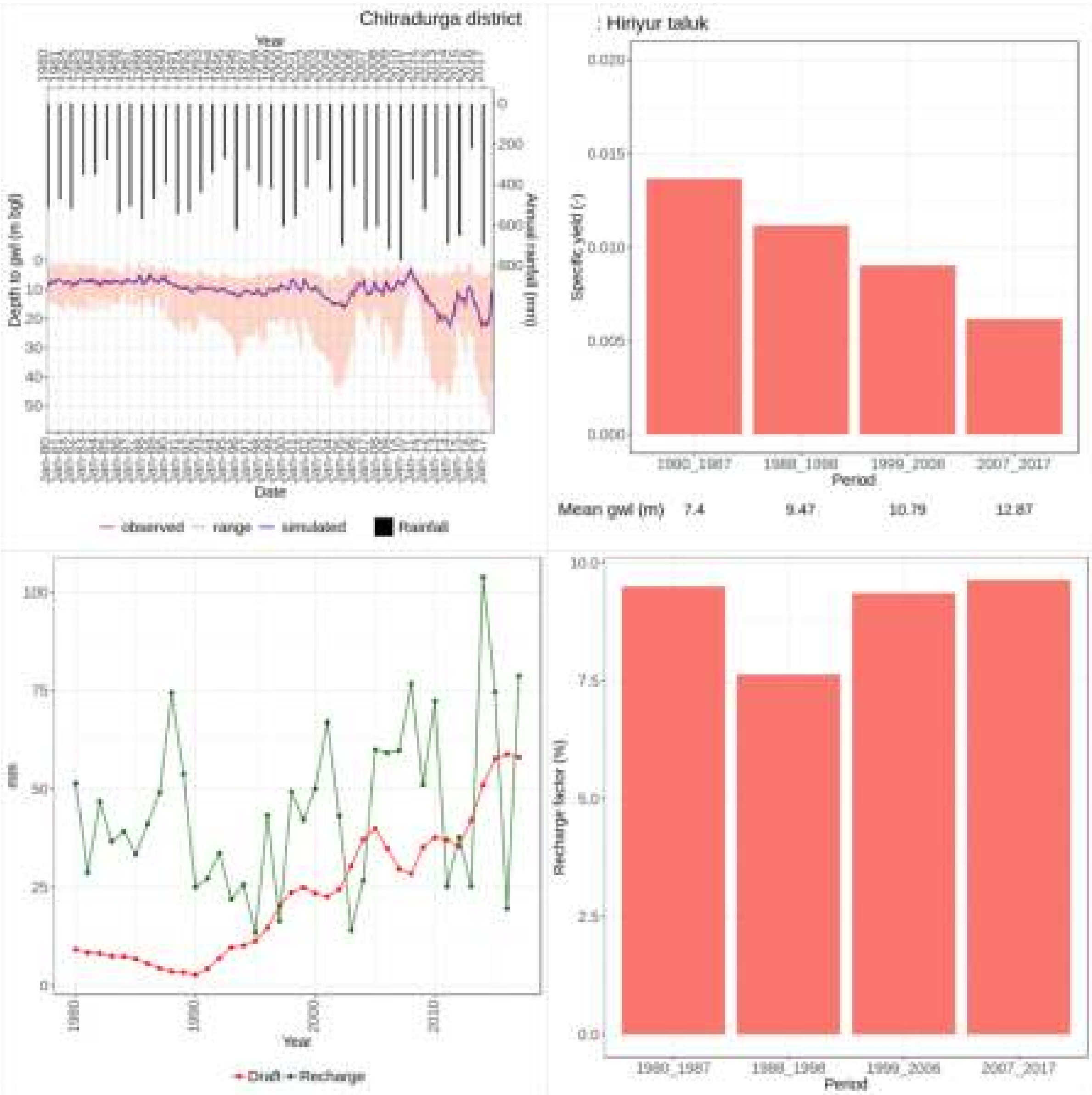

Figure 27 : Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Hiriyur taluk.

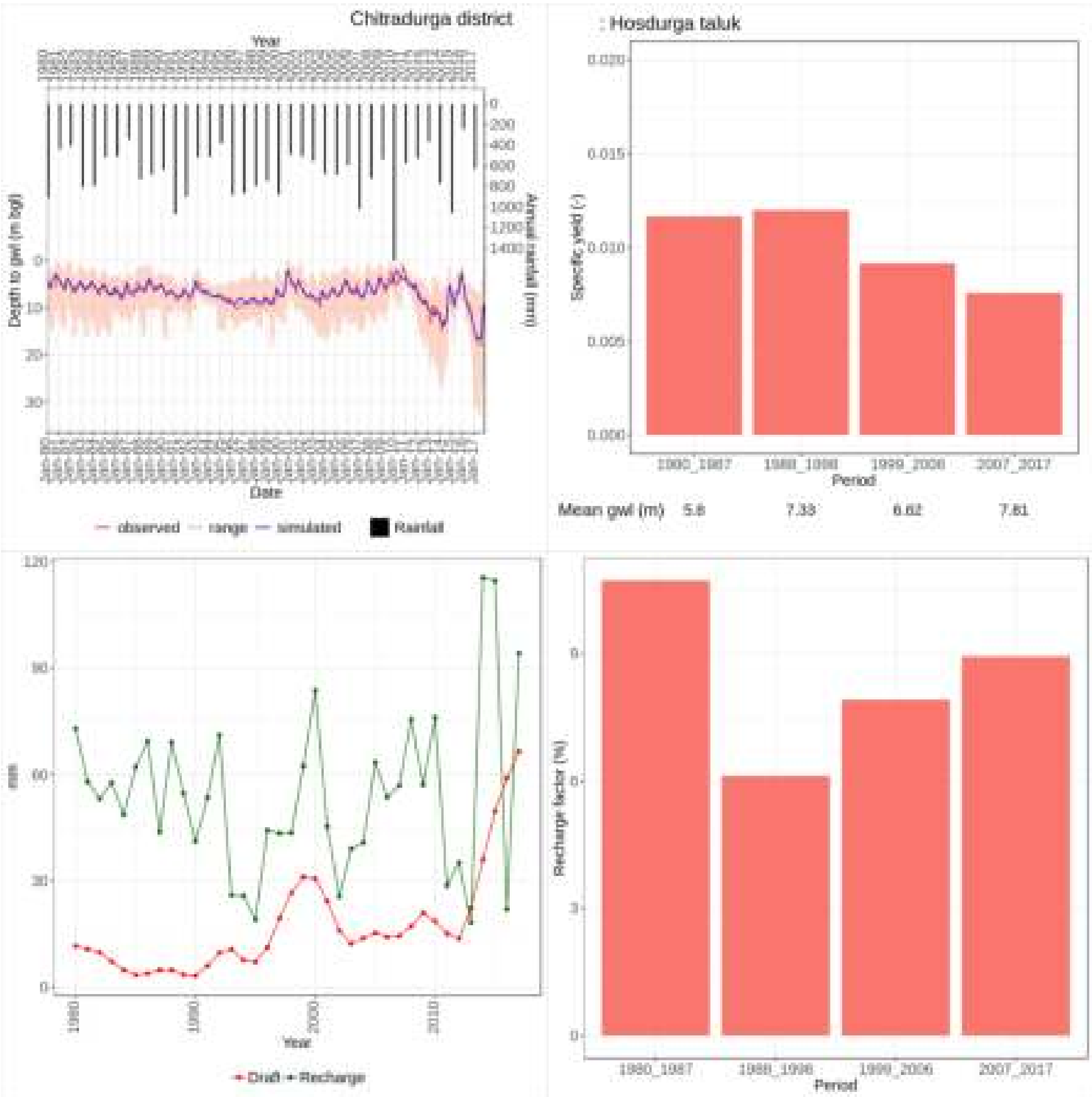

Figure 28 : Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Hosdurga taluk.

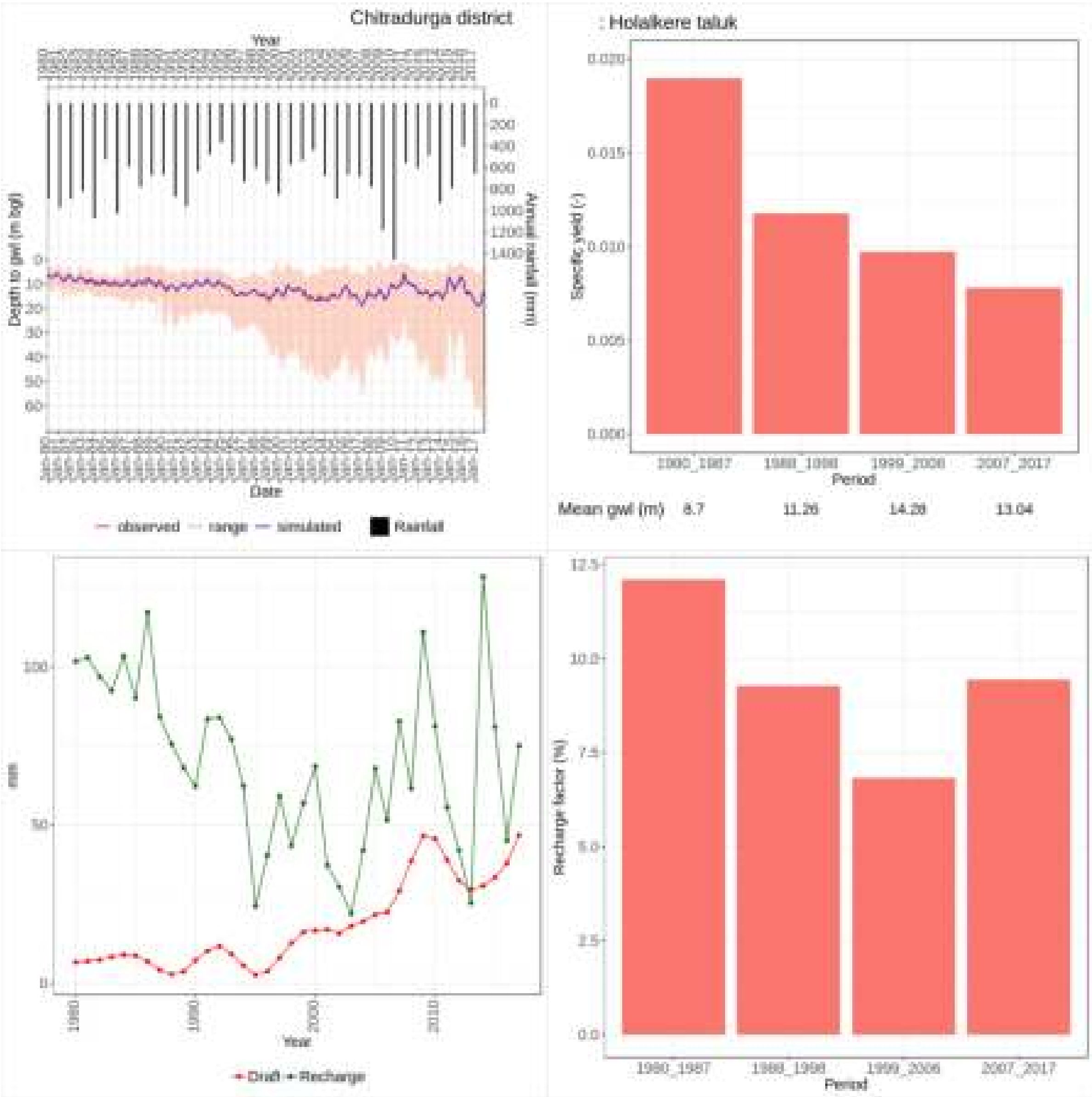

Figure 29 : Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Holalkere taluk.

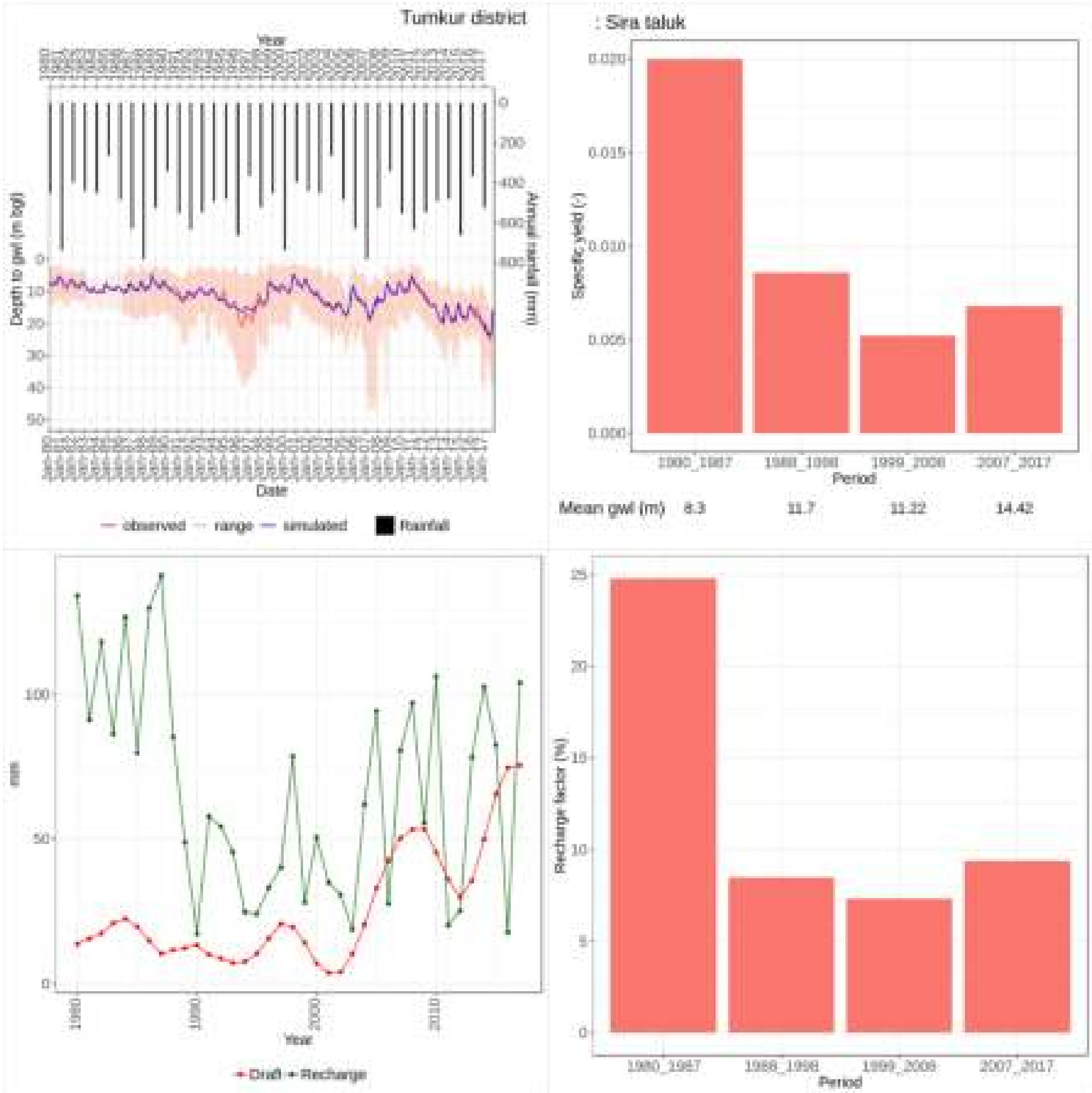

Figure 30 : Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Sira taluk.

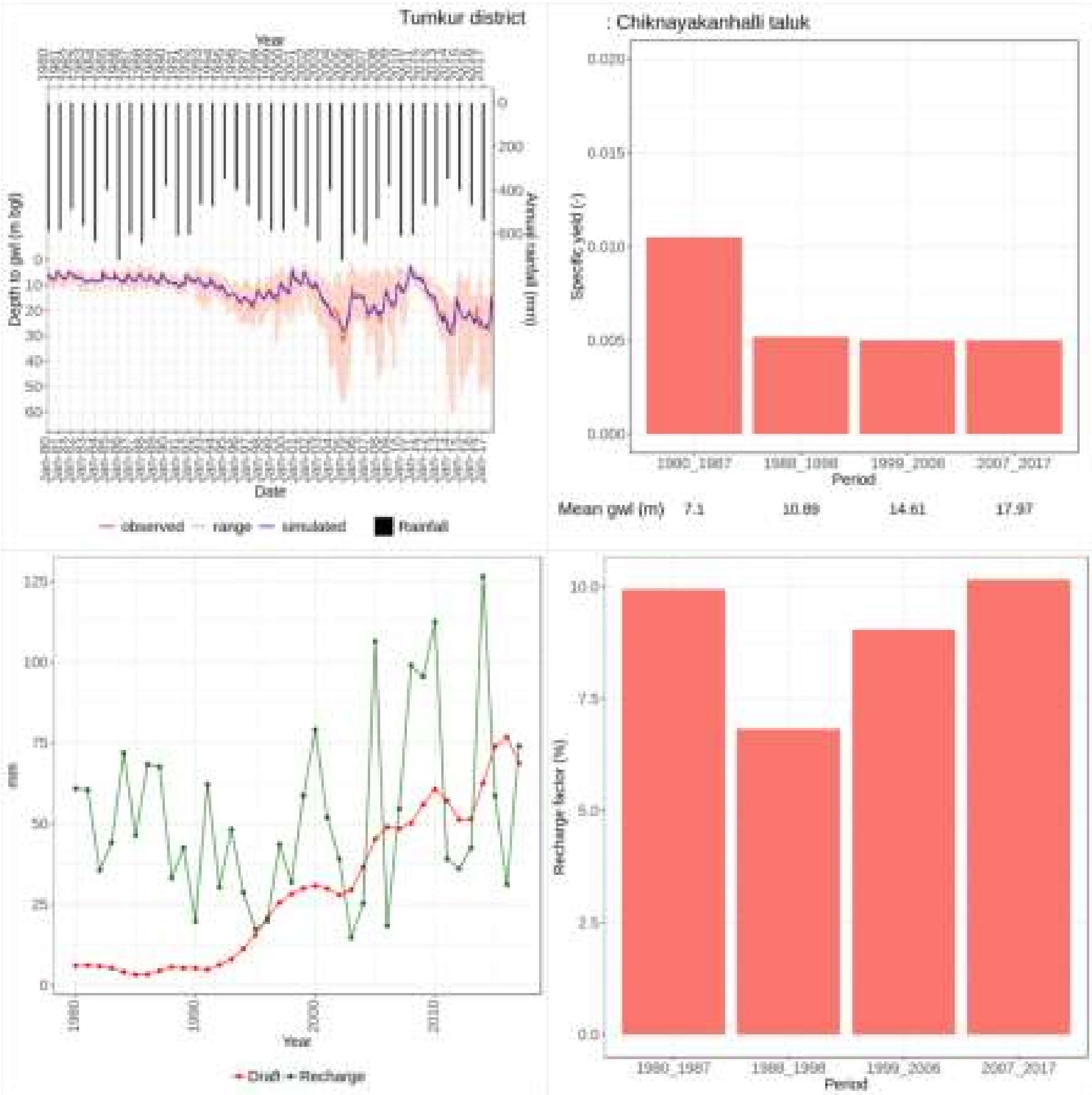

Figure 31 : Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Chiknayakanhalli taluk.

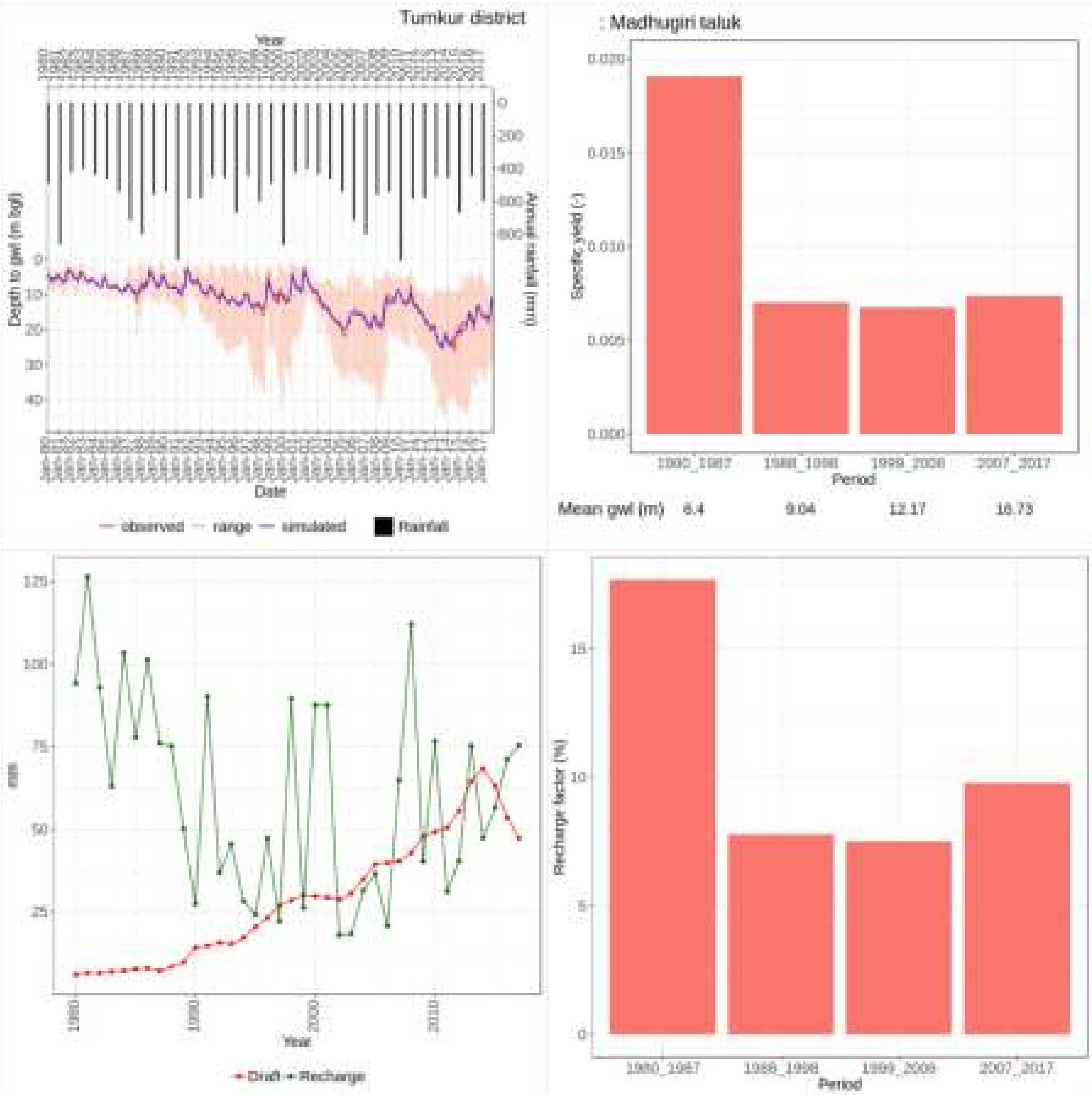

Figure 32 : Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Madhugiri taluk.

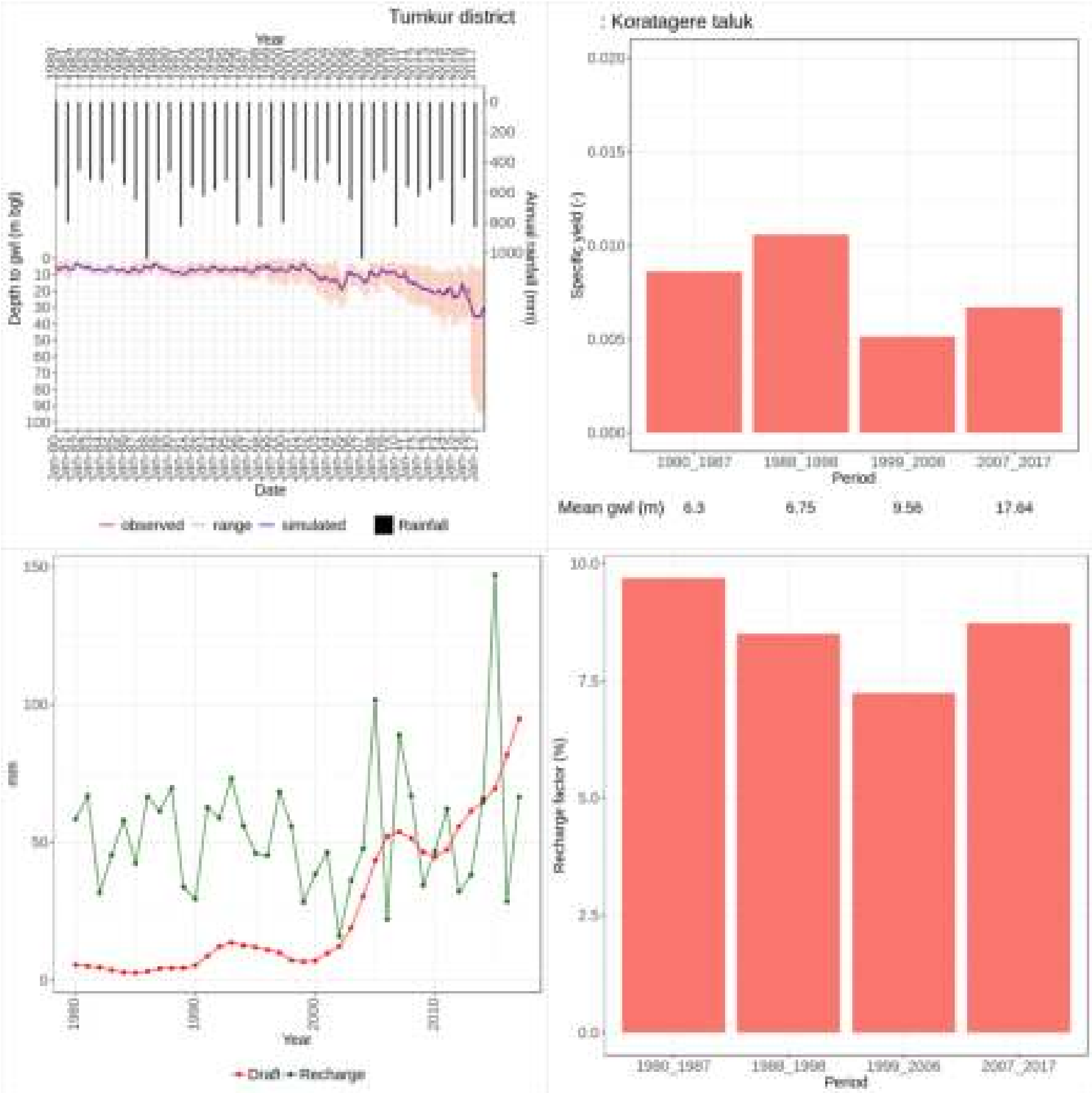

Figure 33 : Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Koratagere taluk.

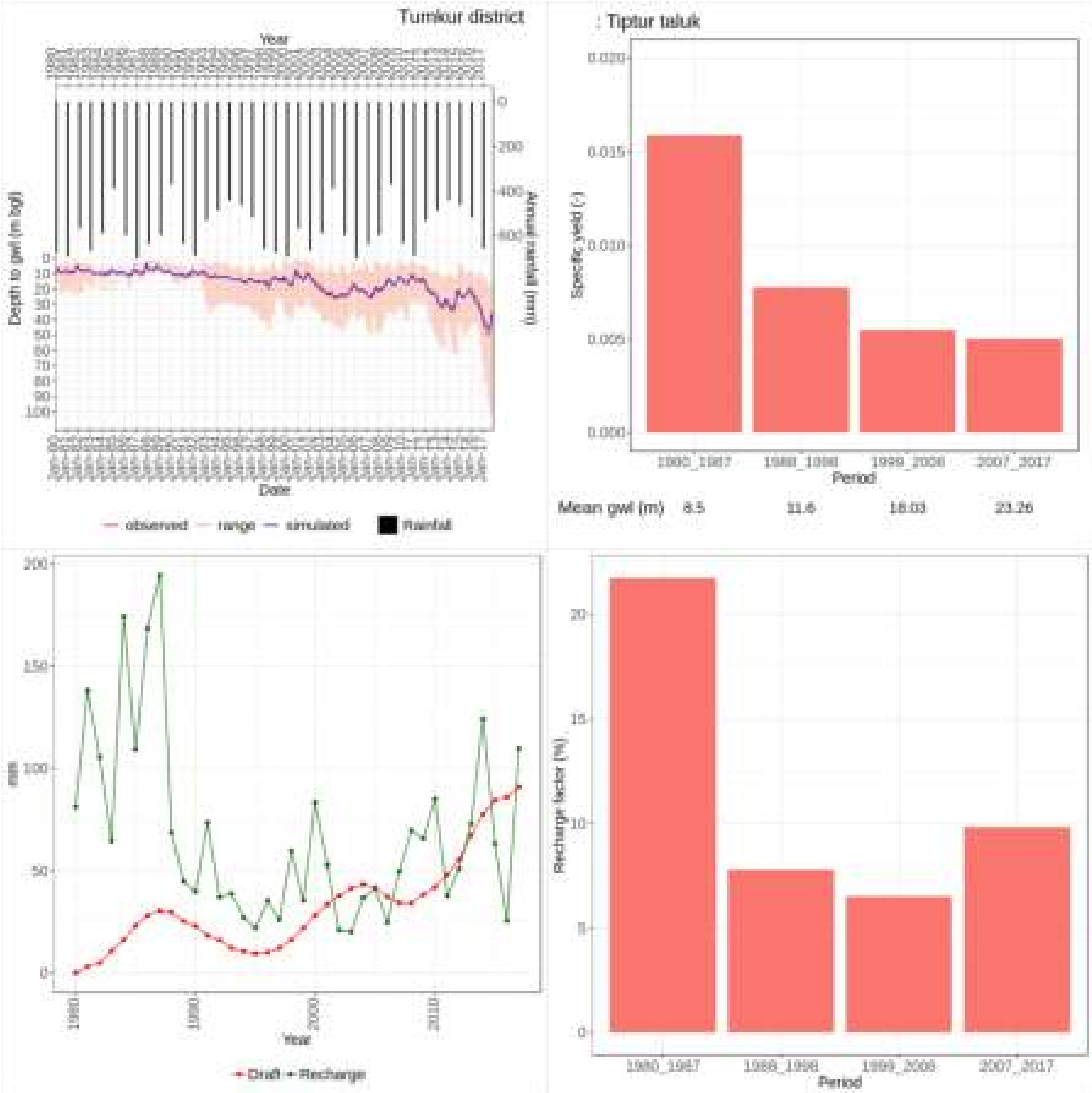

Figure 34 : Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Tiptur taluk.

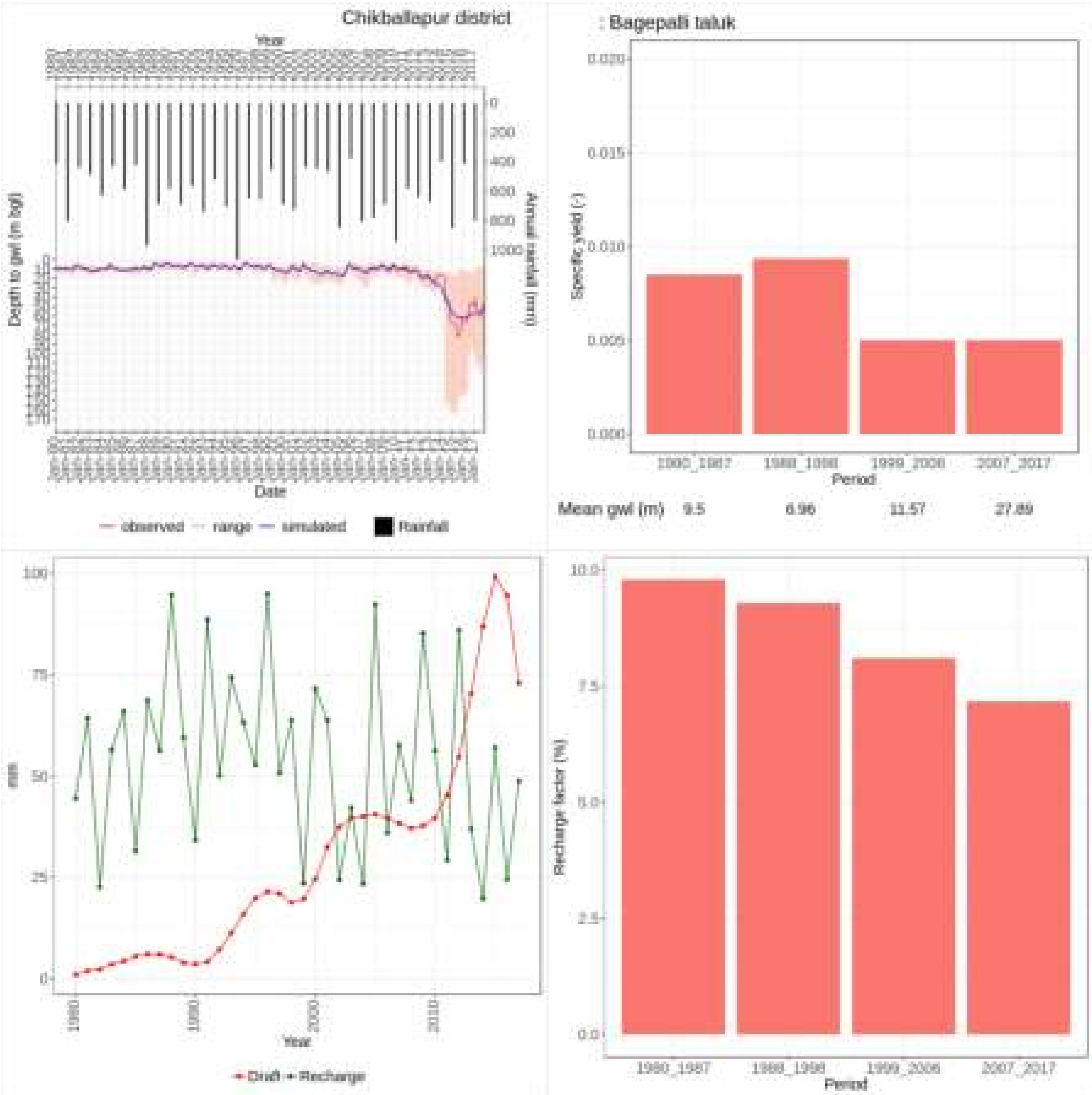

Figure 35 : Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Bagepalli taluk.

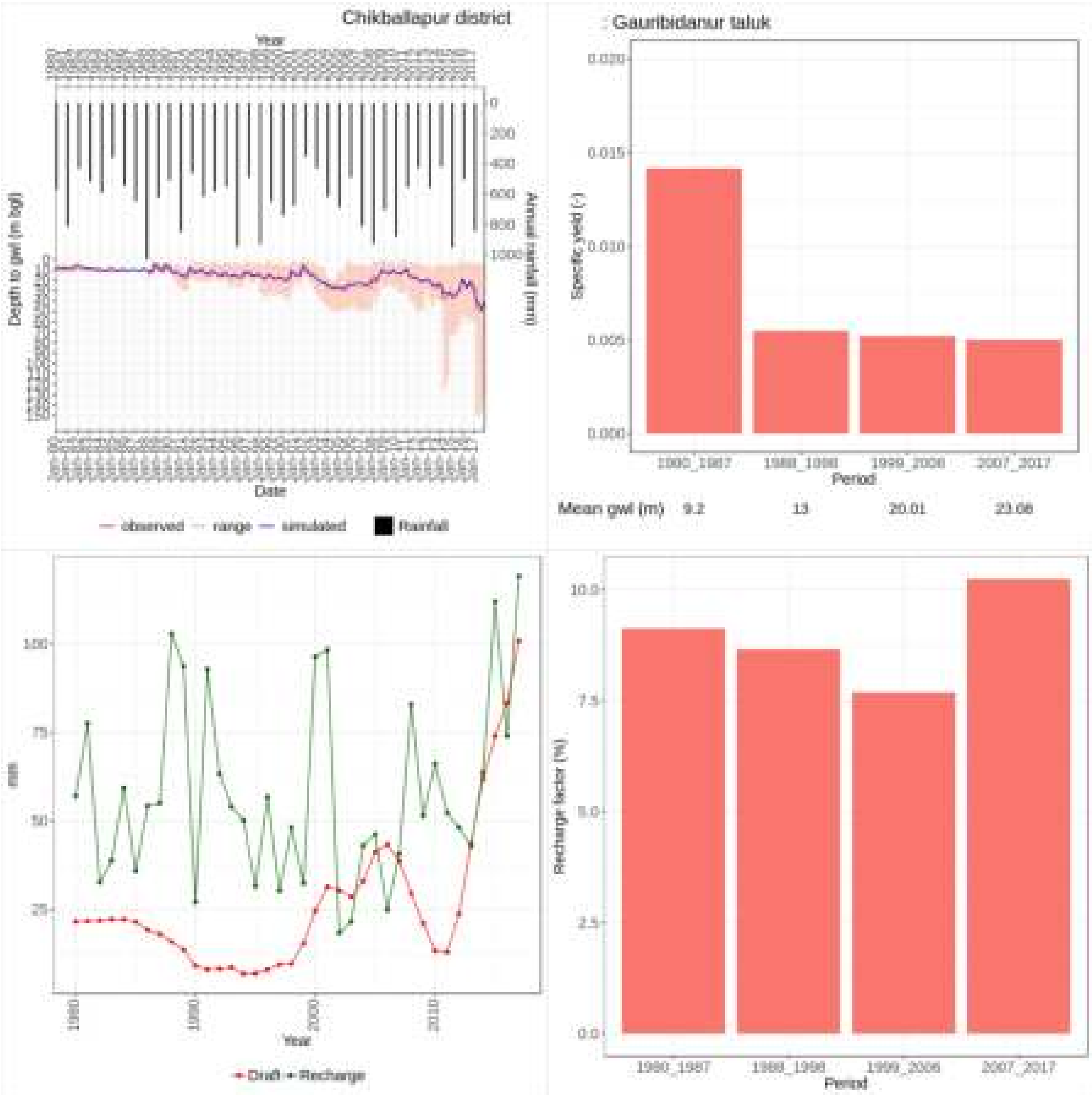

Figure 36 : Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Gauribidanur taluk.

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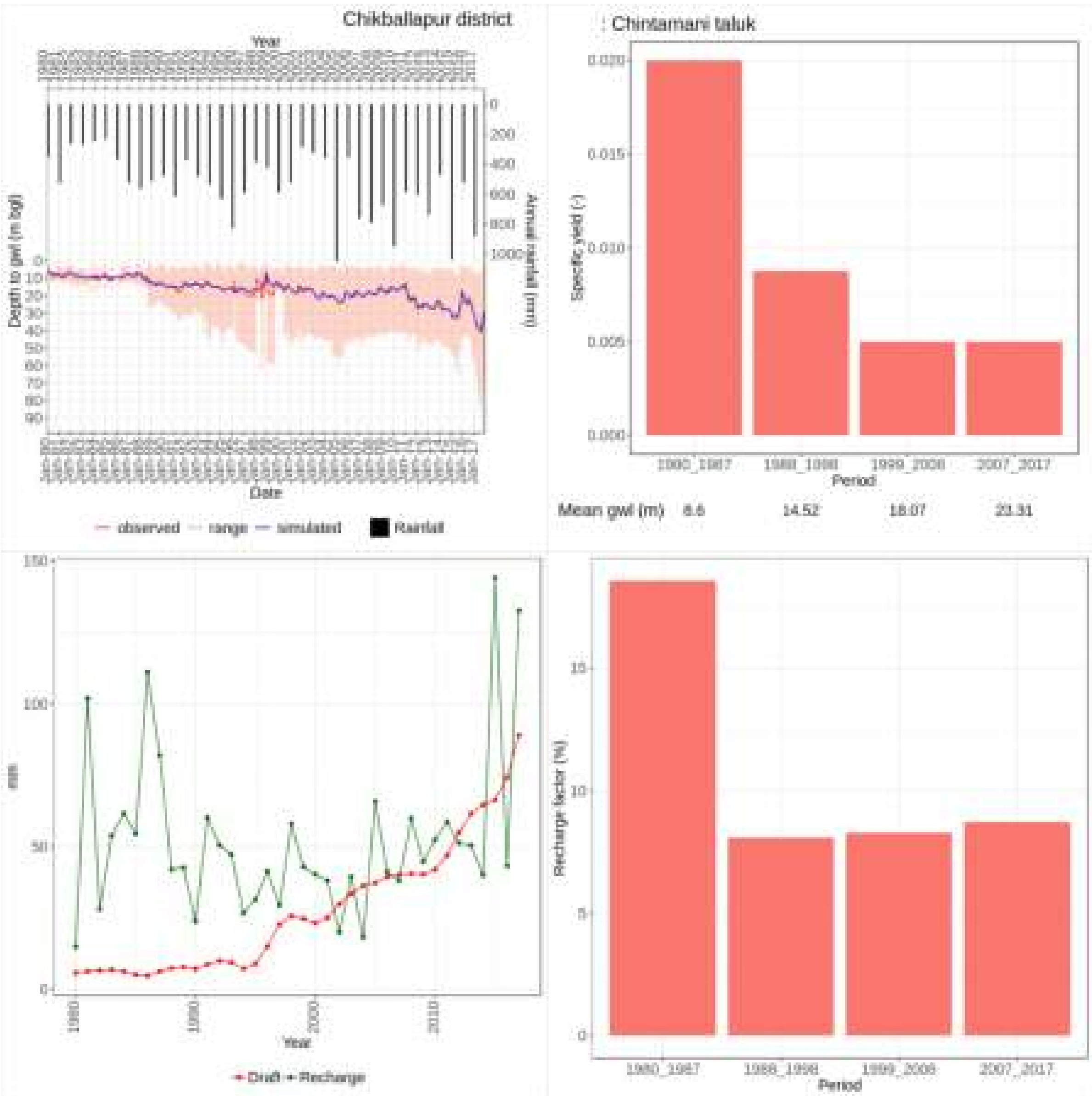


Figure 37: Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Chintamani taluk.

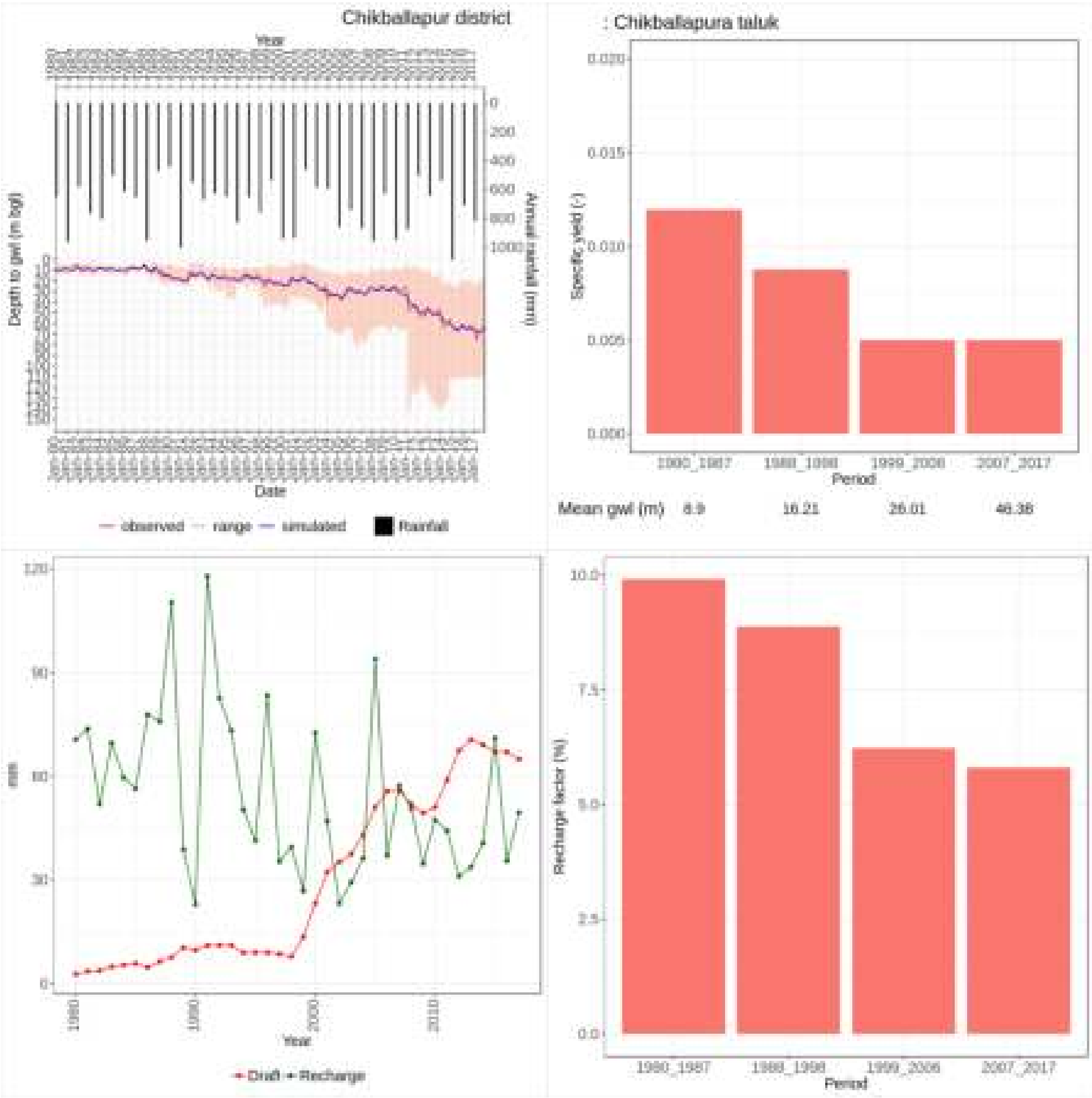


Figure 38 : Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Chikballapura taluk.

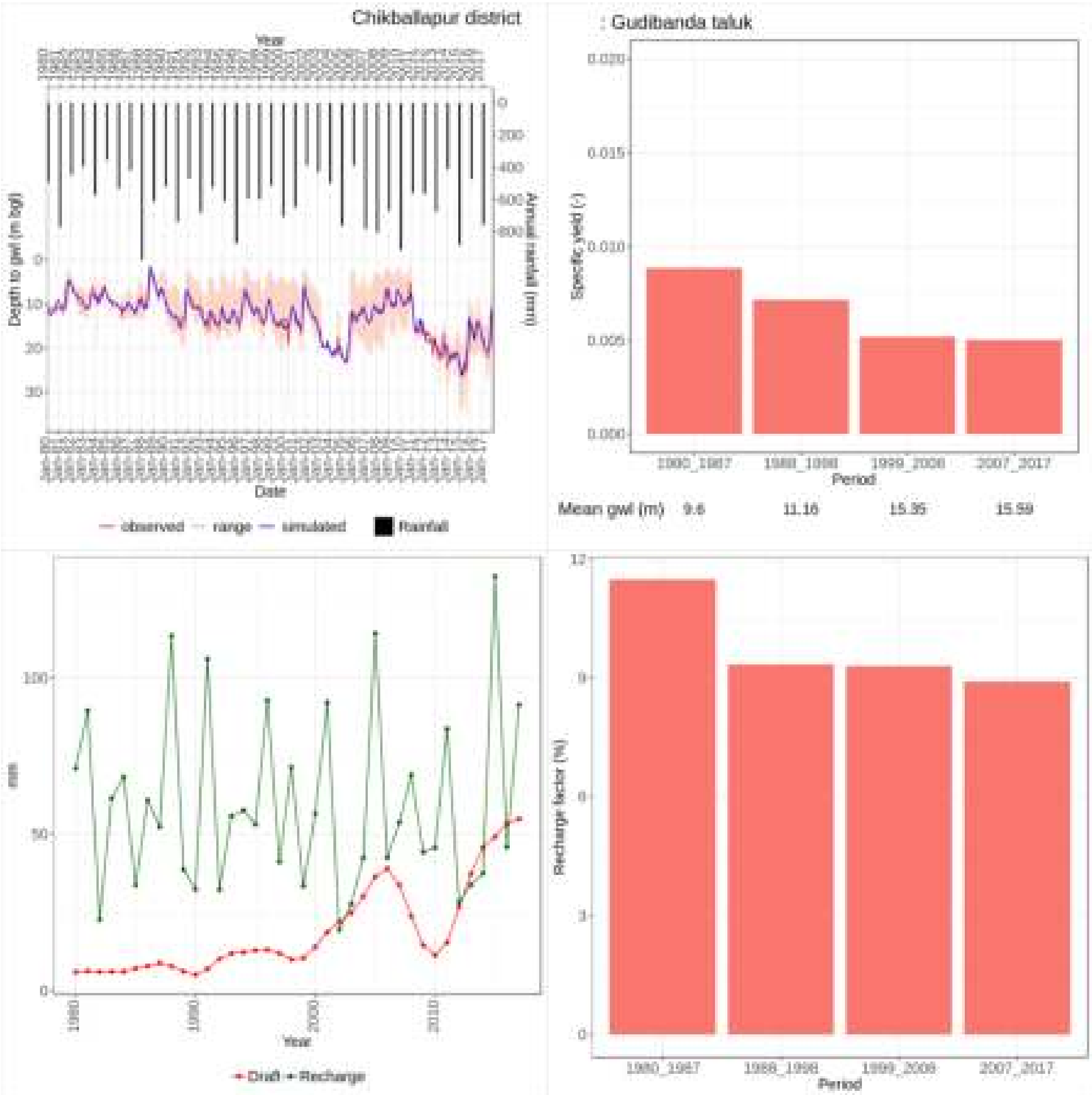


Figure 39 : Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Gudibanda taluk.

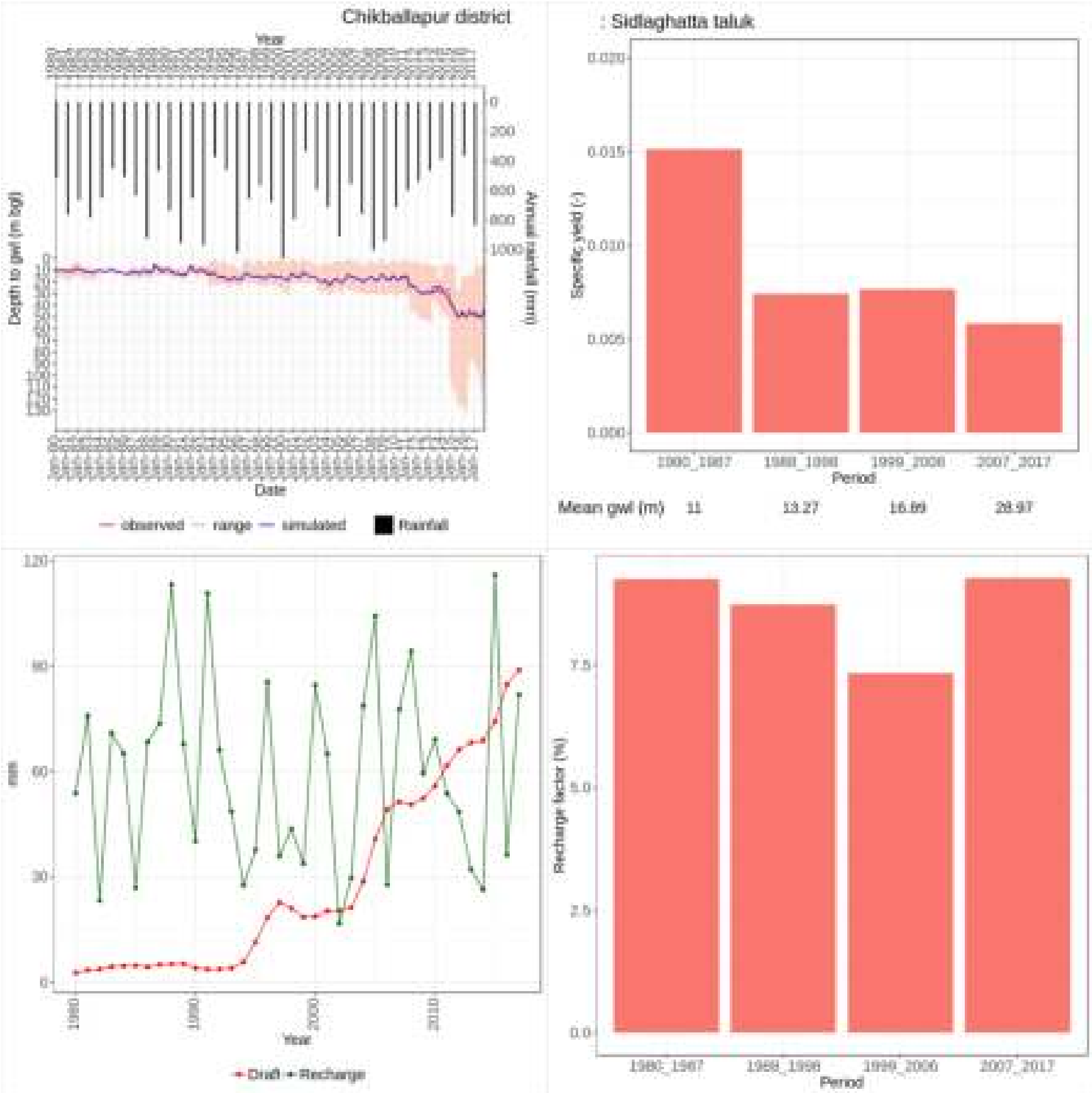


Figure 40 : Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Sidlaghatta taluk.

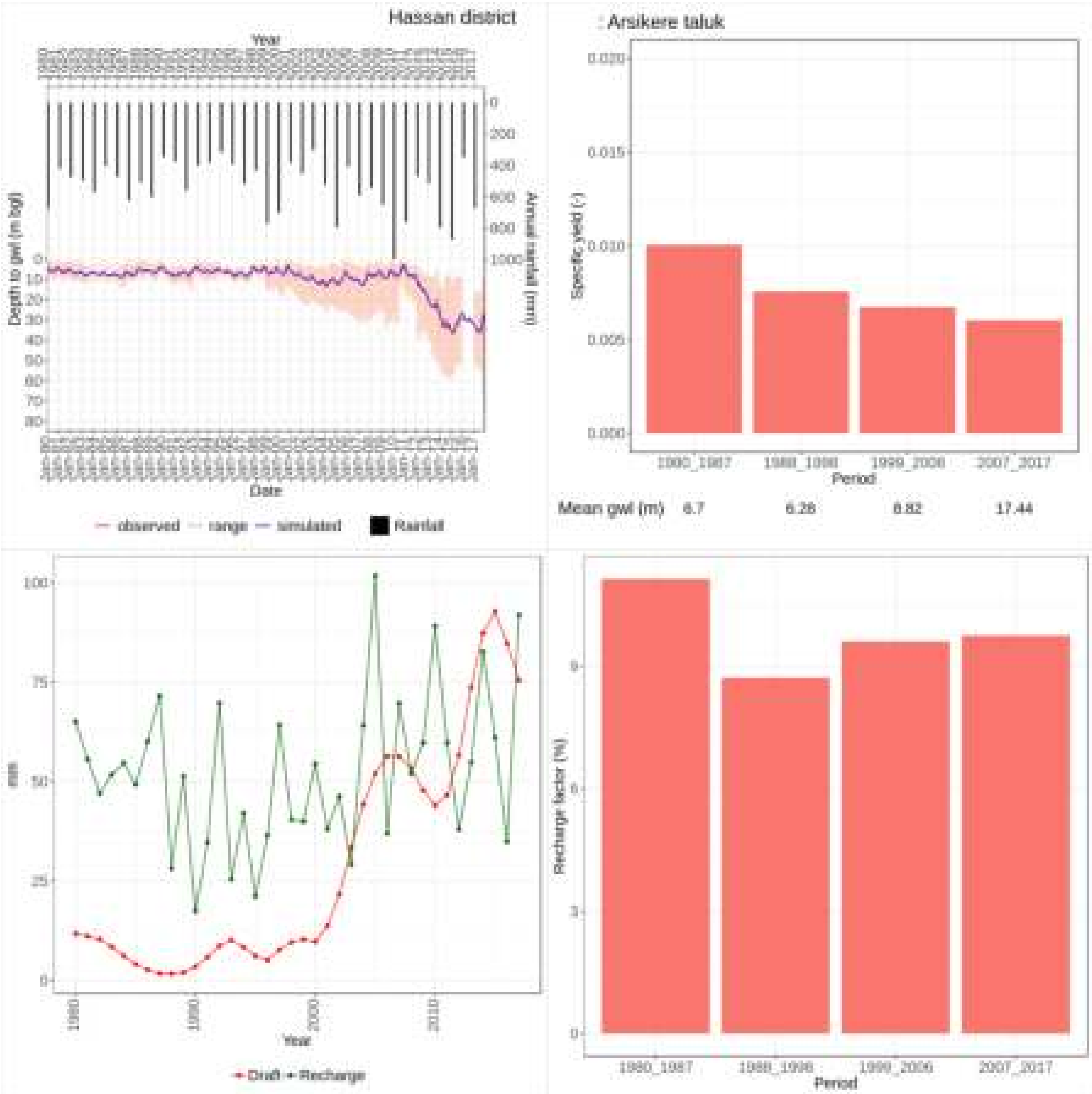


Figure 41 : Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Arsikere taluk.

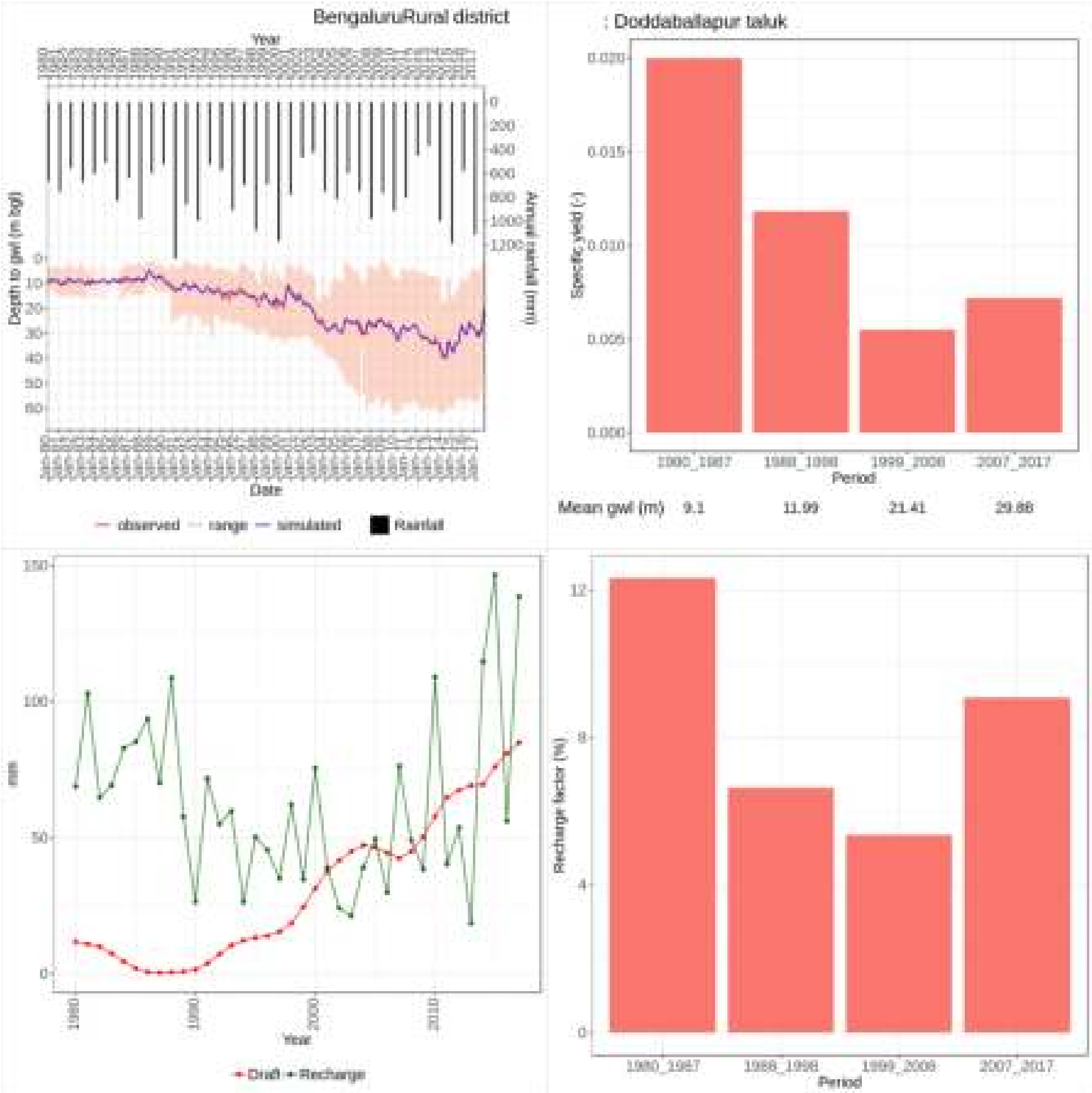


Figure 42 : Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Doddaballapur taluk.

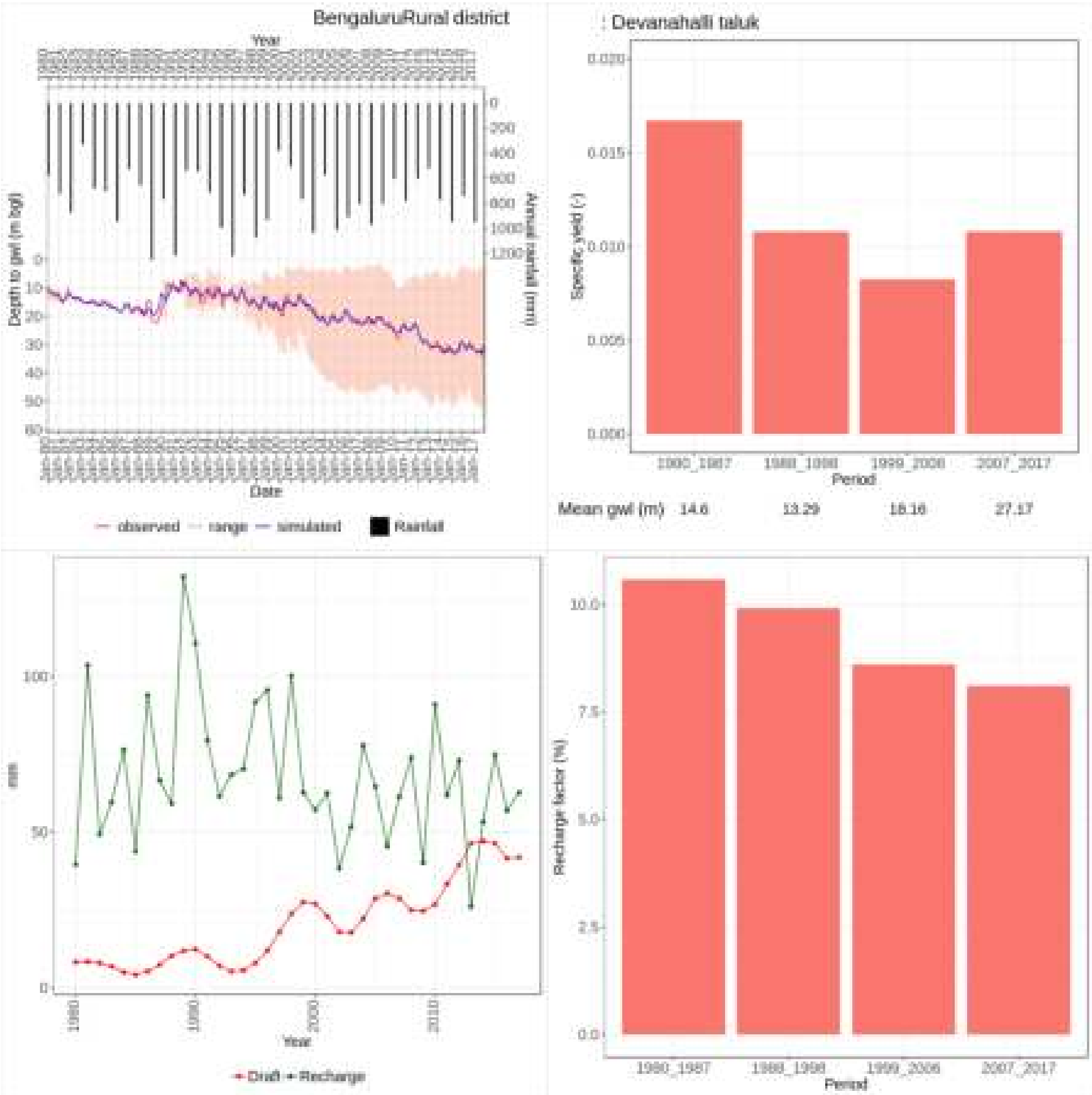


Figure 43 : Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Devanahalli taluk.

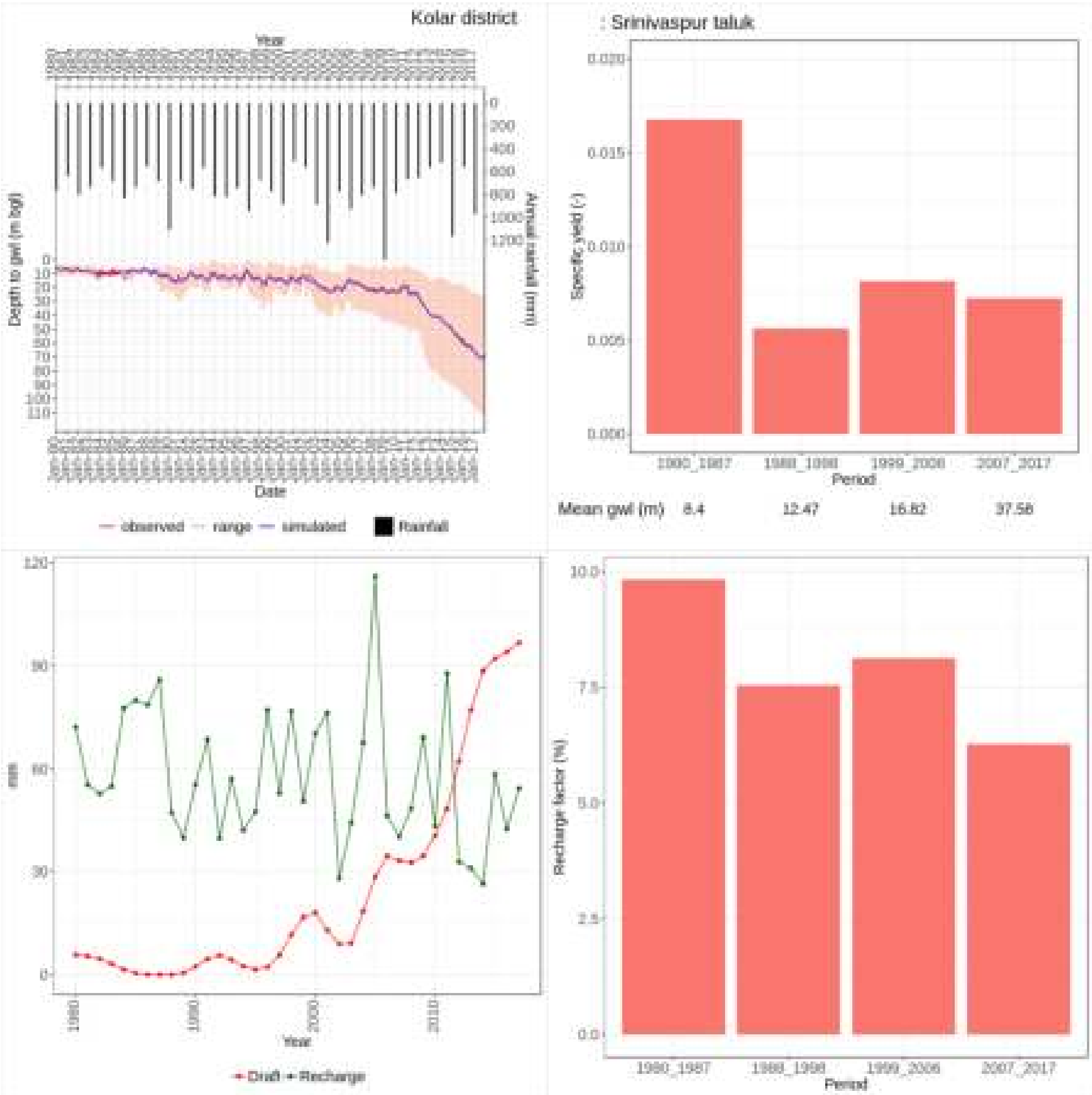


Figure 44 : Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Srinivaspur taluk.

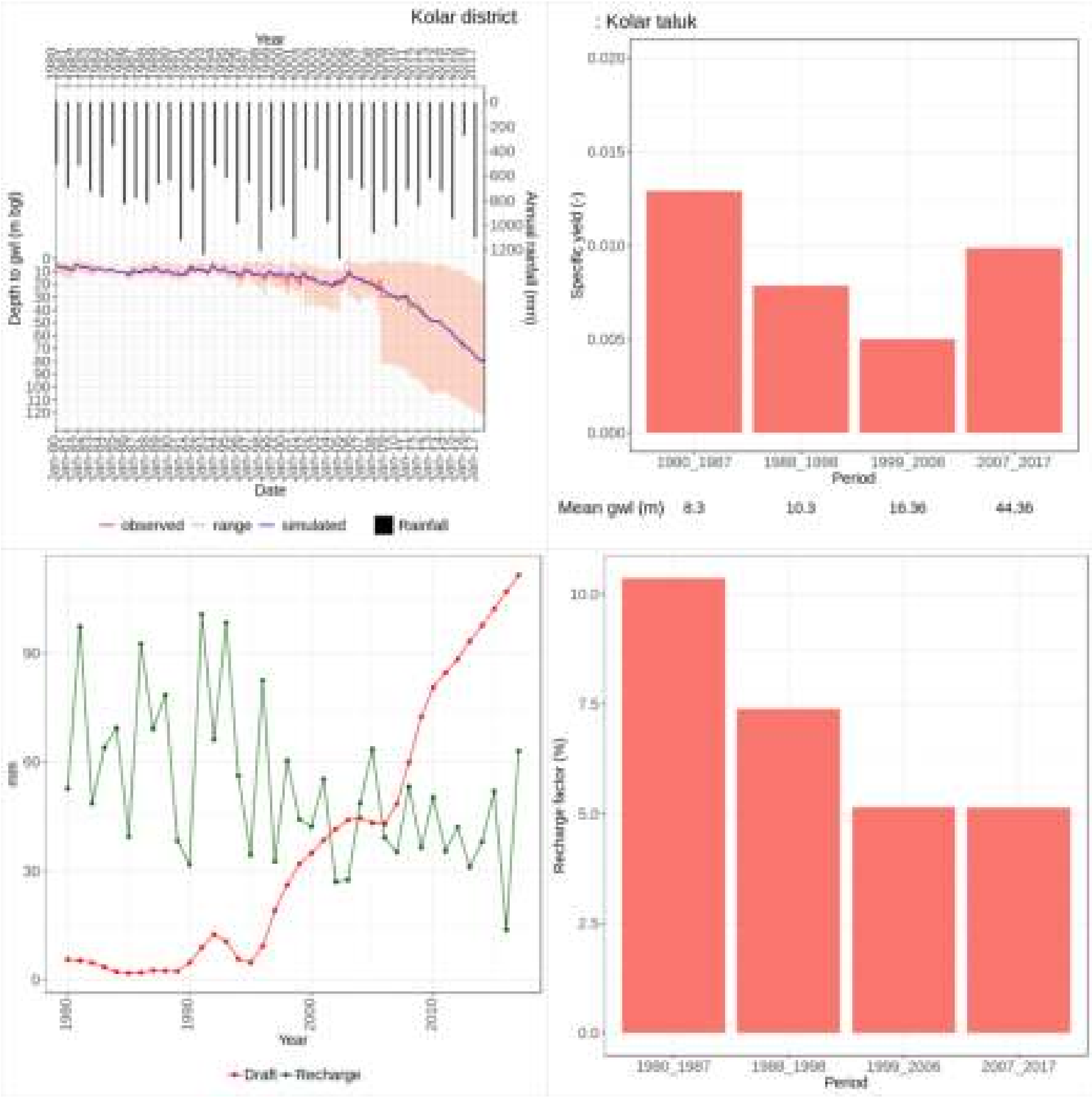


Figure 45 : Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Kolar taluk.

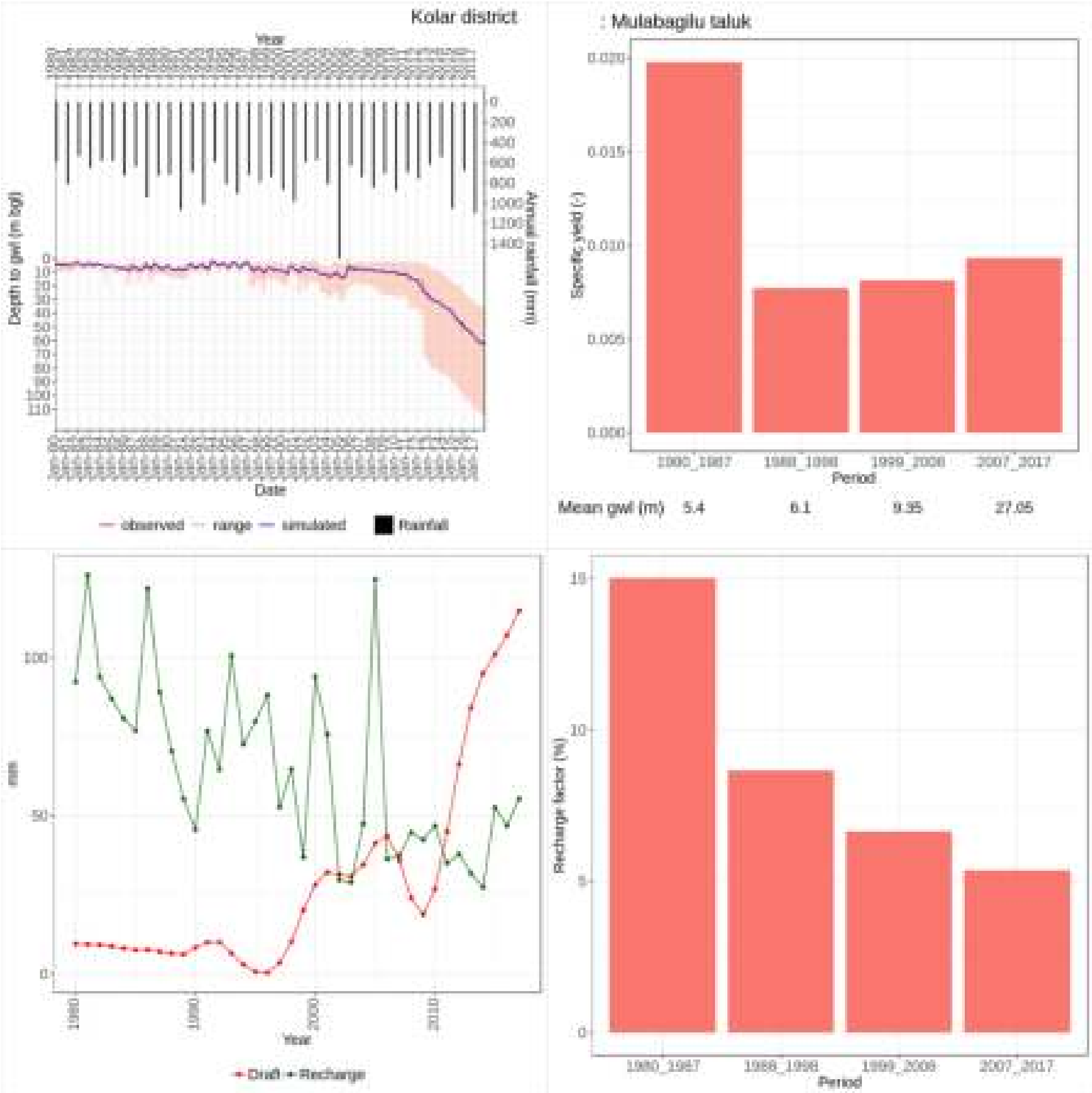


Figure 46 : Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Mulabagilu taluk.

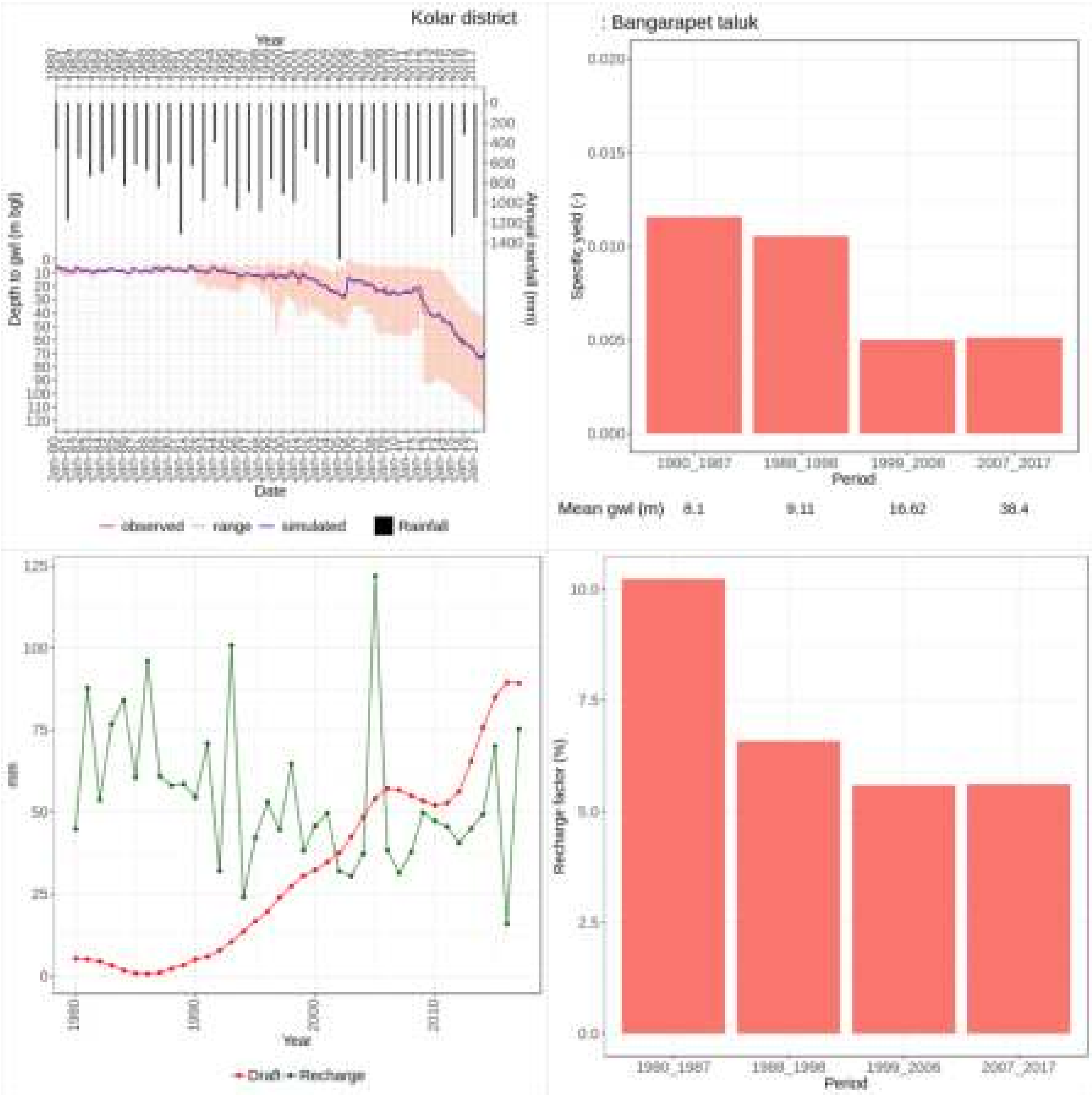


Figure 47 : Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Bangarapet taluk.

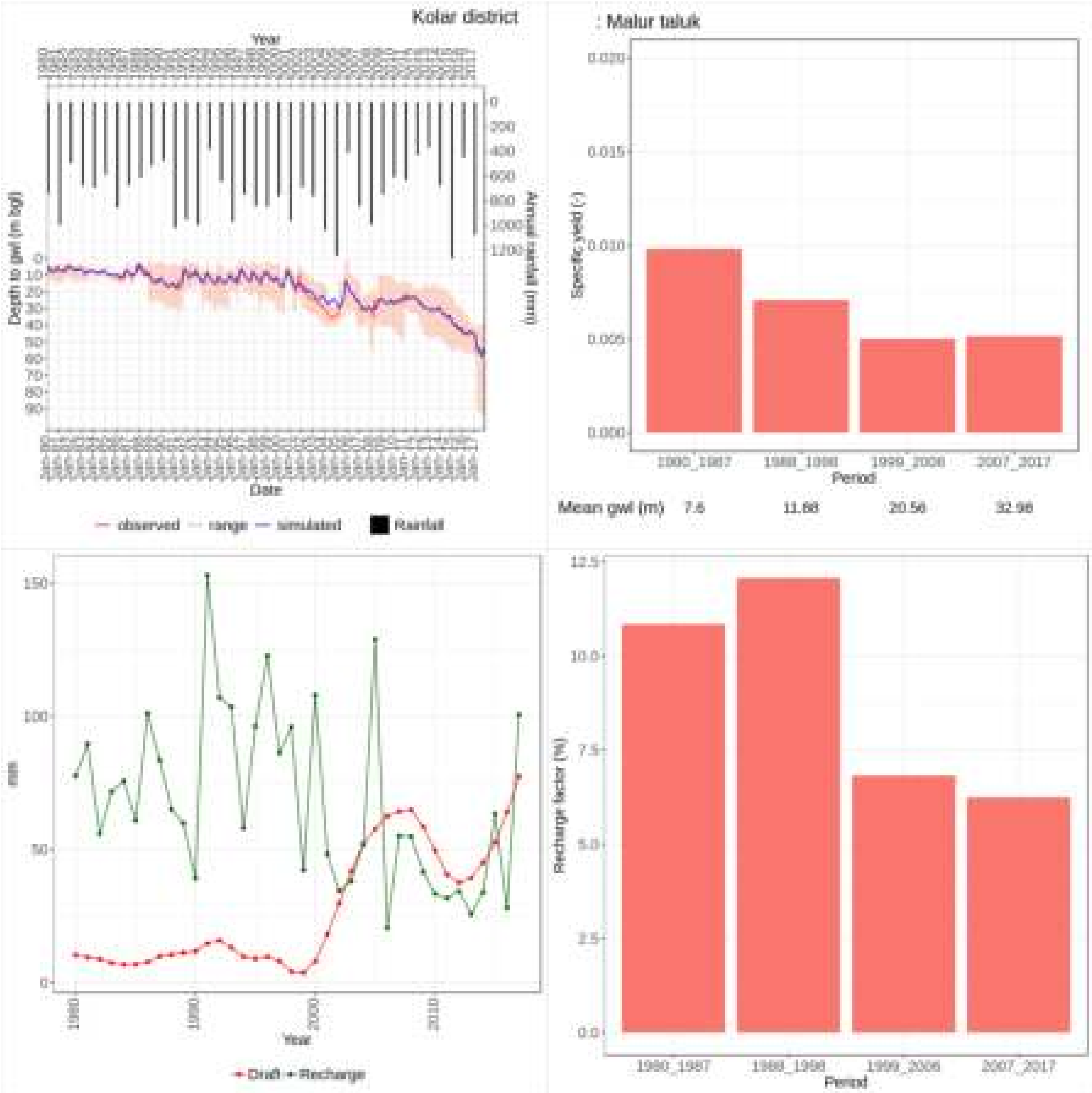


Figure 48 : Estimated parameters and fluxes along with the time series of simulated and observed depth to groundwater table for Malur taluk.

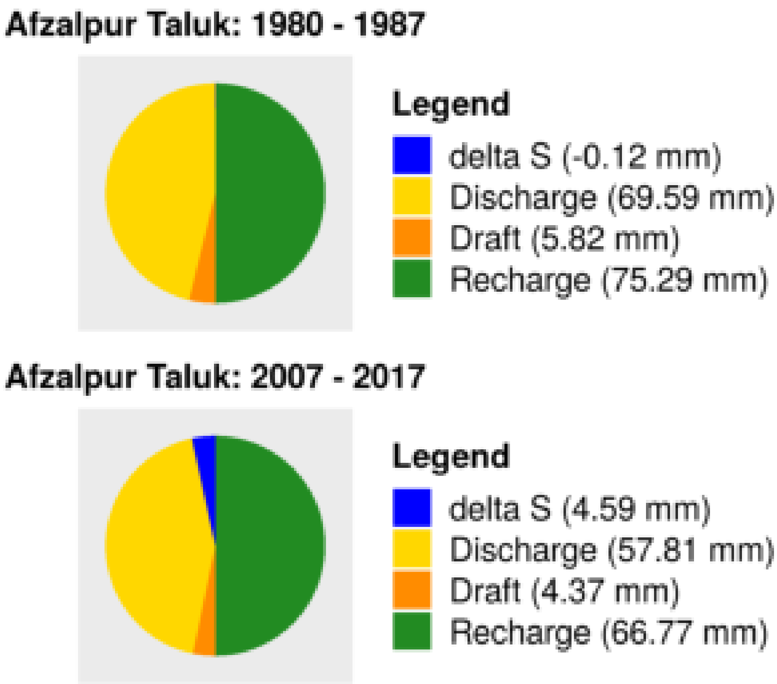


Figure 49: Storage change for Afzalpur taluk in periods (1980-1987) and (2007-2017)

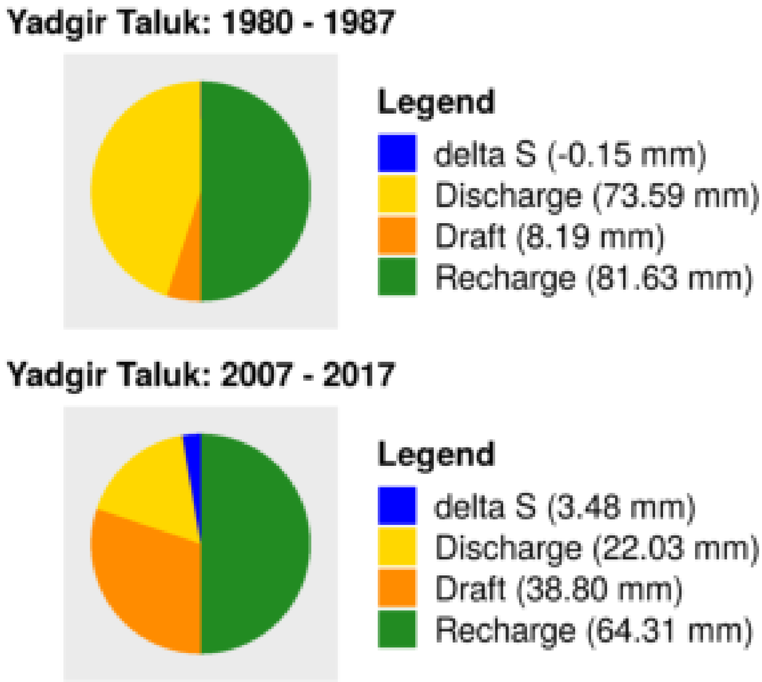


Figure 50: Storage change for Yadgir taluk in periods (1980-1987) and (2007-2017).

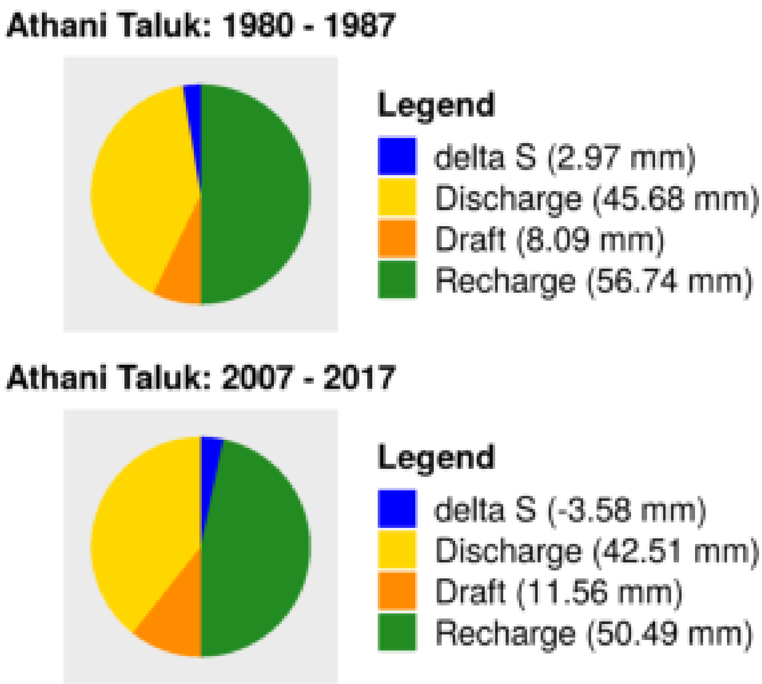


Figure 51: Storage change for Athani taluk in periods (1980-1987) and (2007-2017)

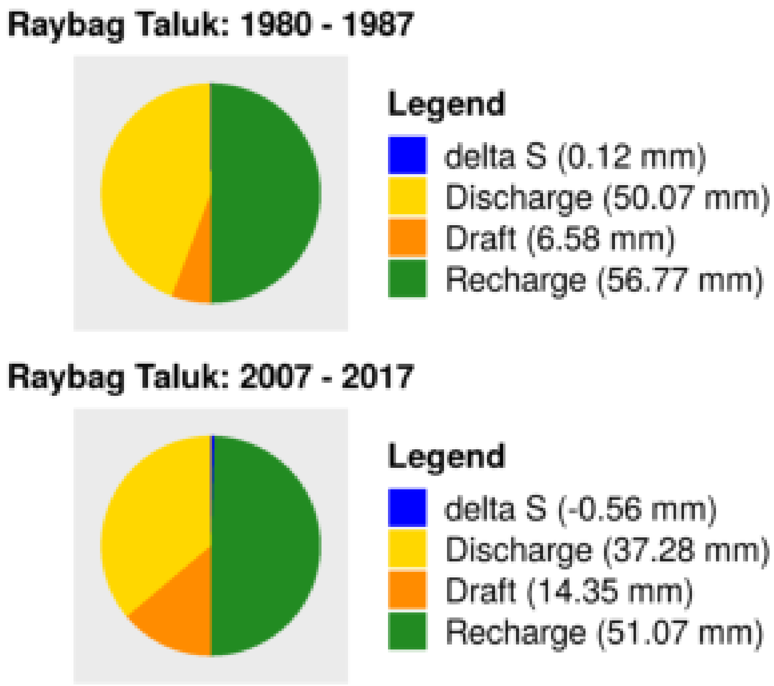


Figure 52: Storage change for Raybag taluk in period (1980-1987) and period (2007-2017)

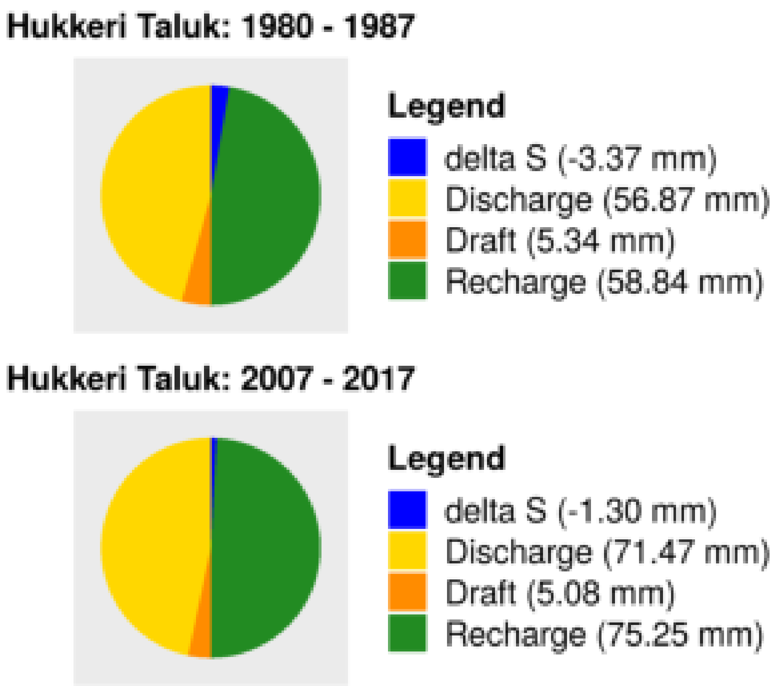


Figure 53: Storage change for Hukkeri taluk in period (1980-1987) and period (2007-2017)

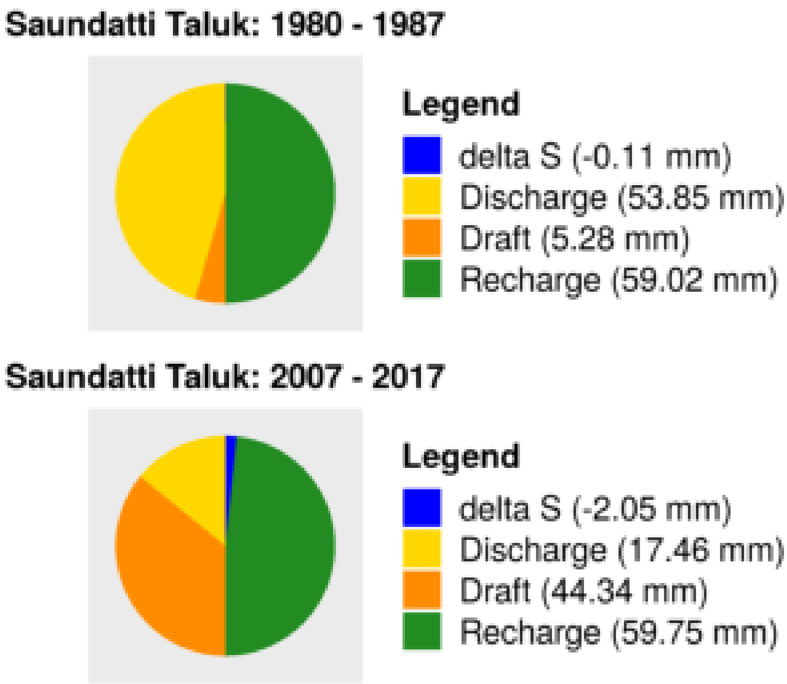


Figure 54: Storage change for Saundatti taluk in period (1980-1987) and period (2007-2017)

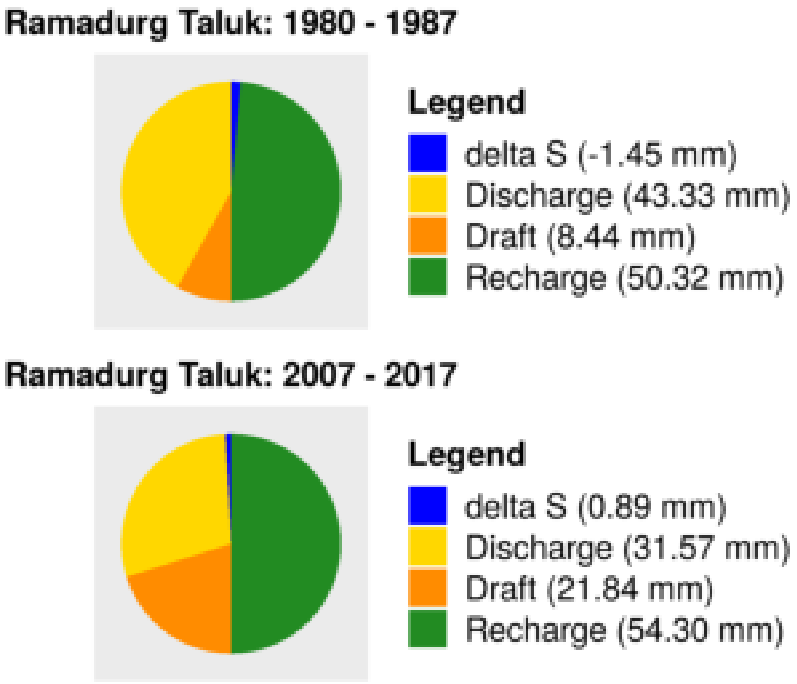


Figure 55: Storage change for Ramdurg taluk in period (1980-1987) and period (2007-2017)

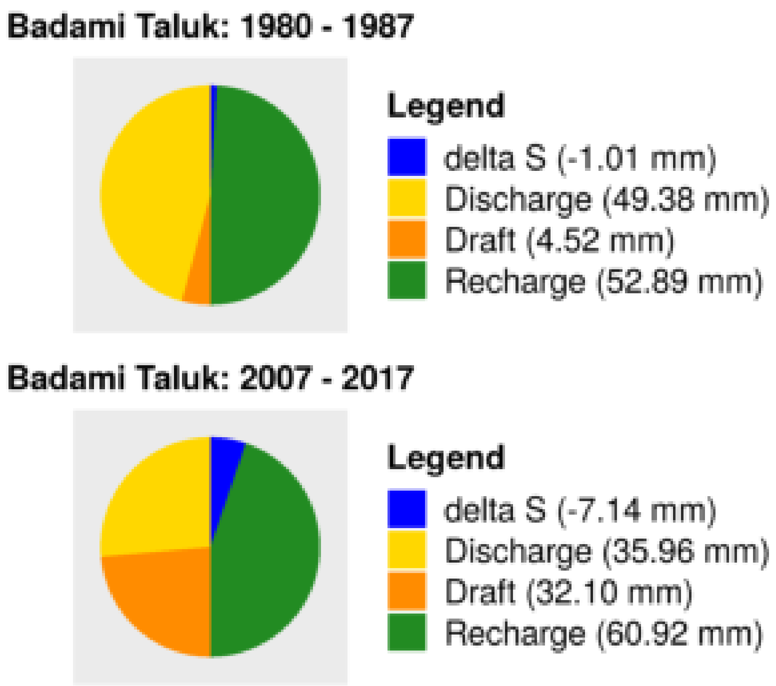


Figure 56: Storage change for Badami taluk in periods (1980-1987) and (2007-2017).

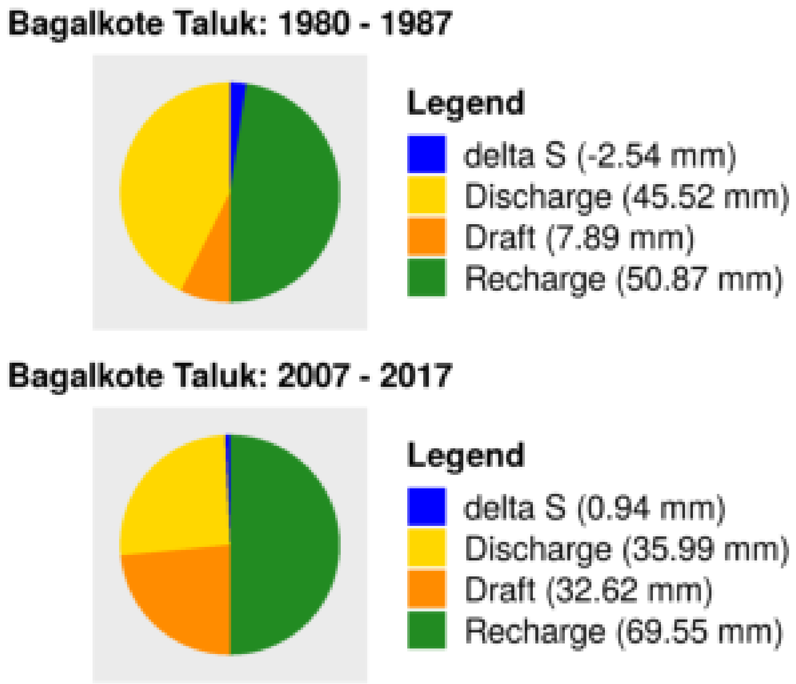


Figure 57: Storage change for Bagalkot taluk in periods (1980-1987) and (2007-2017).

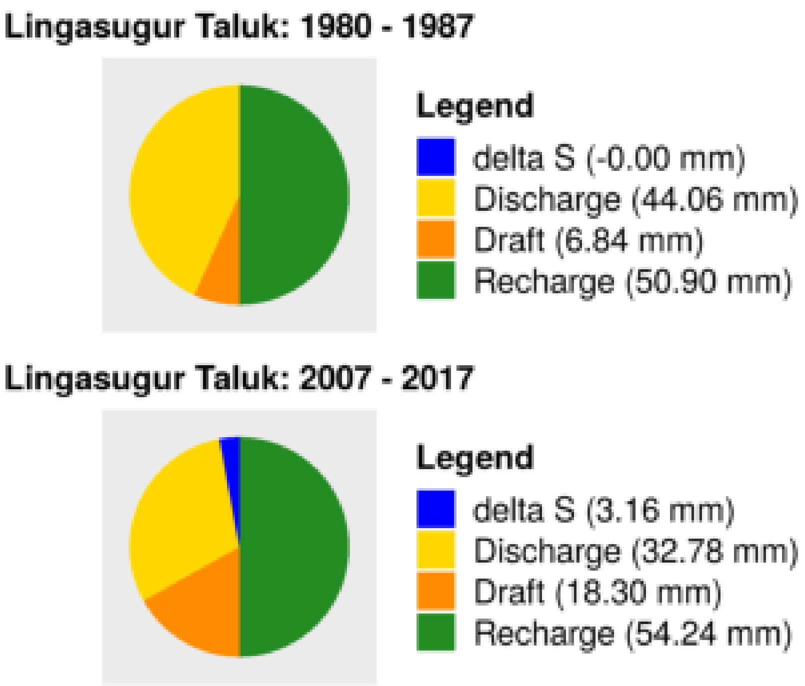


Figure 58: Storage change for Lingasugur taluk in periods (1980-1987) and (2007-2017)

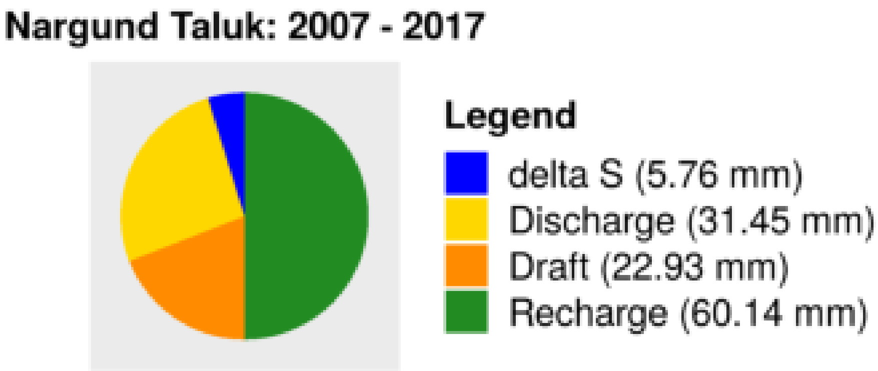


Figure 59: Storage change for Nargund taluk in period (2007-2017). No groundwater observations were available during 1980-87.

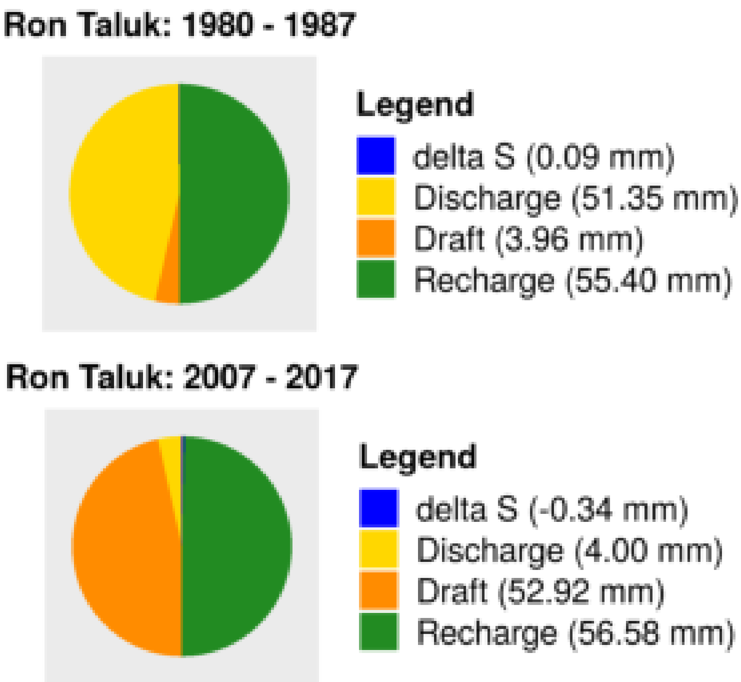


Figure 60: Storage change for Ron taluk in period (1980-1987) and period (2007-2017)

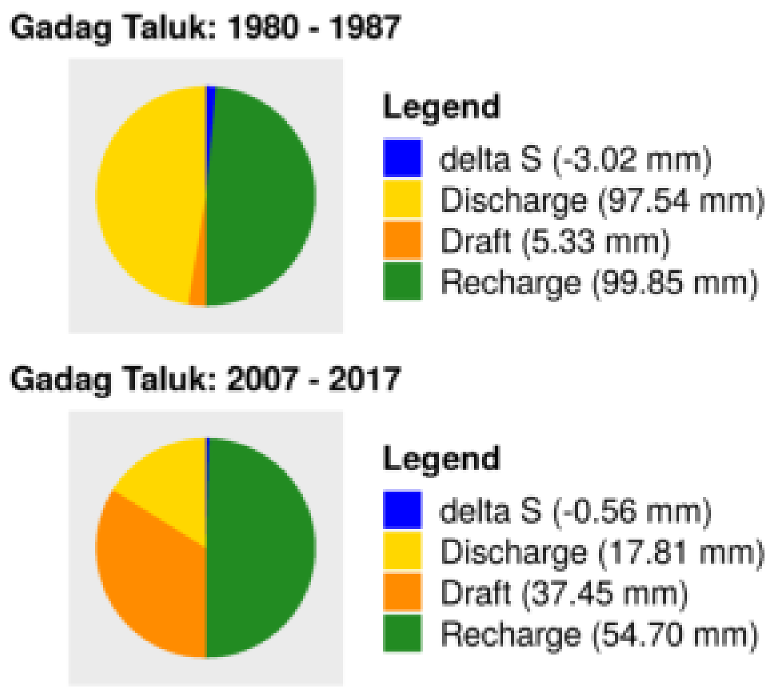


Figure 61: Storage change for Gadag taluk in period (1980-1987) and period (2007-2017)

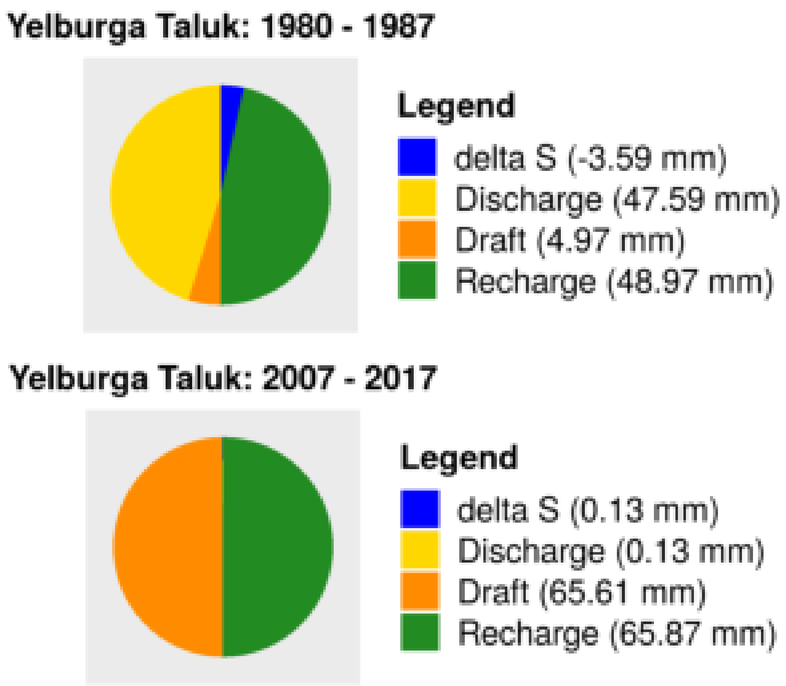


Figure 62: Storage change for Yelburga taluk in periods (1980-1987) and (2007-2017)

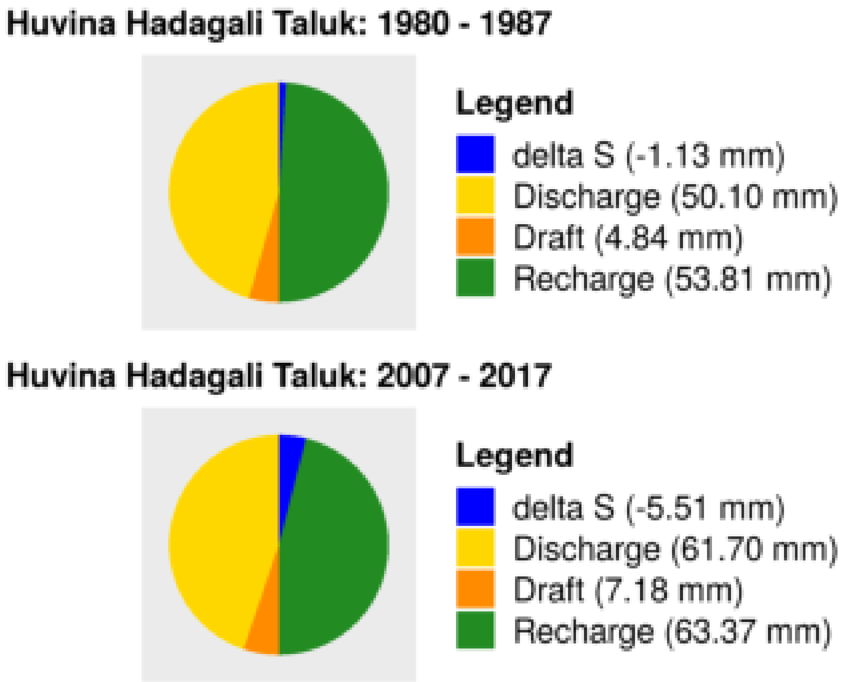


Figure 63: Storage change for Huvina Hadagali in periods (1980-1987) and (2007-2017)

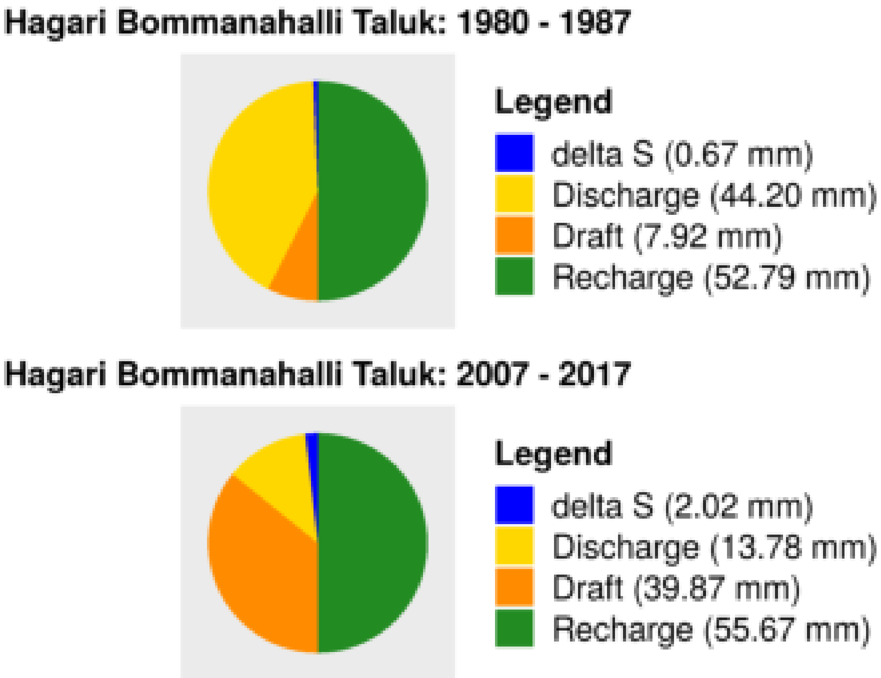


Figure 64: Storage change for H.Bommanahalli taluk in (1980-1987) & (2007-2017)

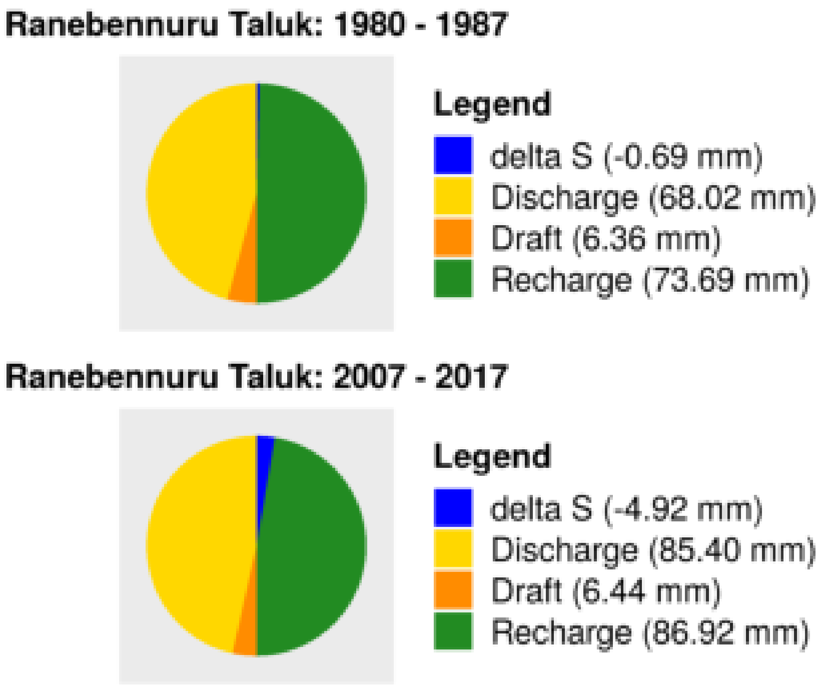


Figure 65: Storage change for Ranebennur taluk in periods (1980-1987) & (2007-2017)

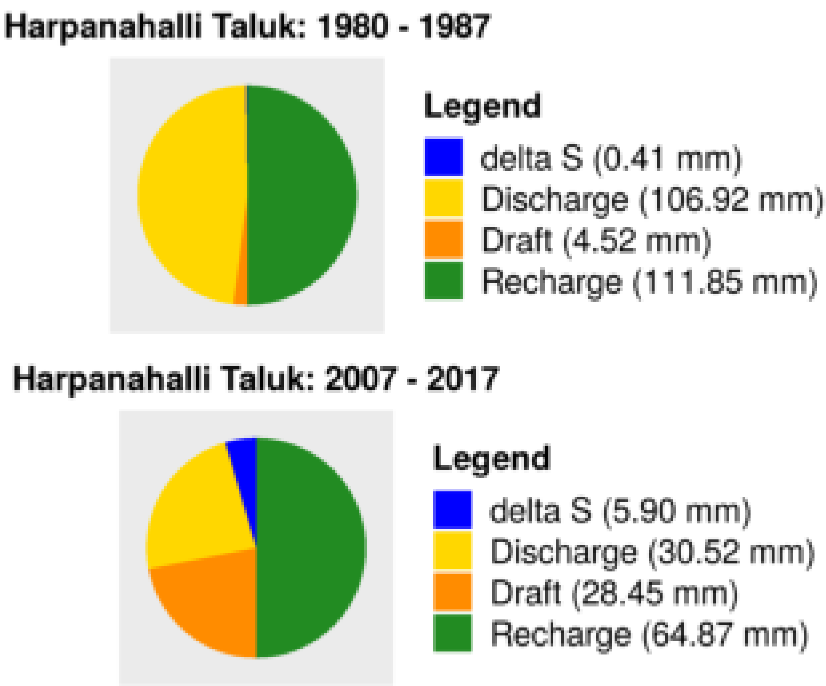


Figure 66: Storage change for Harapanahalli taluk in periods (1980-1987) & (2007-2017)

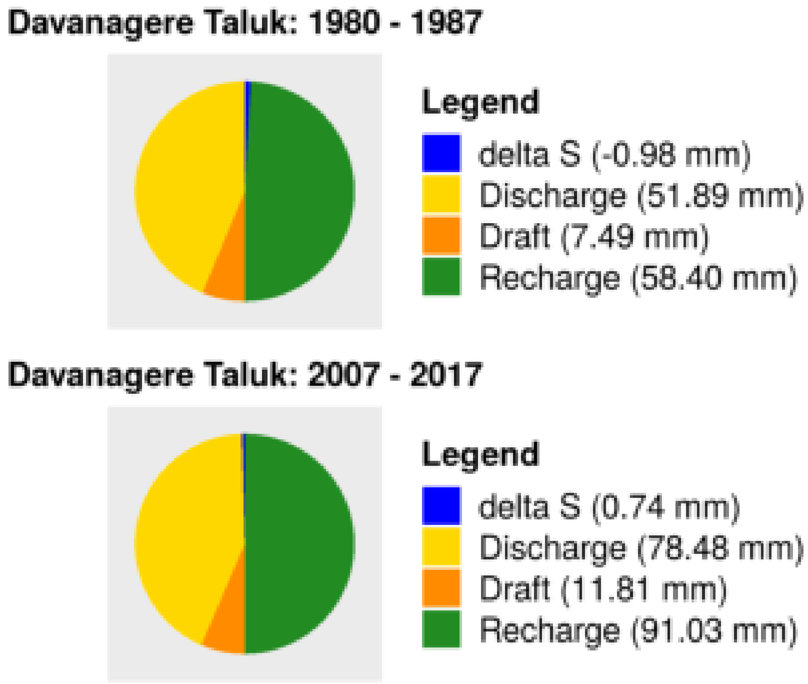


Figure 67: Storage change for Davanagere taluk in period (1980-1987) and period (2007-2017)

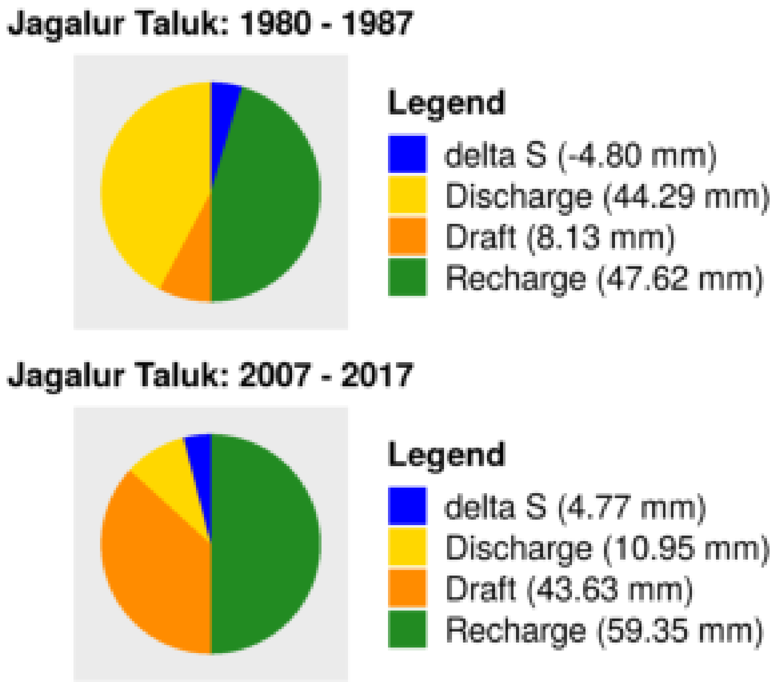


Figure 68: Storage change for Jagalur taluk in period (1980-1987) and (2007-2017)

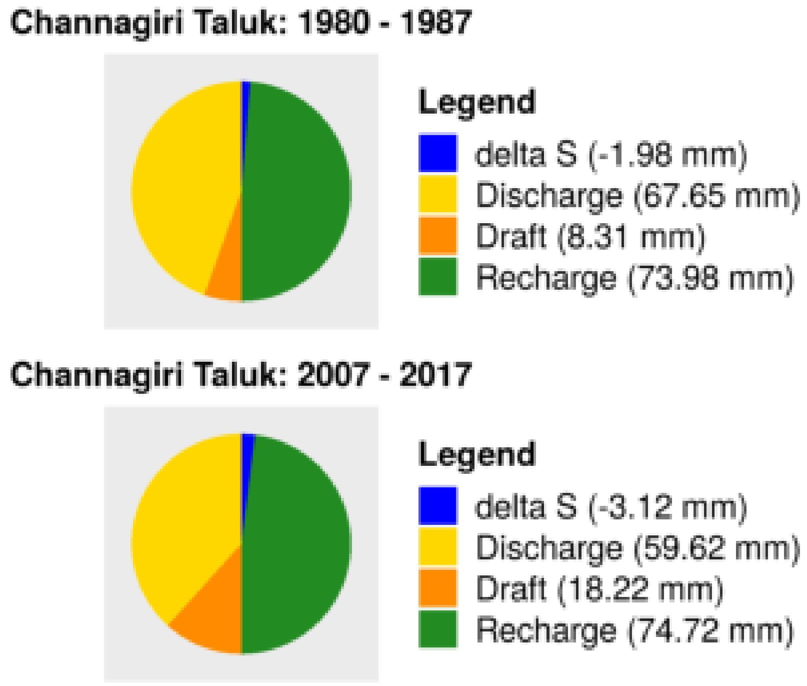


Figure 69: Storage change for Channagiri taluk in periods (1980-1987) & (2007-2017)

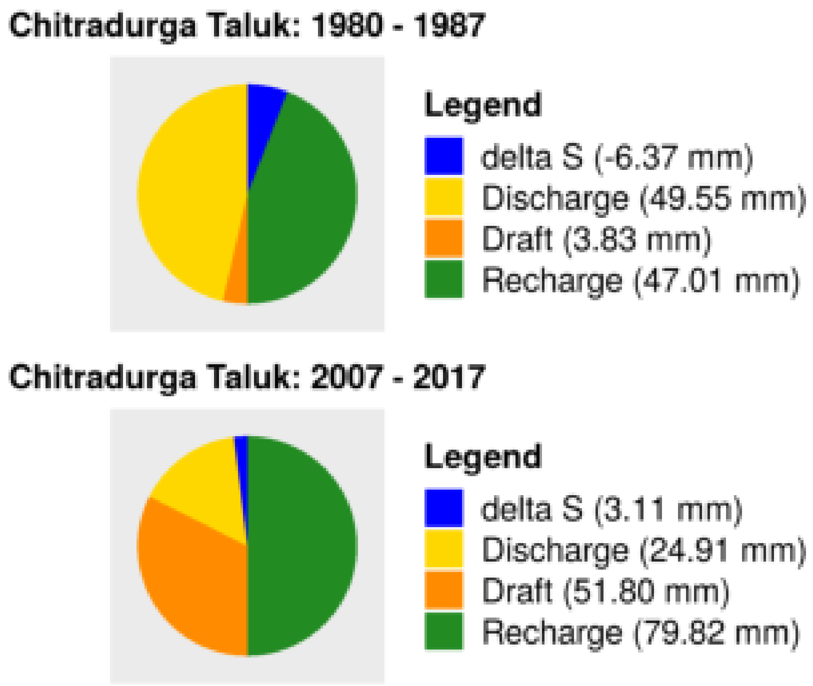


Figure 70: Storage change for Chitradurga taluk in (1980-1987) and (2007-2017)

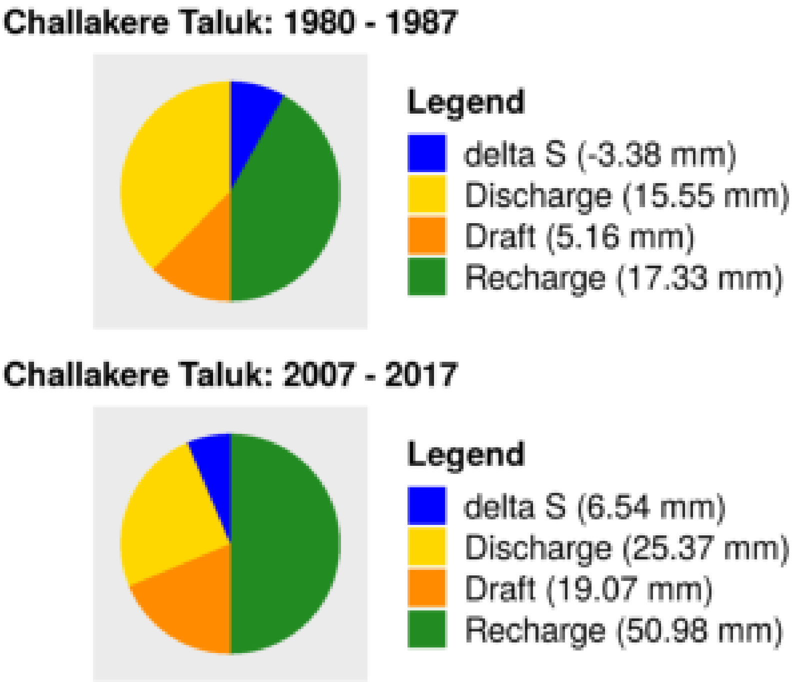


Figure 71: Storage change for Challakere taluk in period (1980-1987) and period (2007-2017)

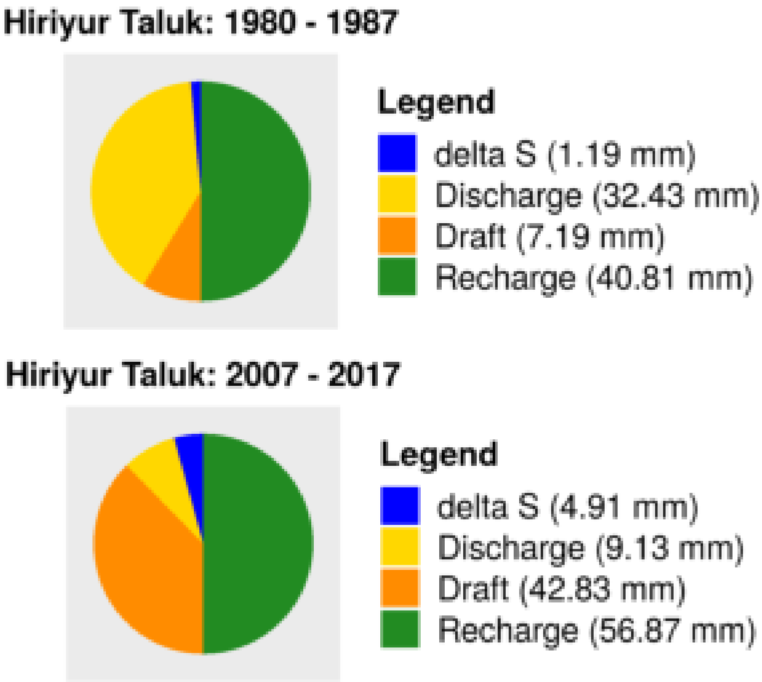


Figure 72: Storage change for Hiriyur taluk in period (1980-1987) and period (2007-2017)

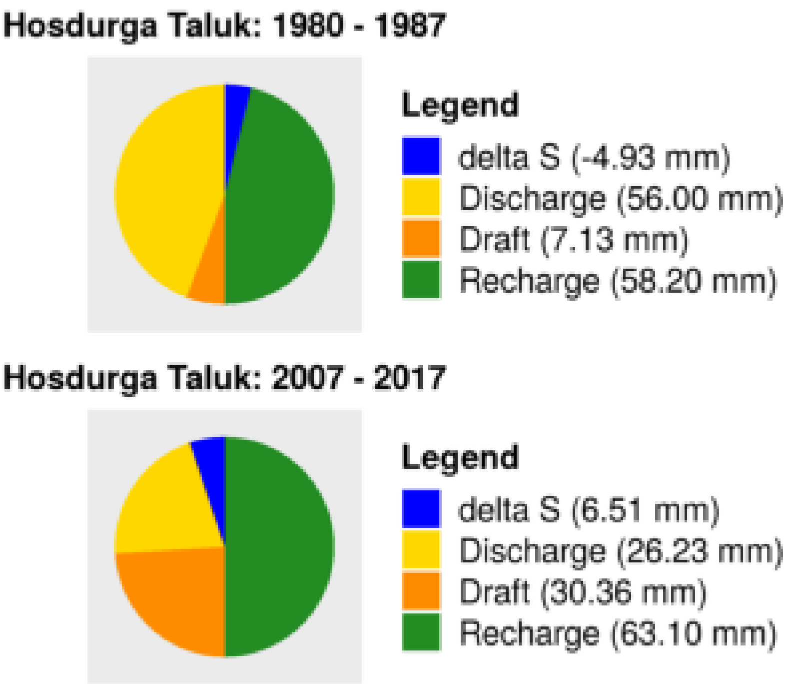


Figure 73: Storage change for Hosdurga taluk in periods (1980-1987) & (2007-2017)

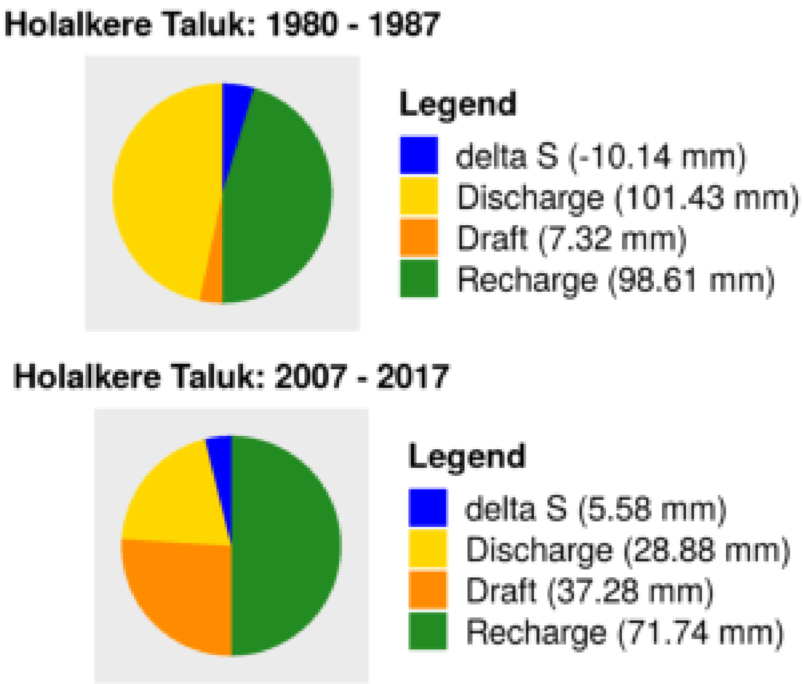


Figure 74: Storage change for Holalkere taluk in period (1980-1987) and period (2007-2017)

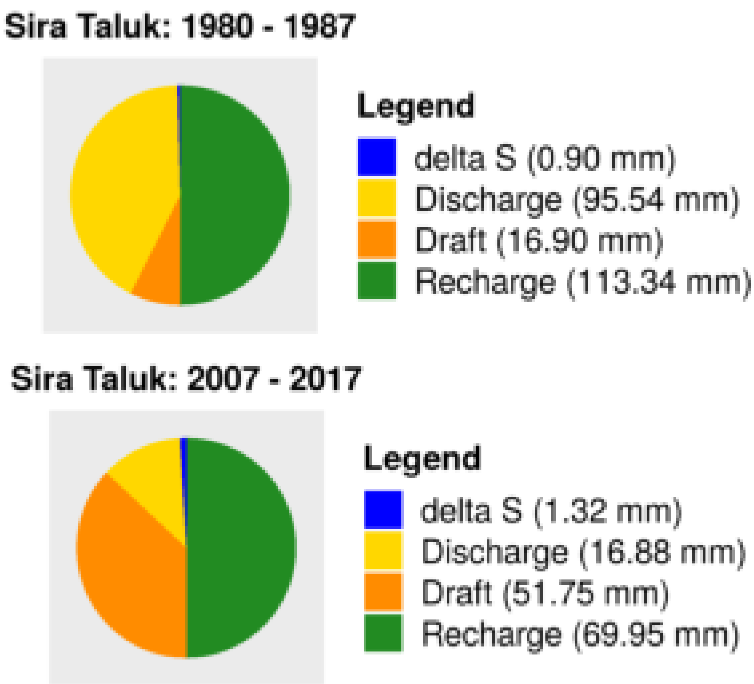


Figure 75: Storage change for Sira taluk in period (1980-1987) and period (2007-2017)

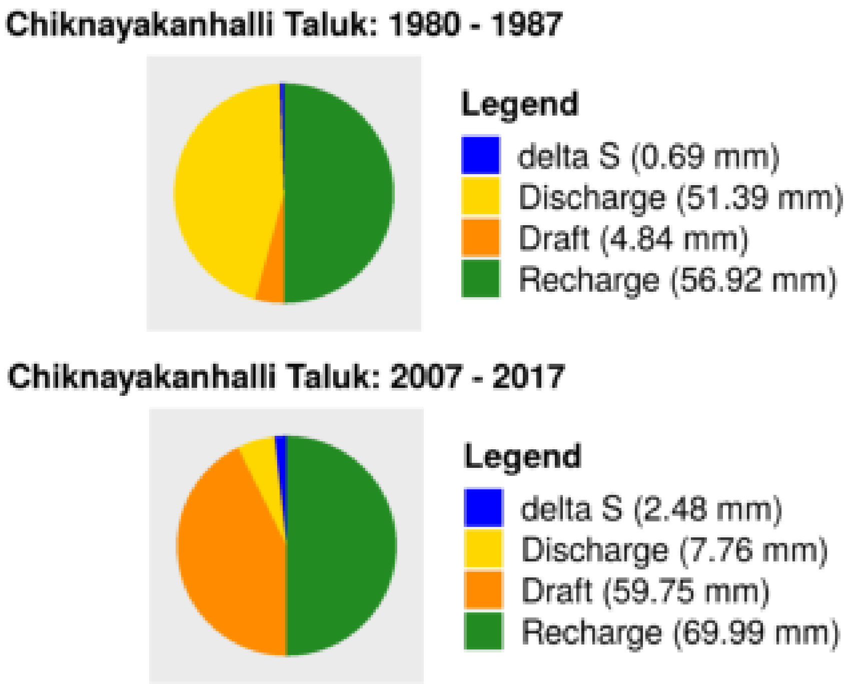


Figure 76: Storage change for Chiknayakanhalli taluk in period (1980-1987) and period (2007-2017)

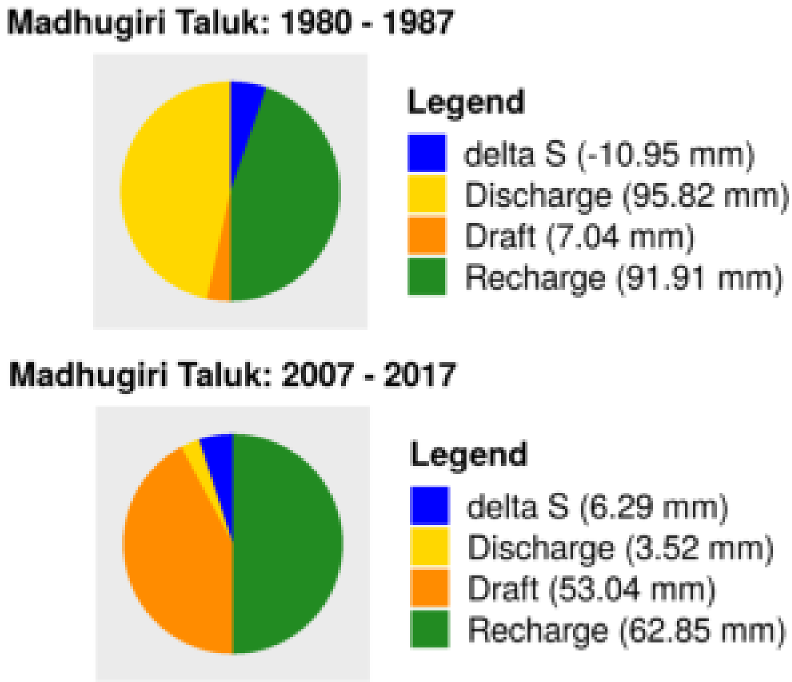


Figure 77: Storage change for Madhugiri taluk in periods (1980-1987) & (2007-2017)

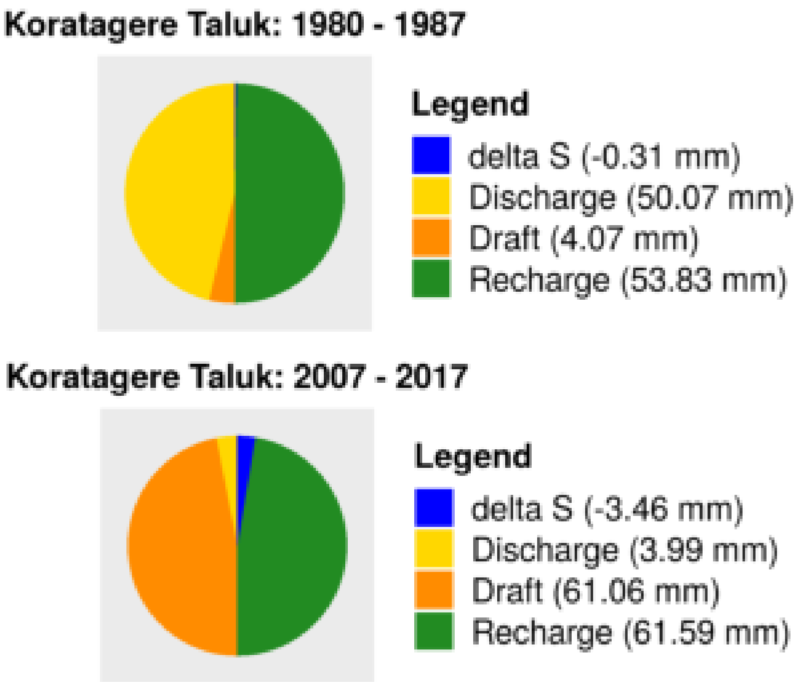


Figure 78: Storage change for Koratagere taluk in periods (1980-1987) &(2007-2017)

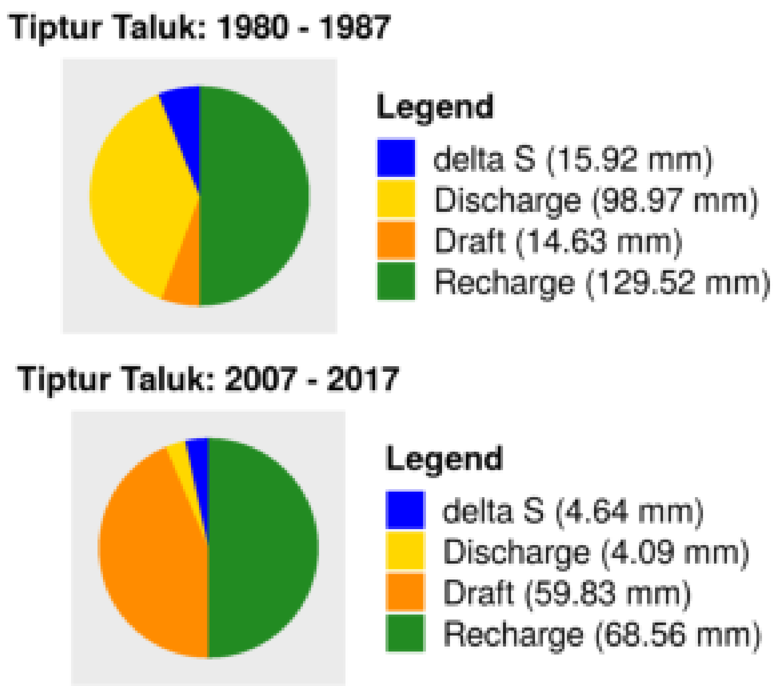


Figure 79: Storage change for Tiptur taluk in periods (1980-1987) & (2007-2017)

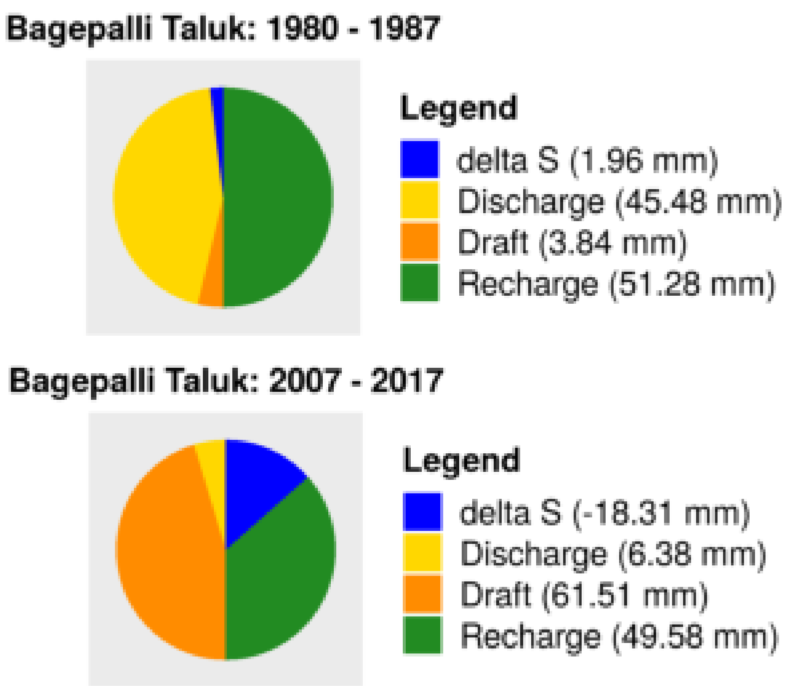


Figure 80: Storage change for Bagepalli taluk in periods (1980-1987) & (2007-2017)

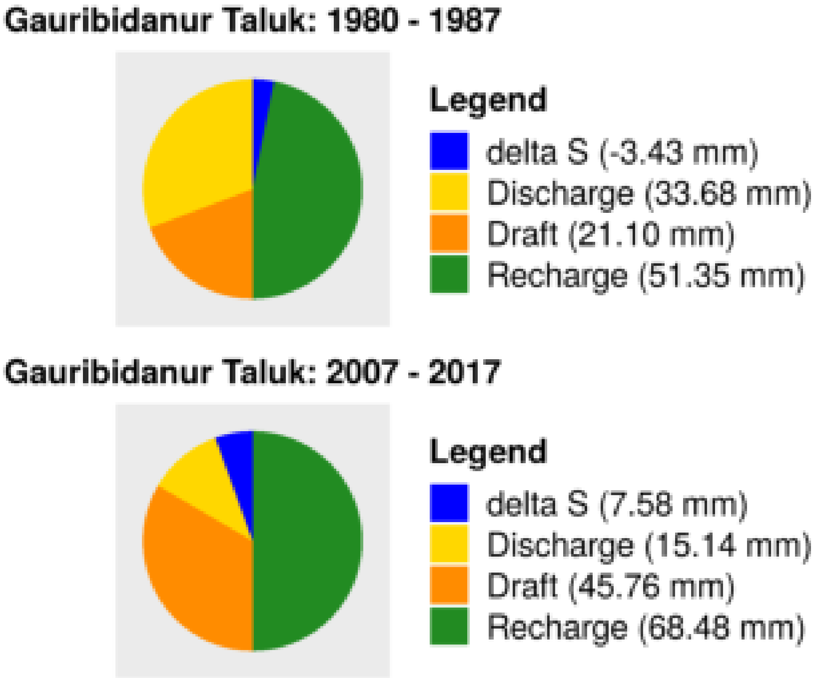


Figure 81: Storage change for Gauribidanur taluk in period (1980-1987) and period (2007-2017)

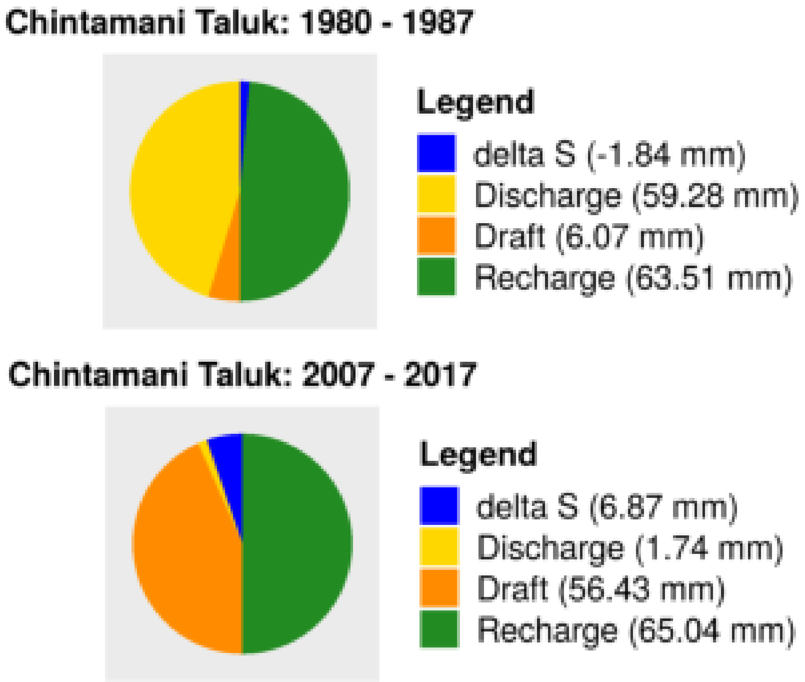


Figure 82: Storage change for Chintamani taluk in period (1980-1987) and period (2007-2017)

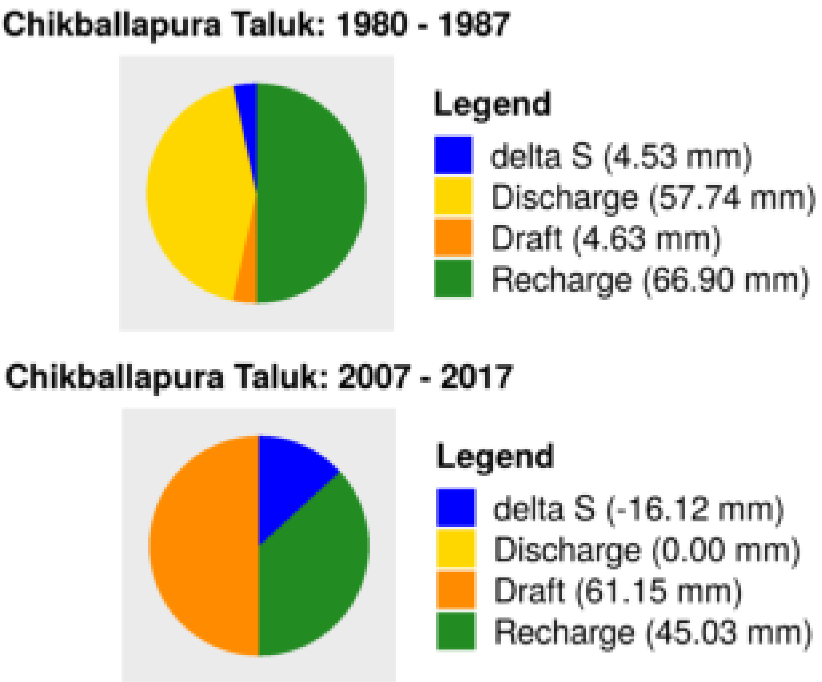


Figure 83: Storage change for Chikballapur taluk in period (1980-1987) and period (2007-2017)

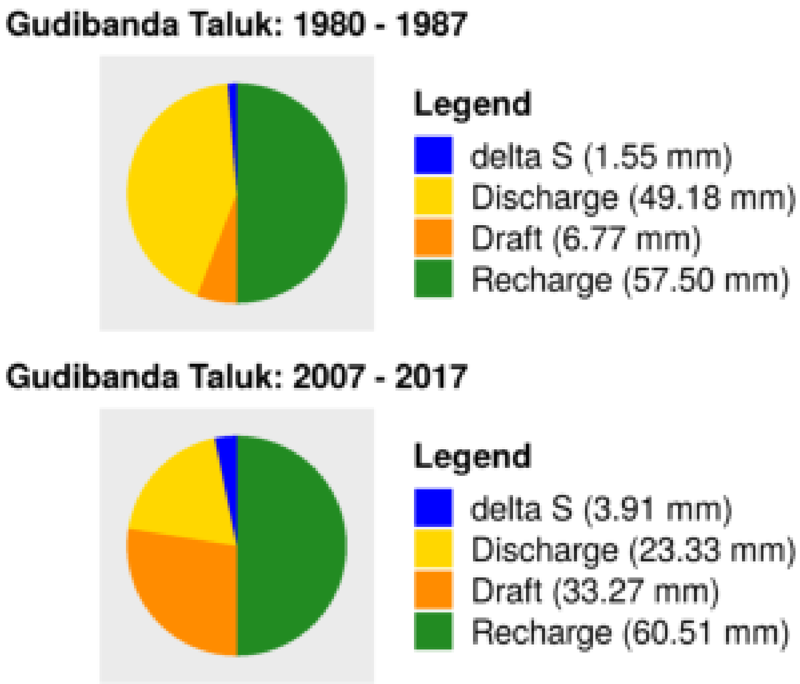


Figure 84: Storage change for Gudibanda taluk in periods (1980-1987) & (2007-2017)

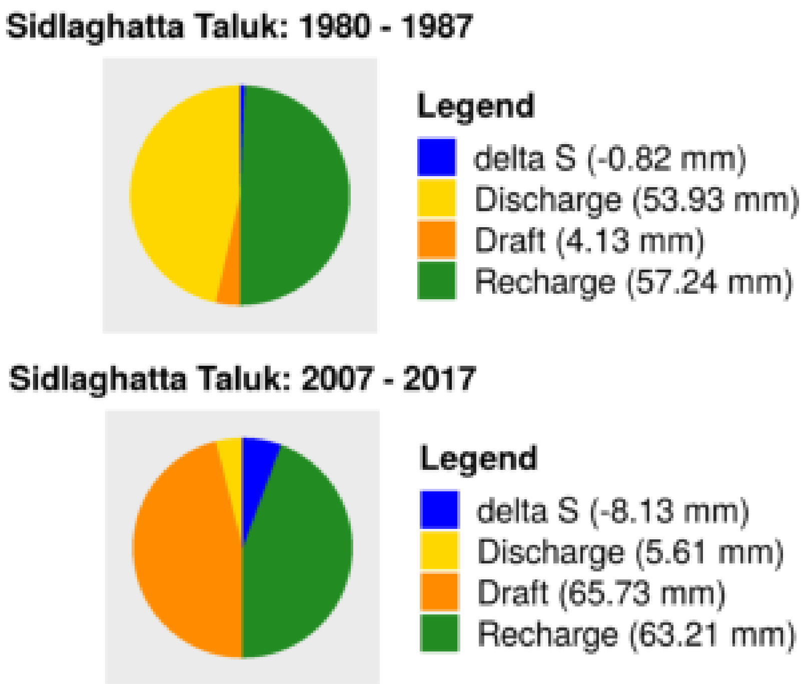


Figure 85: Storage change for Sidlaghatta taluk in periods (1980-1987) & (2007-2017)

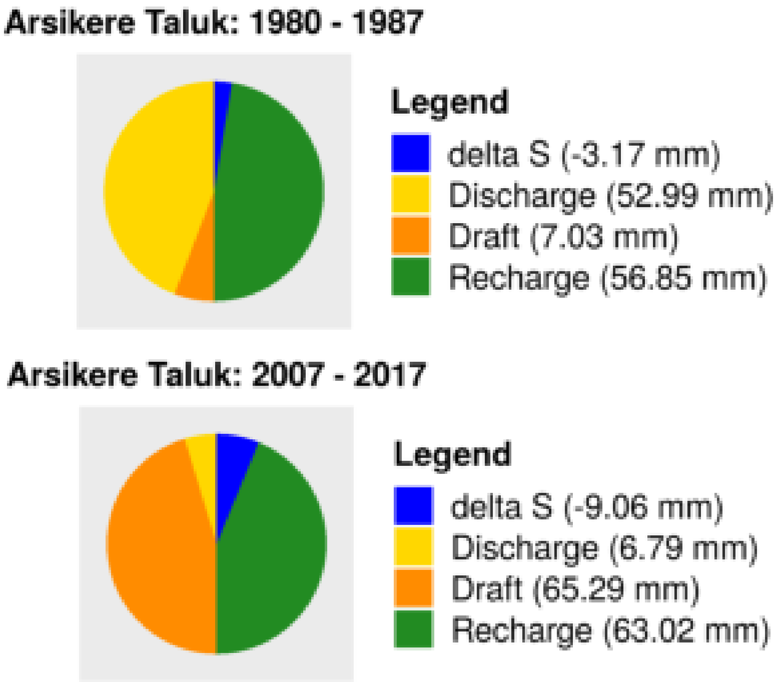


Figure 86: Storage change for Arsikere taluk in period (1980-1987) and period (2007-2017)

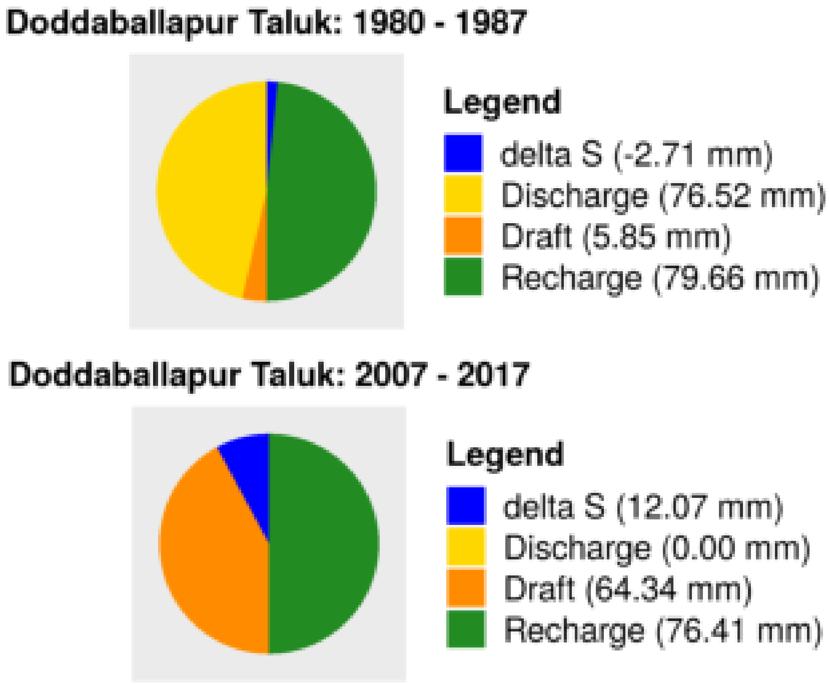


Figure 87: Storage change for Doddaballapur taluk in (1980-1987) & (2007-2017)

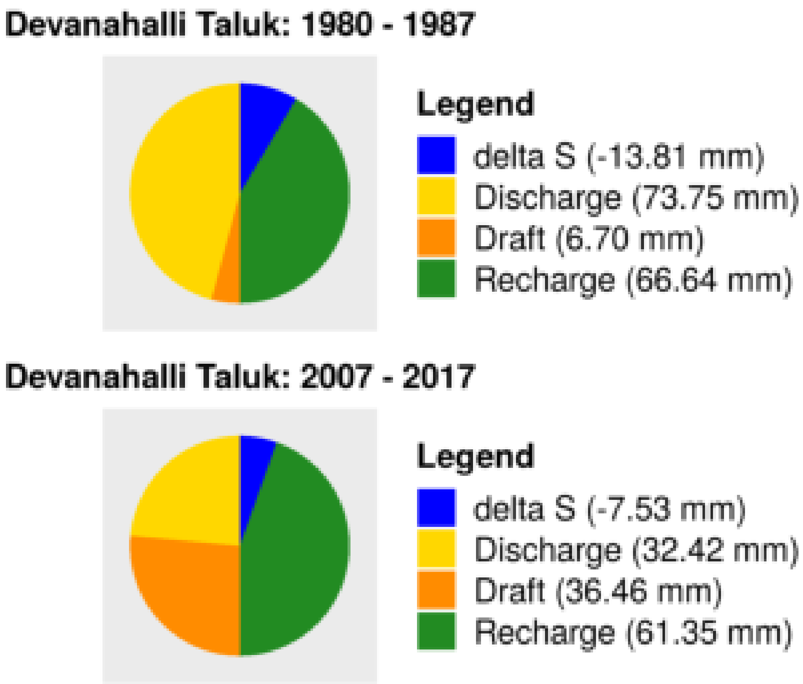


Figure 88: Storage change for Devanahalli taluk in periods (1980-1987) & (2007-2017)

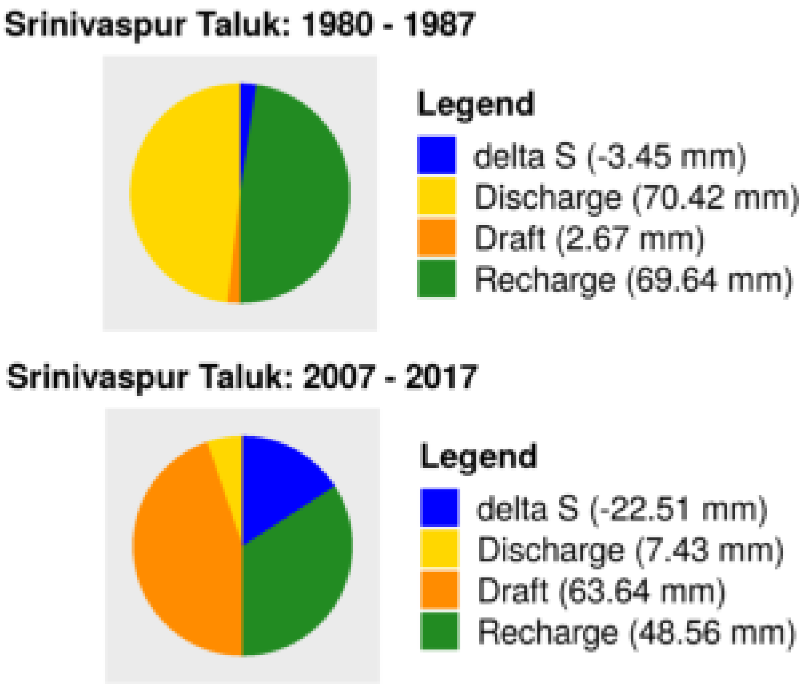


Figure 89: Storage change for Srinivaspur taluk in periods (1980-1987) & (2007-2017)

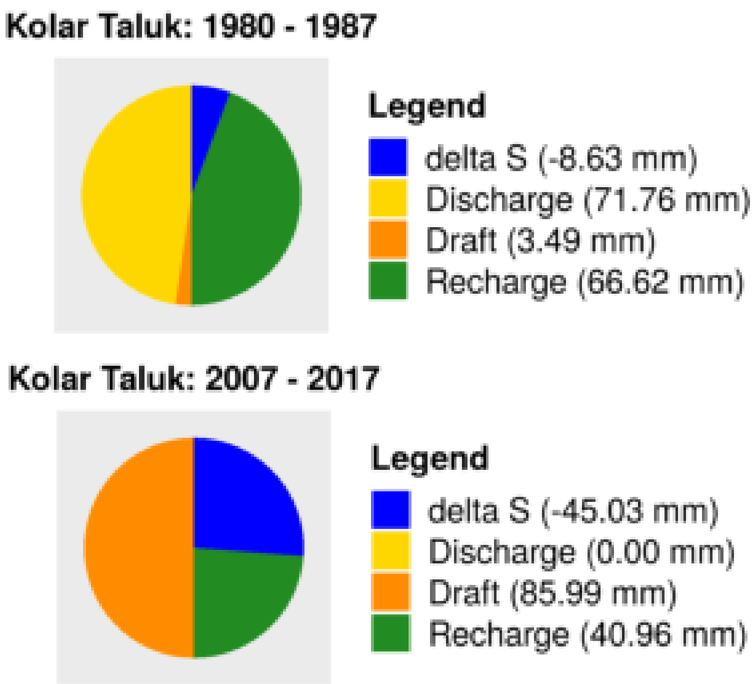


Figure 90: Storage change for Kolar taluk in periods (1980-1987) & (2007-2017)

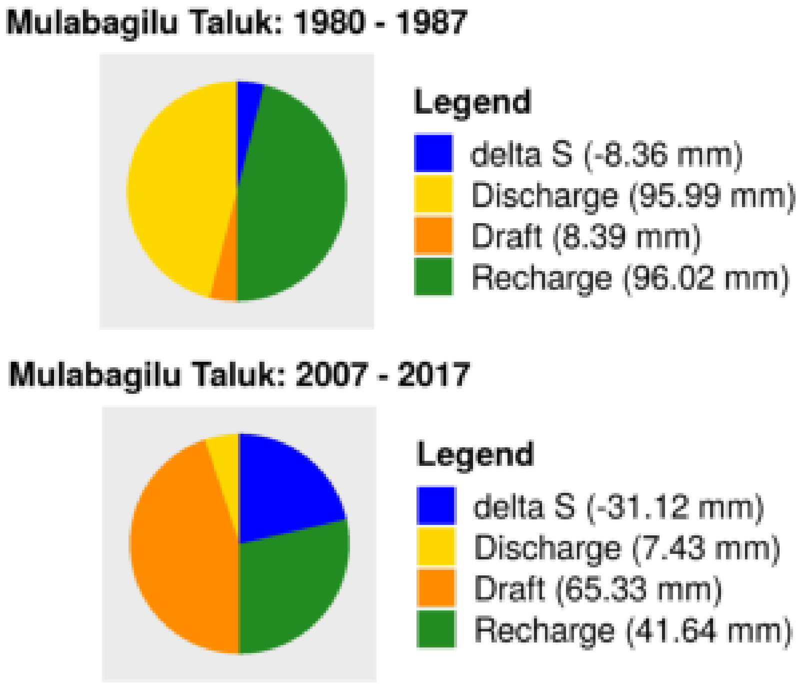


Figure 91: Storage change for Mulabagilu taluk in periods (1980-1987) & (2007-2017)

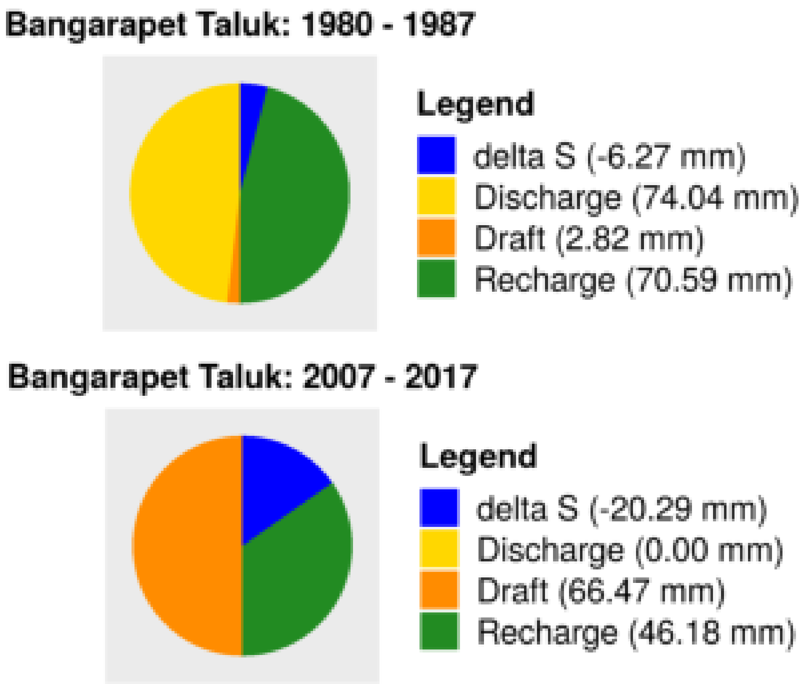


Figure 92: Storage change for Bangarapet taluk in periods (1980-1987) & (2007-2017)

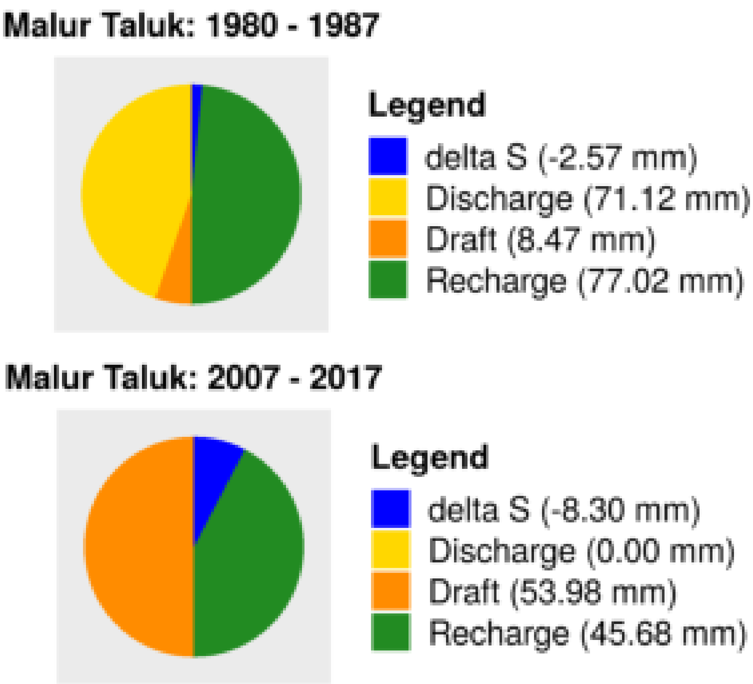


Figure 93: Storage change for Malur taluk in period (1980-1987) and period (2007-2017)

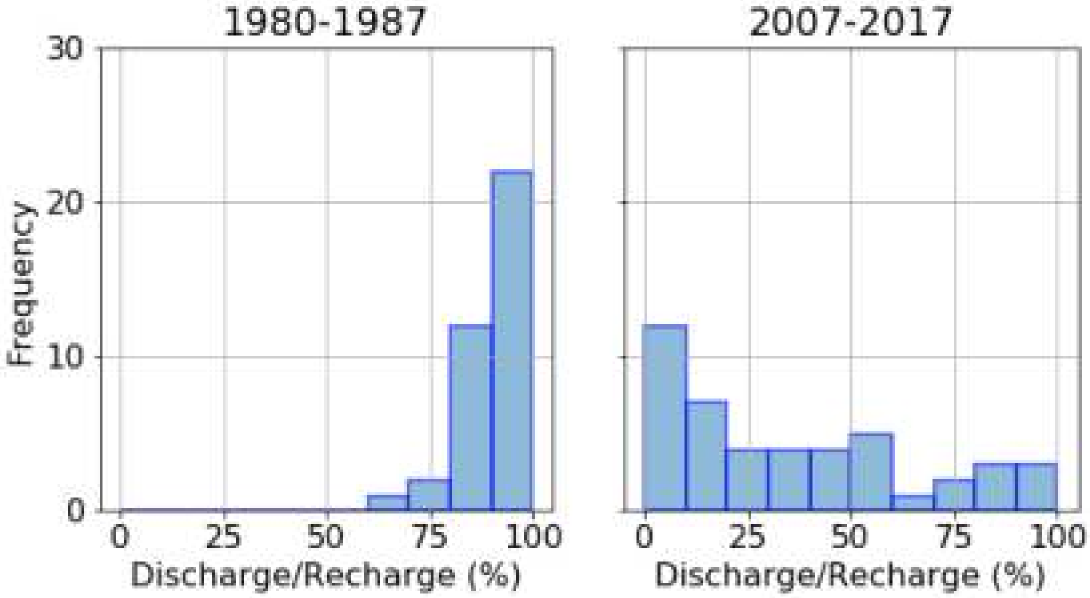


Figure 94: Histogram of the ratio of discharge to recharge over the two periods in 45 taluks.

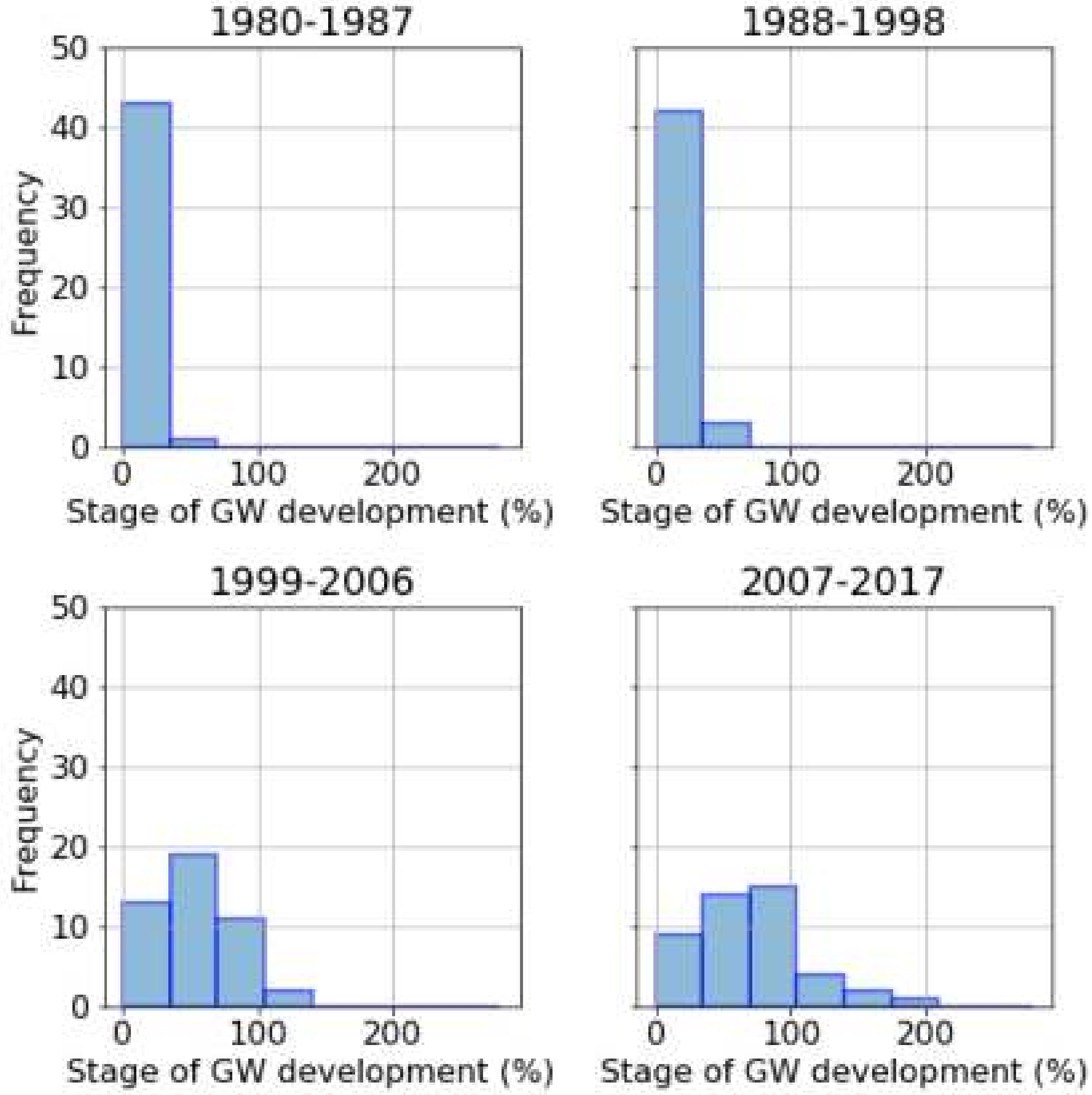


Figure 95: Histogram of the stage of groundwater development over the four periods.

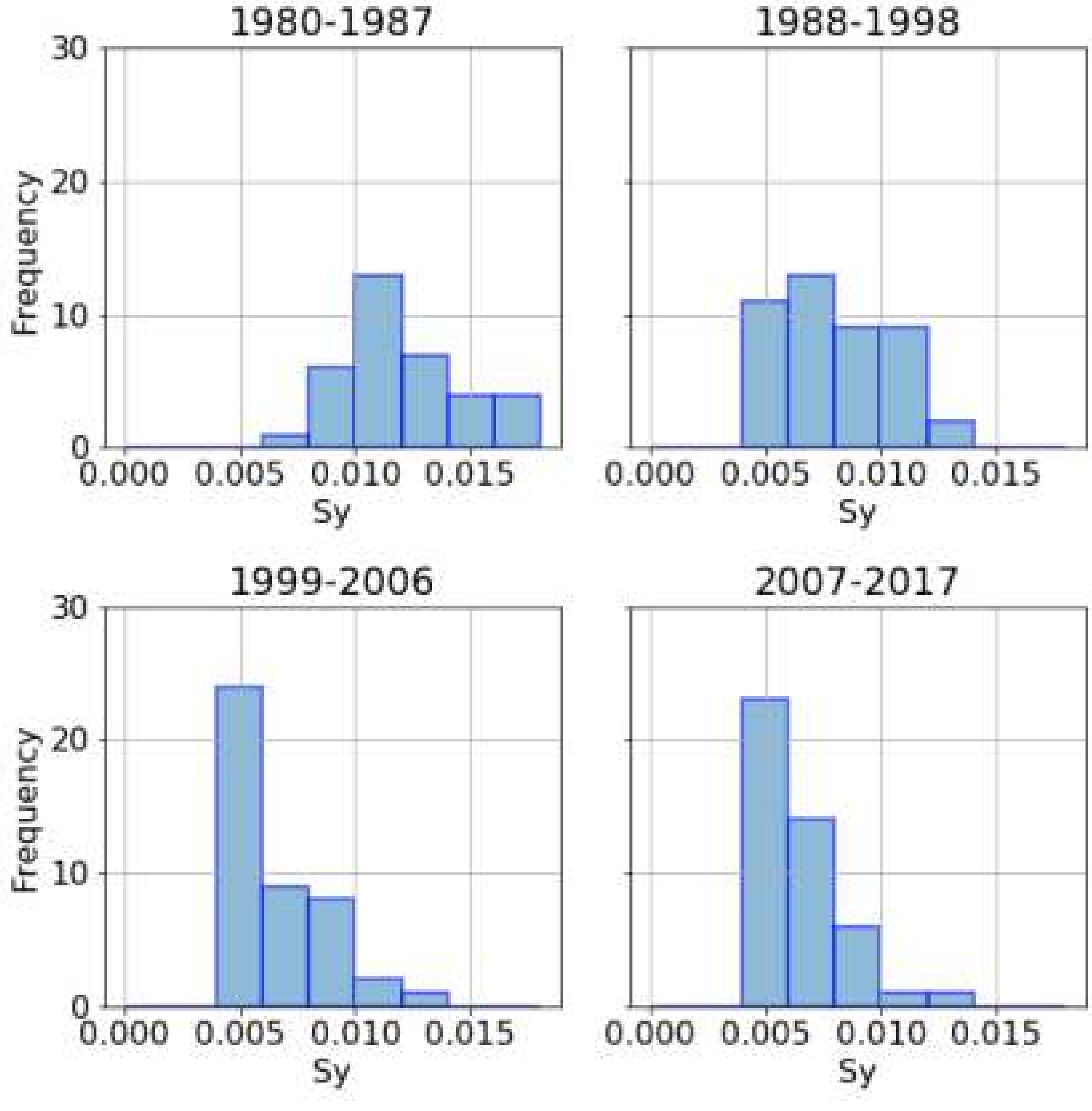


Figure 96: Histogram of the estimated specific yield over the four periods.

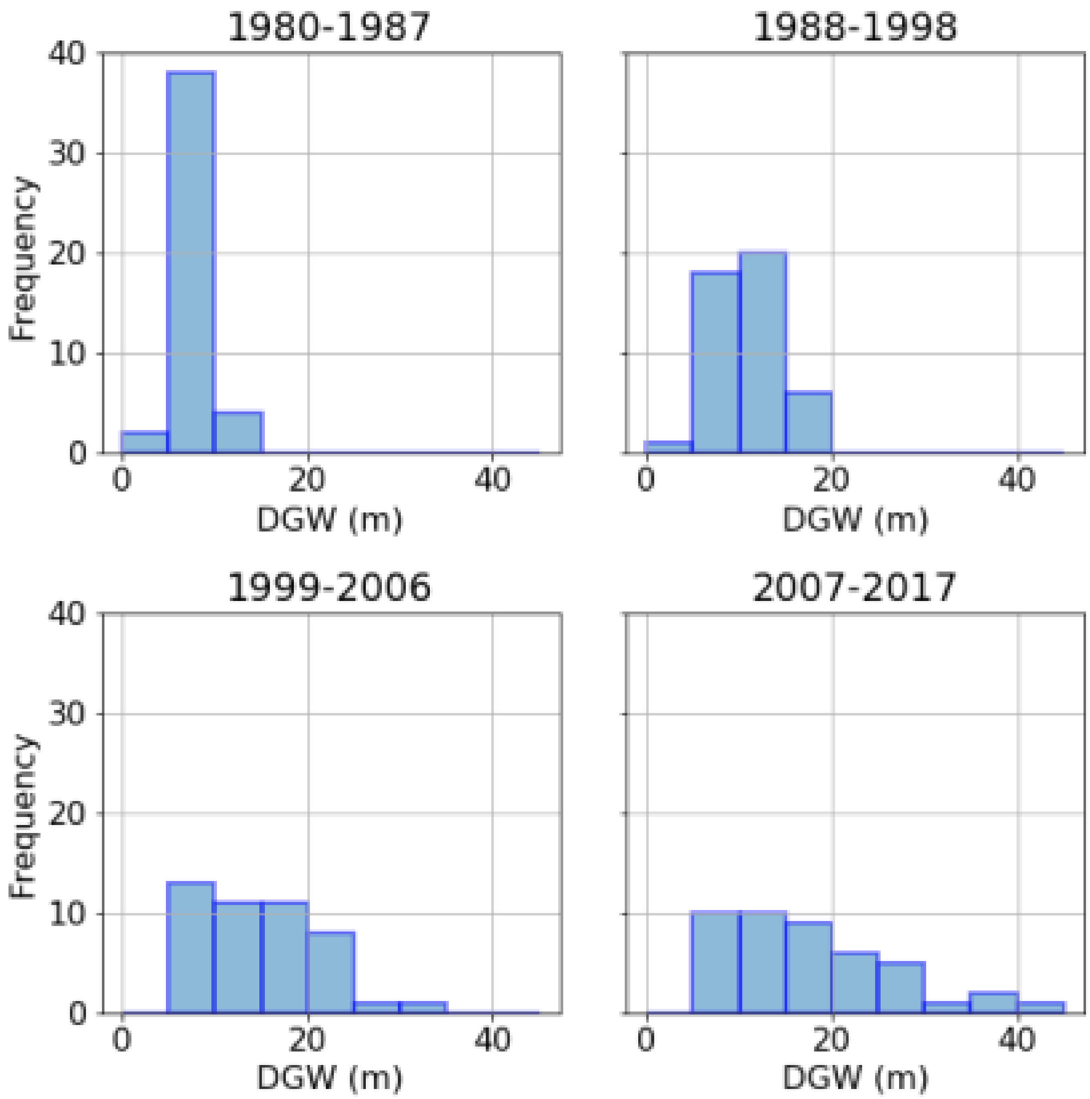
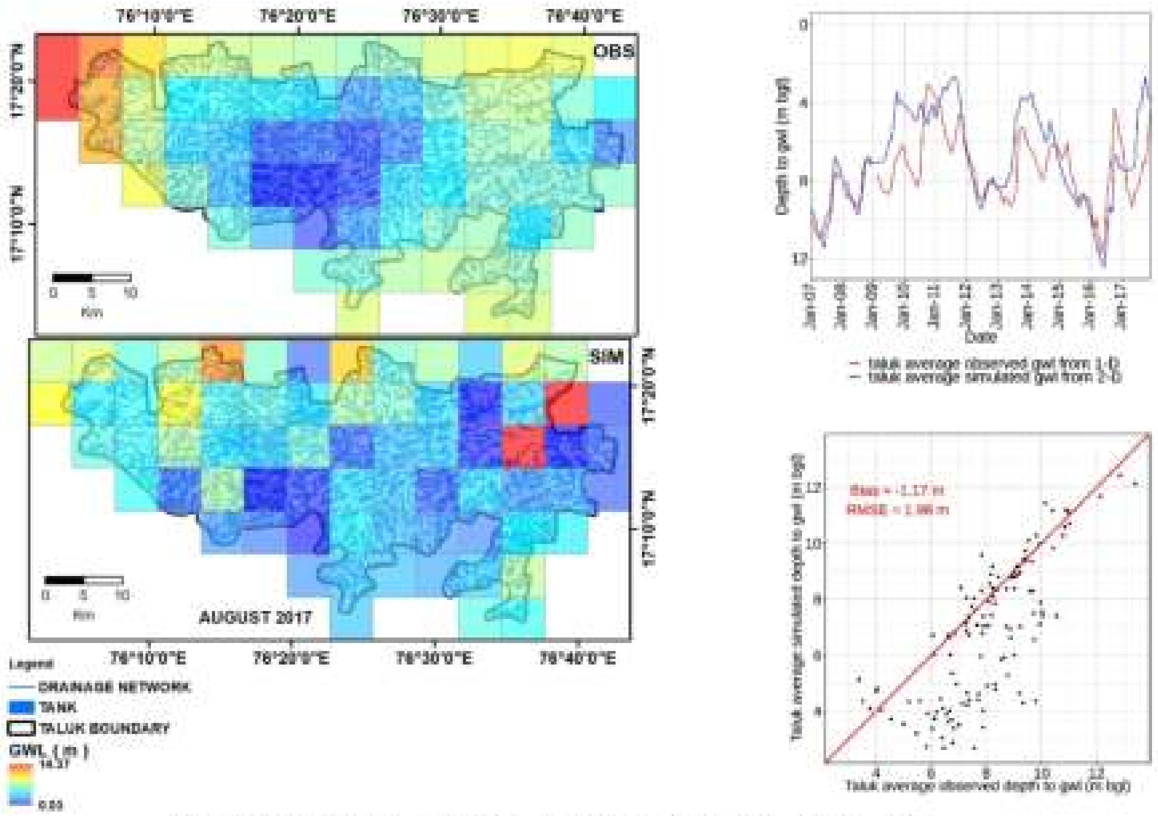


Figure 97: Histogram of the average depth to groundwater (DGW) table over the four periods.



Comparison of observed and simulated groundwater levels using 2D model for Afzalpur Taluk.

Figure 98: Comparison of observed versus simulated groundwater levels using 2D model for Afzalpur taluk.

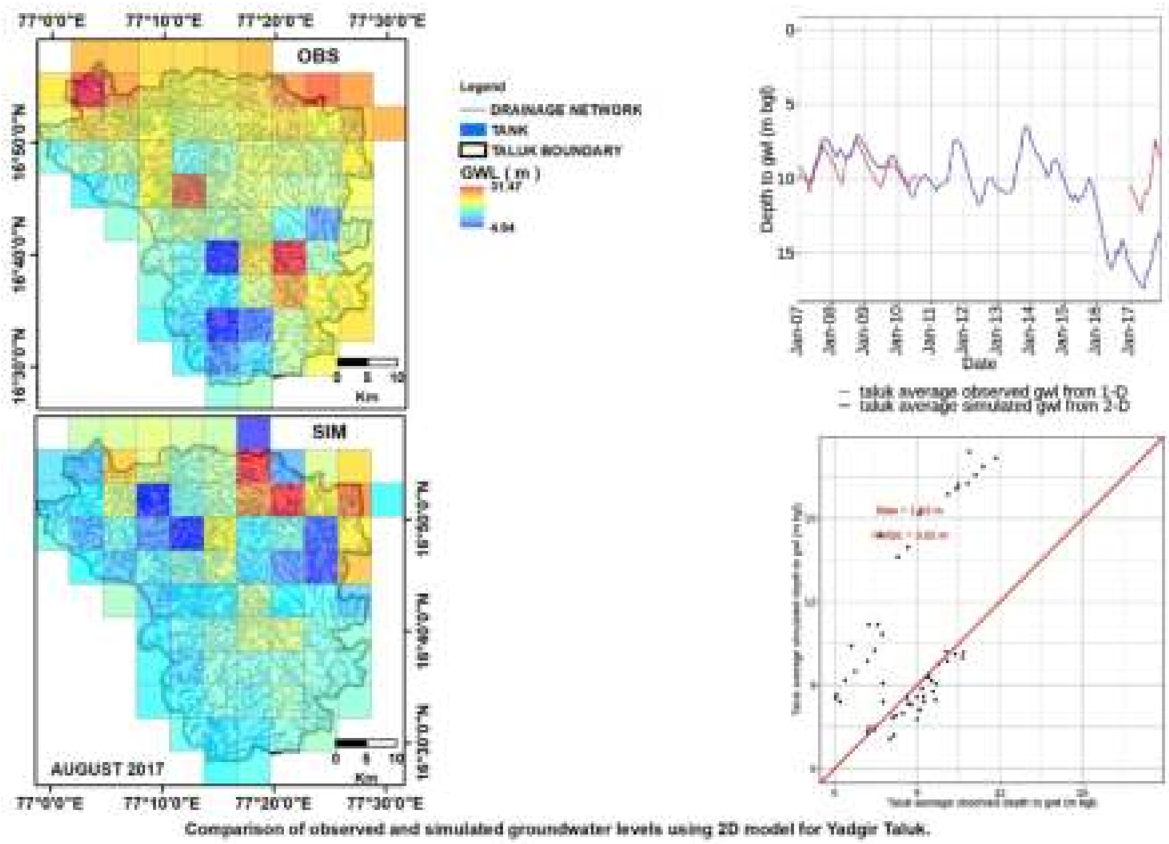


Figure 99: Comparison of observed versus simulated groundwater levels using 2D model for Yadgir taluk.

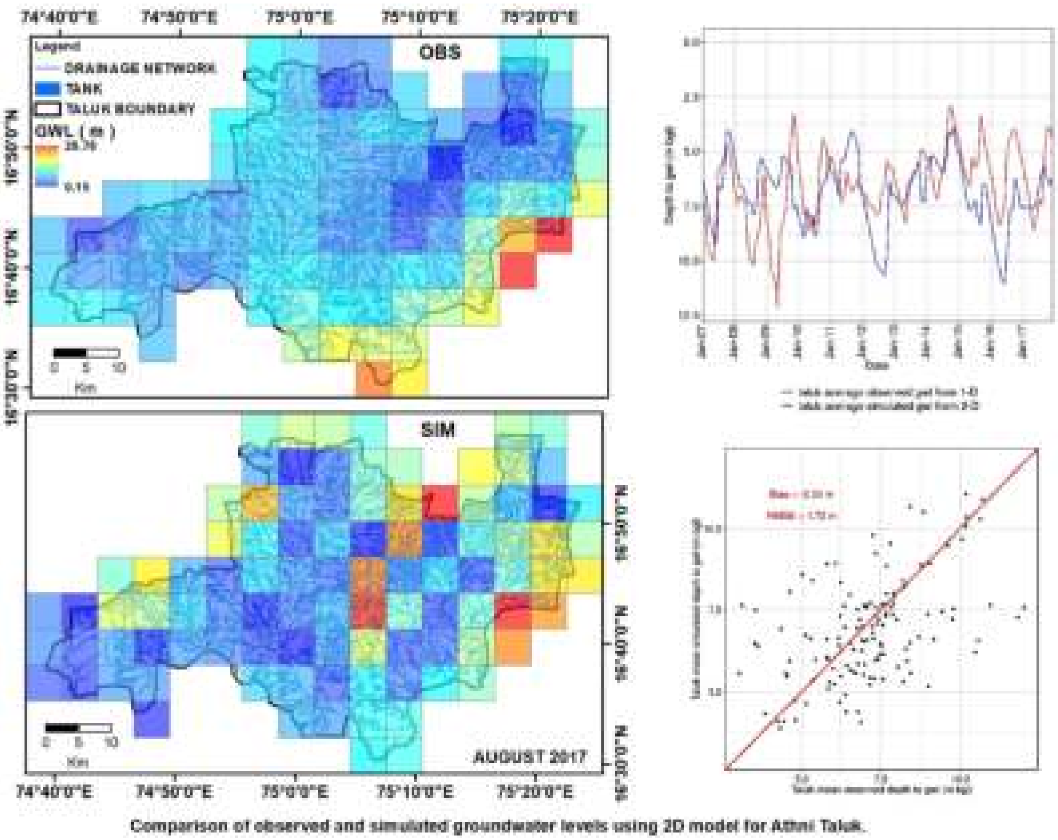


Figure 100: Comparison of observed versus simulated groundwater levels using 2D model for Athani taluk.

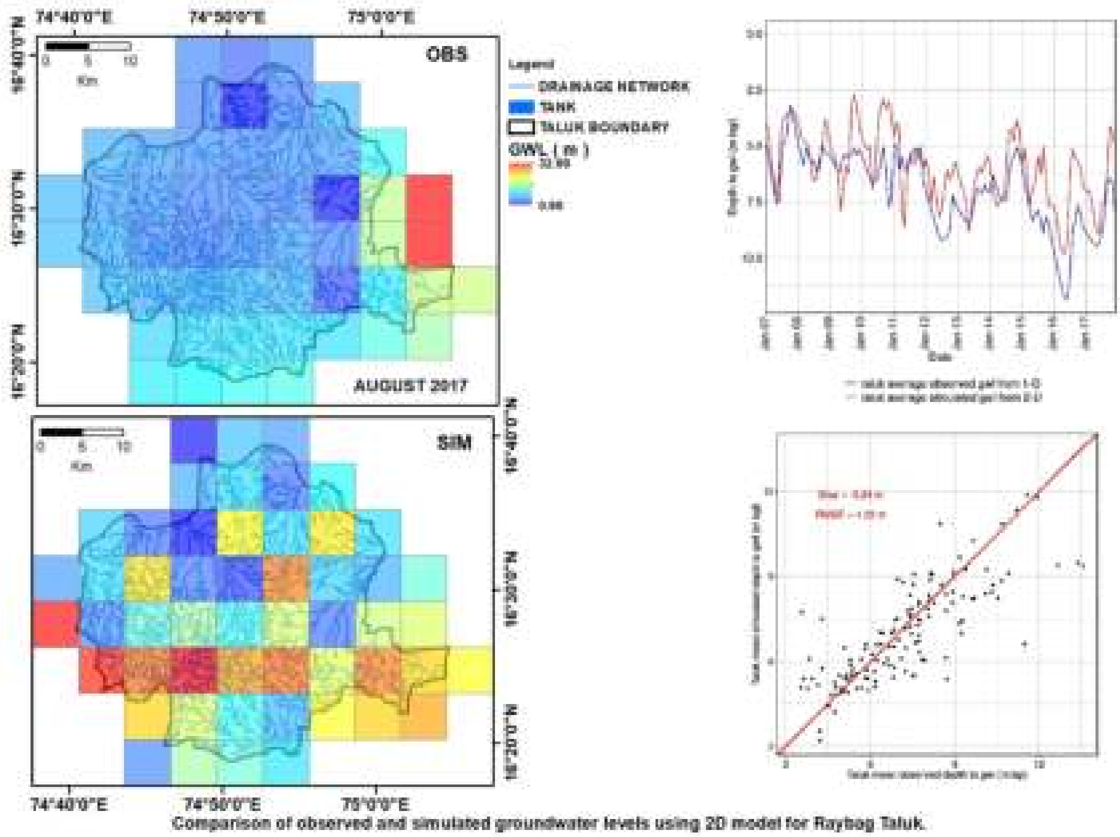


Figure 101: Comparison of observed versus simulated groundwater levels using 2D model for Raybag taluk.

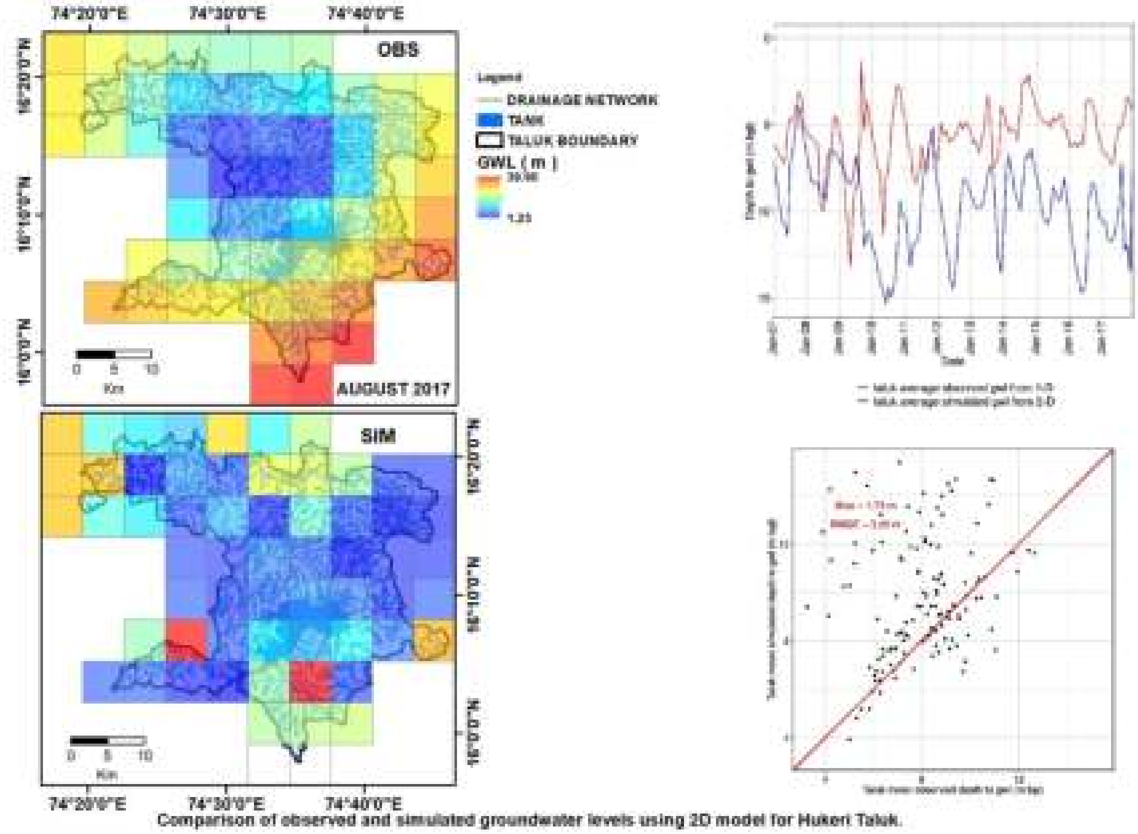


Figure 102: Comparison of observed versus simulated groundwater levels using 2D model for Hukkeri taluk.

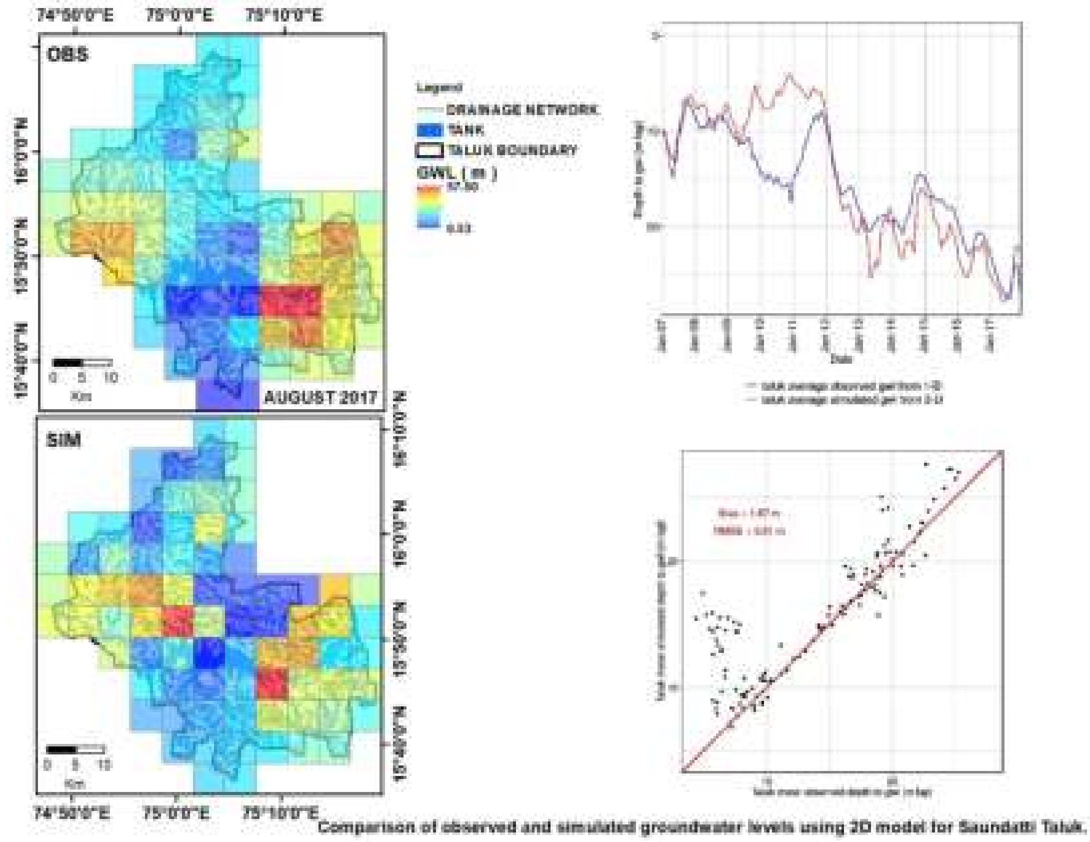


Figure 103: Comparison of observed versus simulated groundwater levels using 2D model for Saundatti taluk.

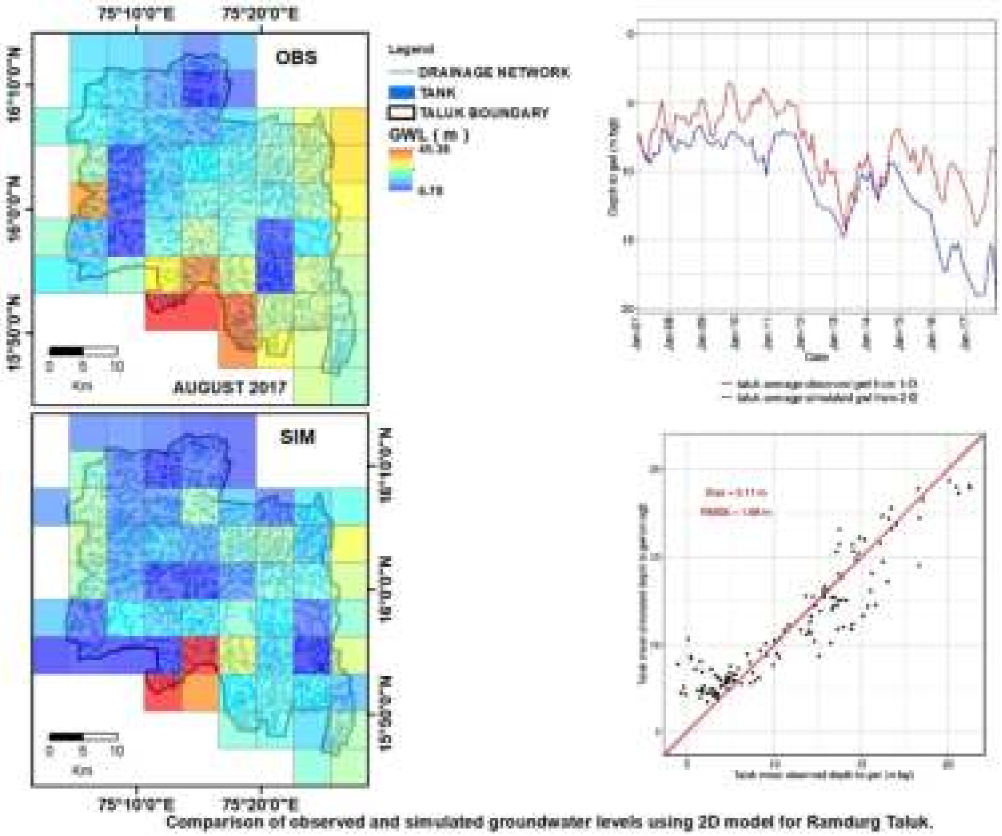


Figure 104: Comparison of observed versus simulated groundwater levels using 2D model for Ramadurg taluk.

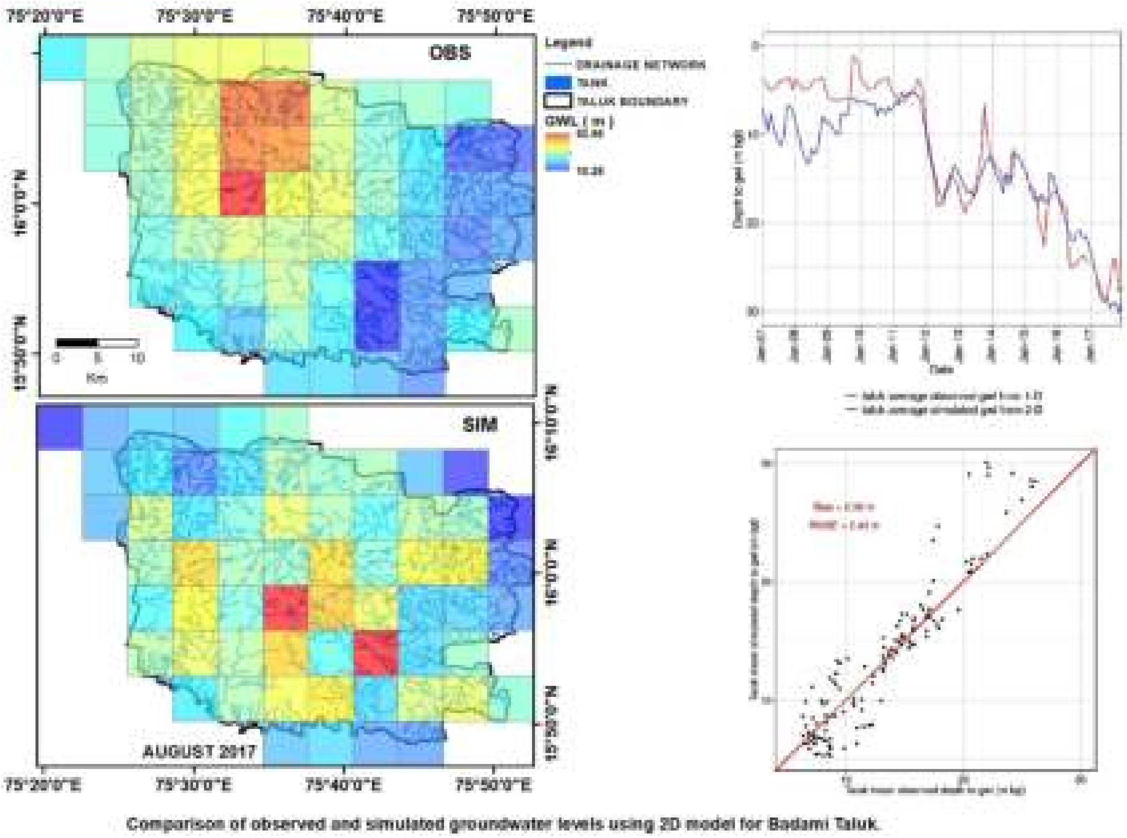


Figure 105: Comparison of observed versus simulated groundwater levels using 2D model for Badami taluk.

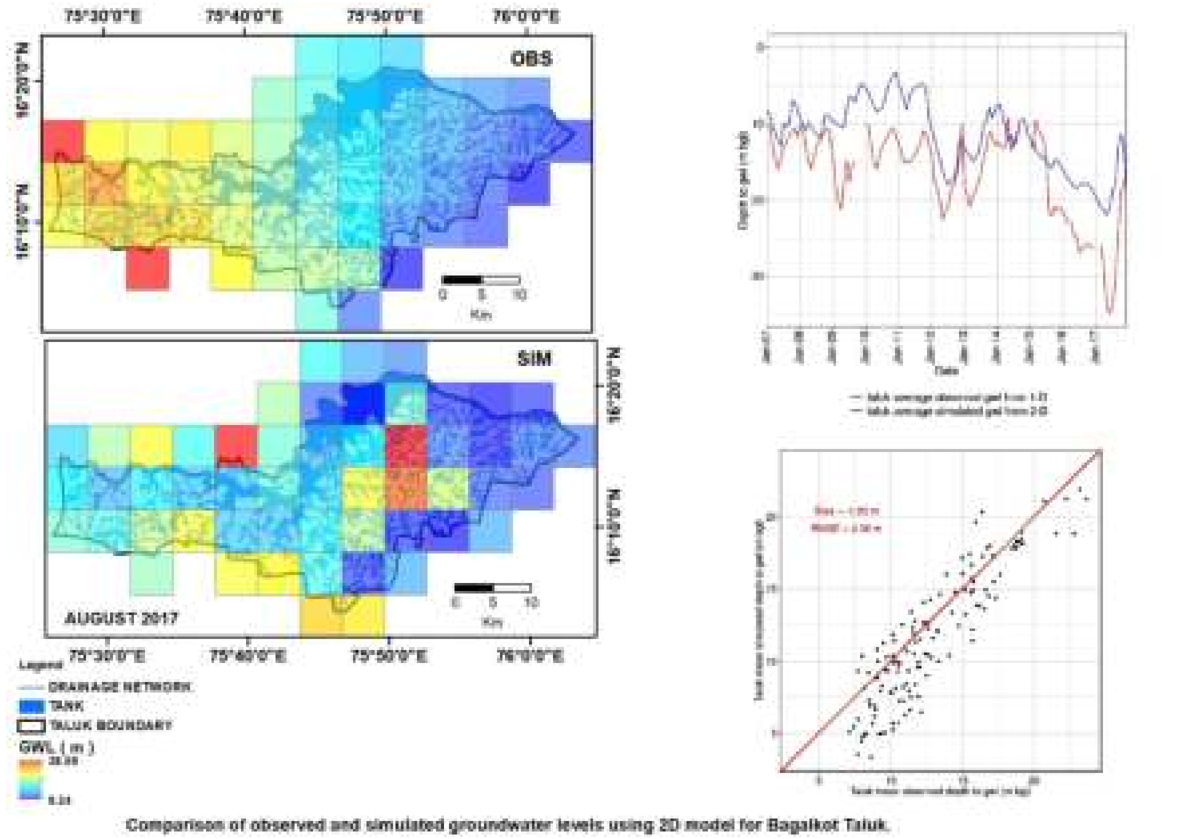


Figure 106: Comparison of observed versus simulated groundwater levels using 2D model for Bagalkot taluk.

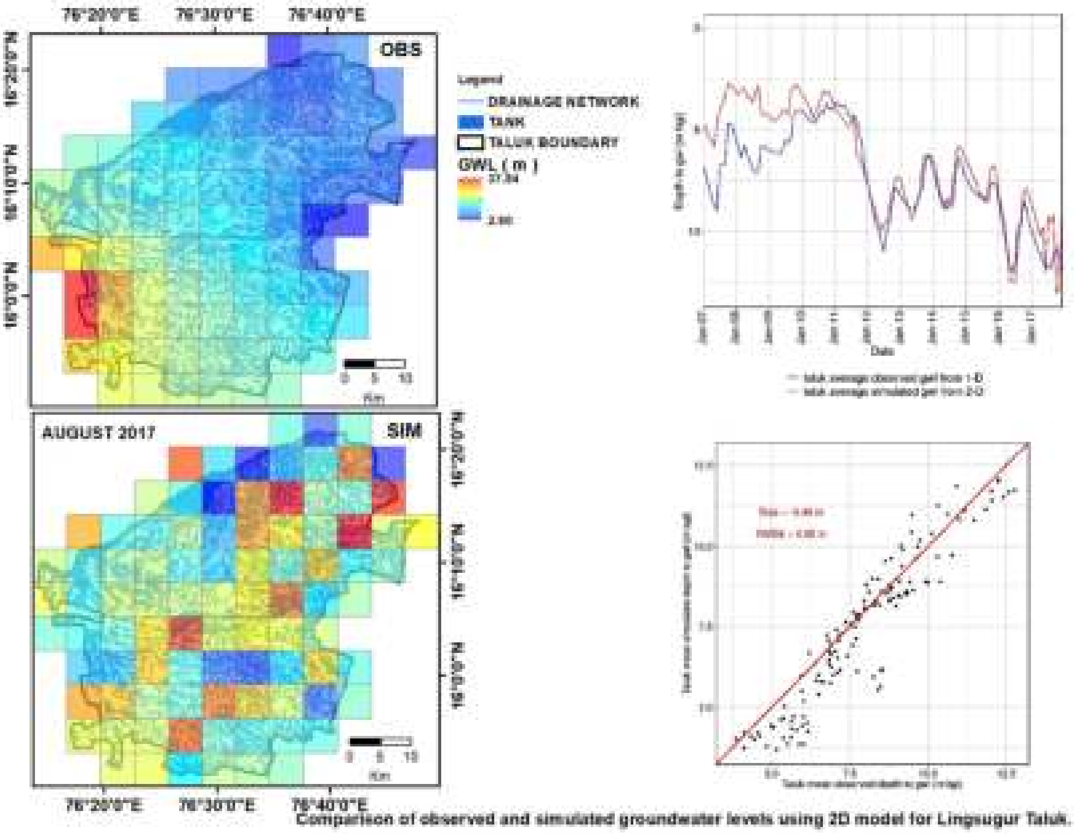


Figure 107: Comparison of observed versus simulated groundwater levels using 2D model for Lingasugur taluk.

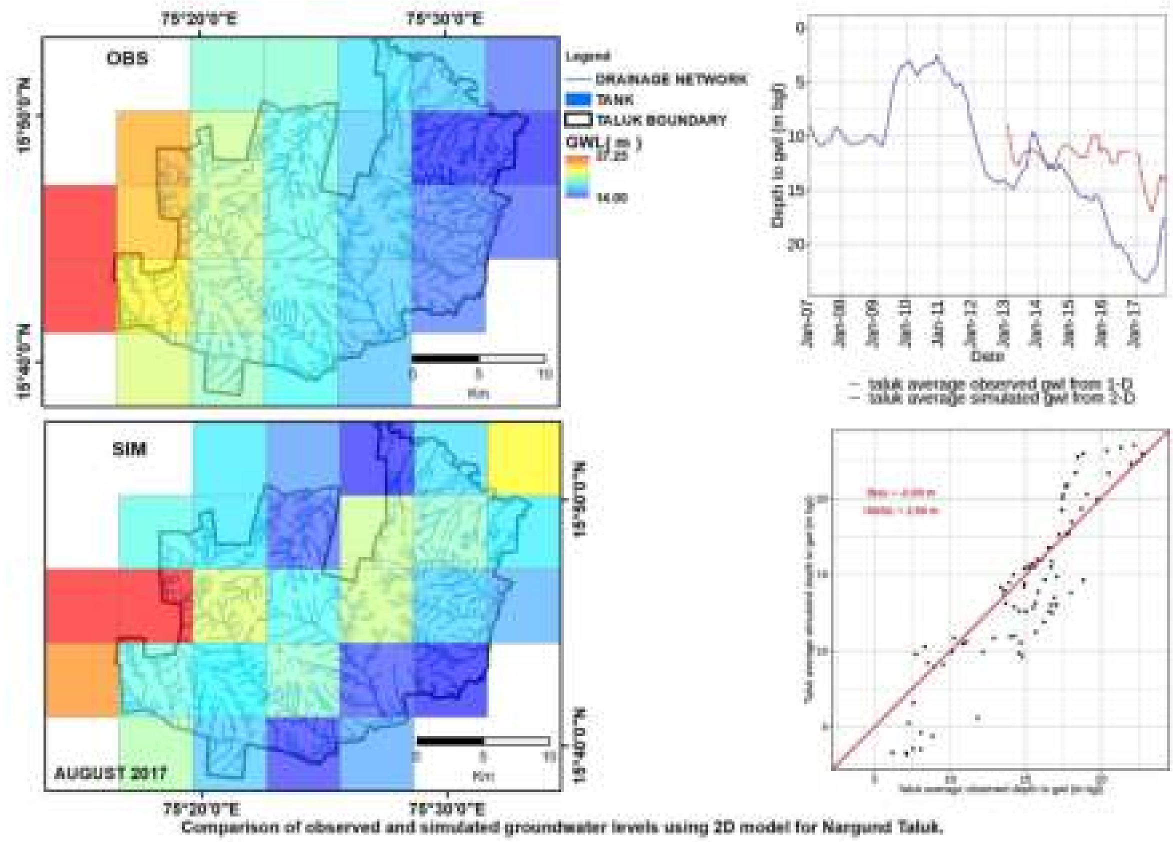
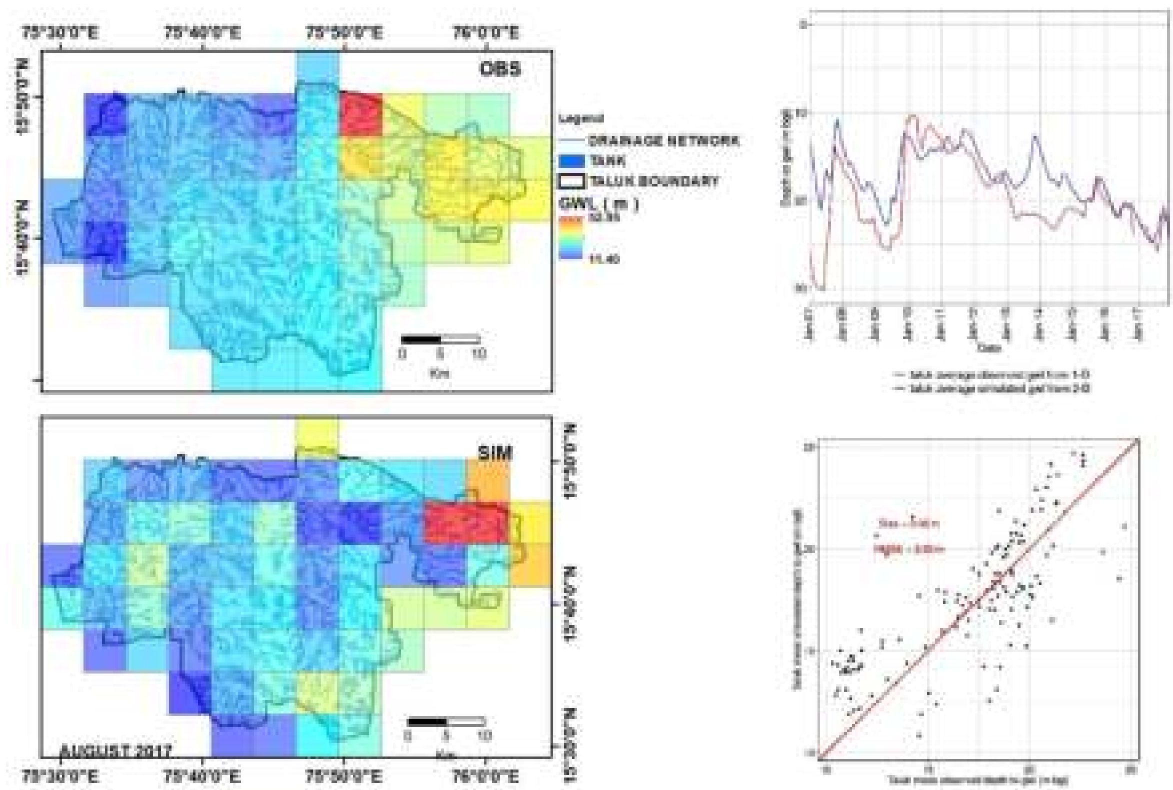
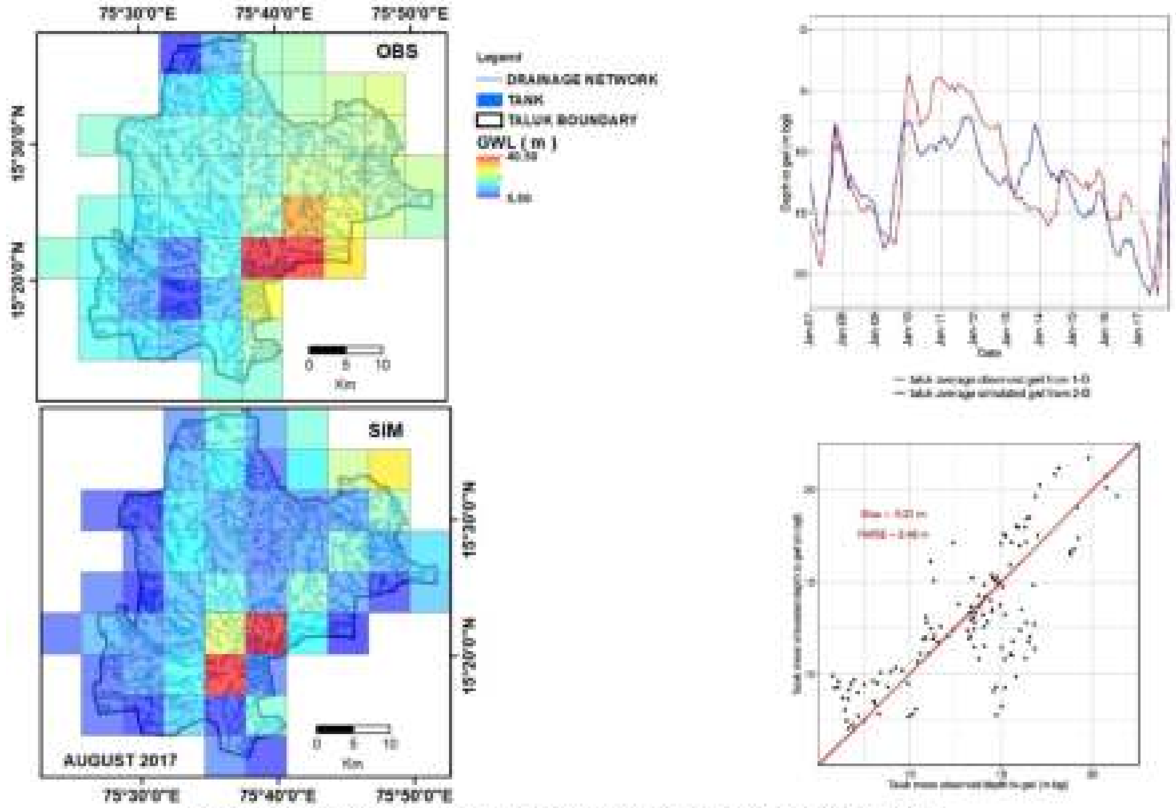


Figure 108: Comparison of observed versus simulated groundwater levels using 2D model for Nargund taluk.



Comparison of observed and simulated groundwater levels using 2D model for Ron Taluk.

Figure 109: Comparison of observed versus simulated groundwater levels using 2D model for Ron taluk.



Comparison of observed and simulated groundwater levels using 2D model for Gadag Taluk.

Figure 110: Comparison of observed versus simulated groundwater levels using 2D model for Gadag taluk.

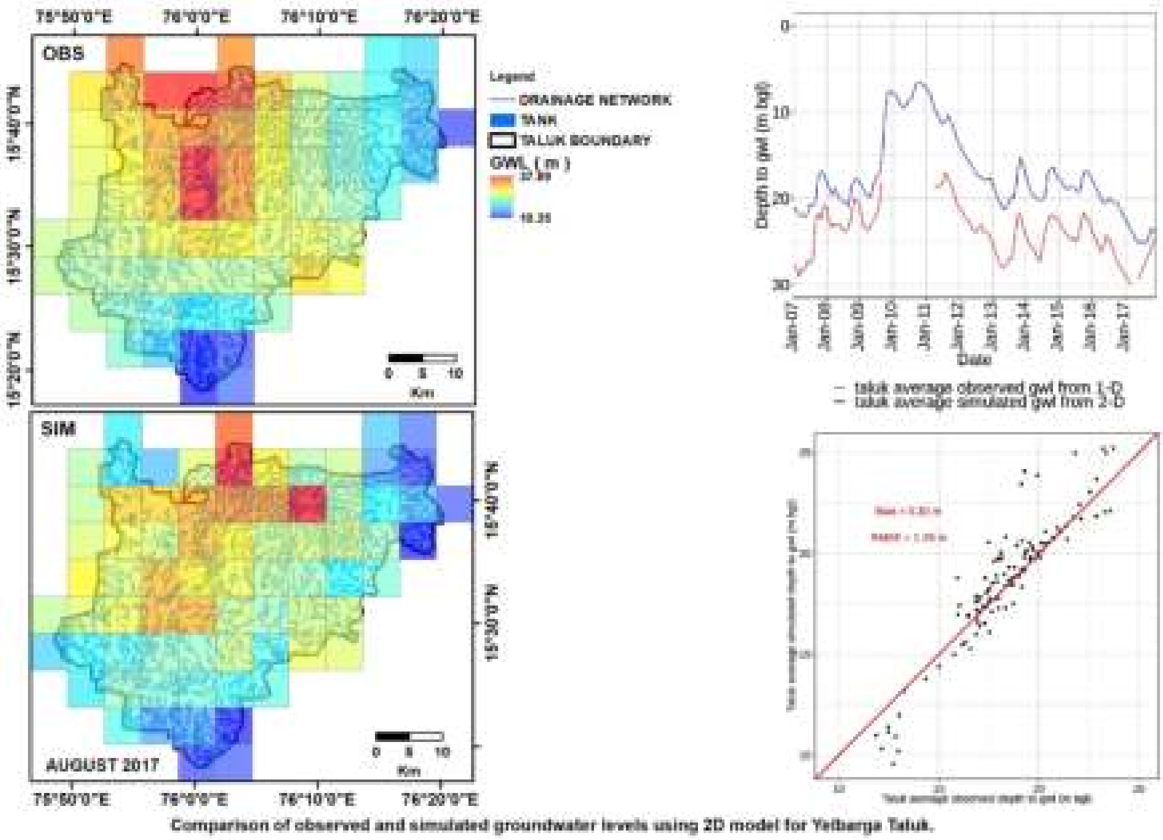


Figure 111: Comparison of observed versus simulated groundwater levels using 2D model for Yelburga taluk.

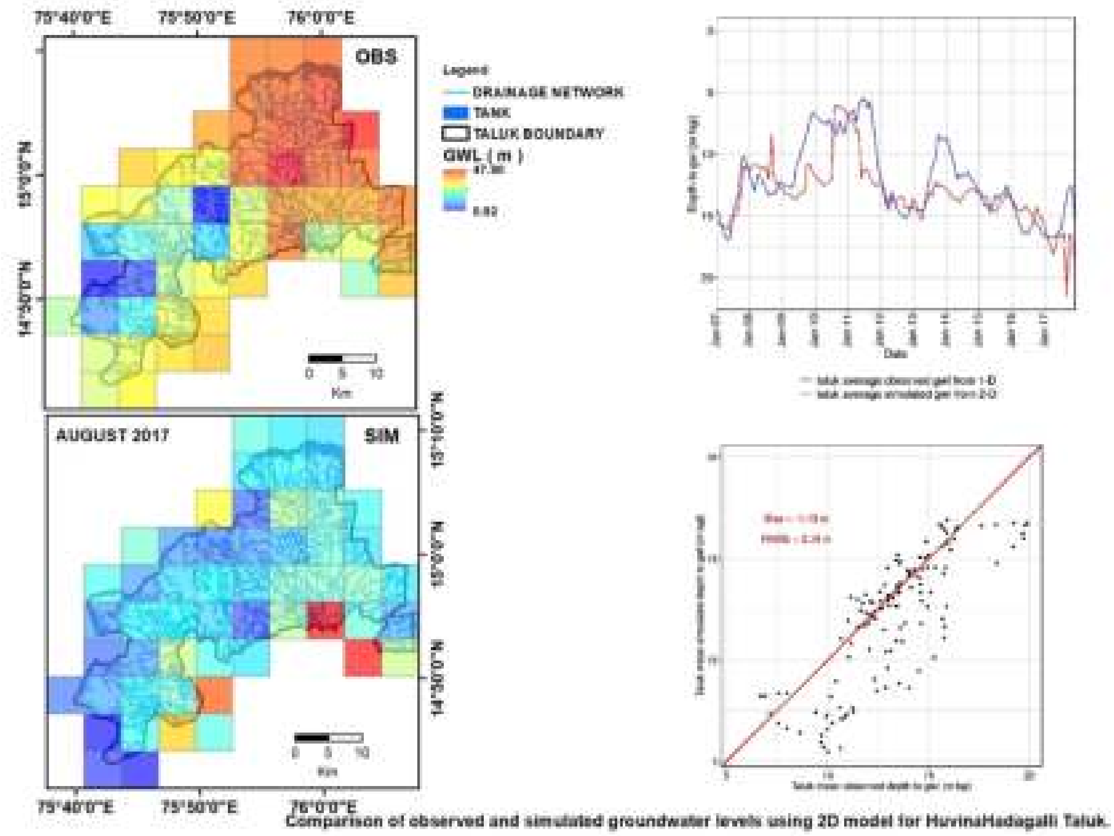


Figure 112: Comparison of observed versus simulated groundwater levels using 2D model for HuvinaHadagali taluk.

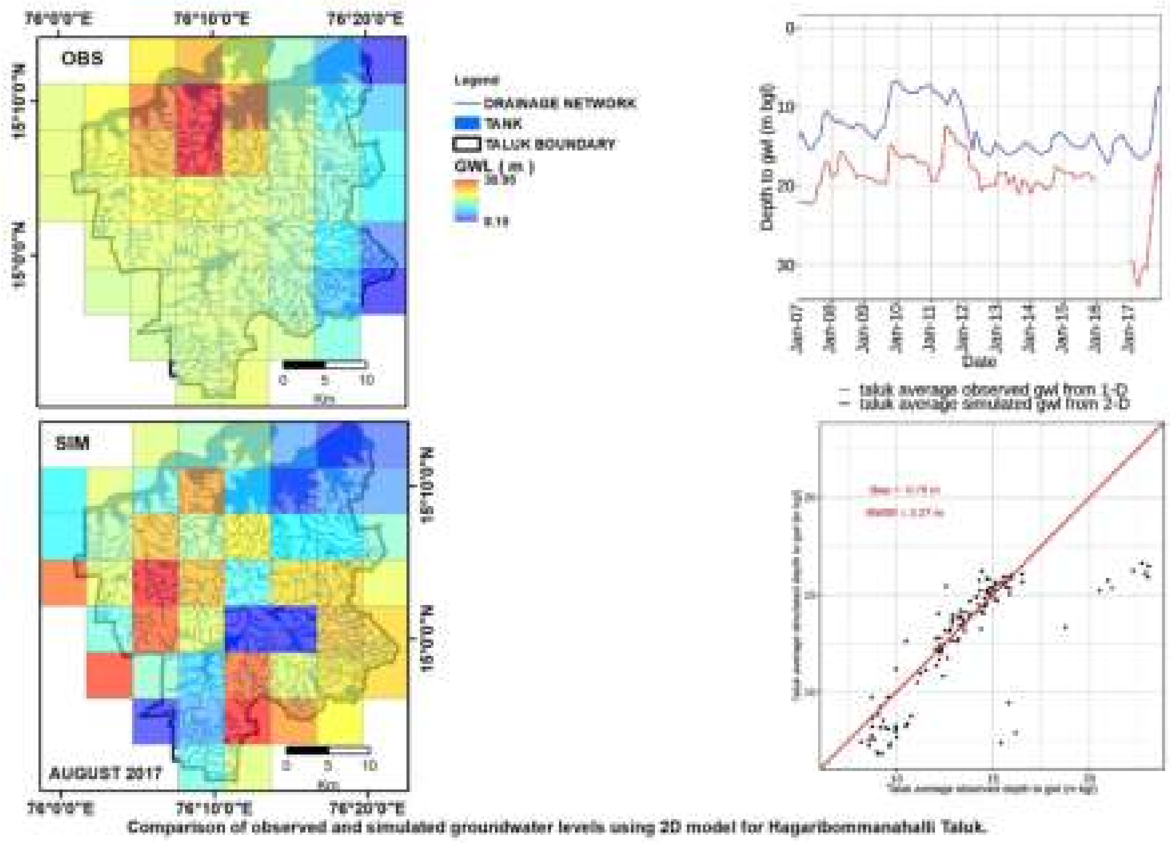


Figure 113: Comparison of observed versus simulated groundwater levels using 2D model for HagariBommanahalli taluk.

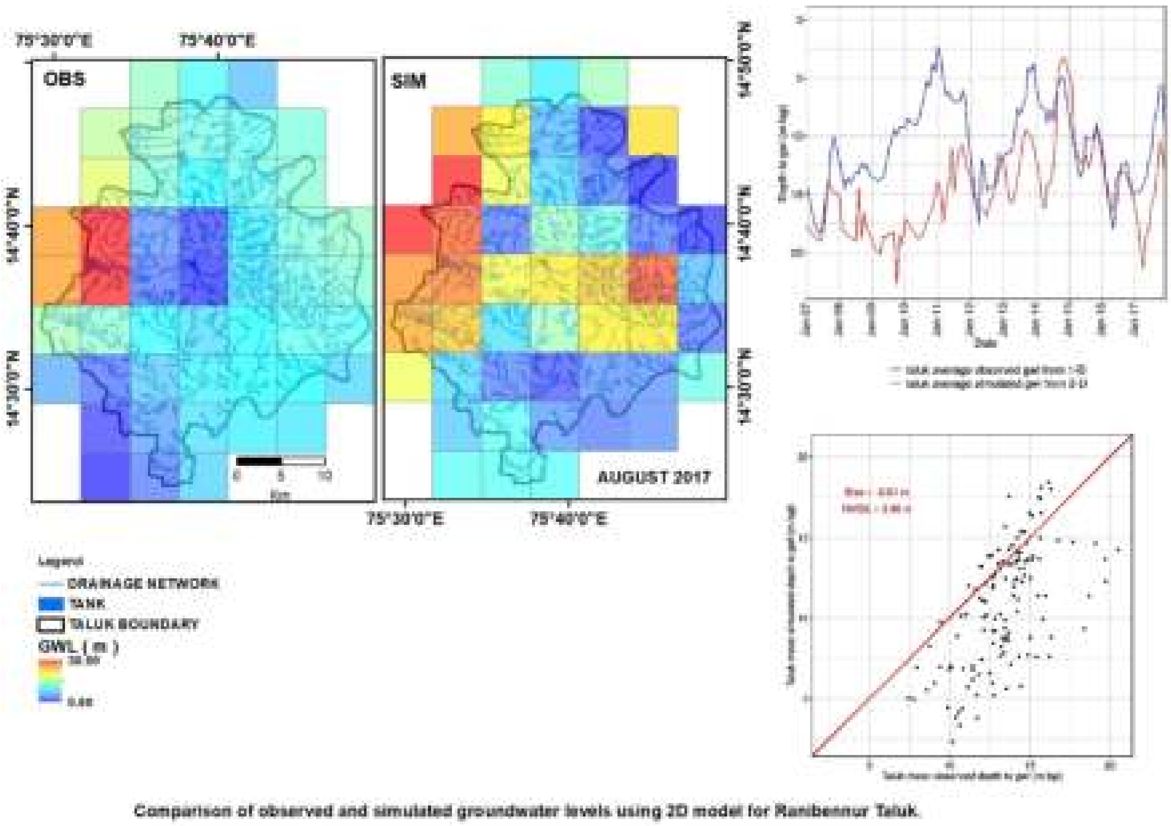


Figure 114: Comparison of observed versus simulated groundwater levels using 2D model for Ranebennuru taluk.

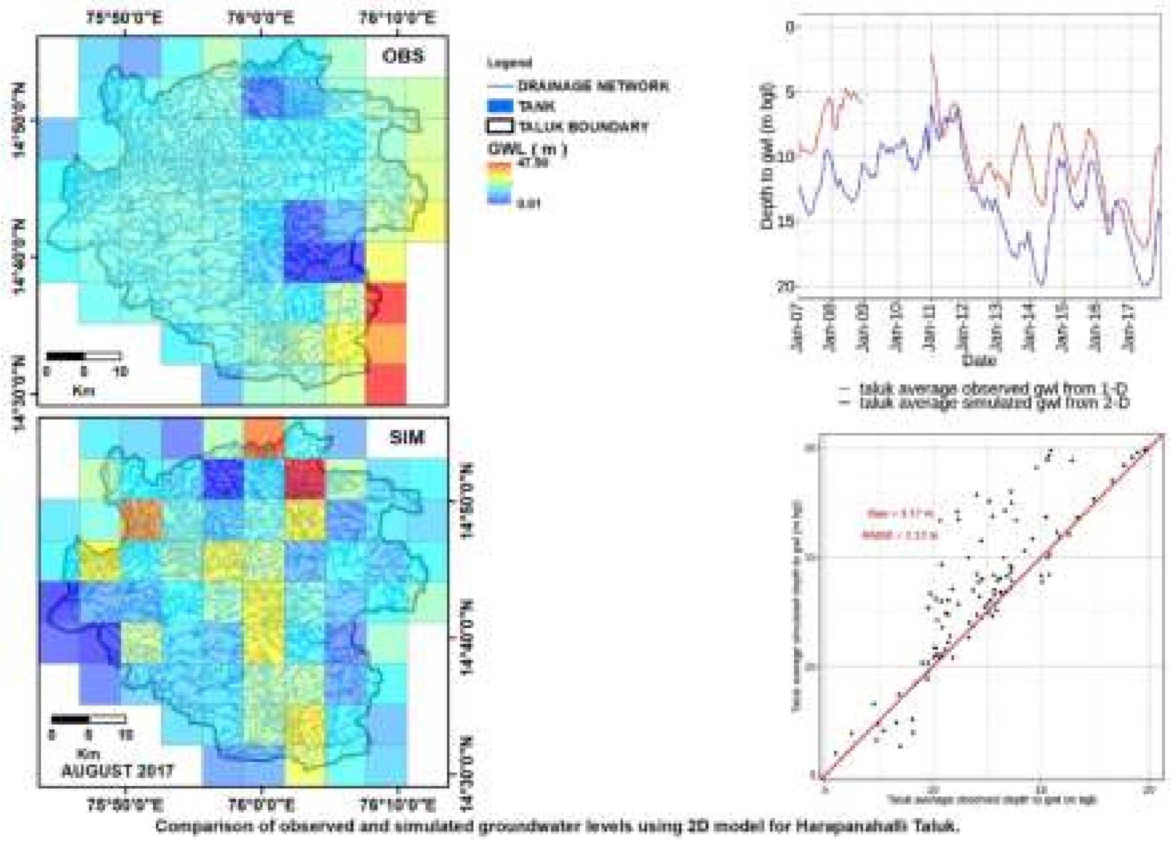


Figure 115: Comparison of observed versus simulated groundwater levels using 2D model for Harapanahalli taluk.

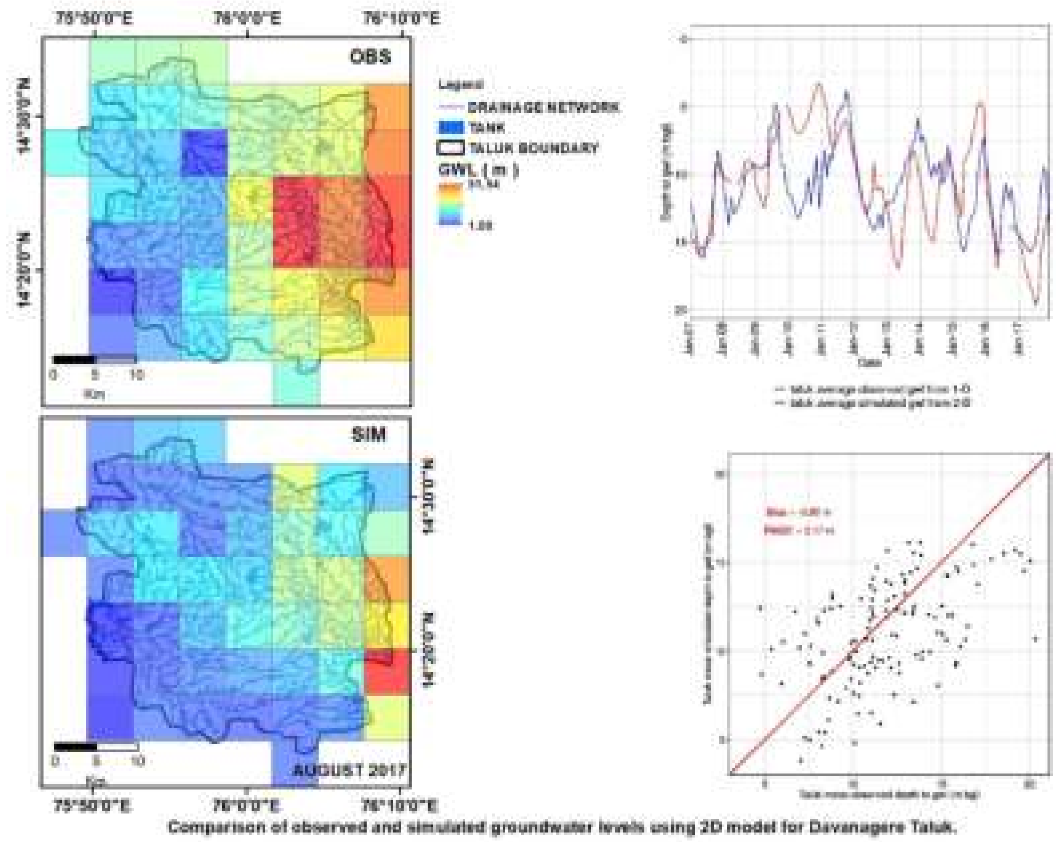


Figure 116: Comparison of observed versus simulated groundwater levels using 2D model for Devanagere taluk.

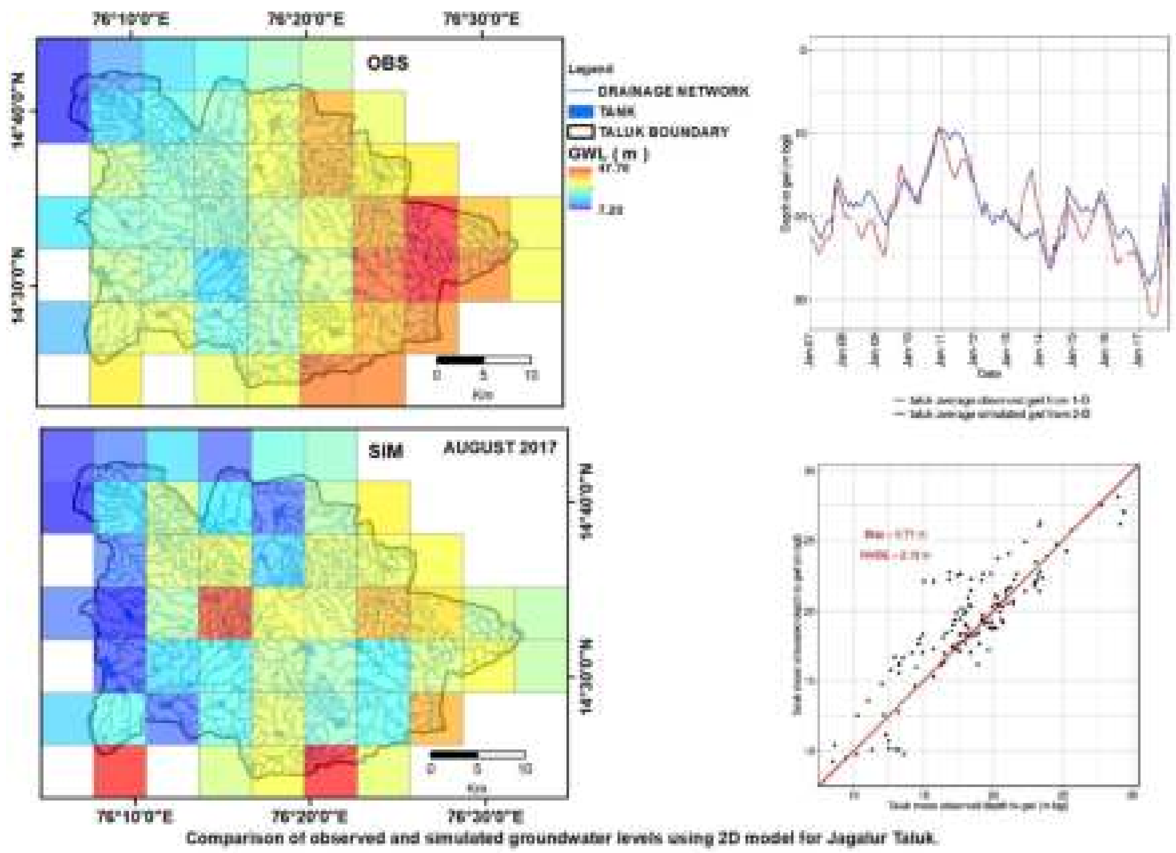


Figure 117: Comparison of observed versus simulated groundwater levels using 2D model for Jagalur taluk.

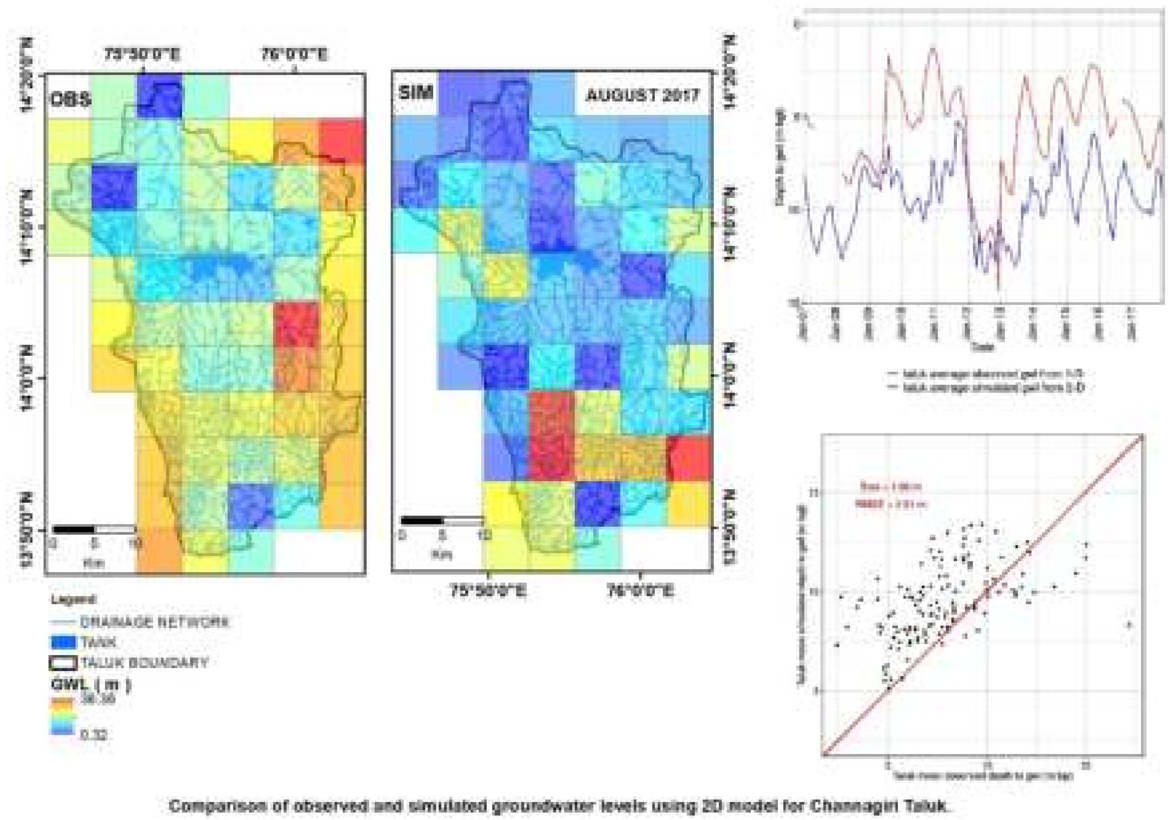


Figure 118: Comparison of observed versus simulated groundwater levels using 2D model for Channagiri taluk.

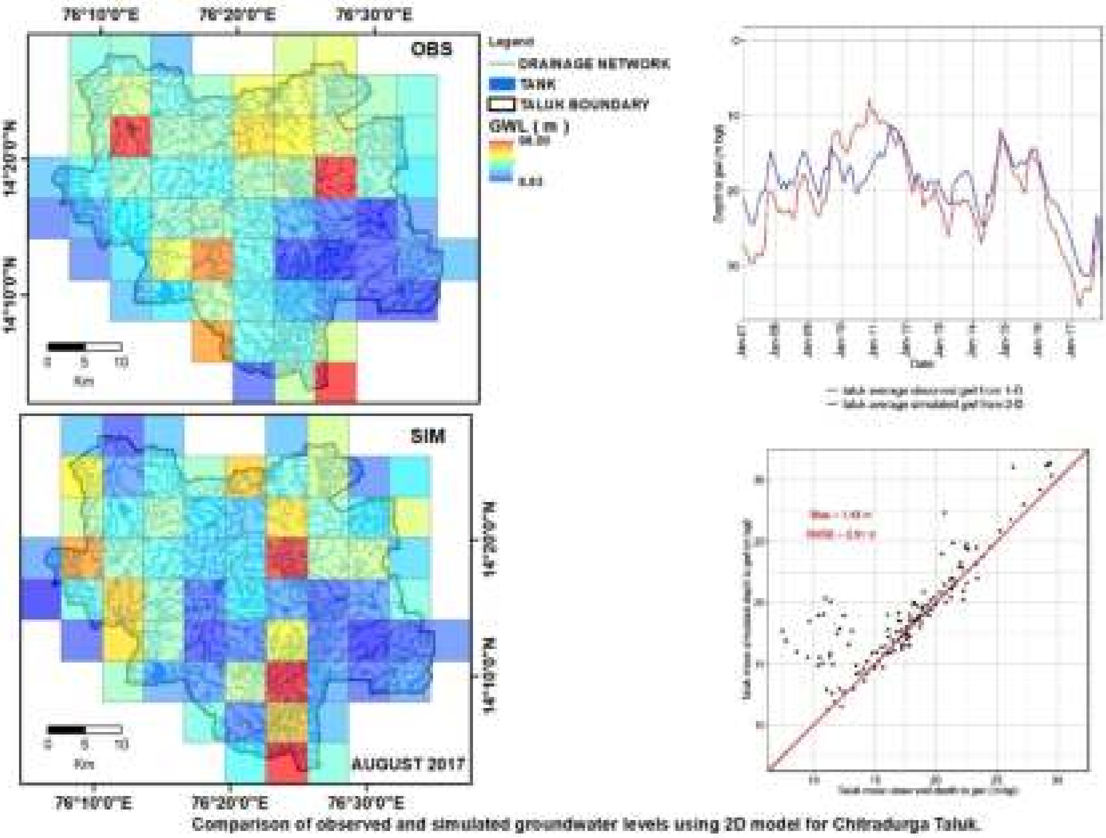


Figure 119: Comparison of observed versus simulated groundwater levels using 2D model for Chitradurga taluk.

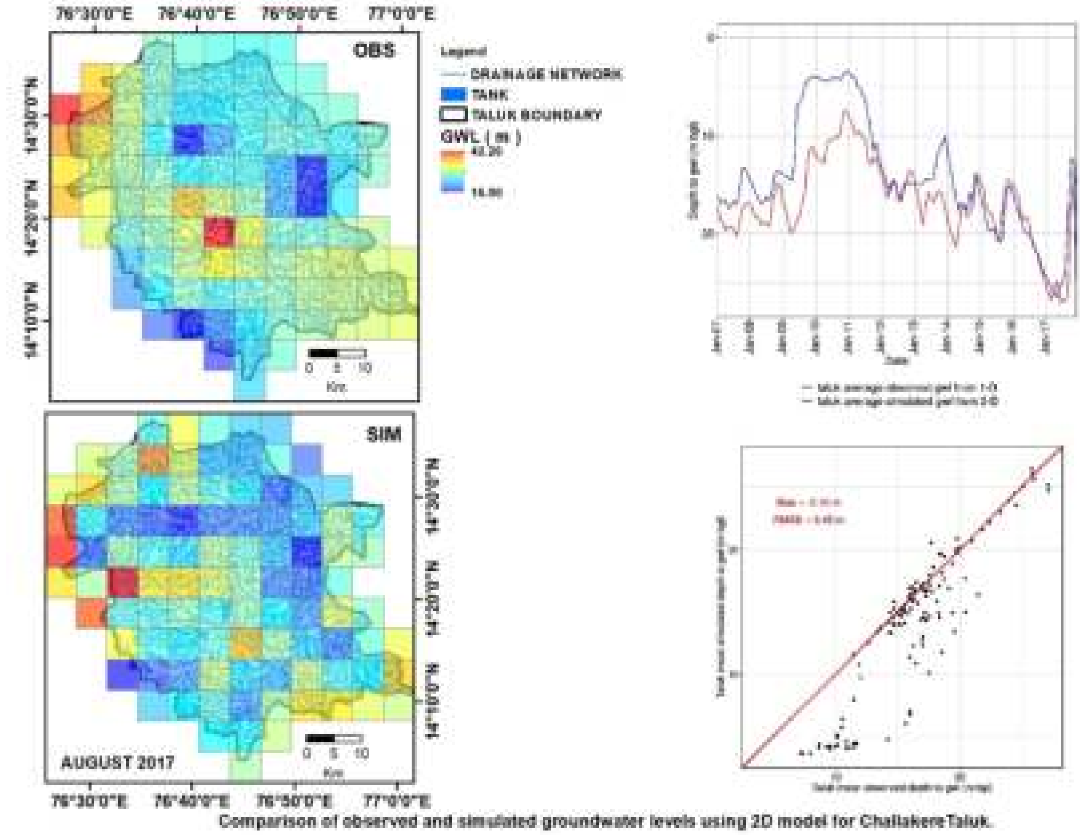
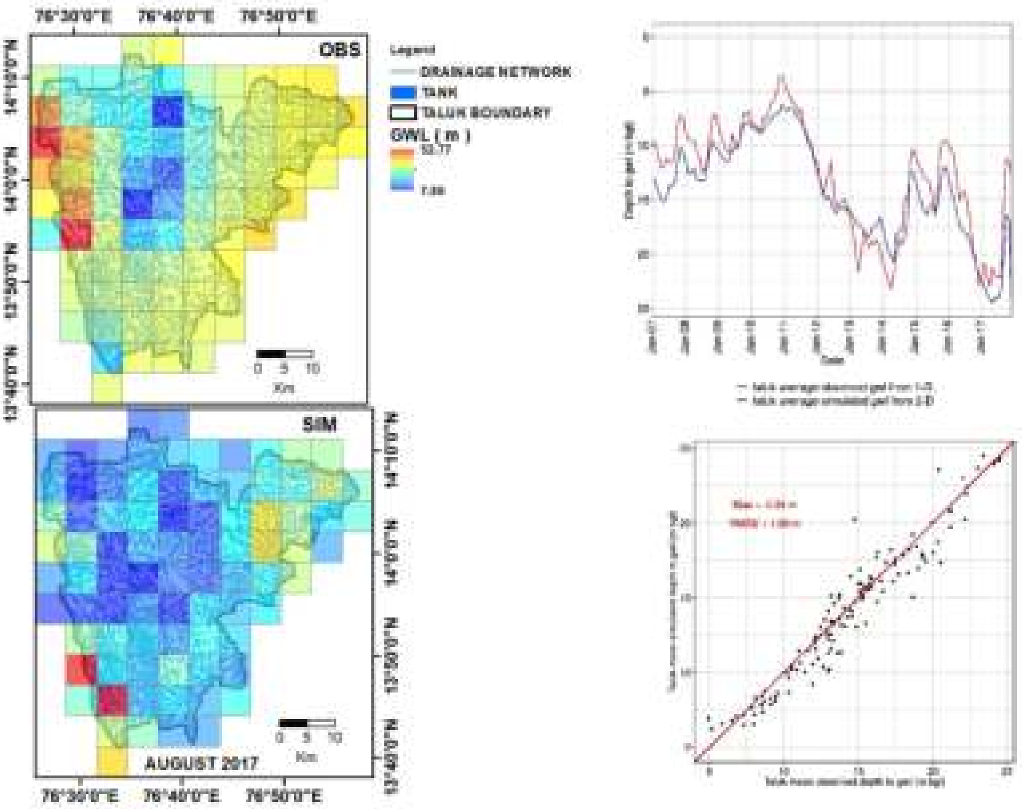


Figure 120: Comparison of observed versus simulated groundwater levels using 2D model for Challakere taluk.



Comparison of observed and simulated groundwater levels using 2D model for Hiriyur Taluk.

Figure 121: Comparison of observed versus simulated groundwater levels using 2D model for Hiriyur taluk.

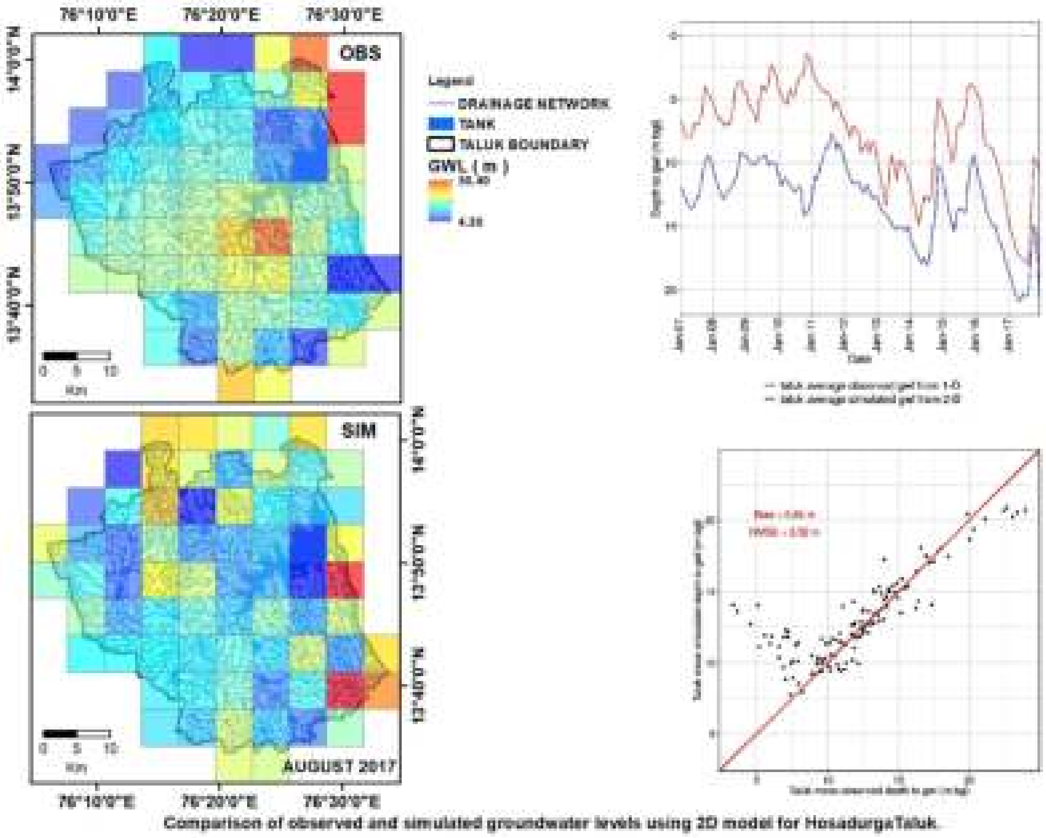


Figure 122: Comparison of observed versus simulated groundwater levels using 2D model for Hosadurga taluk.

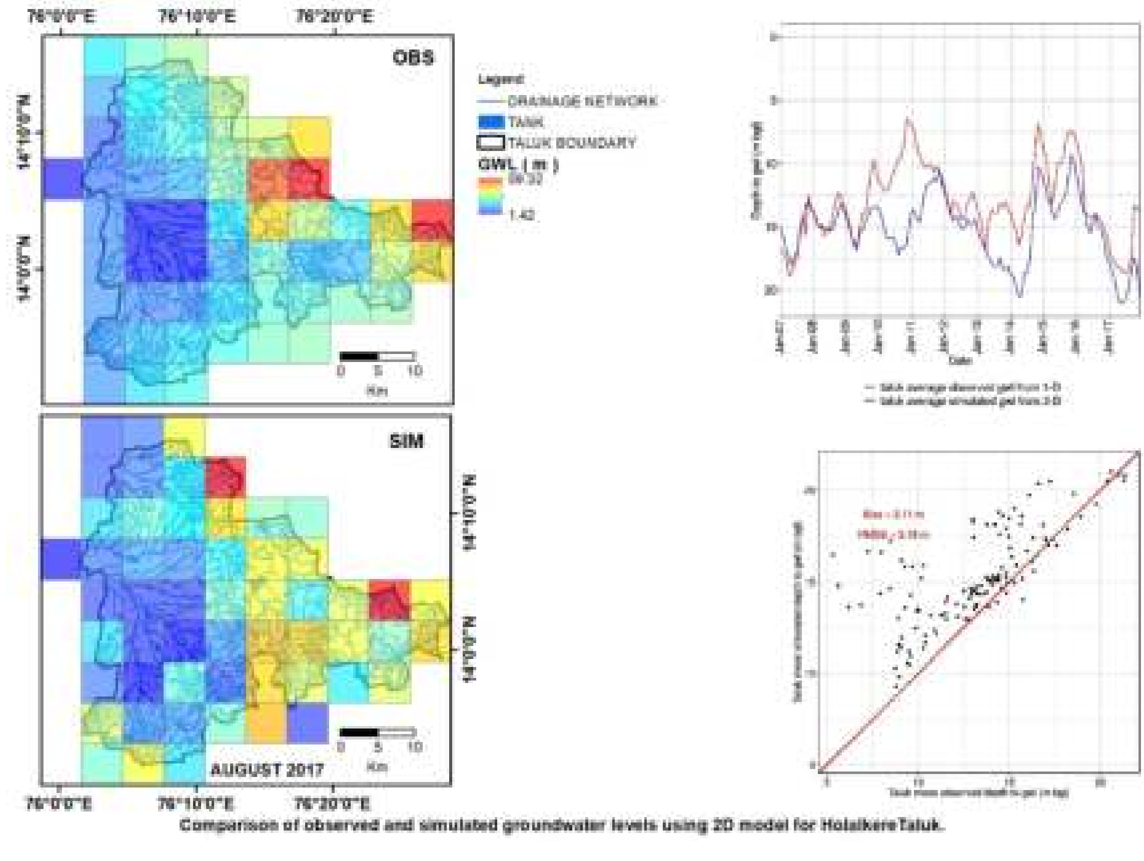
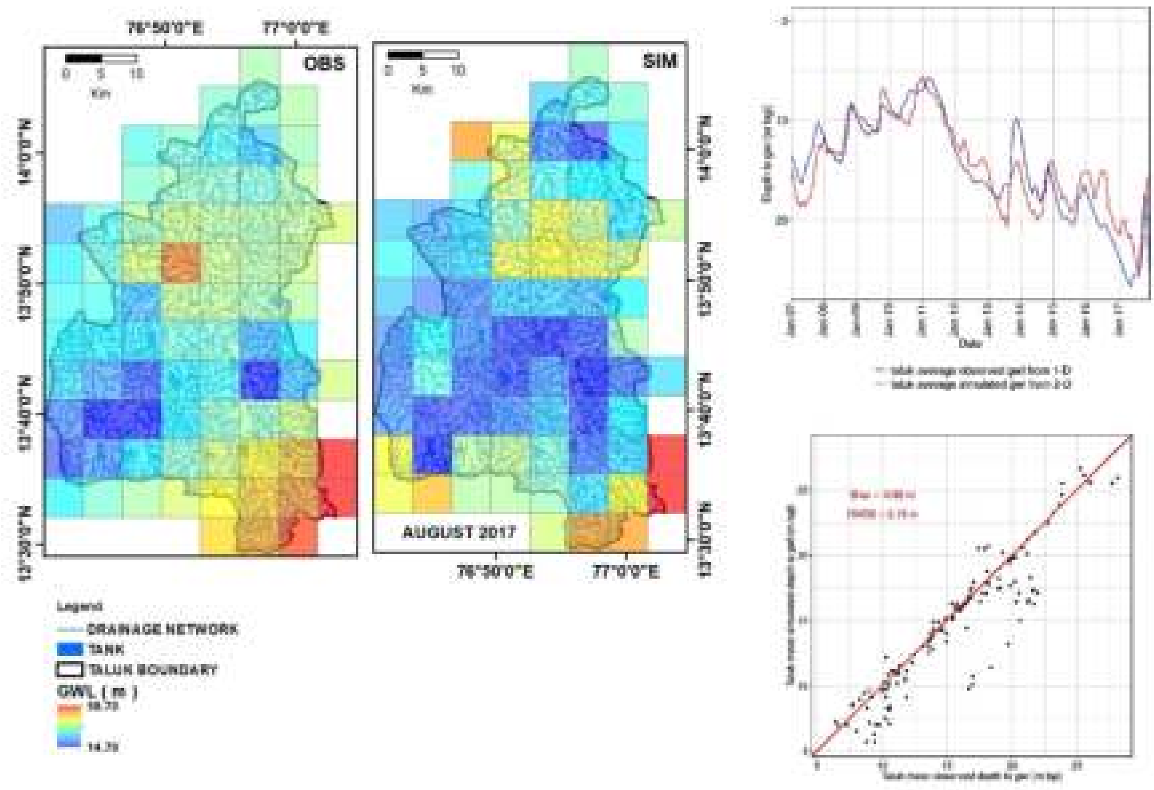


Figure 123: Comparison of observed versus simulated groundwater levels using 2D model for Holalkere taluk.



Comparison of observed and simulated groundwater levels using 2D model for Sira Taluk.

Figure 124: Comparison of observed versus simulated groundwater levels using 2D model for Sira taluk.

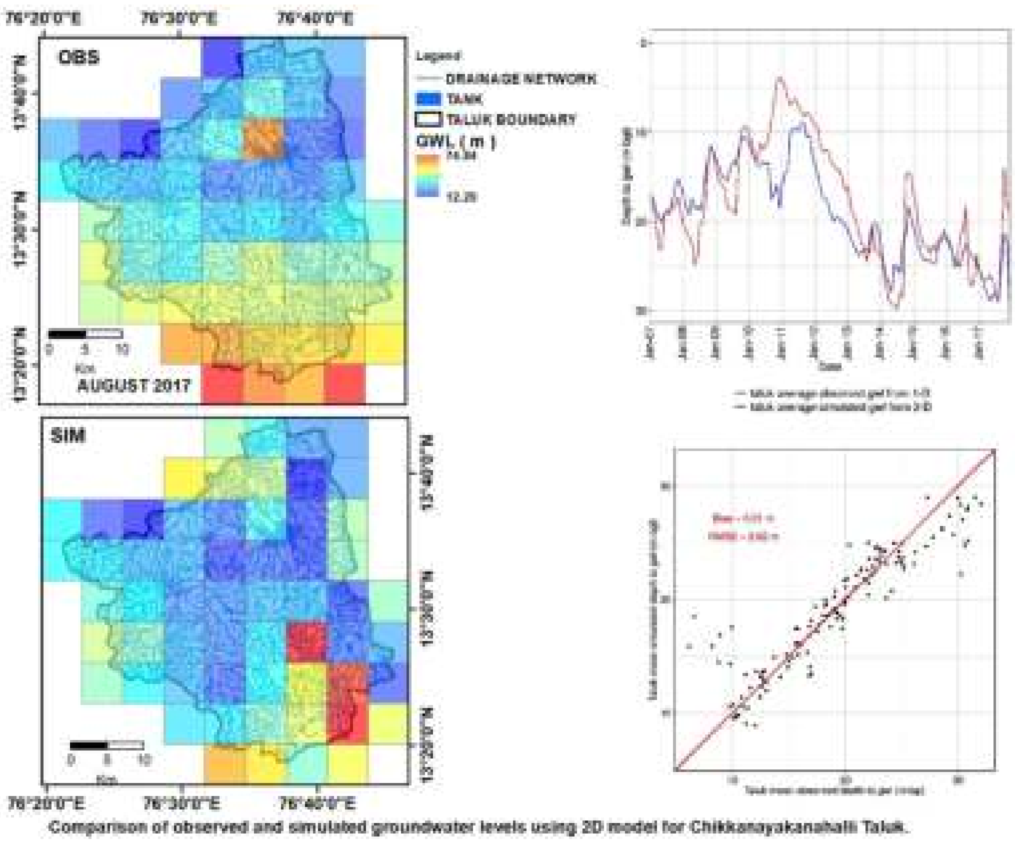


Figure 125: Comparison of observed versus simulated groundwater levels using 2D model for Chikkanayakanahalli taluk.

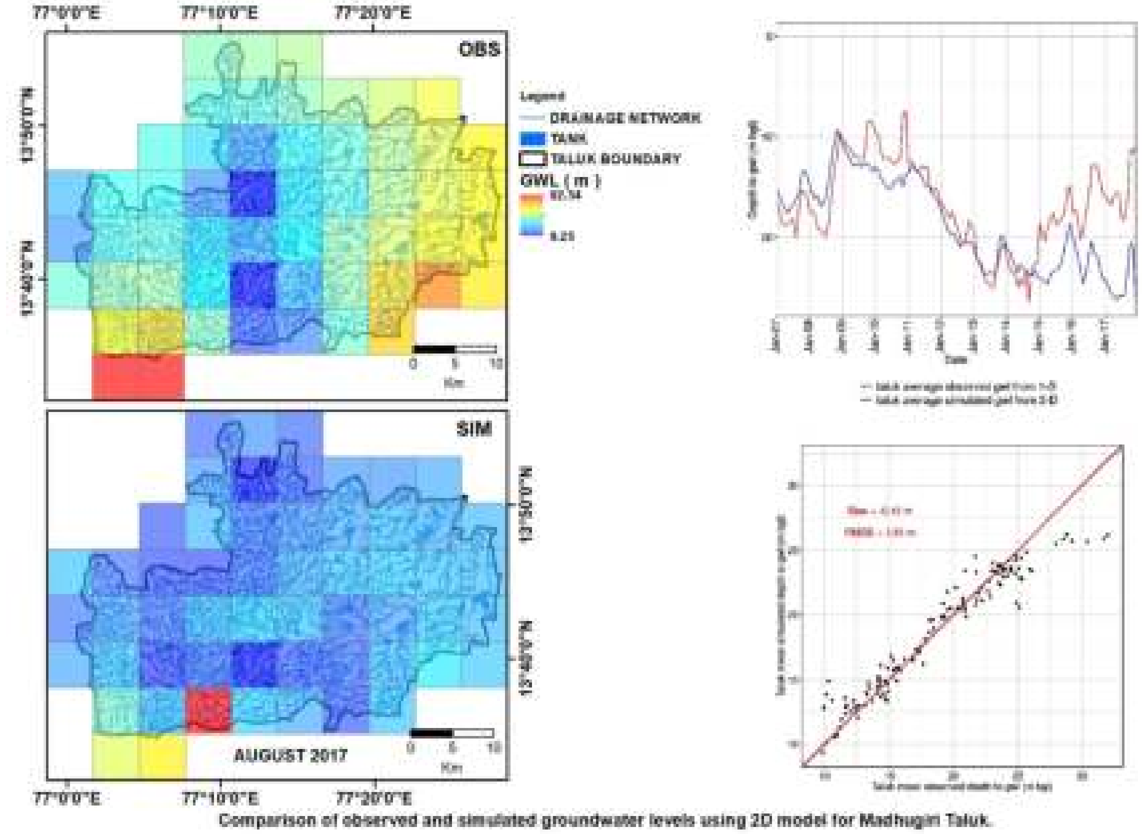


Figure 126: Comparison of observed versus simulated groundwater levels using 2D model for Madhugiri taluk.

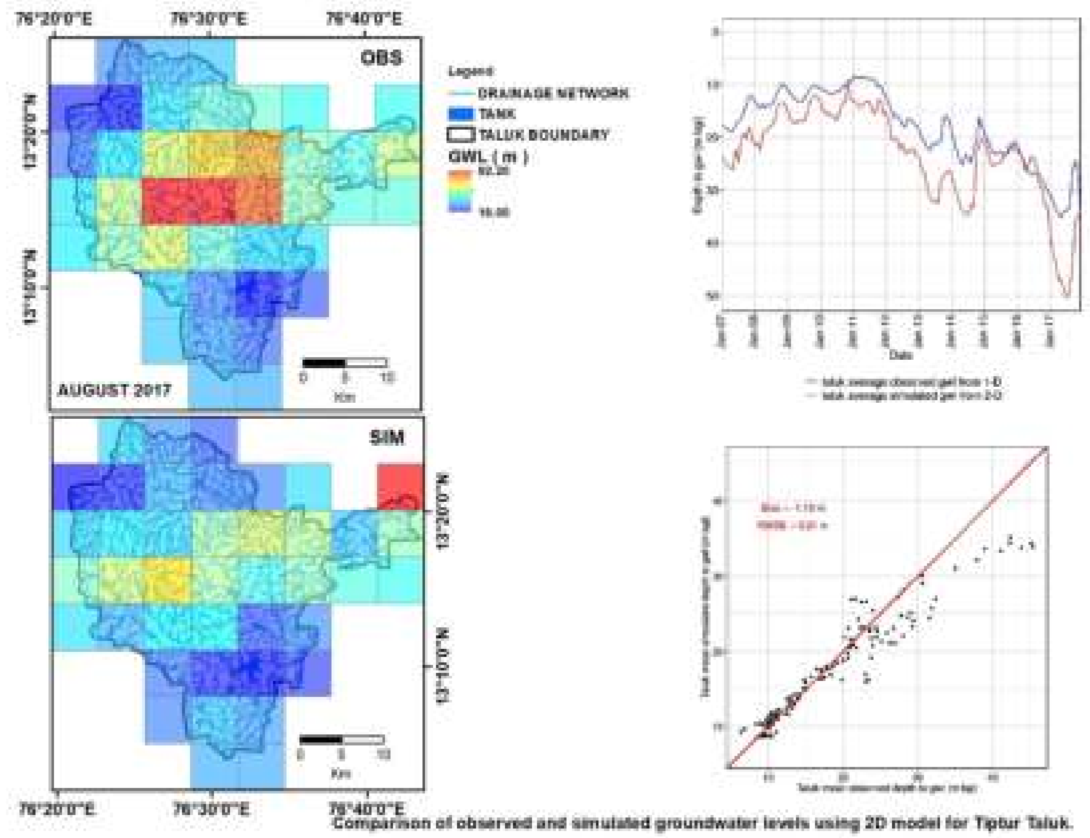


Figure 127: Comparison of observed versus simulated groundwater levels using 2D model for Tiptur taluk.

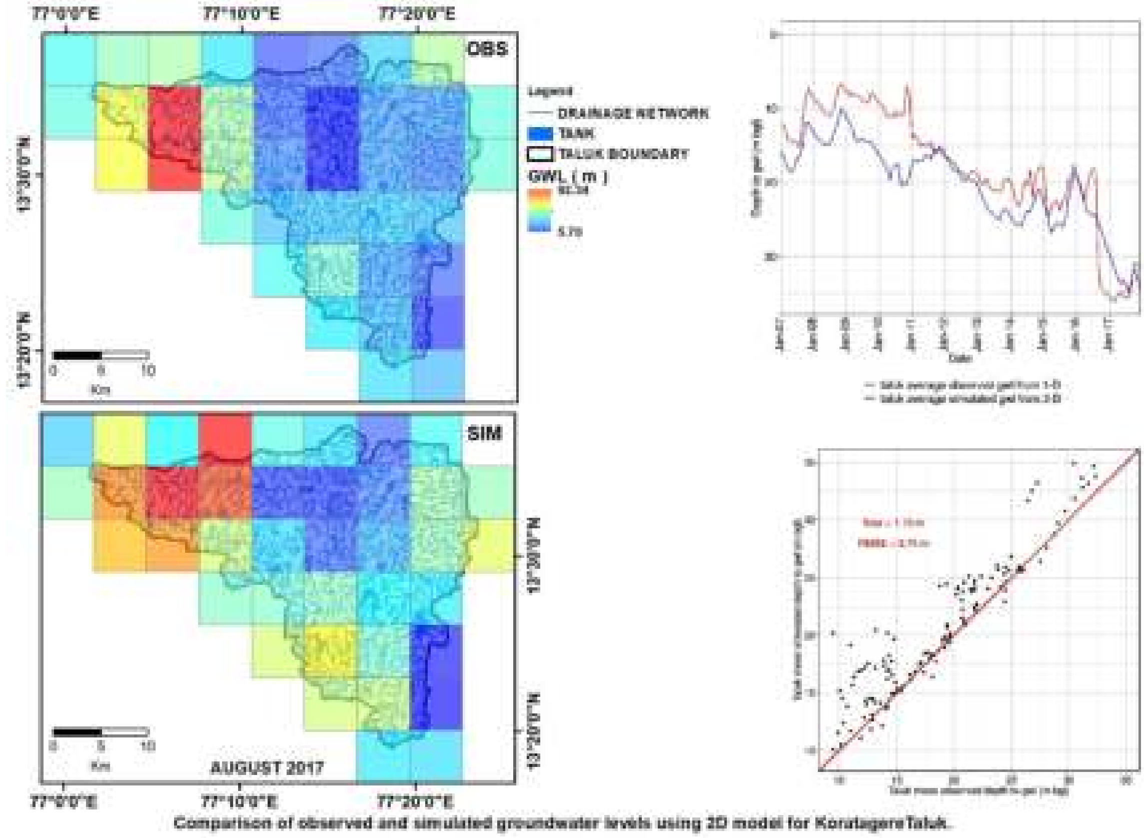


Figure 128: Comparison of observed versus simulated groundwater levels using 2D model for Bagepalli taluk.

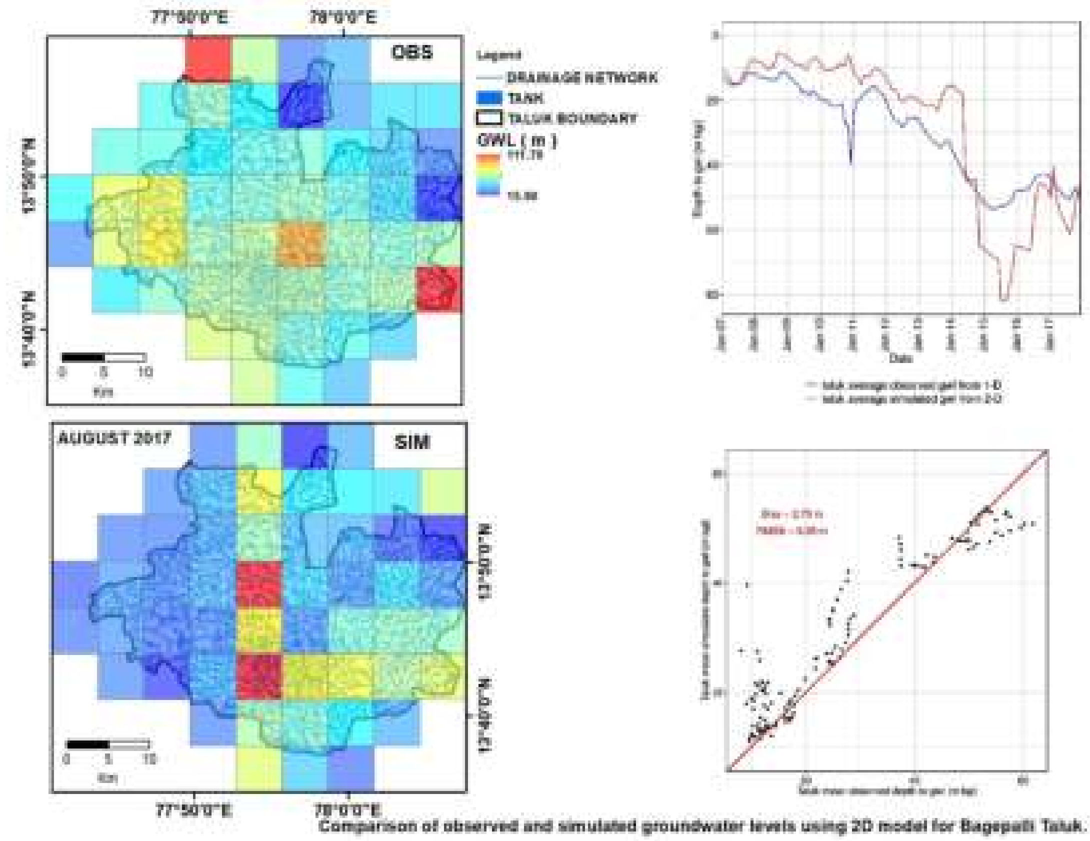


Figure 129: Comparison of observed versus simulated groundwater levels using 2D model for Bagepalli taluk.

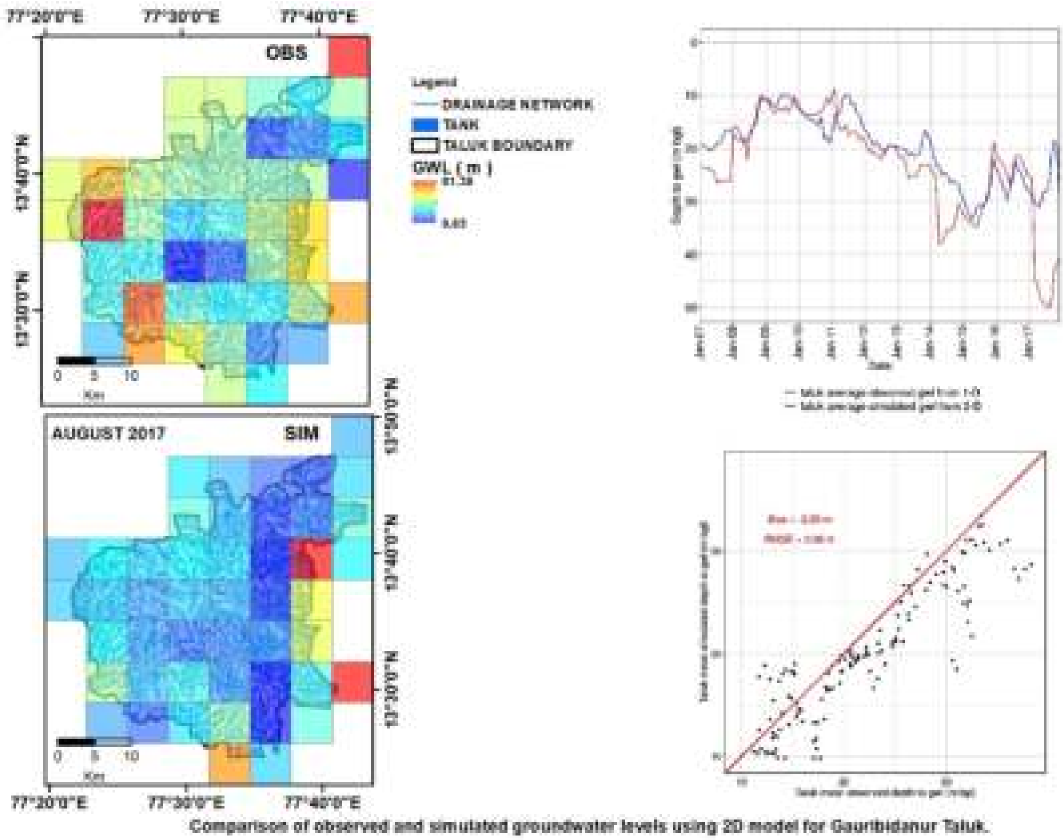


Figure 130: Comparison of observed versus simulated groundwater levels using 2D model for Gauribidanur taluk.

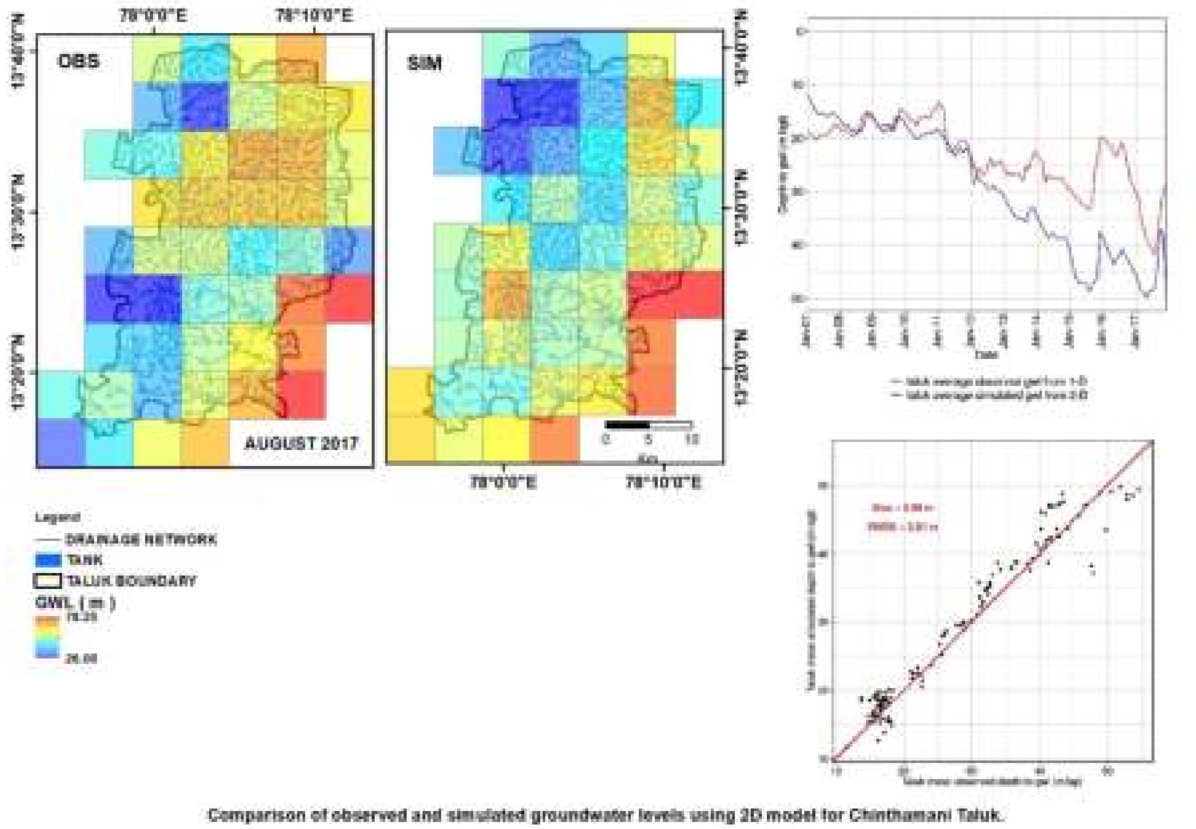


Figure 131: Comparison of observed versus simulated groundwater levels using 2D model for Chintamani taluk.

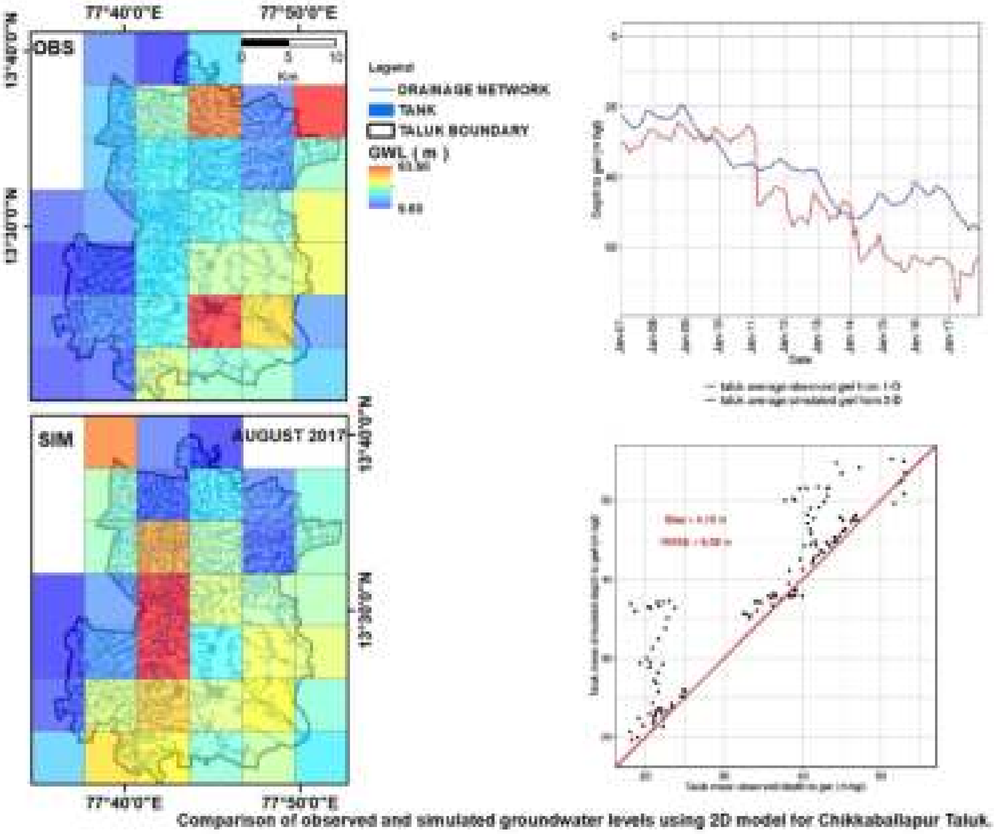


Figure 132: Comparison of observed versus simulated groundwater levels using 2D model for Chikballapura taluk.

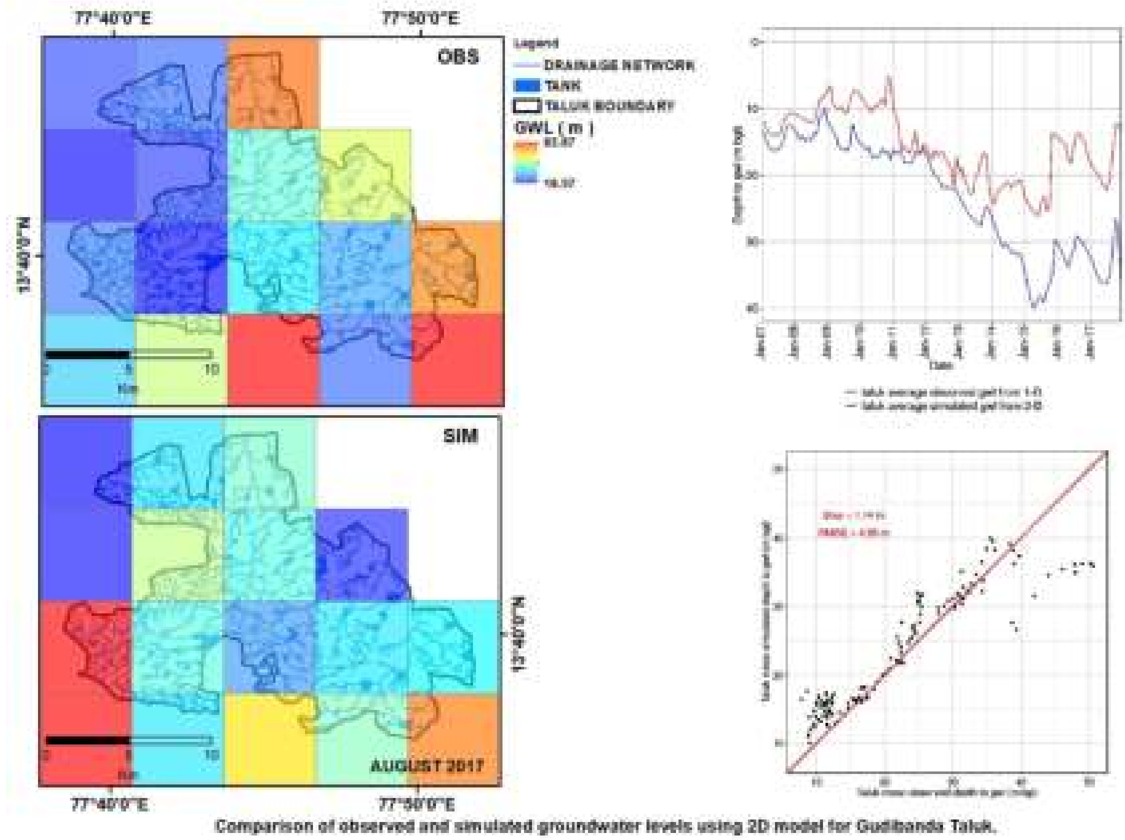


Figure 133: Comparison of observed versus simulated groundwater levels using 2D model for Gudibanda taluk.

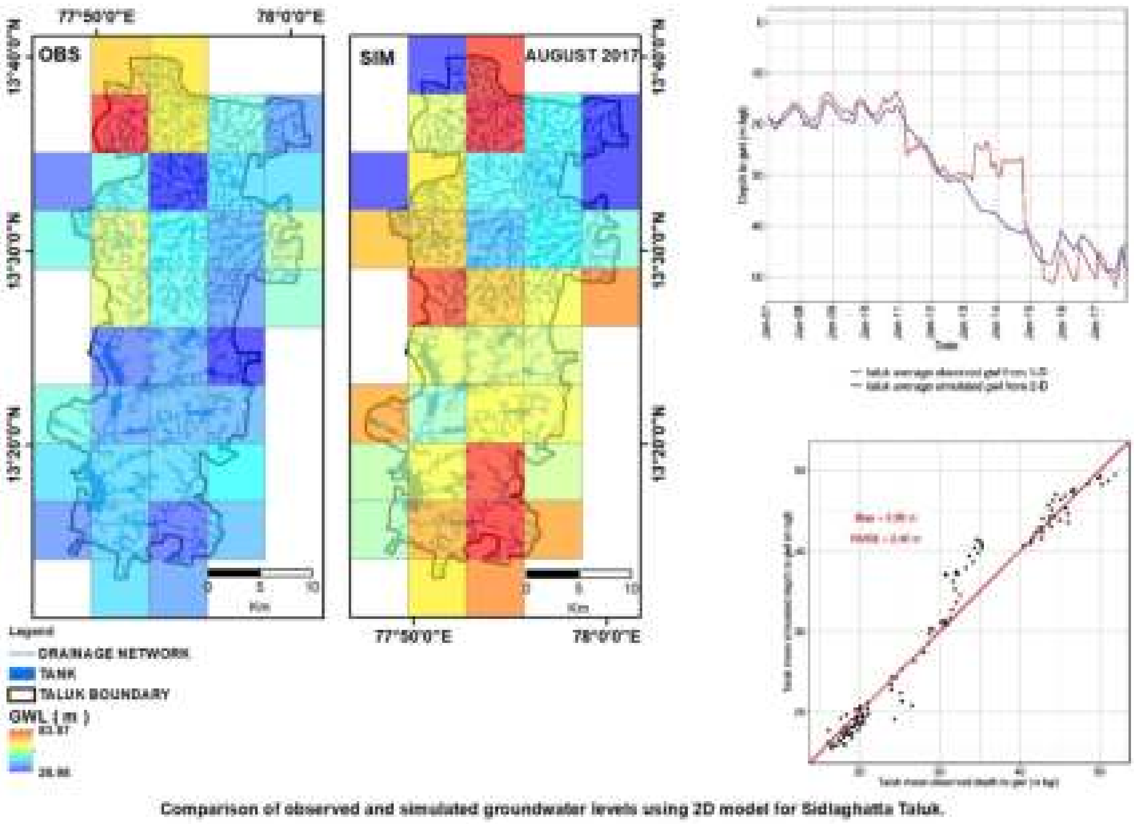


Figure 134: Comparison of observed versus simulated groundwater levels using 2D model for Sidlaghatta taluk.

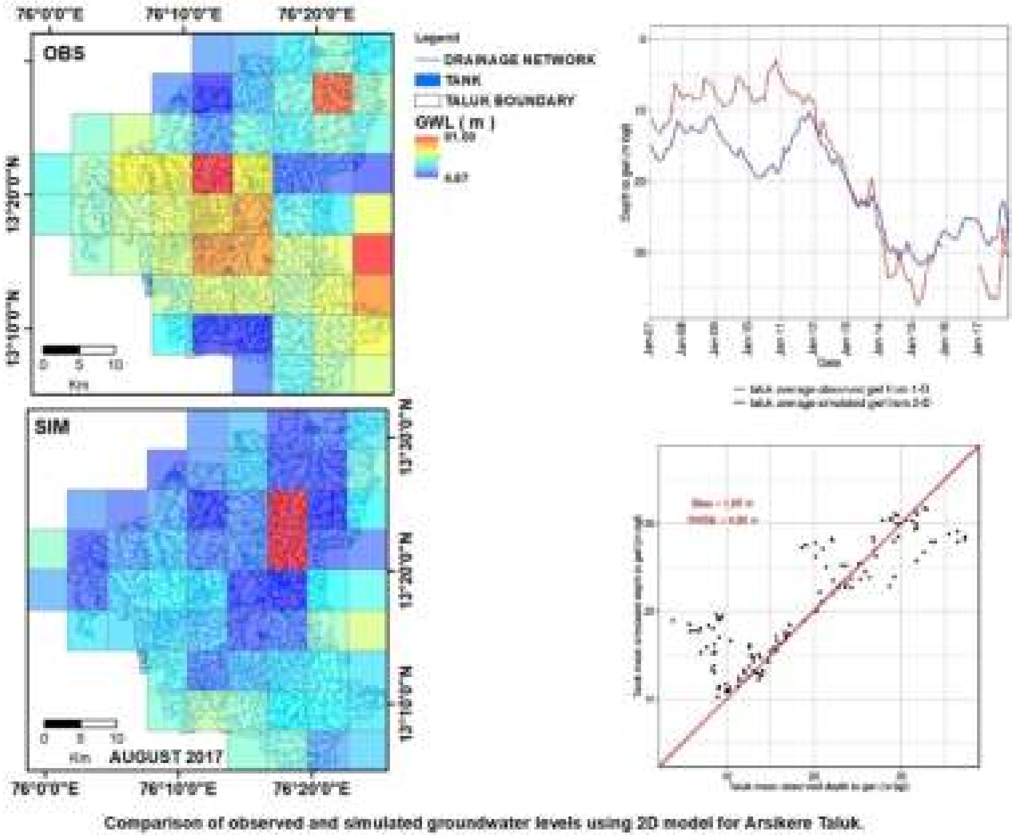


Figure 135: Comparison of observed versus simulated groundwater levels using 2D model for Arsikere taluk.

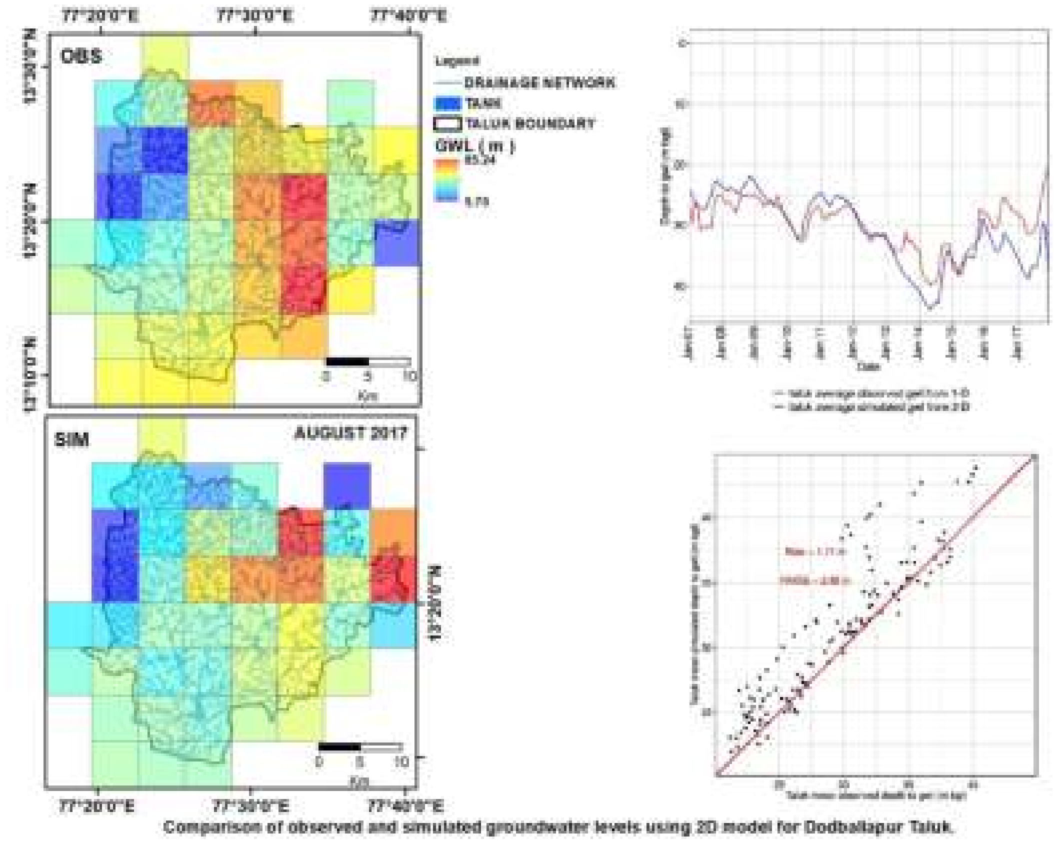


Figure 136: Comparison of observed versus simulated groundwater levels using 2D model for Doddaballapur taluk.

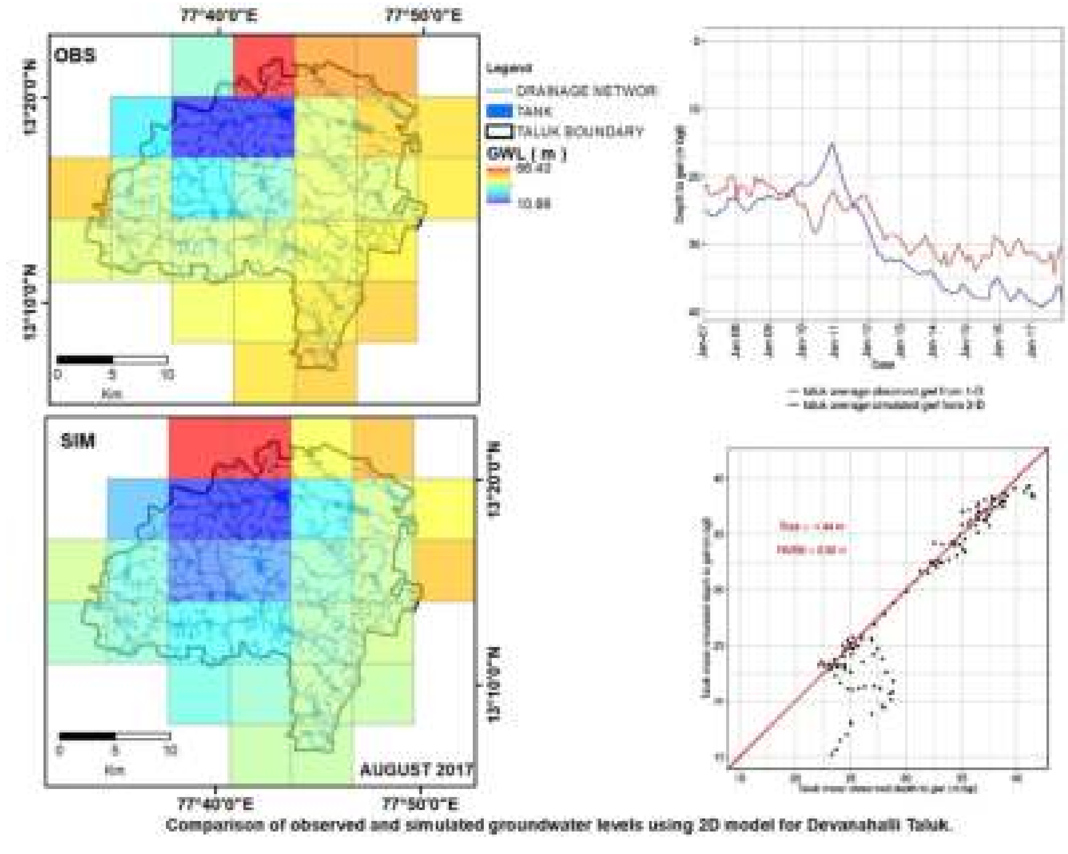


Figure 137: Comparison of observed versus simulated groundwater levels using 2D model for Devanahalli taluk.

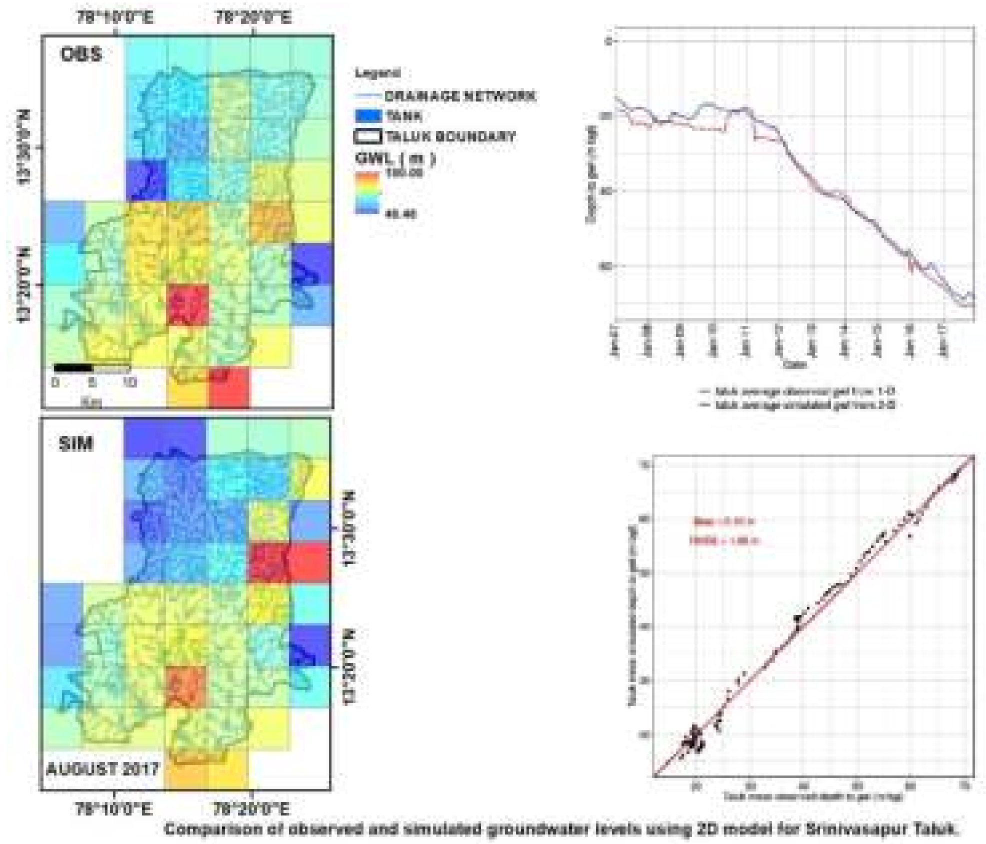


Figure 138: Comparison of observed versus simulated groundwater levels using 2D model for Srinivasapur taluk.

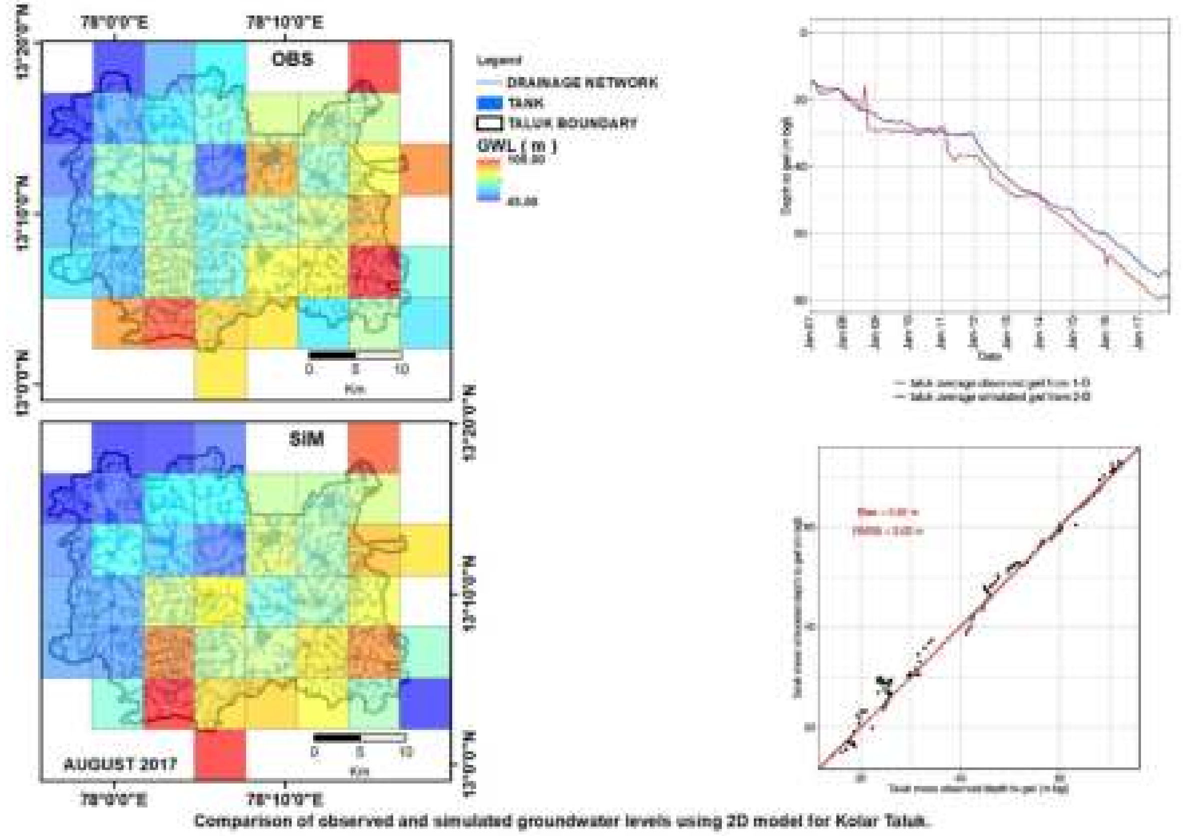


Figure 139: Comparison of observed versus simulated groundwater levels using 2D model for Kolar taluk.

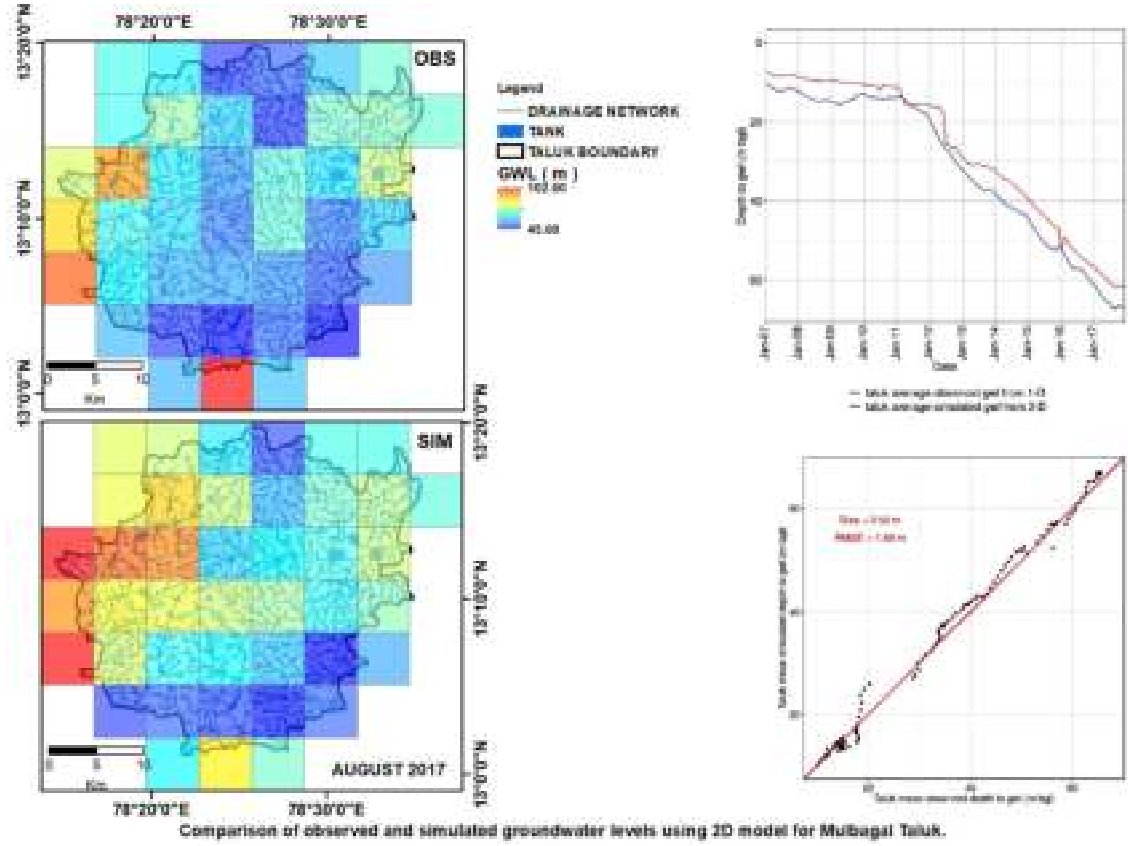


Figure 140: Comparison of observed versus simulated groundwater levels using 2D model for Mulabagilu taluk.

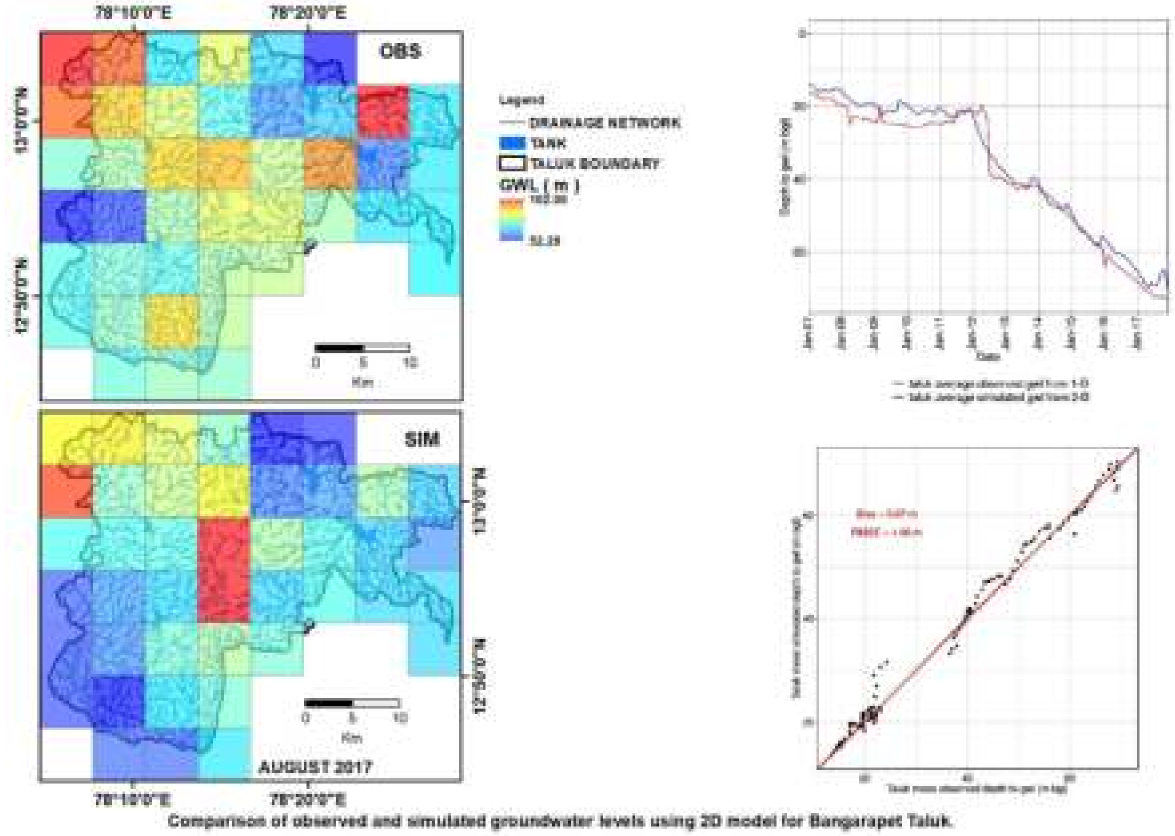


Figure 141: Comparison of observed versus simulated groundwater levels using 2D model for Bangarapet taluk.

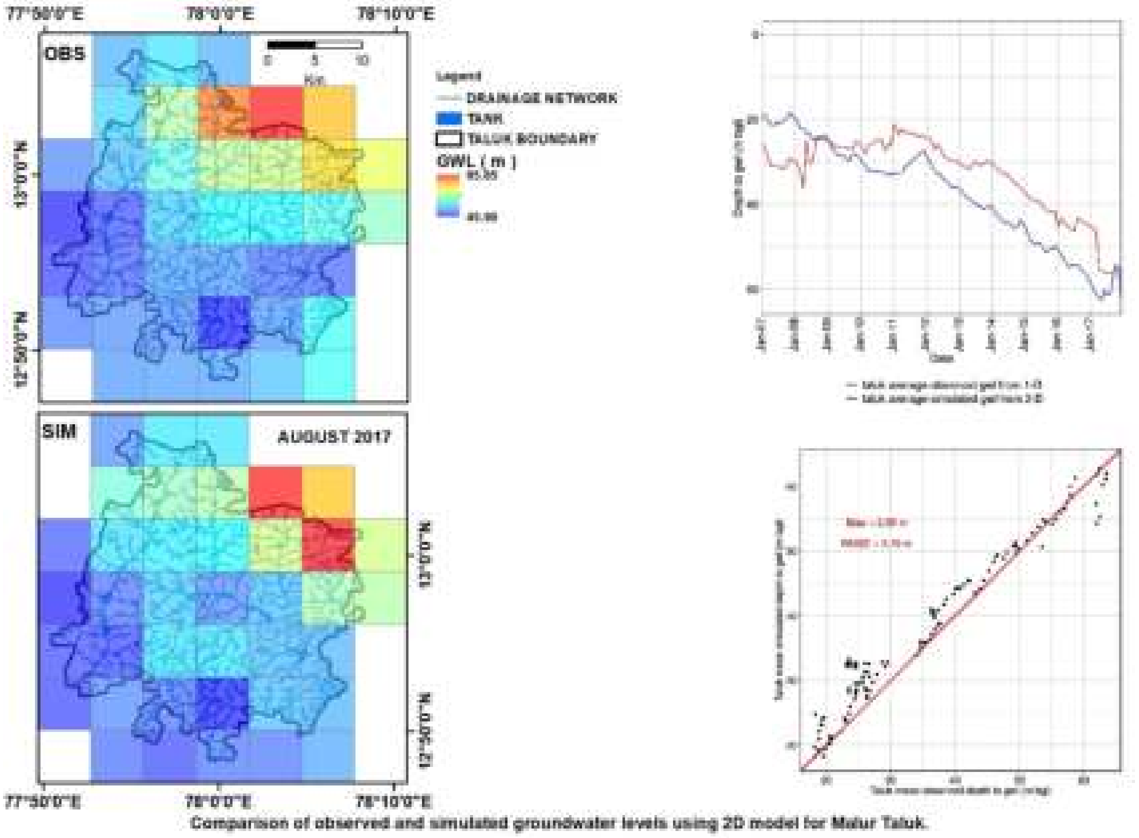


Figure 142: Comparison of observed versus simulated groundwater levels using 2D model for Malur taluk.

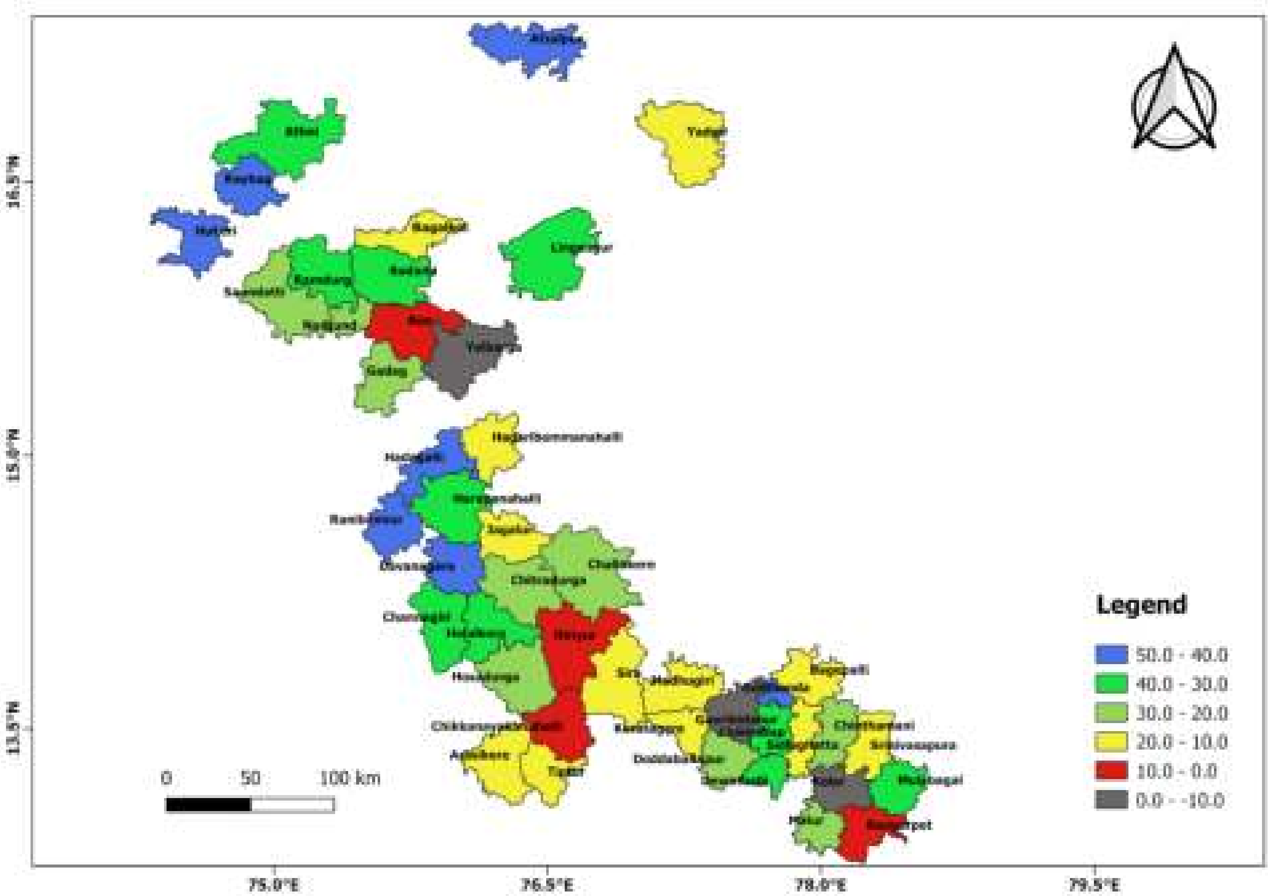


Figure 143: Spatial distribution of the ratio of lateral flux to recharge (%) for all 45 taluk during 2007-2017. A positive flux representation here means a net export from the taluk and a negative flux means a net import to the taluk.

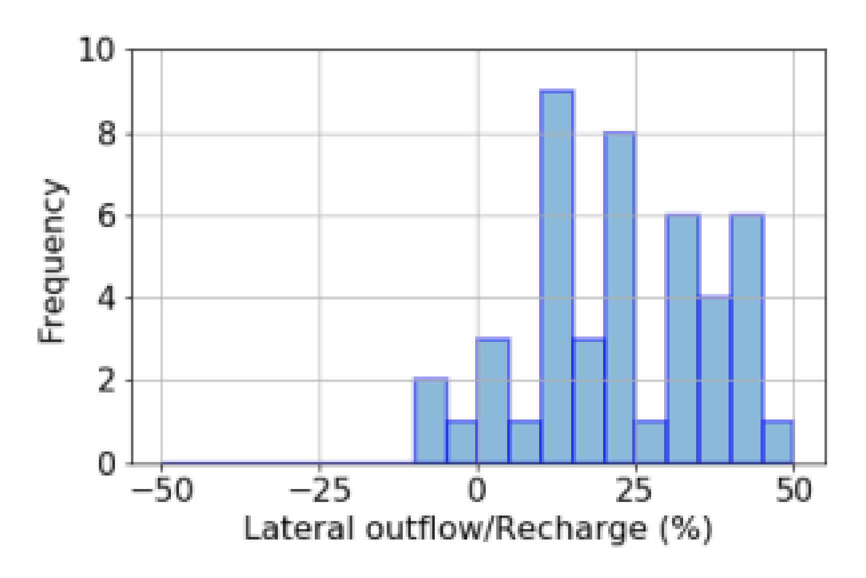


Figure 144: Histogram of the ratio of lateral flux to recharge for all 45 taluk during 2007-2017.

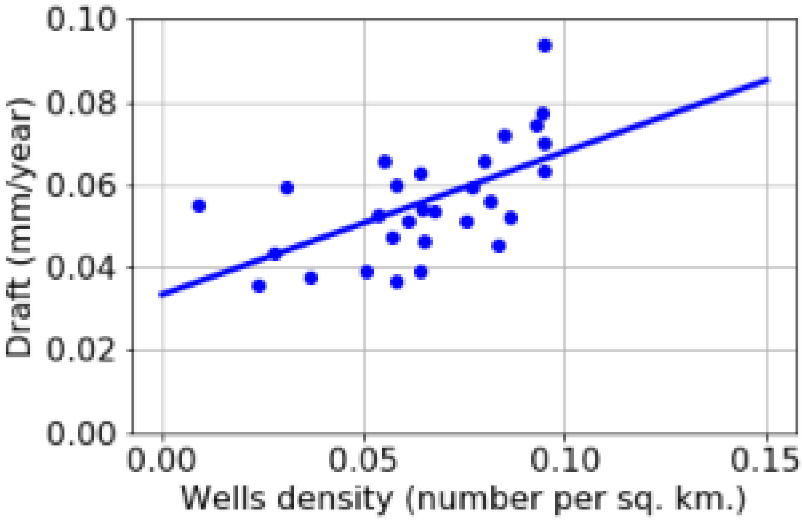


Figure 145: Comparison of the mean estimated draft over year 2007-2017 with the well density as per 5th MI survey. Only the taluks having well density upto 0.1 (number of wells per hectare) are considered.

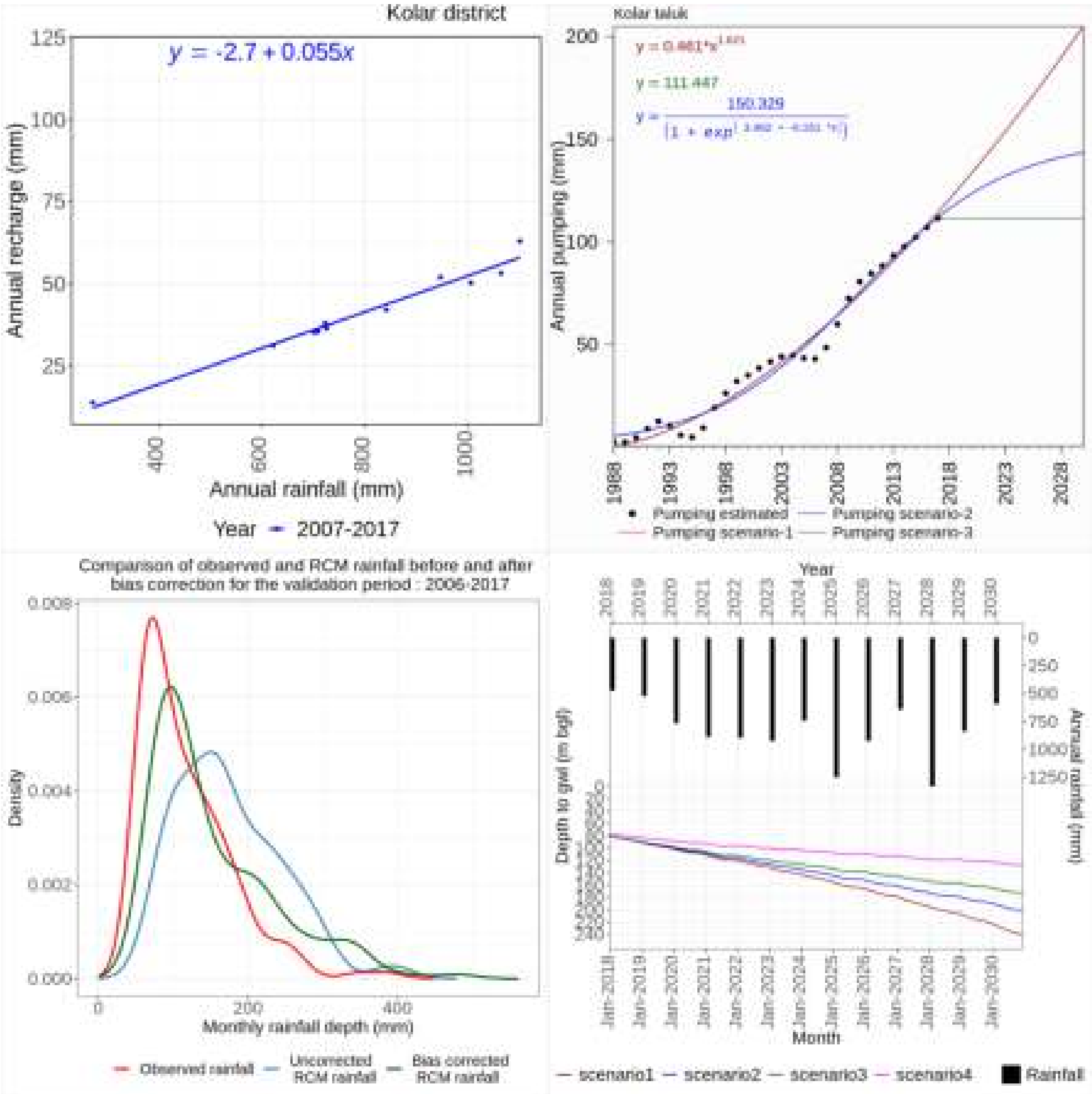


Figure 146: Simulation of future groundwater levels with four pumping scenarios for Kolar taluk .

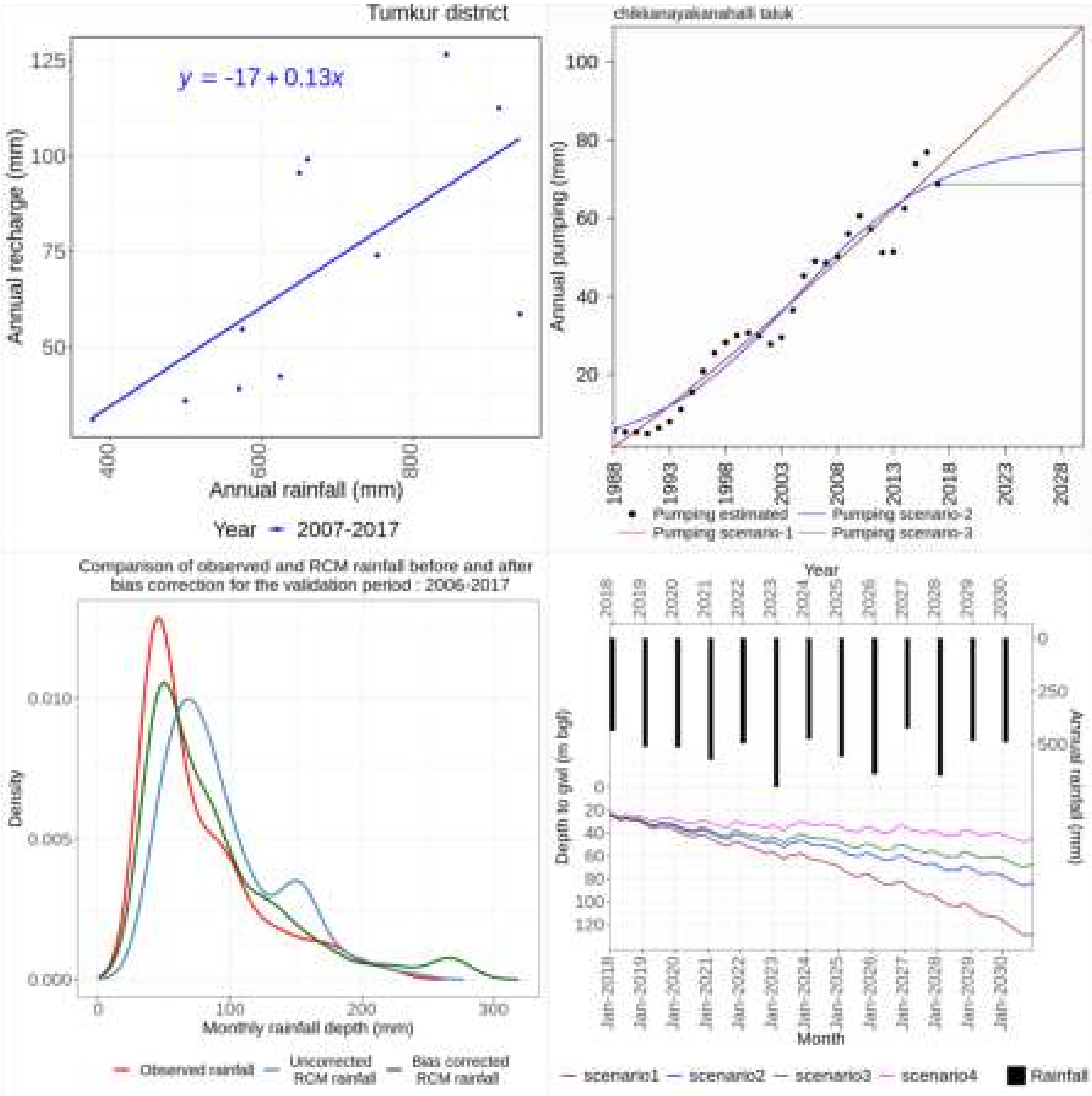


Figure 147: Simulation of future groundwater levels with four pumping scenarios for Chikkanayakanahalli taluk.

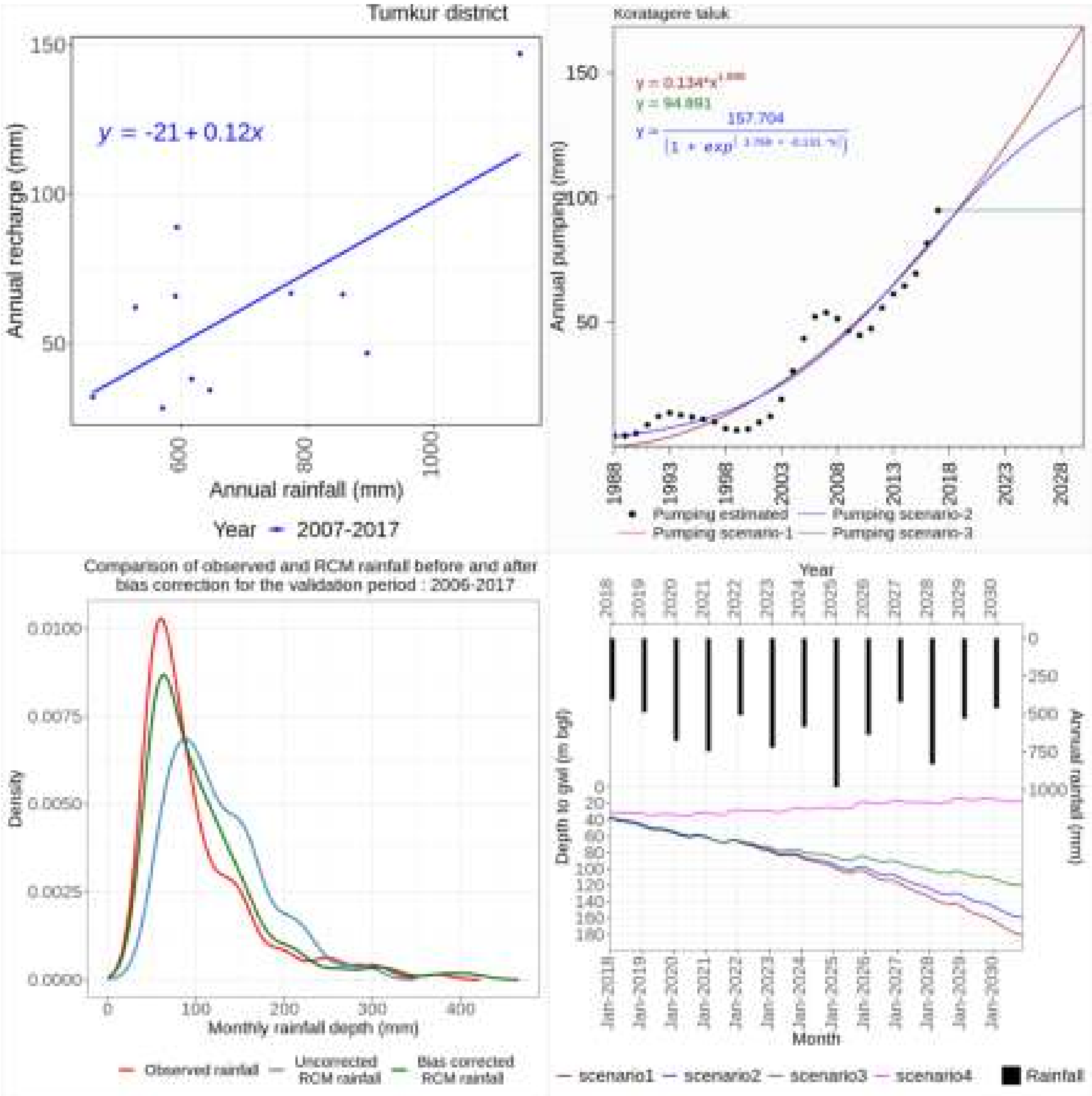


Figure 148: Simulation of future groundwater levels with four pumping scenarios for Koratagere taluk .

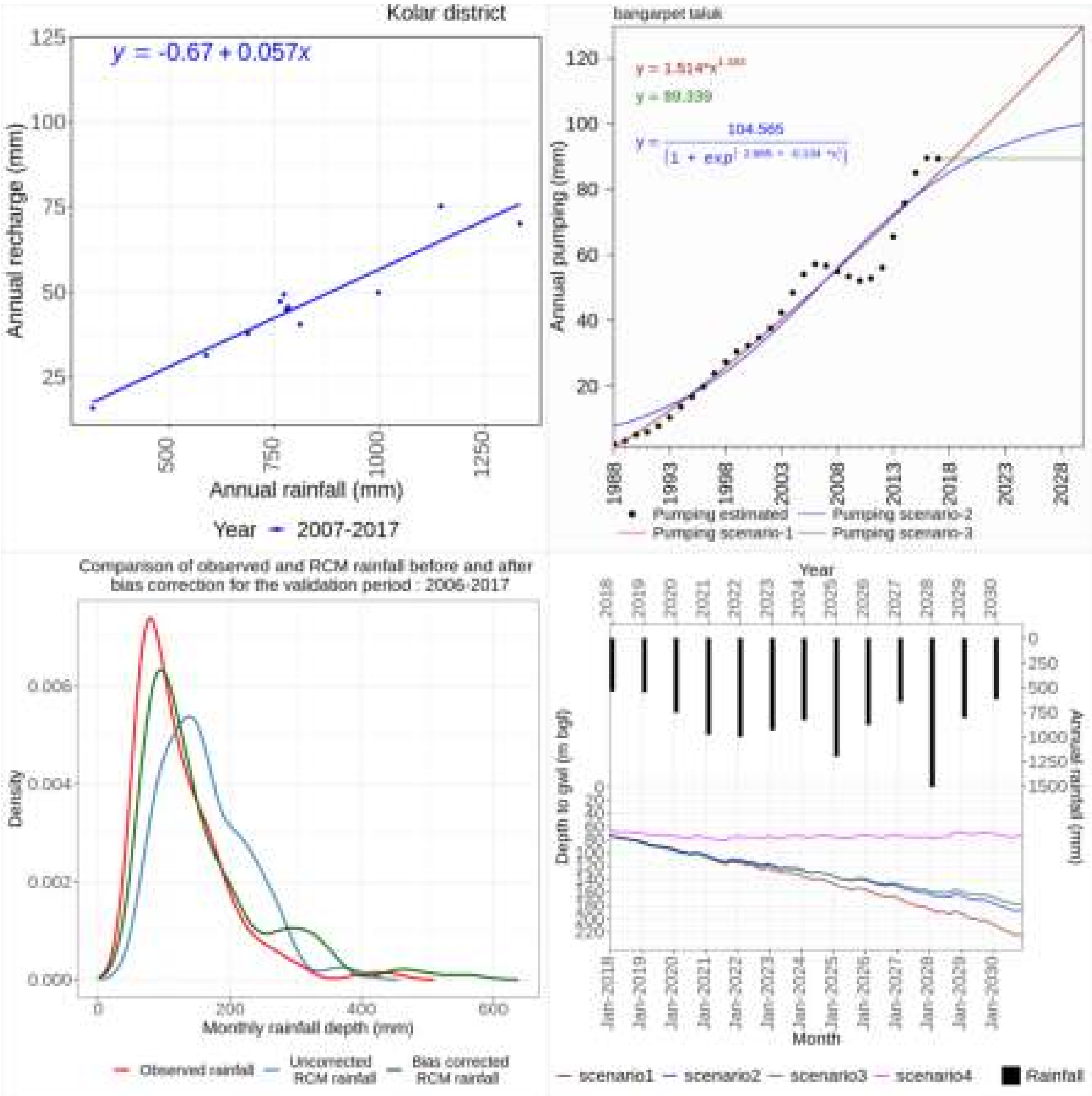


Figure 149: Simulation of future groundwater levels with four pumping scenarios for Bangarapet taluk .

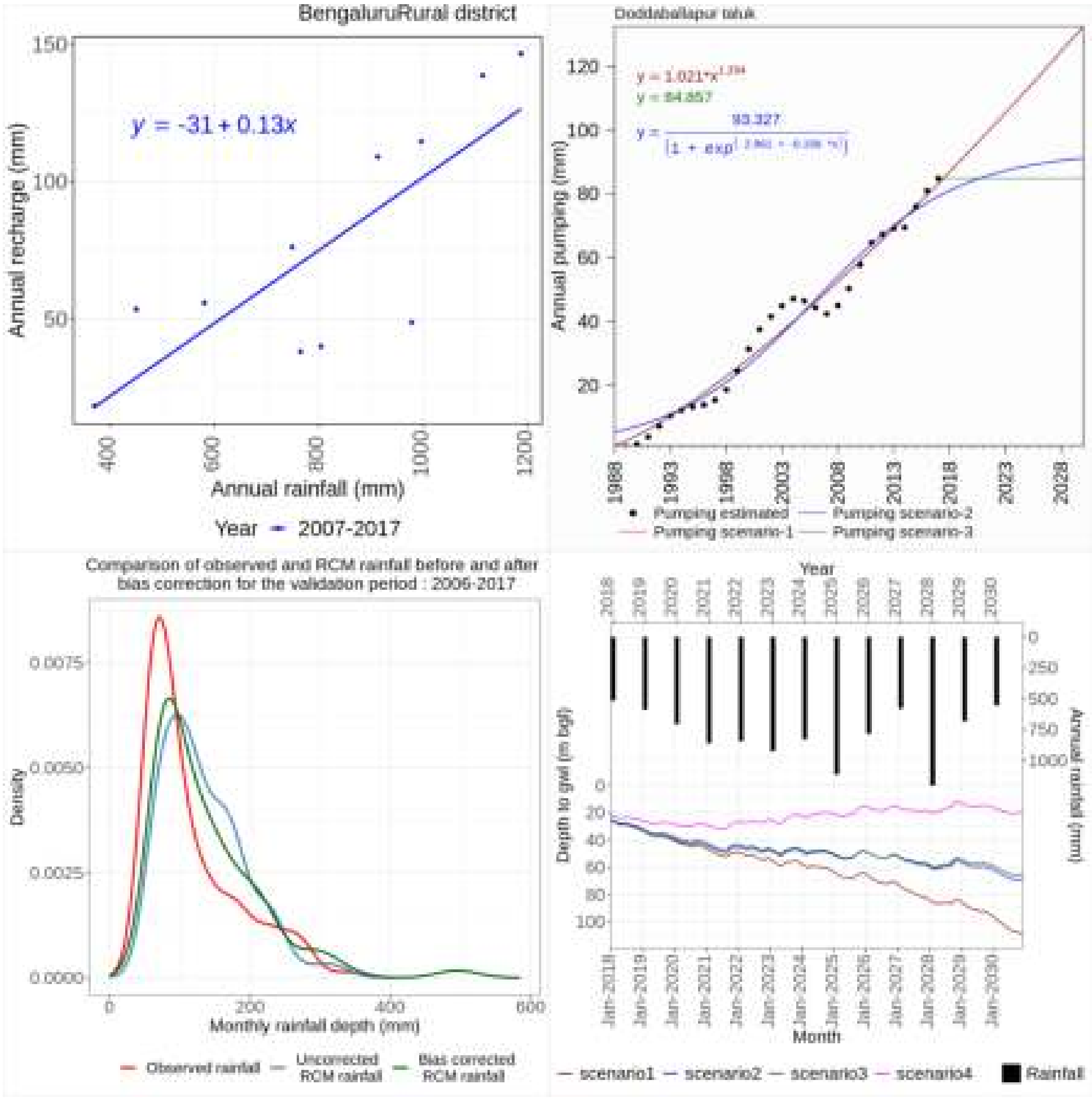


Figure 150: Simulation of future groundwater levels with four pumping scenarios for for Doddaballapur taluk.

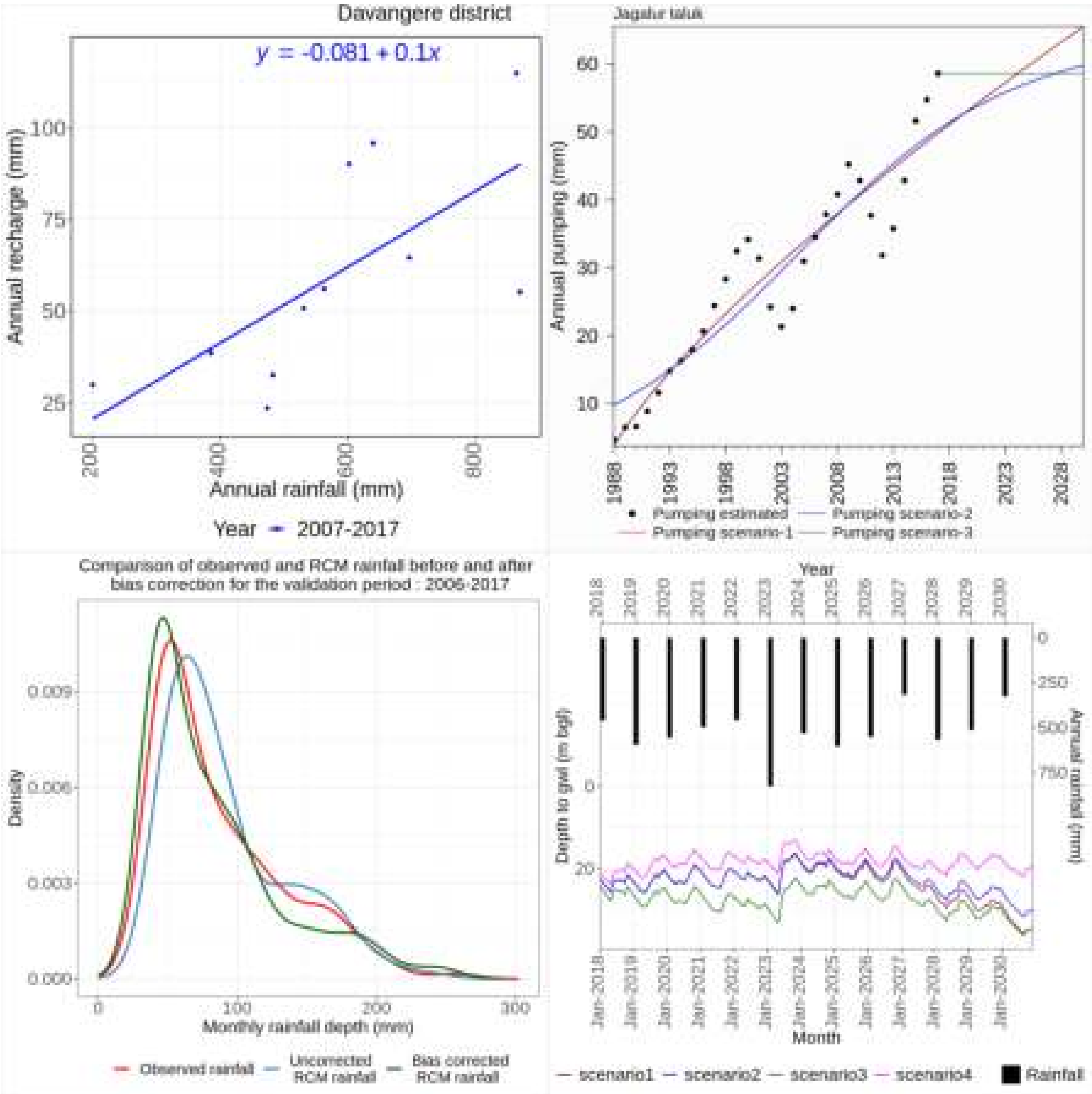


Figure 151: Simulation of future groundwater levels with four pumping scenarios for for Jagalur taluk.

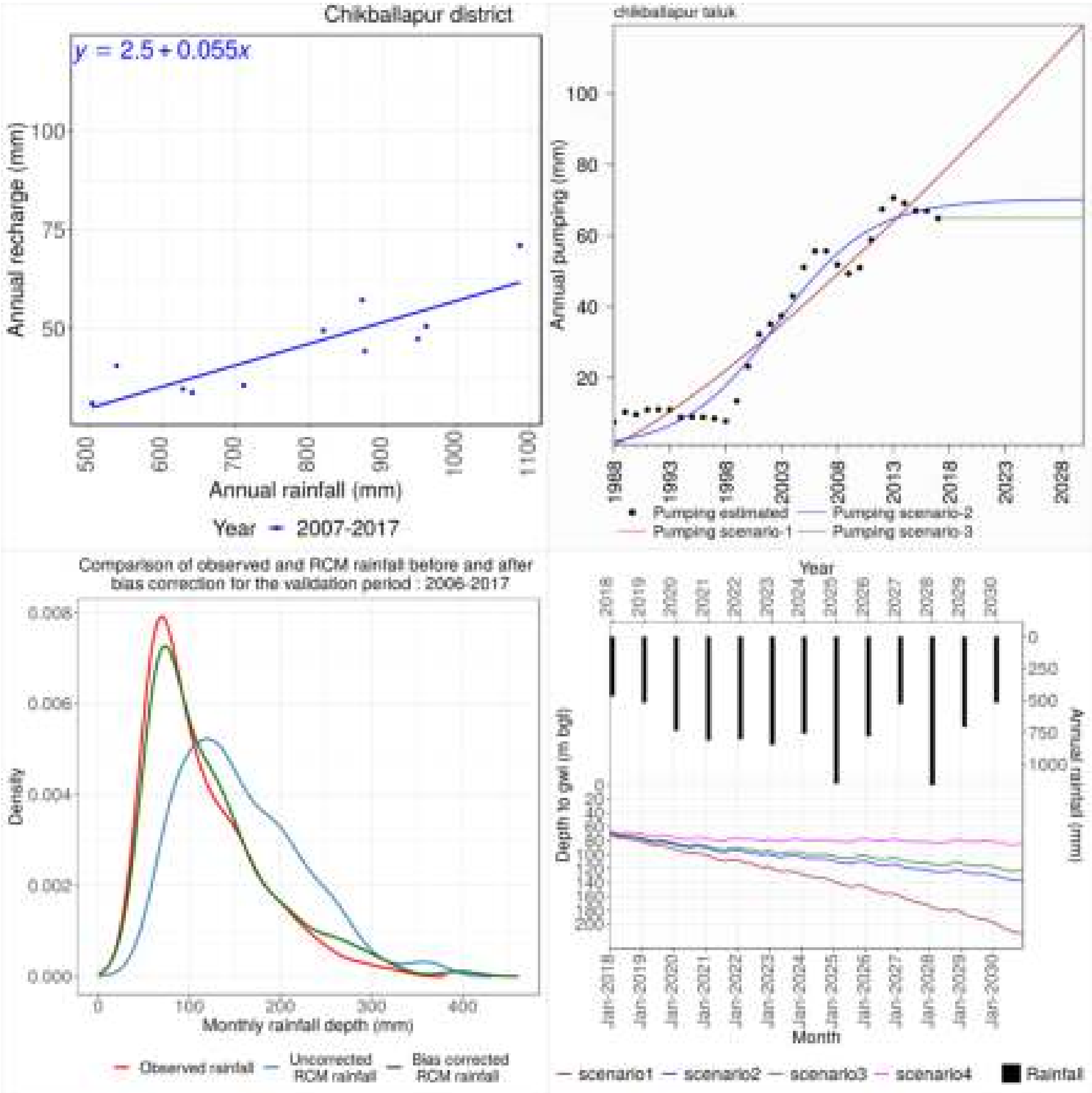


Figure 152: Simulation of future groundwater levels with four pumping scenarios for for Chikkaballapura taluk.

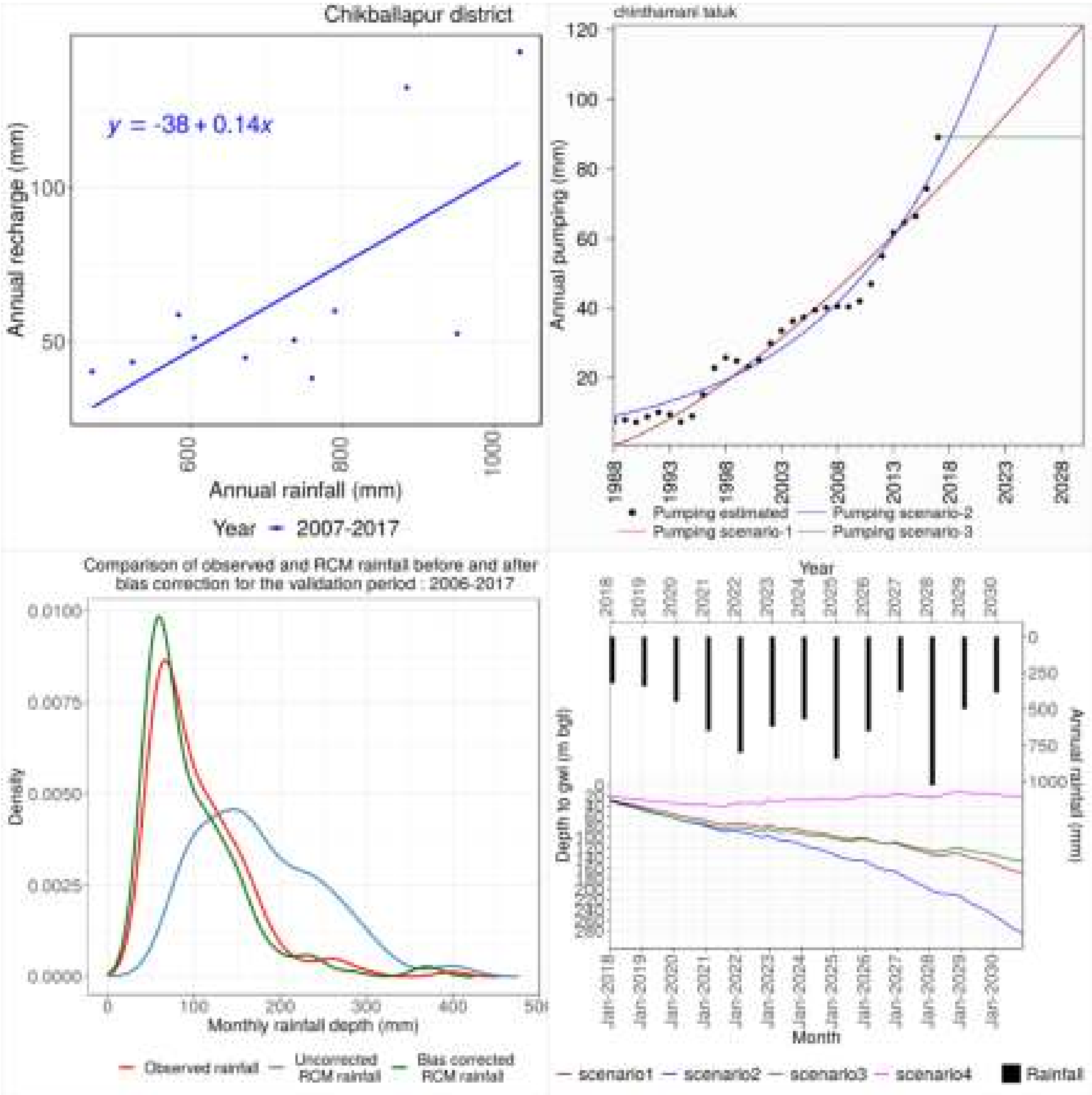


Figure 153: Simulation of future groundwater levels with four pumping scenarios for for Chintamani taluk.

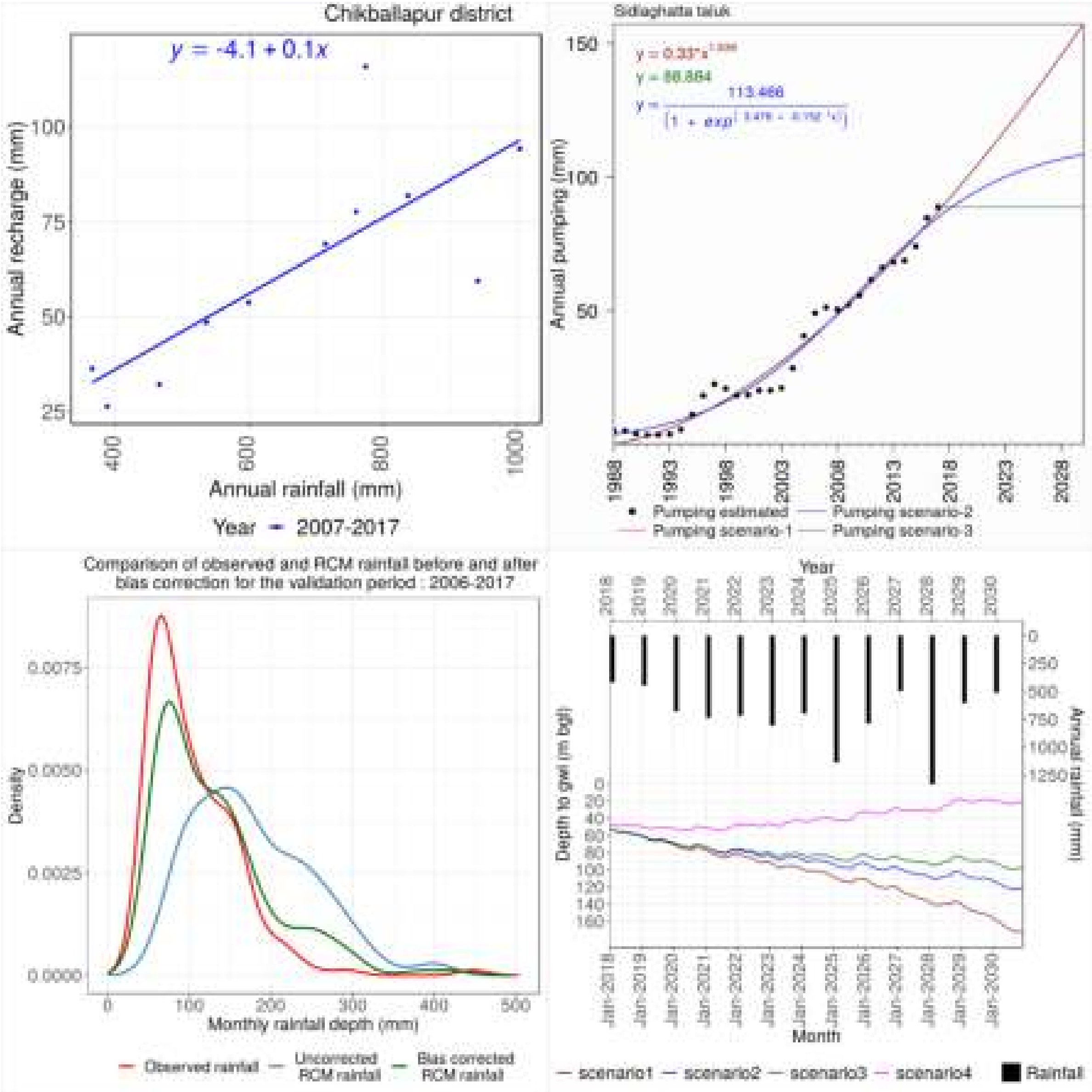


Figure 154: Simulation of future groundwater levels with four pumping scenarios for for Sidlaghatta taluk.

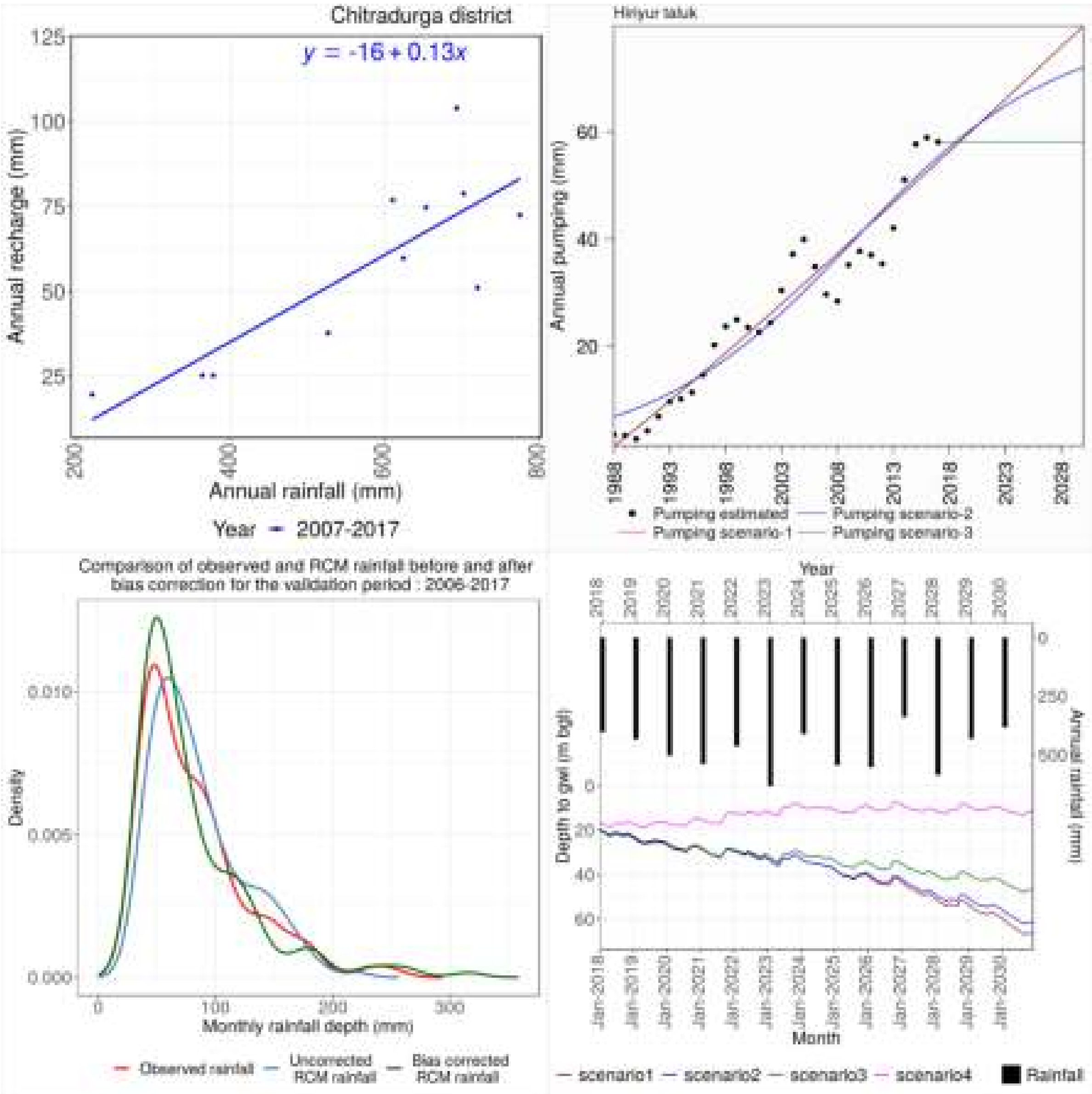


Figure 155: Simulation of future groundwater levels with four pumping scenarios for for Hiriyur taluk.

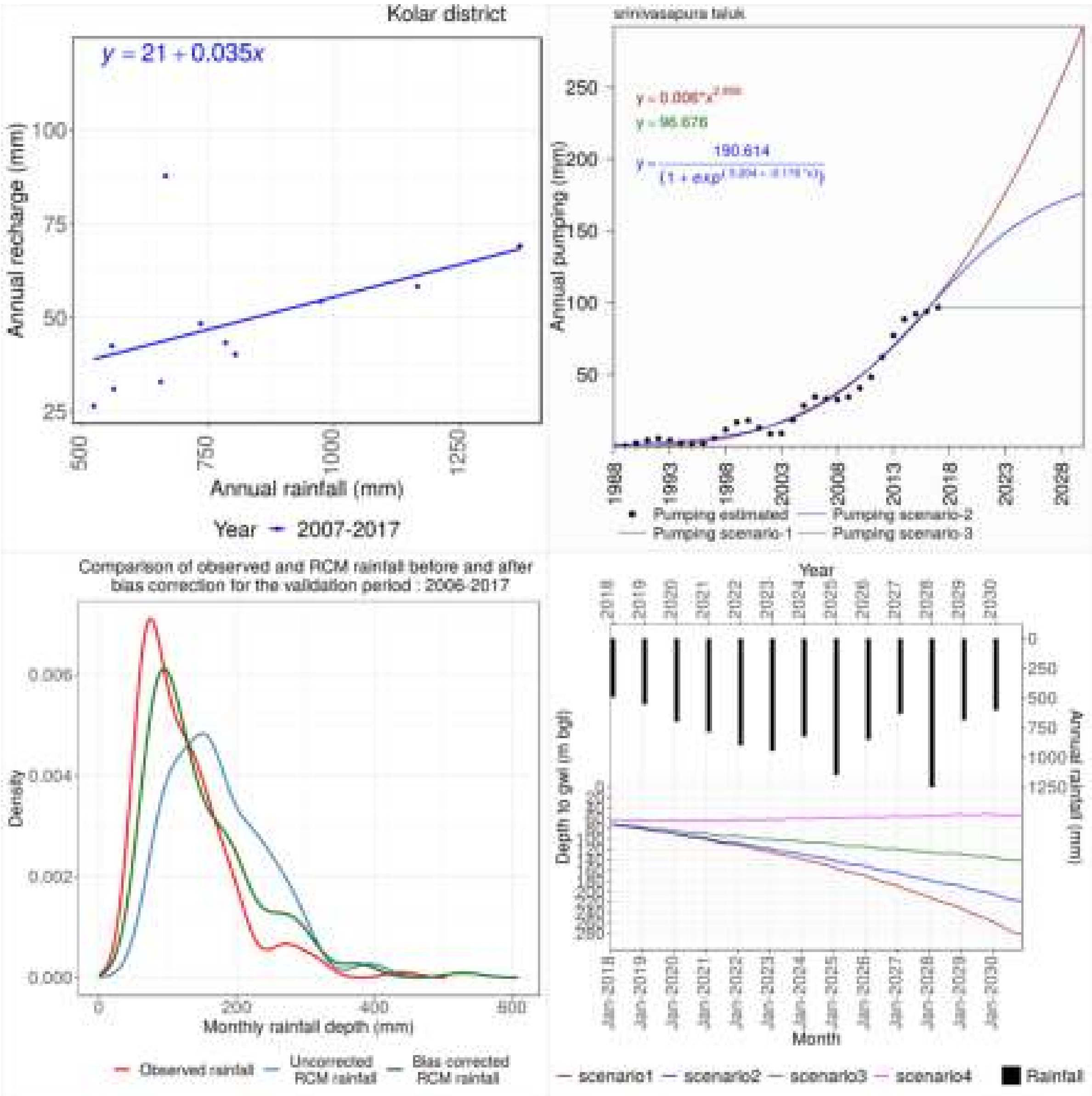


Figure 156: Simulation of future groundwater levels with four pumping scenarios for Srinivasapura taluk.

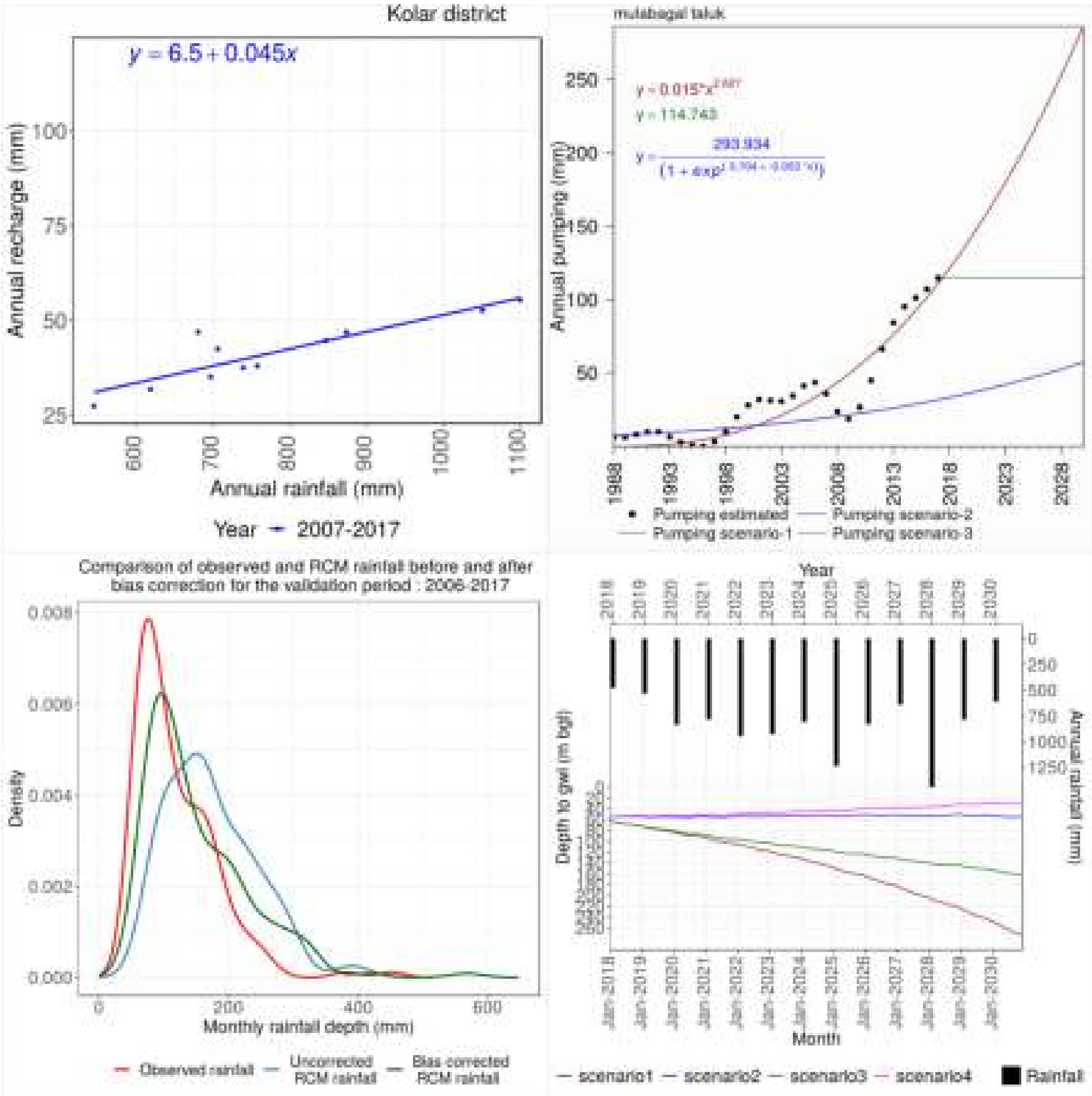


Figure 157: Simulation of future groundwater levels with four pumping scenarios for Mulabagal taluk.

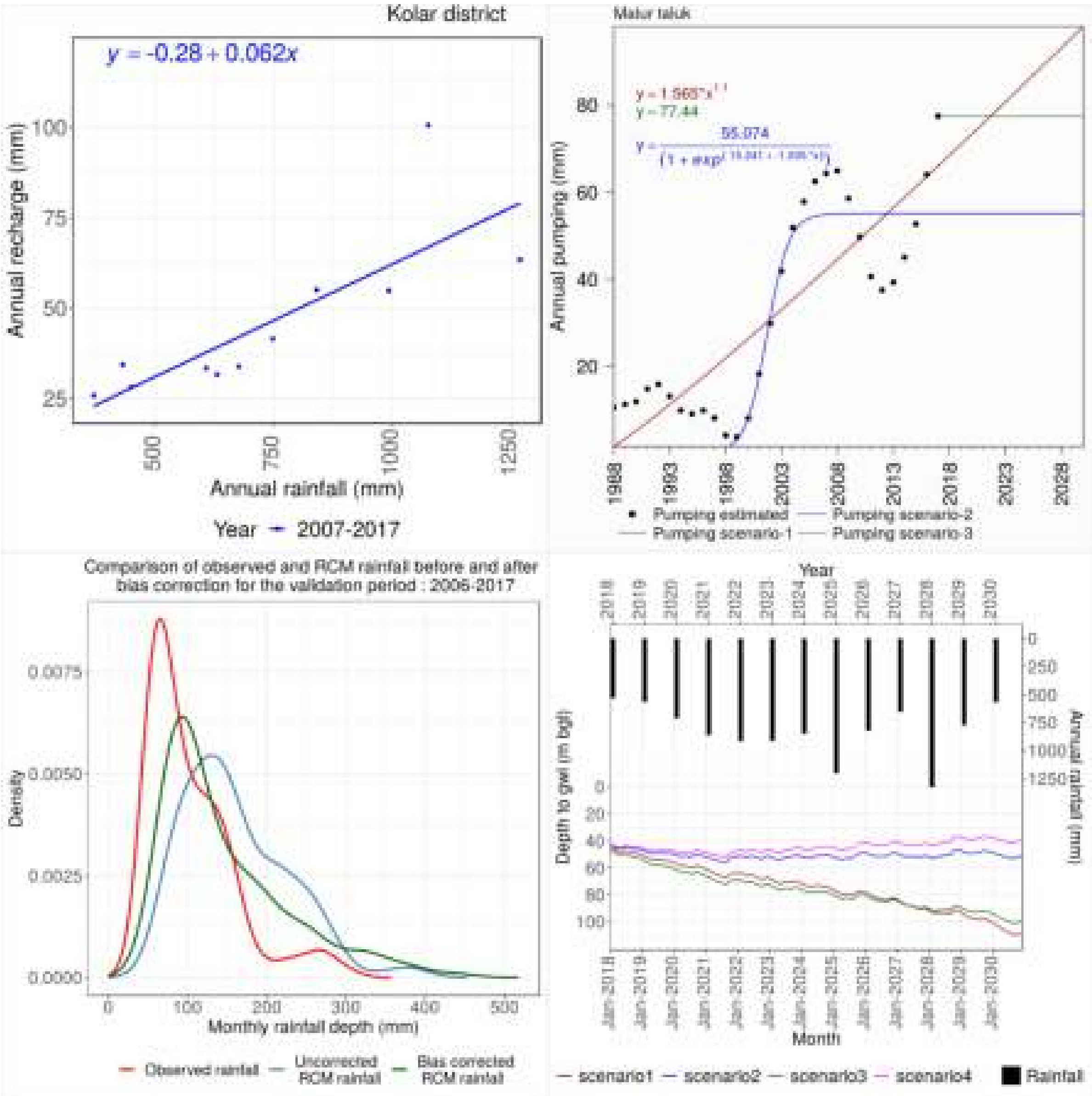


Figure 158: Simulation of future groundwater levels with four pumping scenarios for Malur taluk.

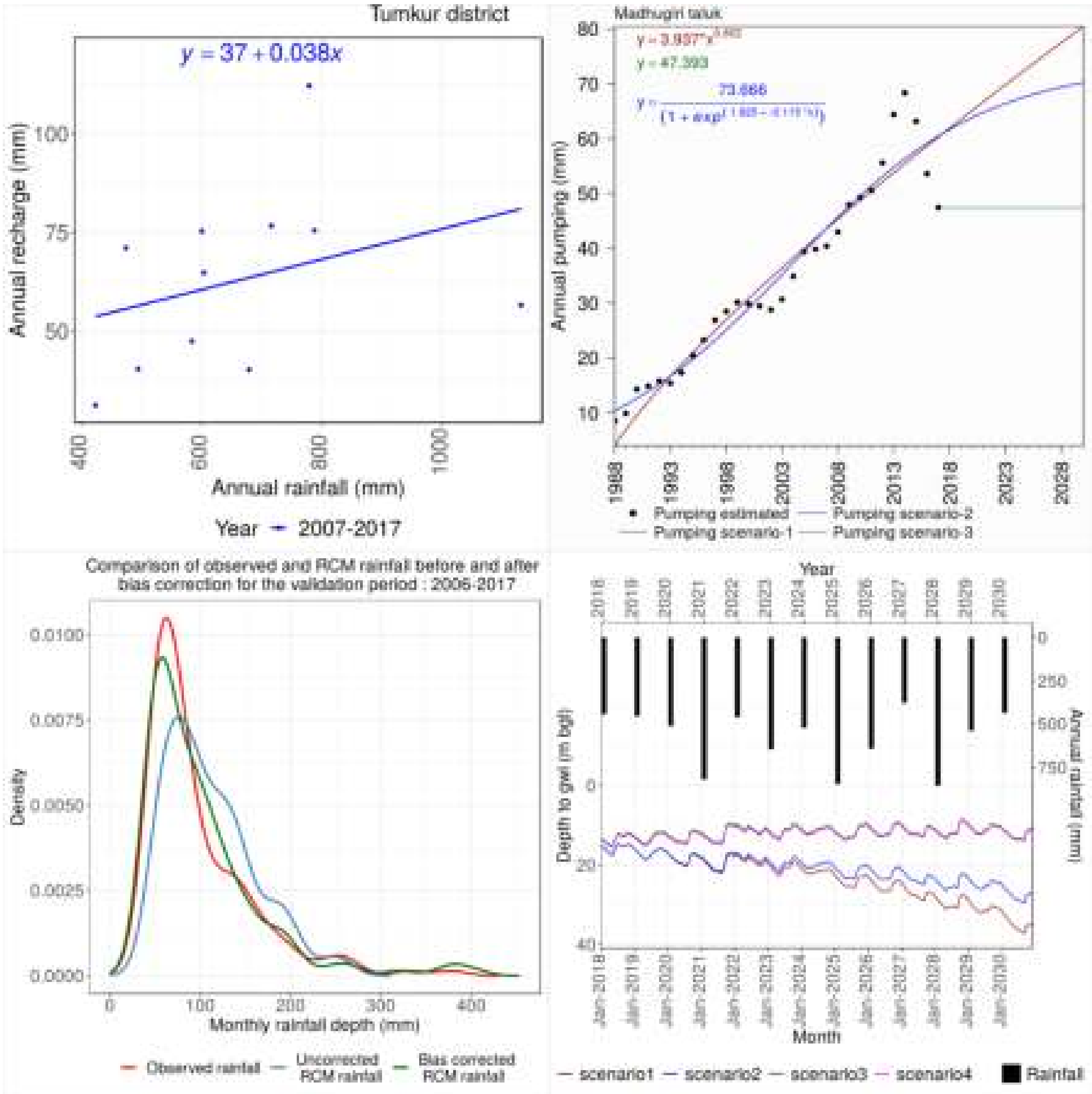


Figure 159: Simulation of future groundwater levels with four pumping scenarios for Madhugiri taluk.

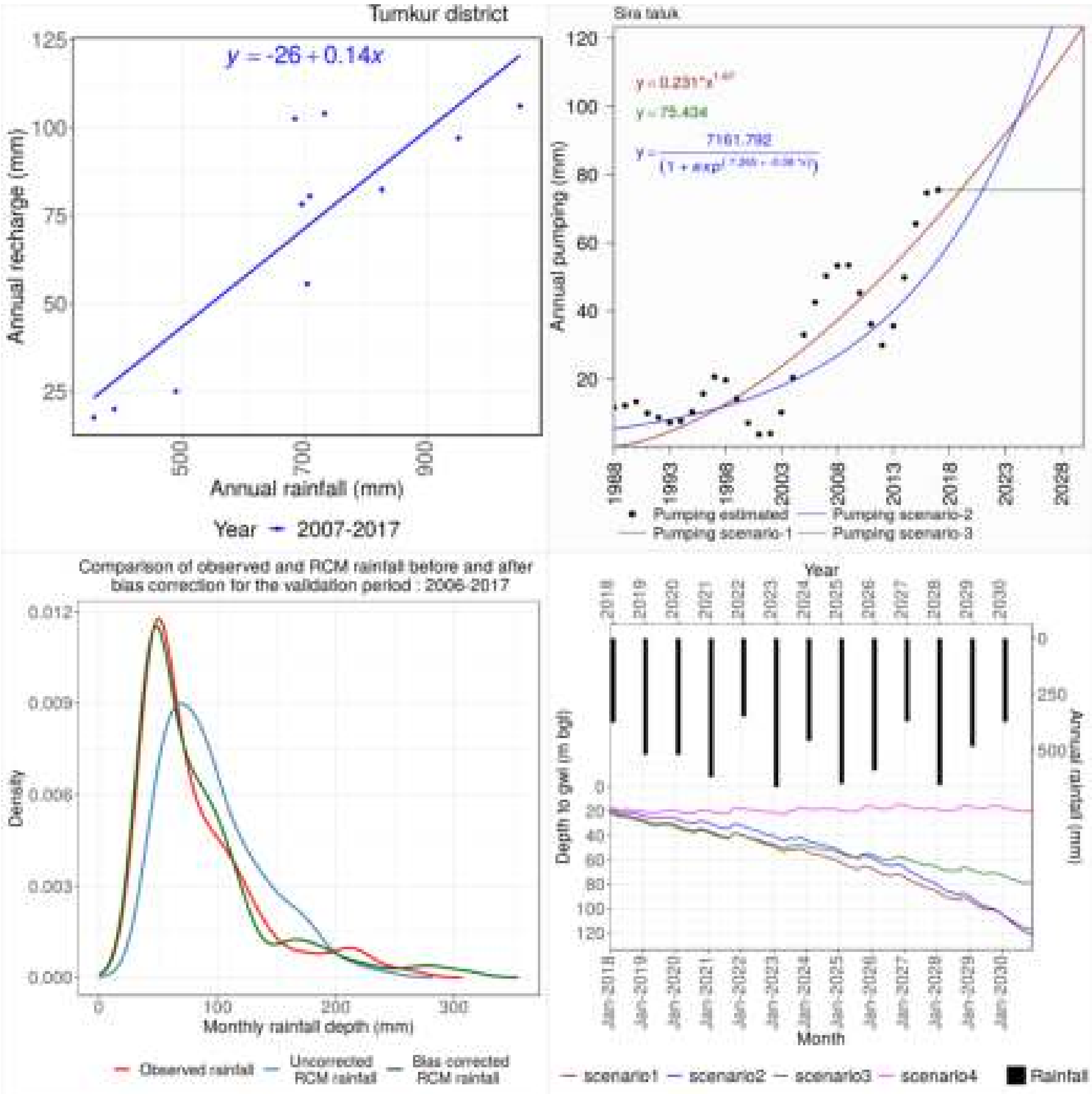


Figure 160: Simulation of future groundwater levels with four pumping scenarios for Sira taluk.

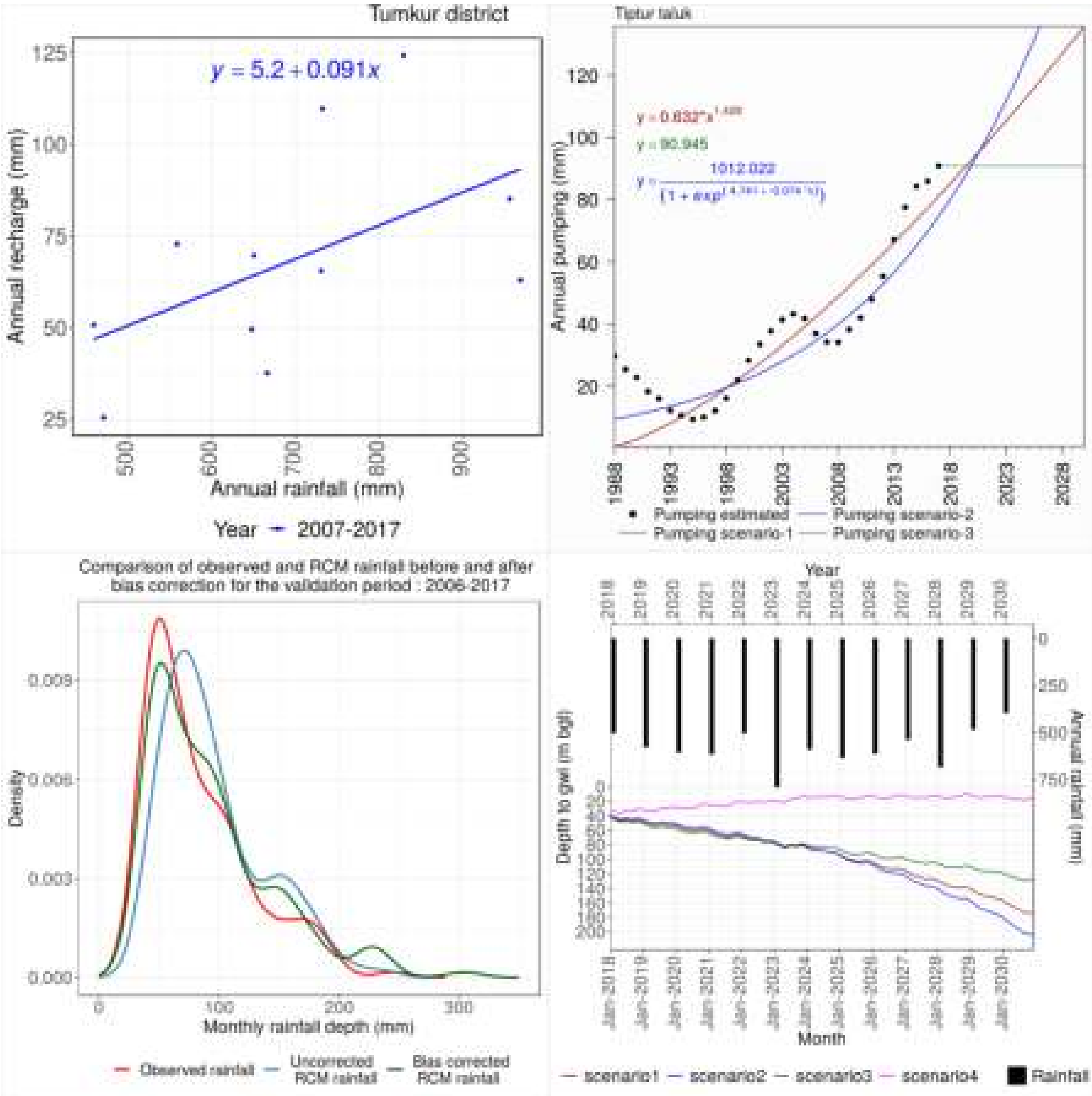


Figure 161: Simulation of future groundwater levels with four pumping scenarios for Tiptur taluk.

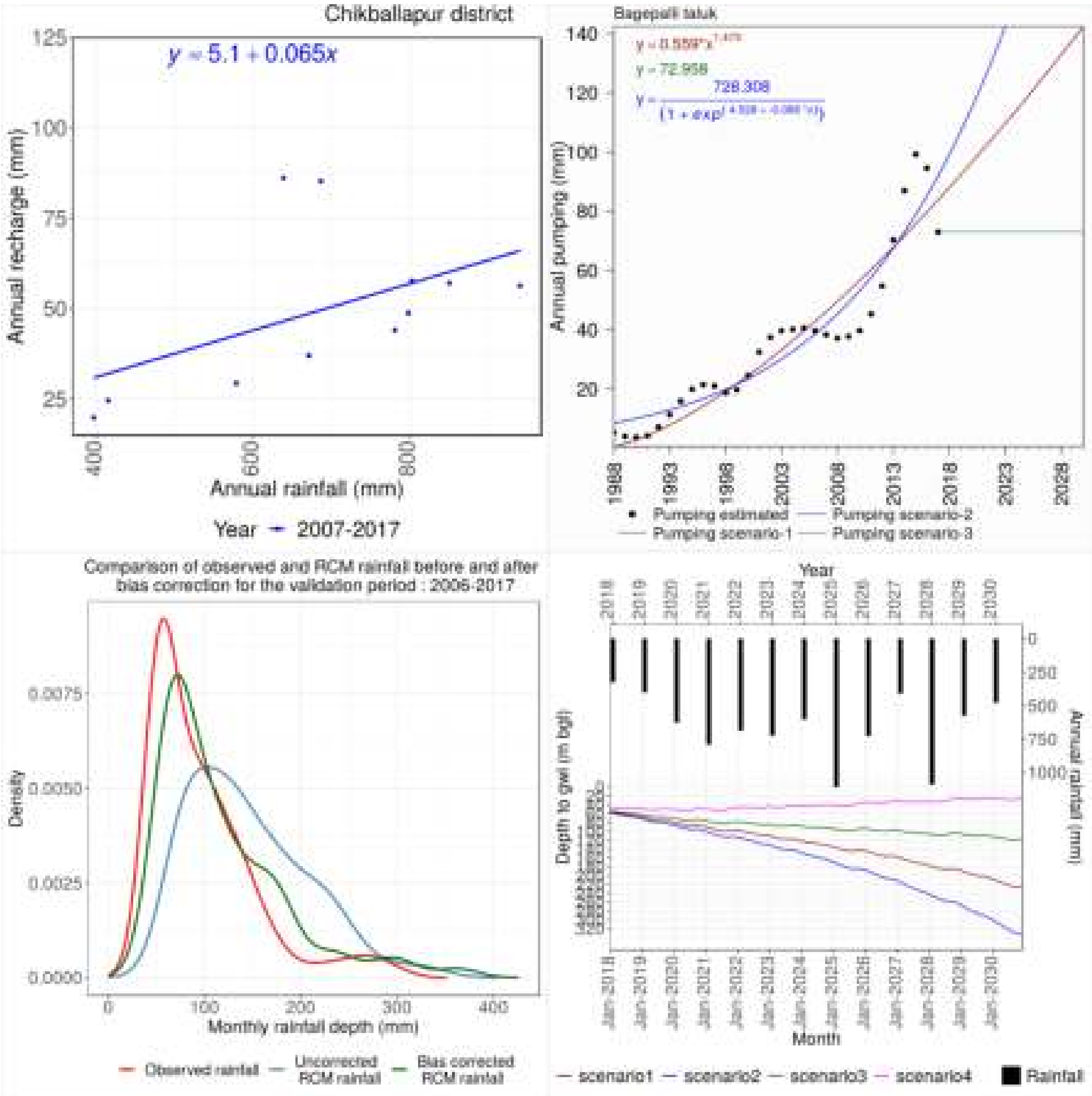


Figure 162: Simulation of future groundwater levels with four pumping scenarios for Bagepalli taluk.

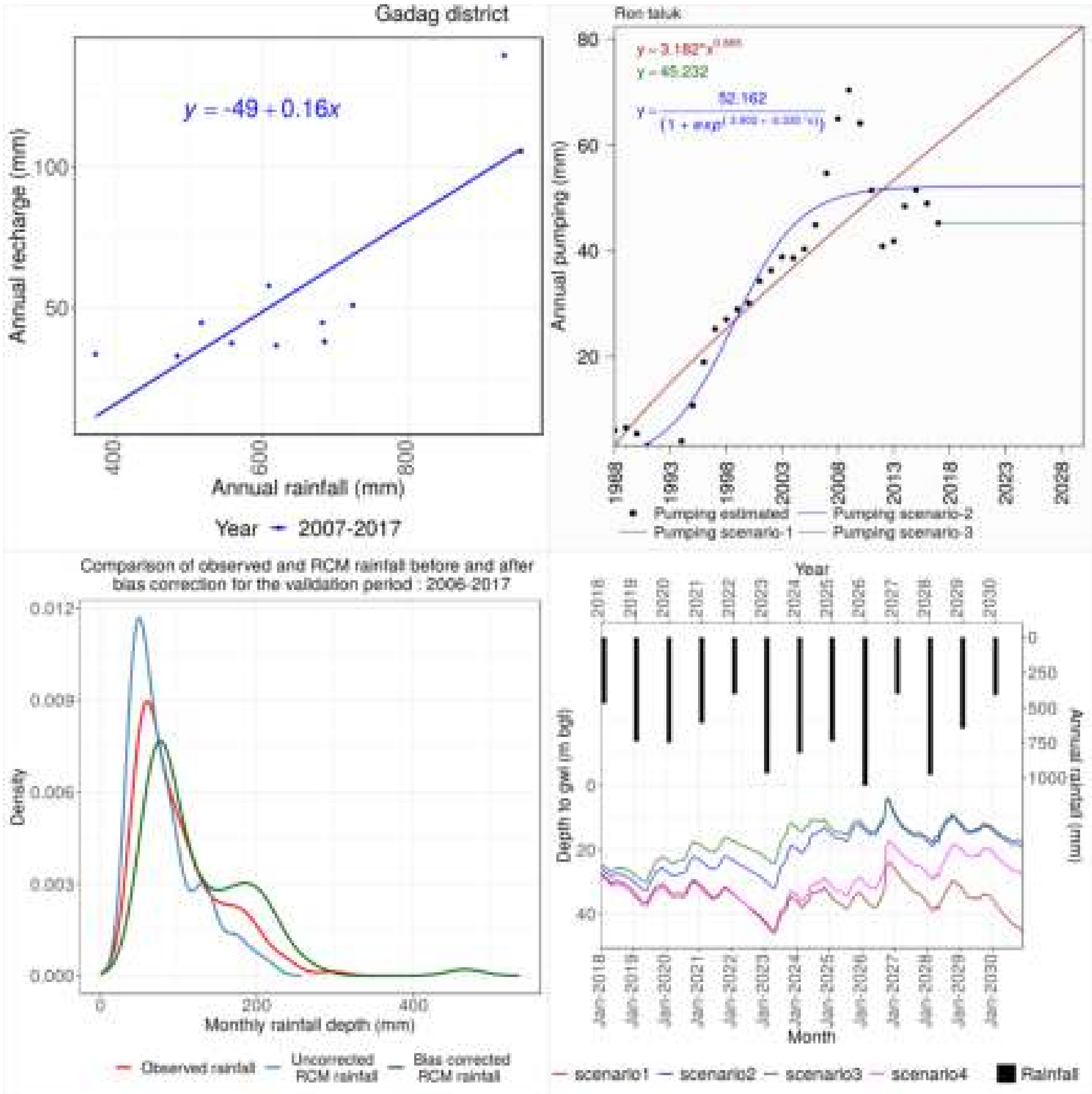


Figure 163: Simulation of future groundwater levels with four pumping scenarios for Ron taluk.

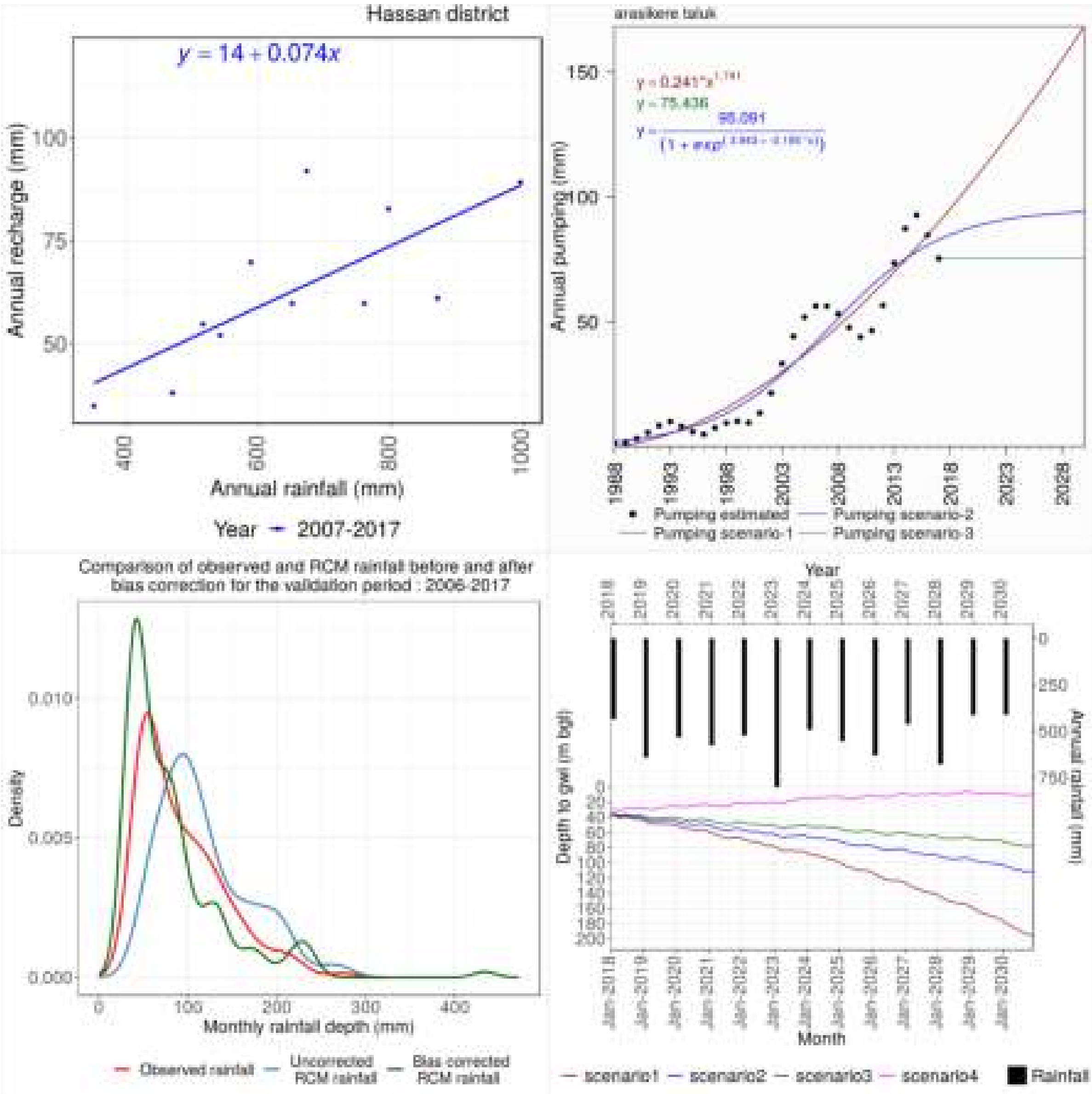


Figure 164: Simulation of future groundwater levels with four pumping scenarios for Arasikere taluk.

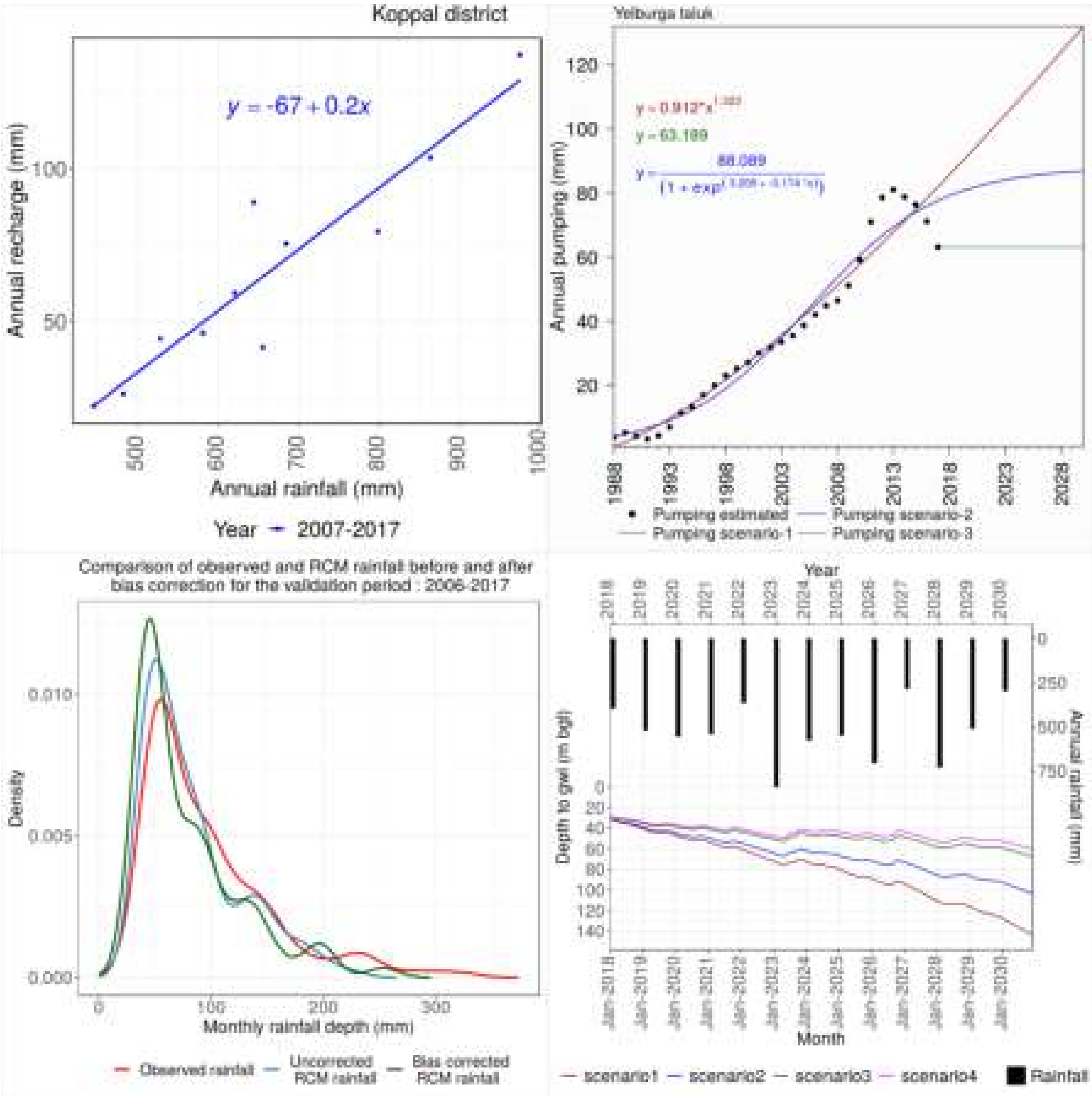


Figure 165: Simulation of future groundwater levels with four pumping scenarios for Yelburga taluk.

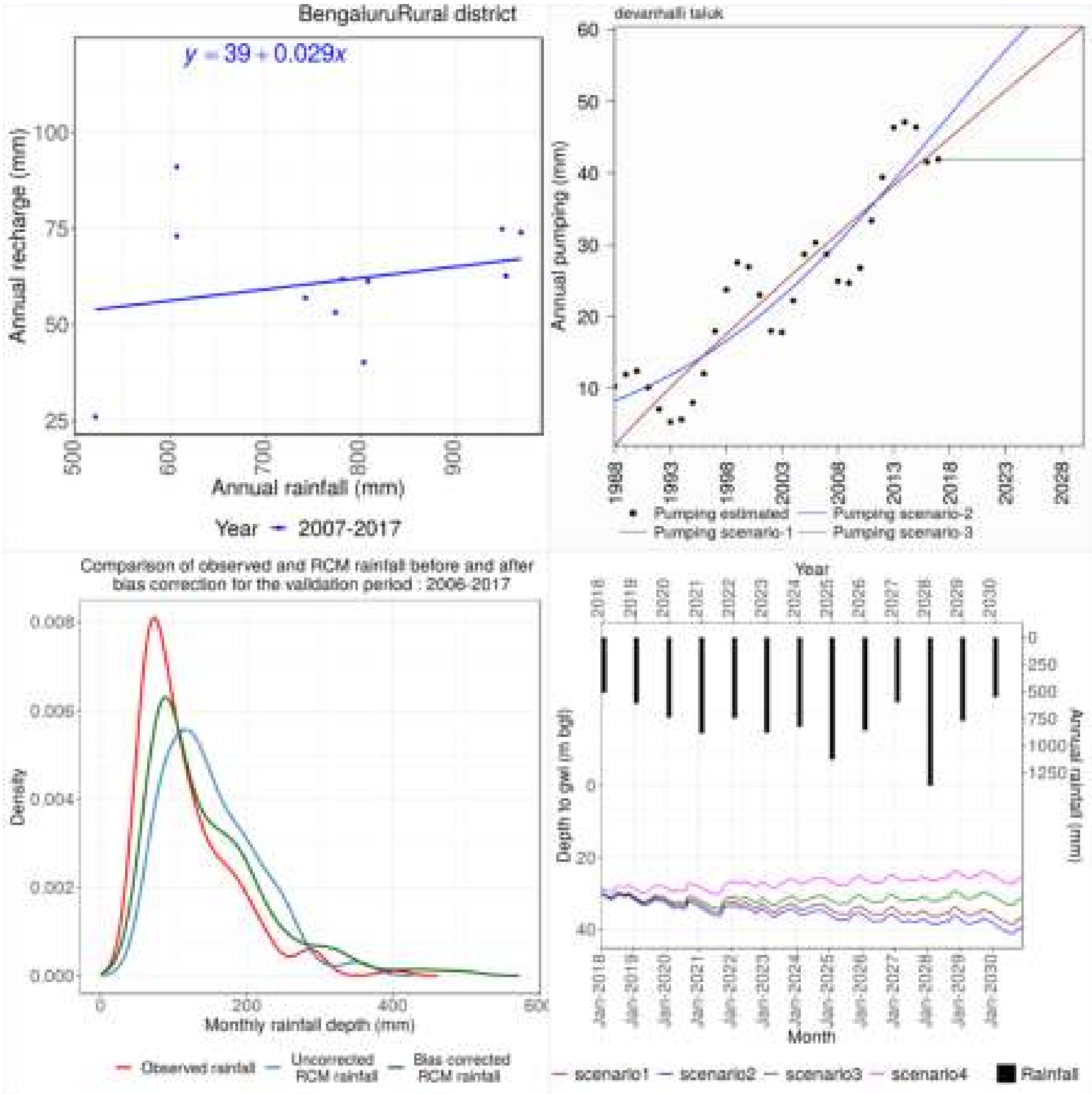


Figure 166: Simulation of future groundwater levels with four pumping scenarios for Devanahalli taluk.

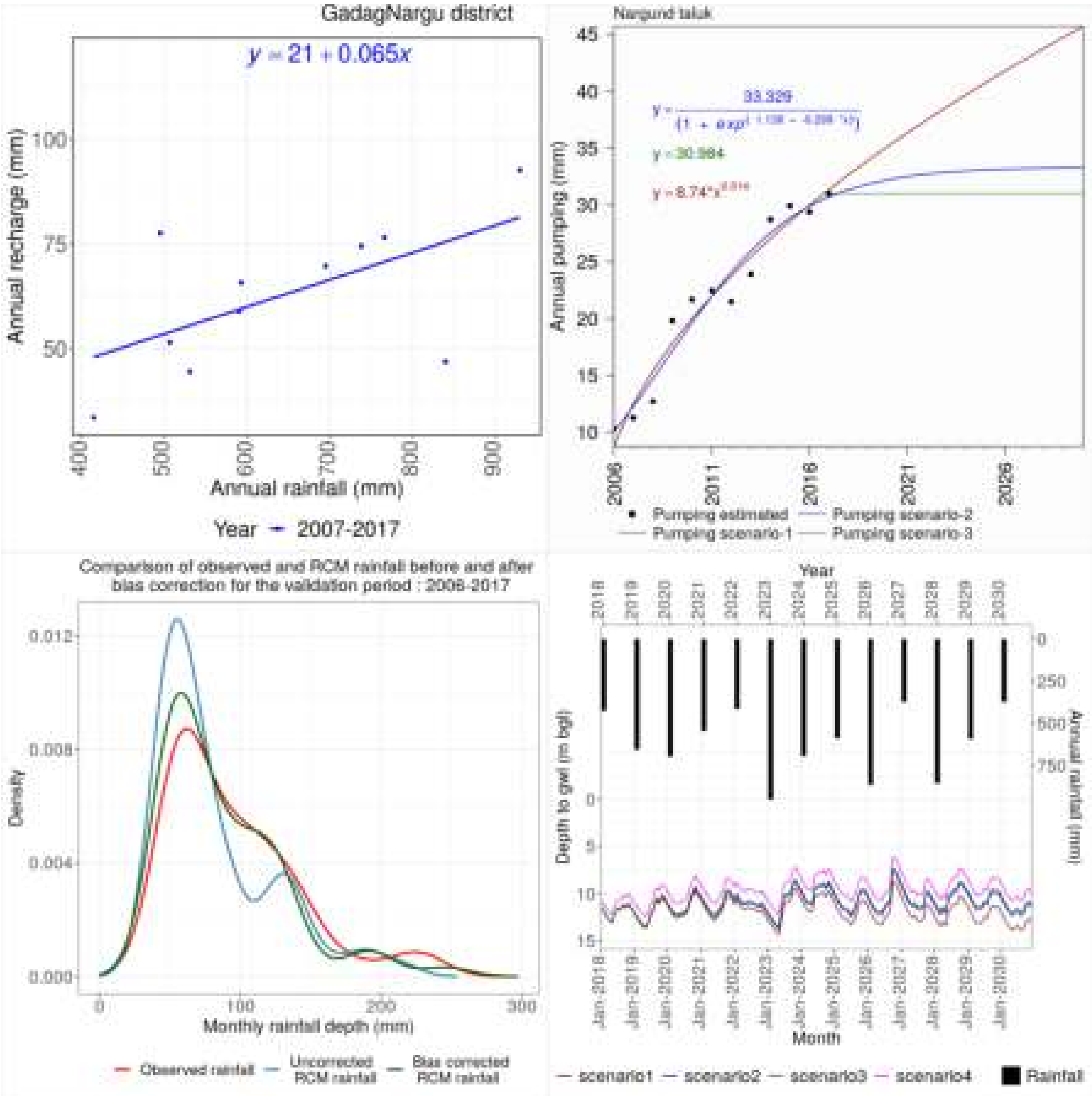


Figure 167: Simulation of future groundwater levels with four pumping scenarios for Nargund taluk.

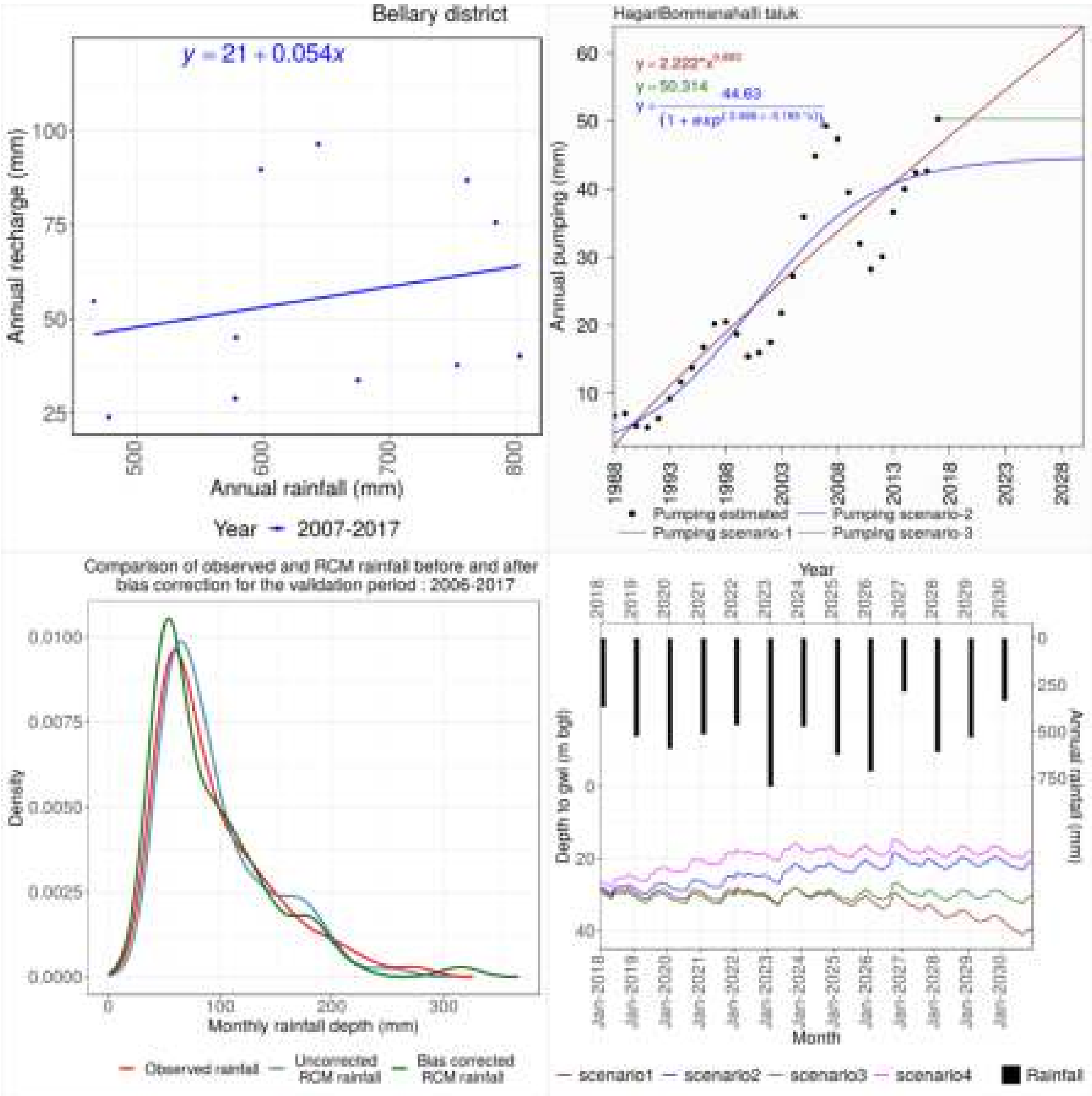


Figure 168: Simulation of future groundwater levels with four pumping scenarios for Hagaribommanahalli taluk.

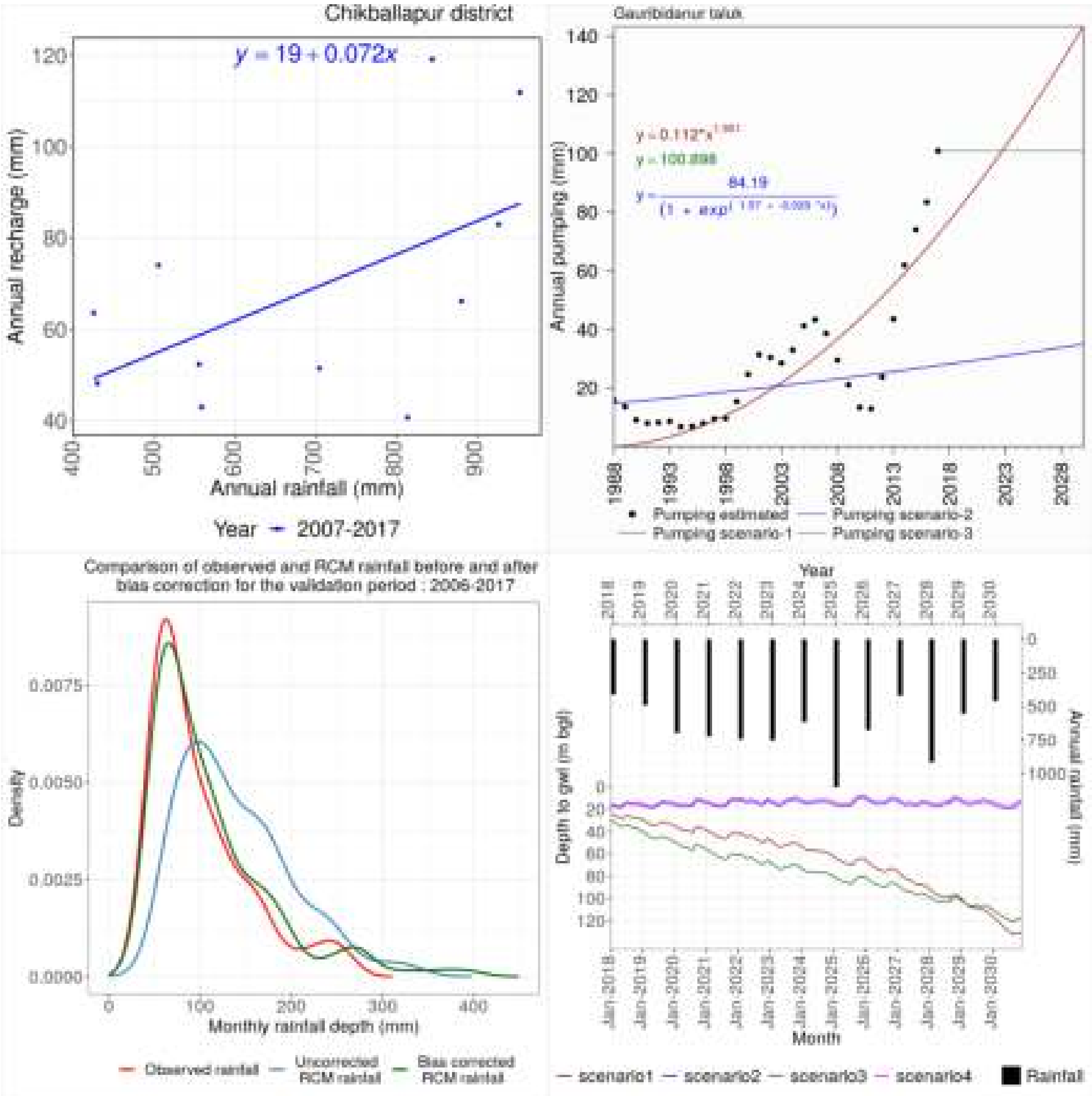


Figure 169: Simulation of future groundwater levels with four pumping scenarios for Gauribidanur taluk.

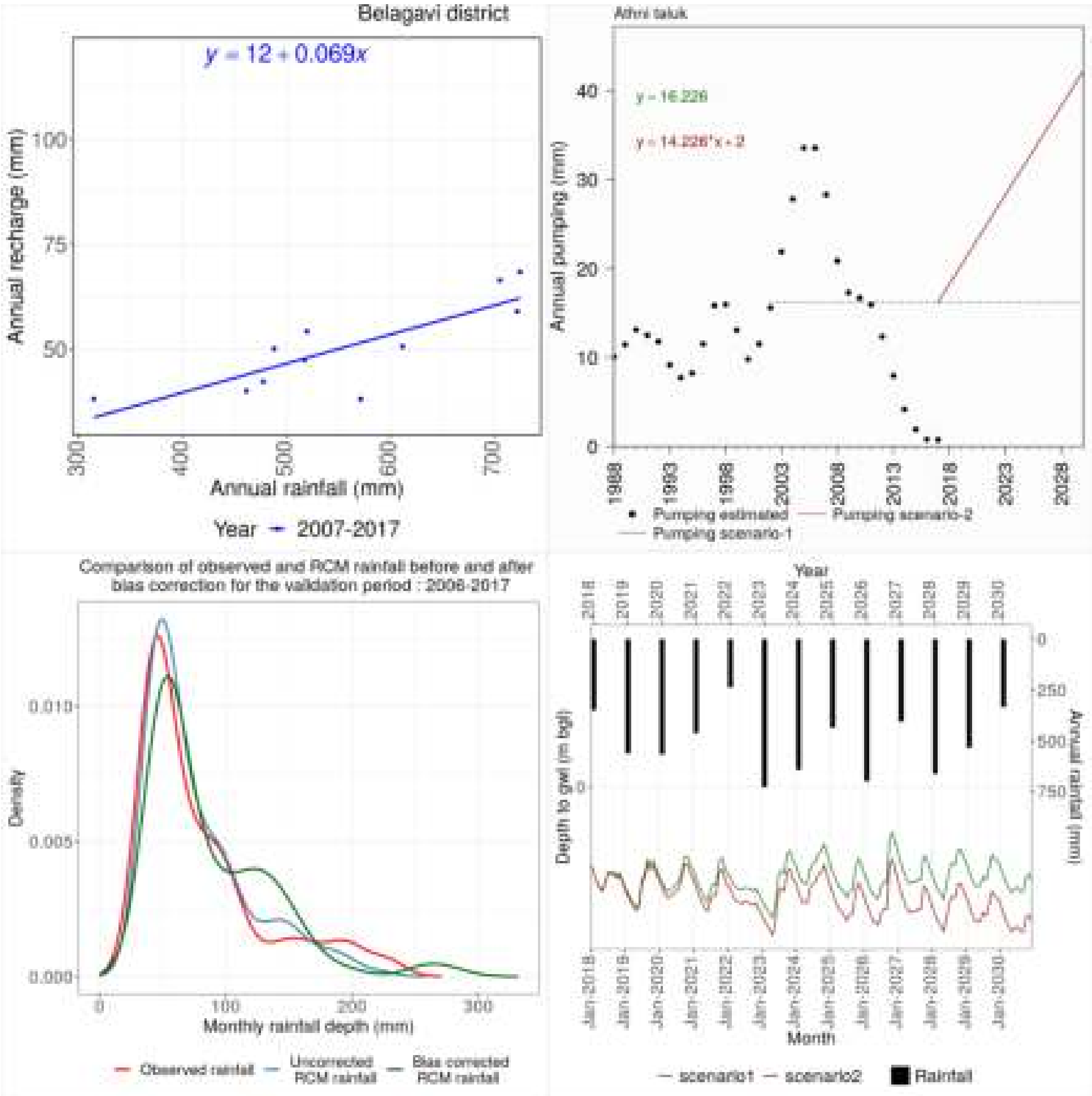


Figure 170: Simulation of future groundwater levels with four pumping scenarios for Athni taluk.

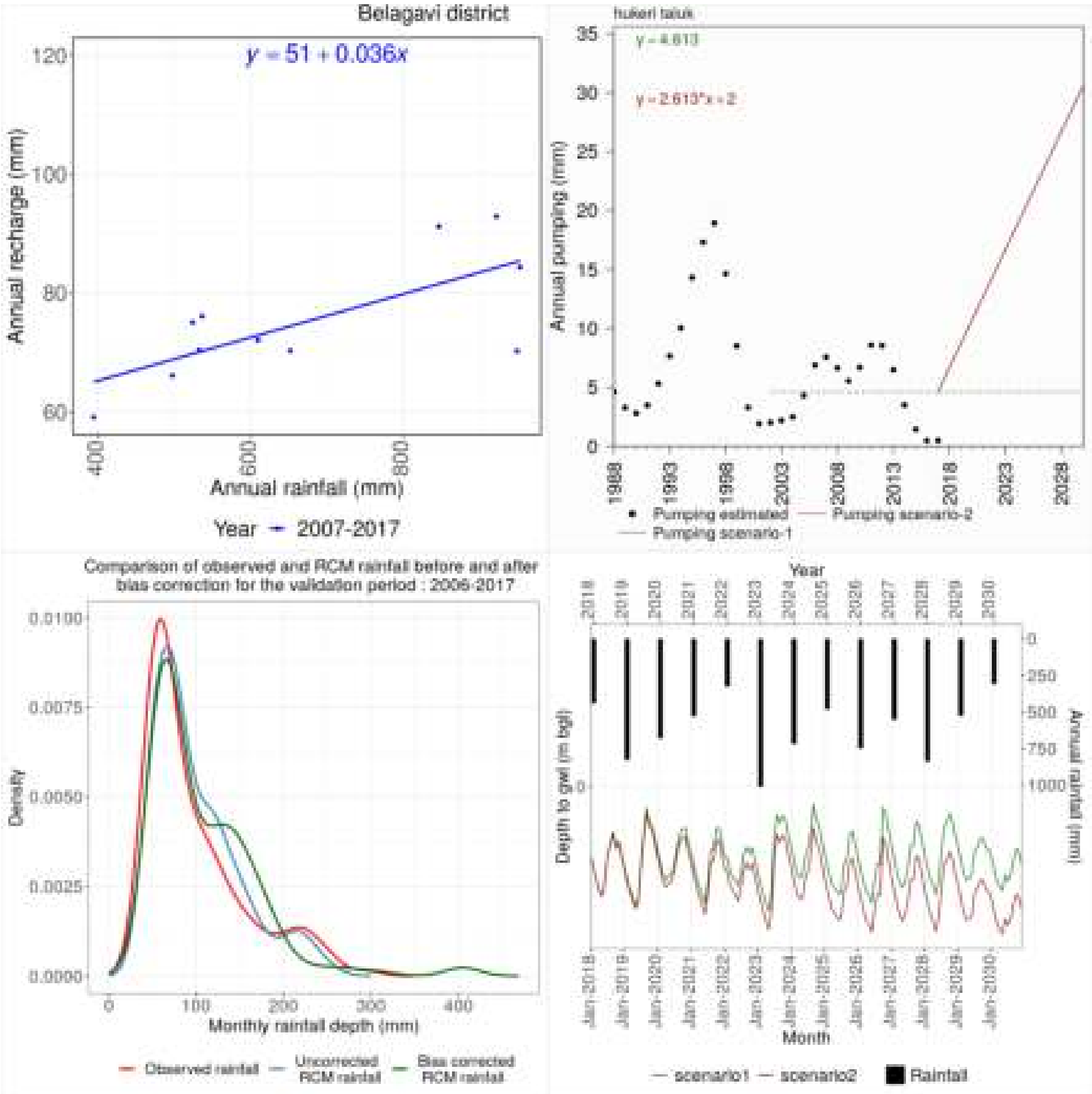


Figure 171: Simulation of future groundwater levels with four pumping scenarios for Hukeri taluk.

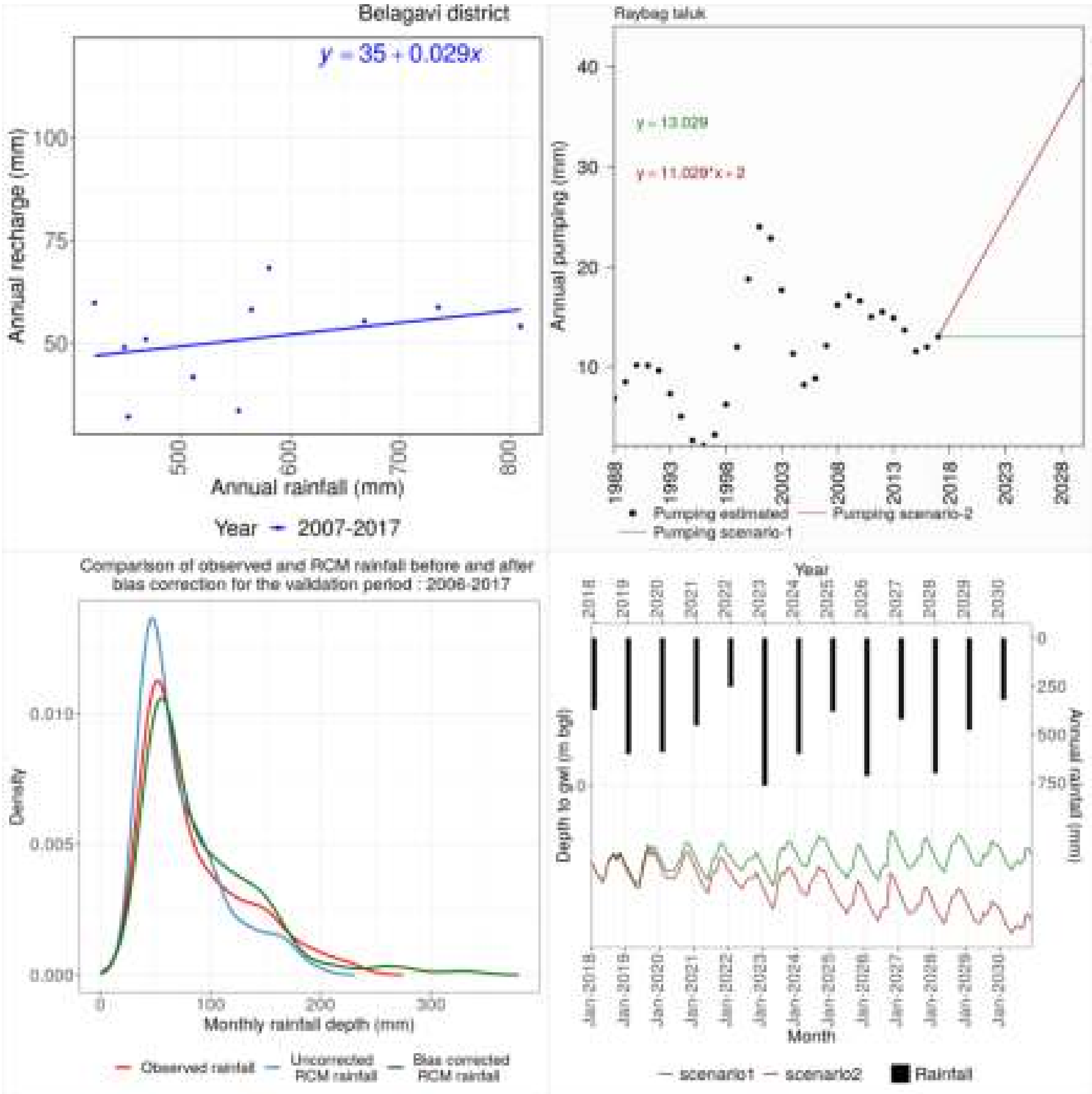


Figure 172: Simulation of future groundwater levels with four pumping scenarios for Raybag taluk.

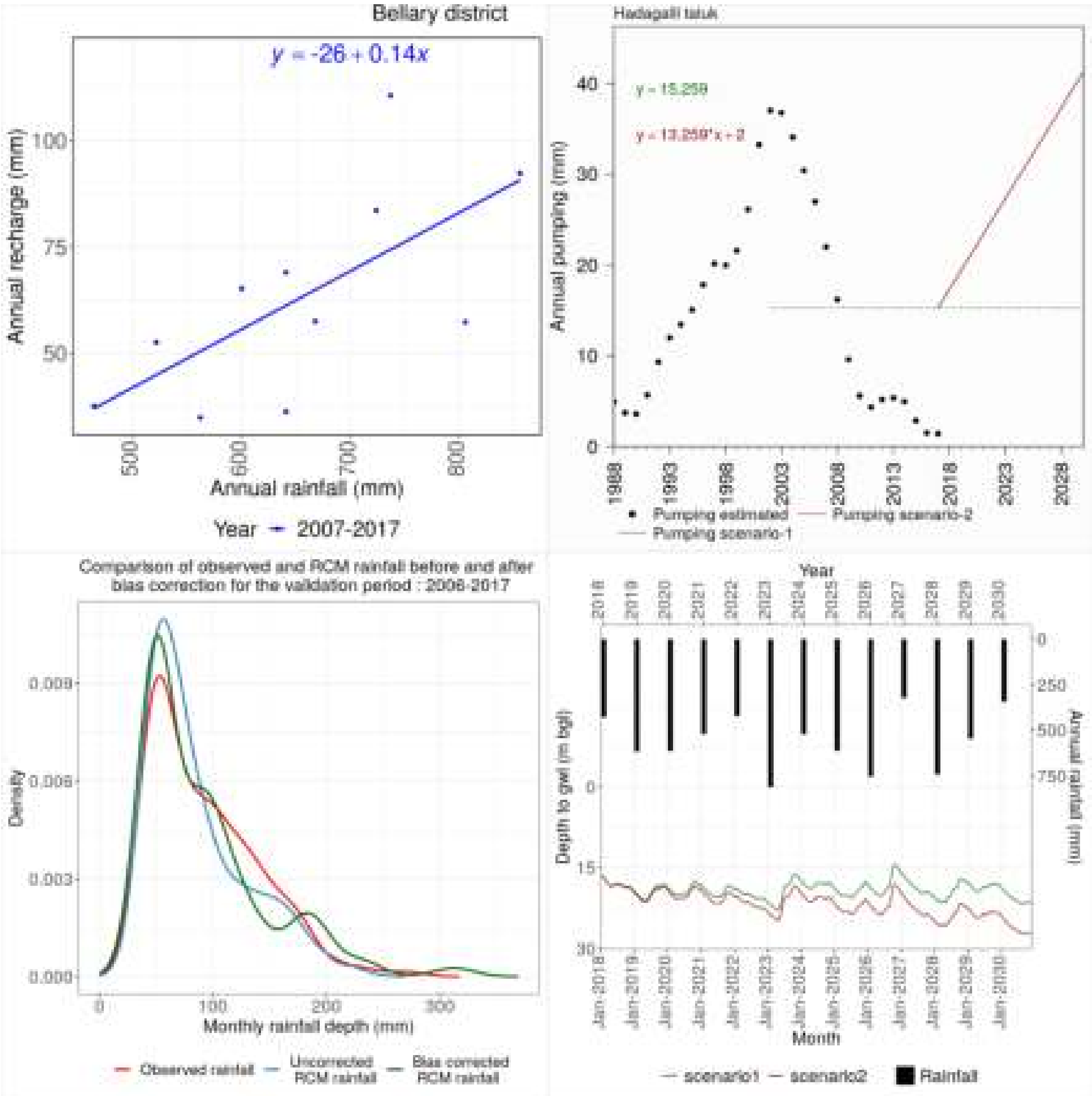


Figure 173: Simulation of future groundwater levels with four pumping scenarios for Hadagali taluk.

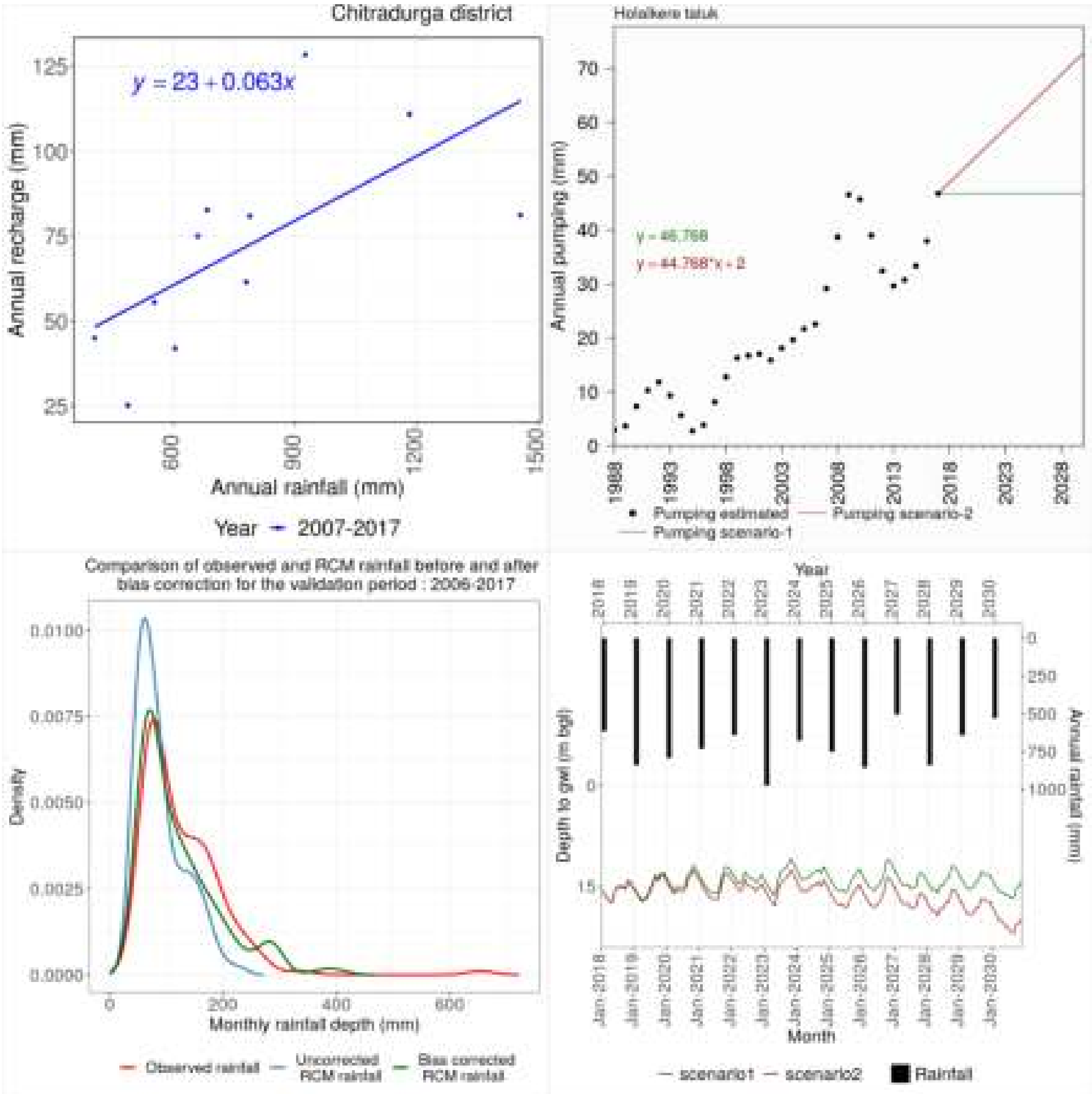


Figure 174: Simulation of future groundwater levels with four pumping scenarios for Holalkere taluk.

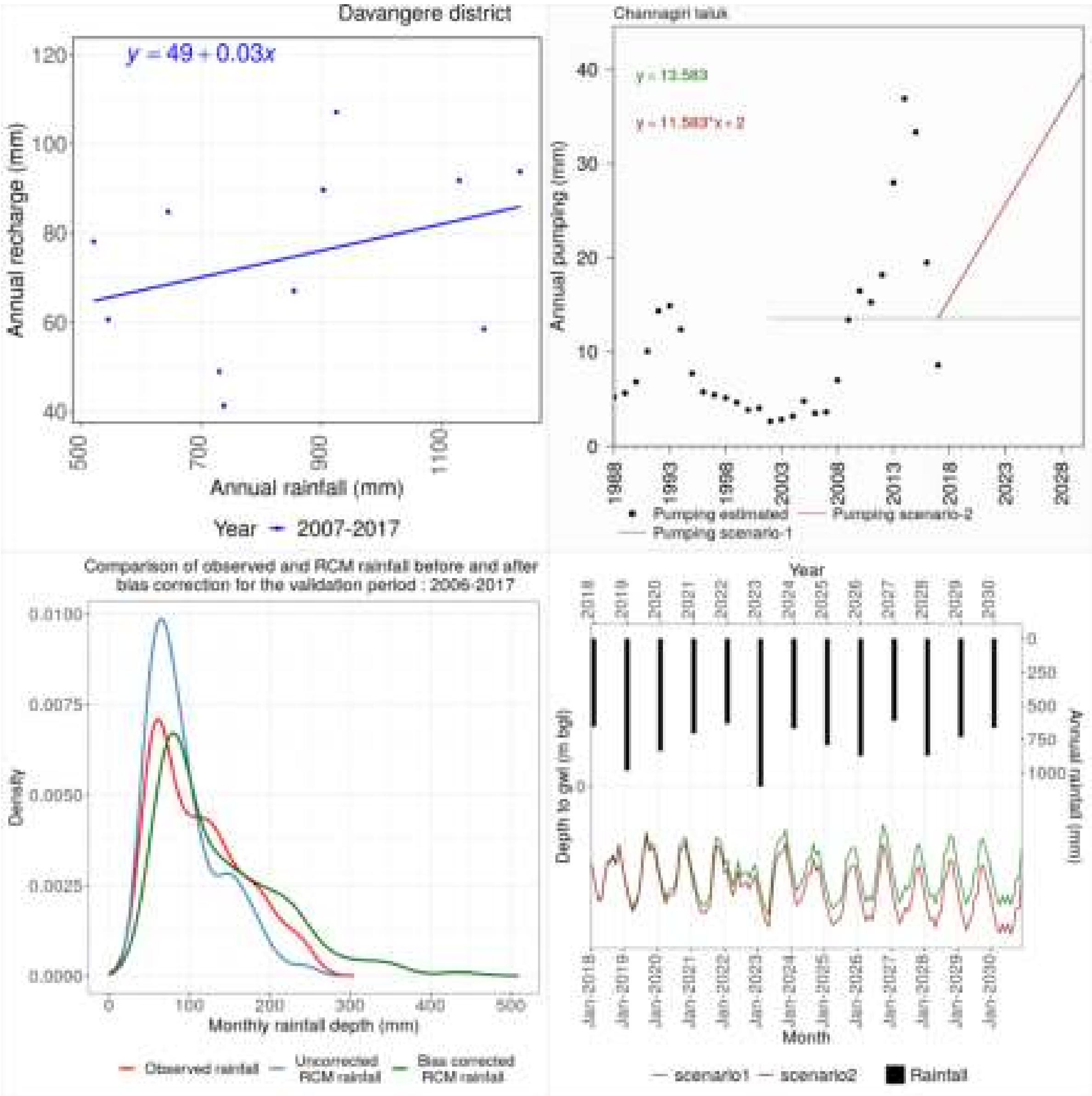


Figure 175: Simulation of future groundwater levels with four pumping scenarios for Channagiri taluk.

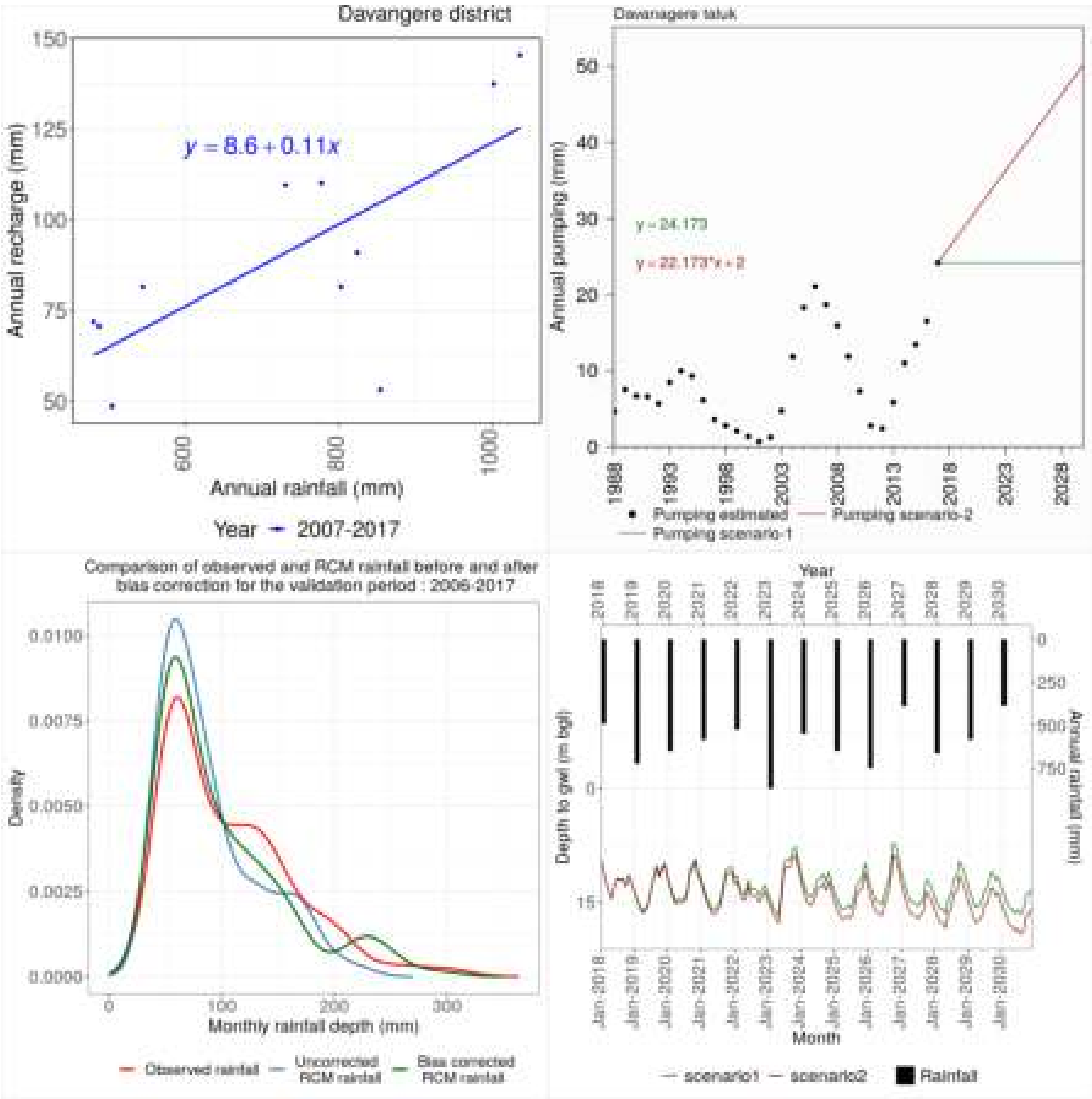


Figure 176: Simulation of future groundwater levels with four pumping scenarios for Davanagere taluk.

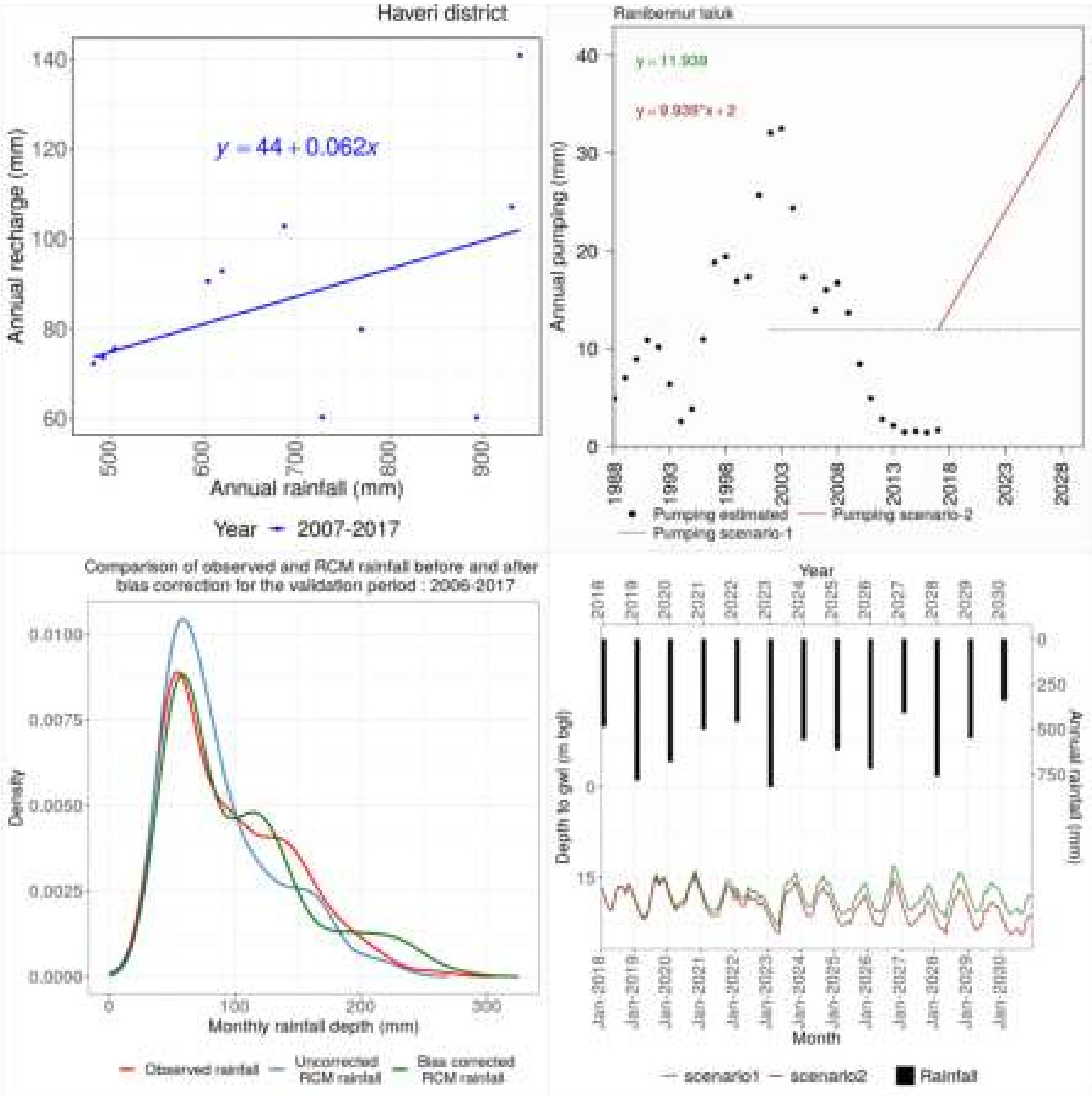


Figure 177: Simulation of future groundwater levels with four pumping scenarios for Ranebennur taluk.

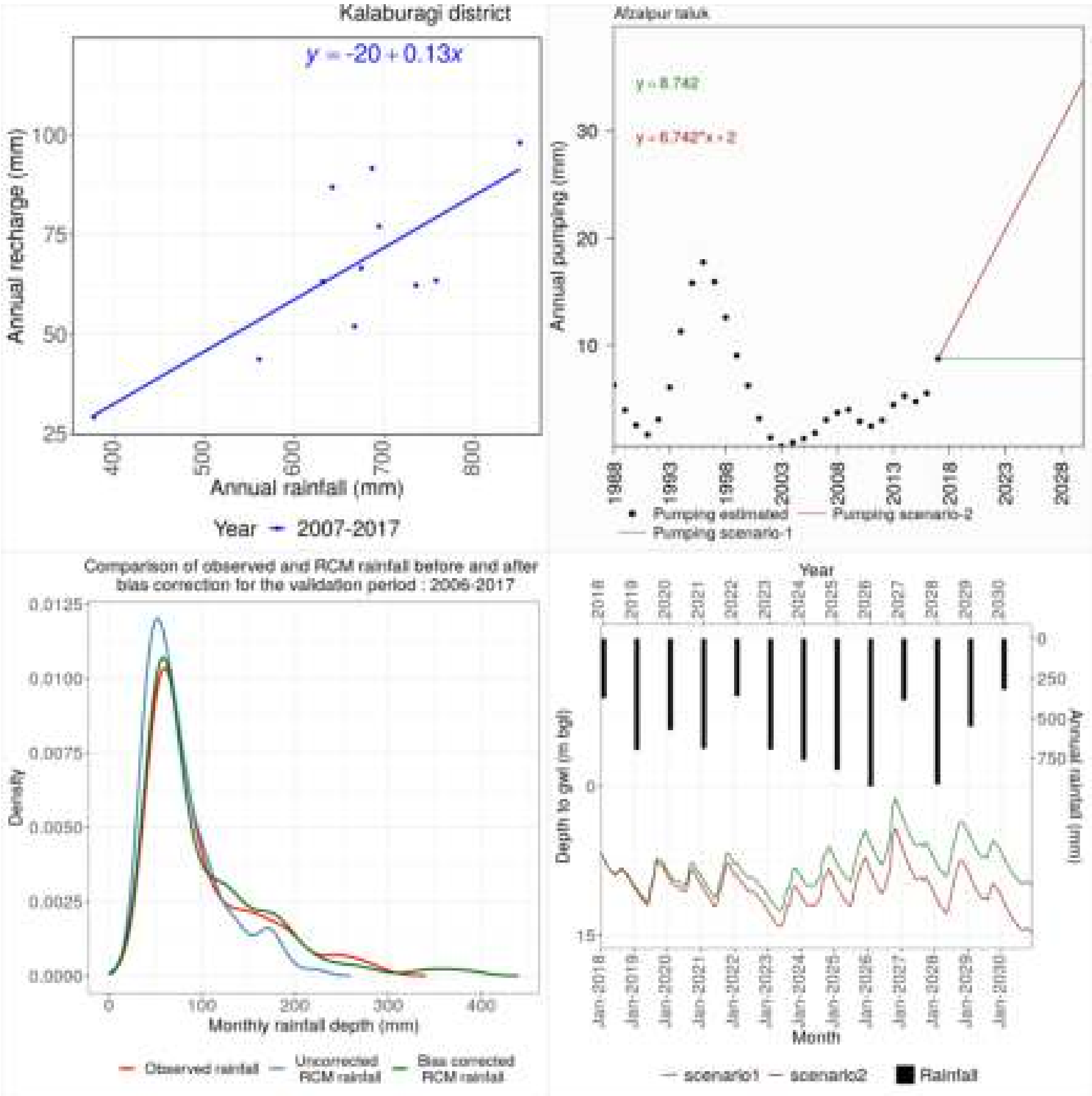


Figure 178: Simulation of future groundwater levels with four pumping scenarios for Afzalpur taluk.

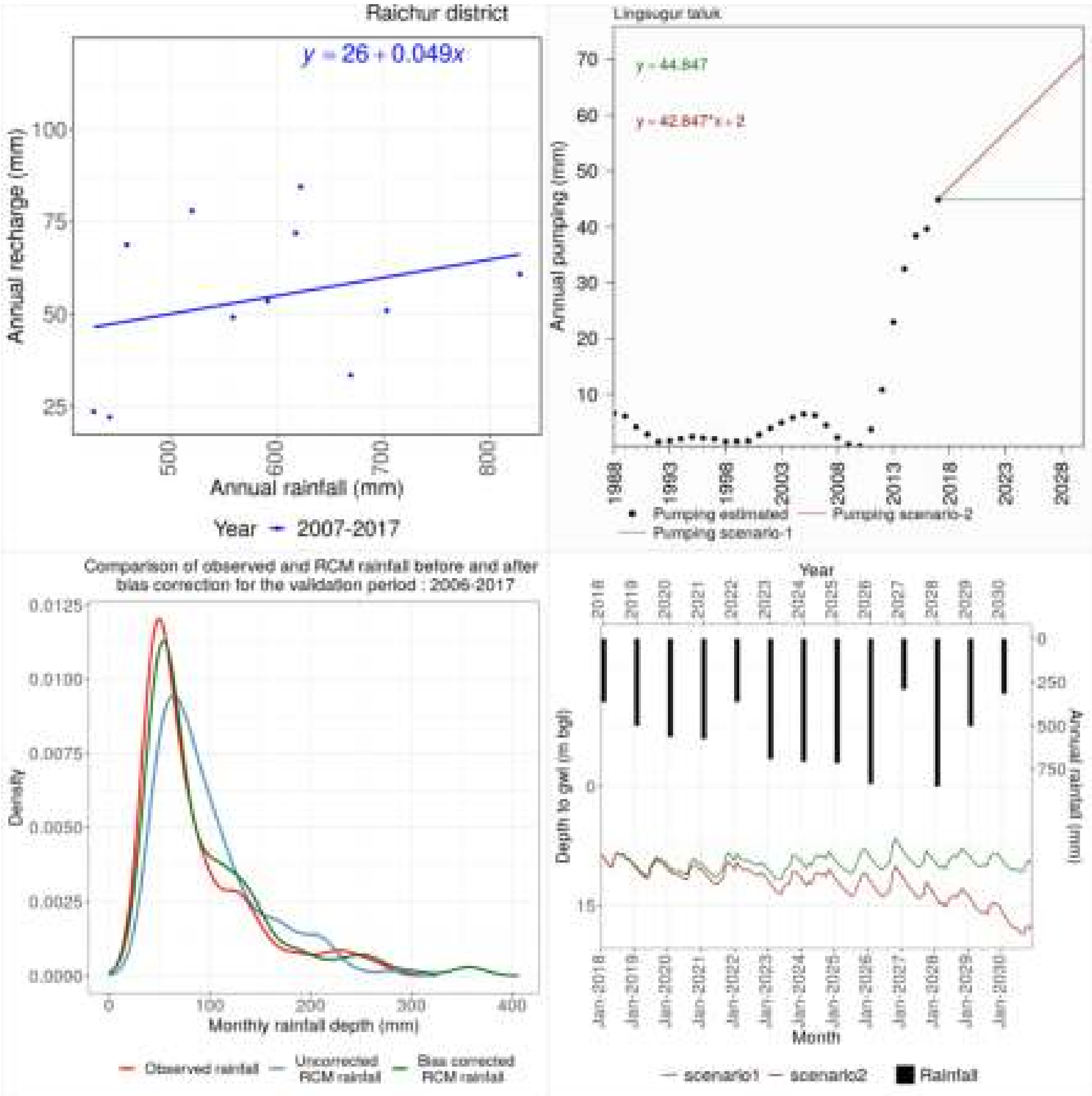


Figure 179: Simulation of future groundwater levels with four pumping scenarios for Lingsugur taluk.

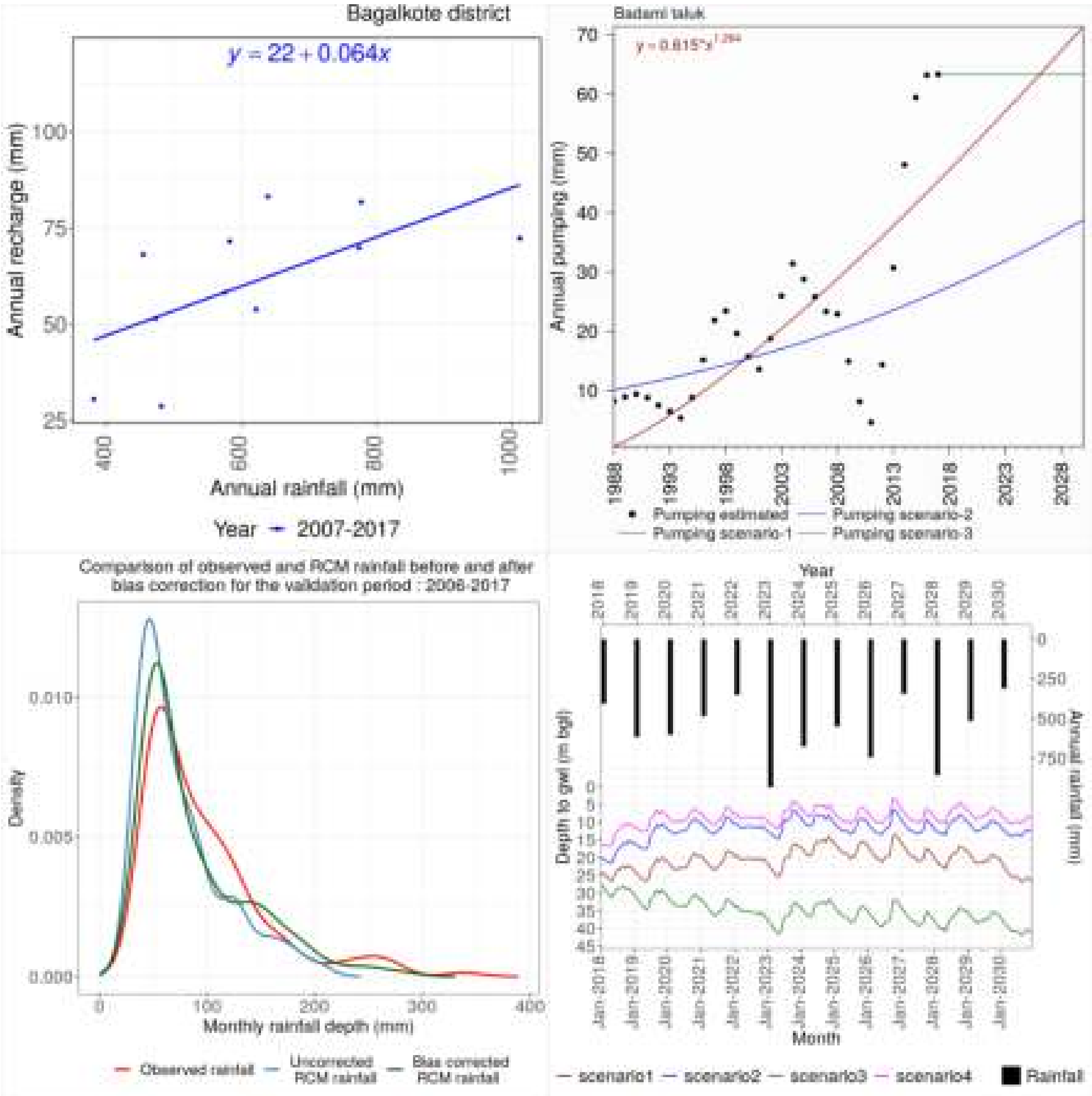


Figure 180: Simulation of future groundwater levels with four pumping scenarios for Badami taluk.

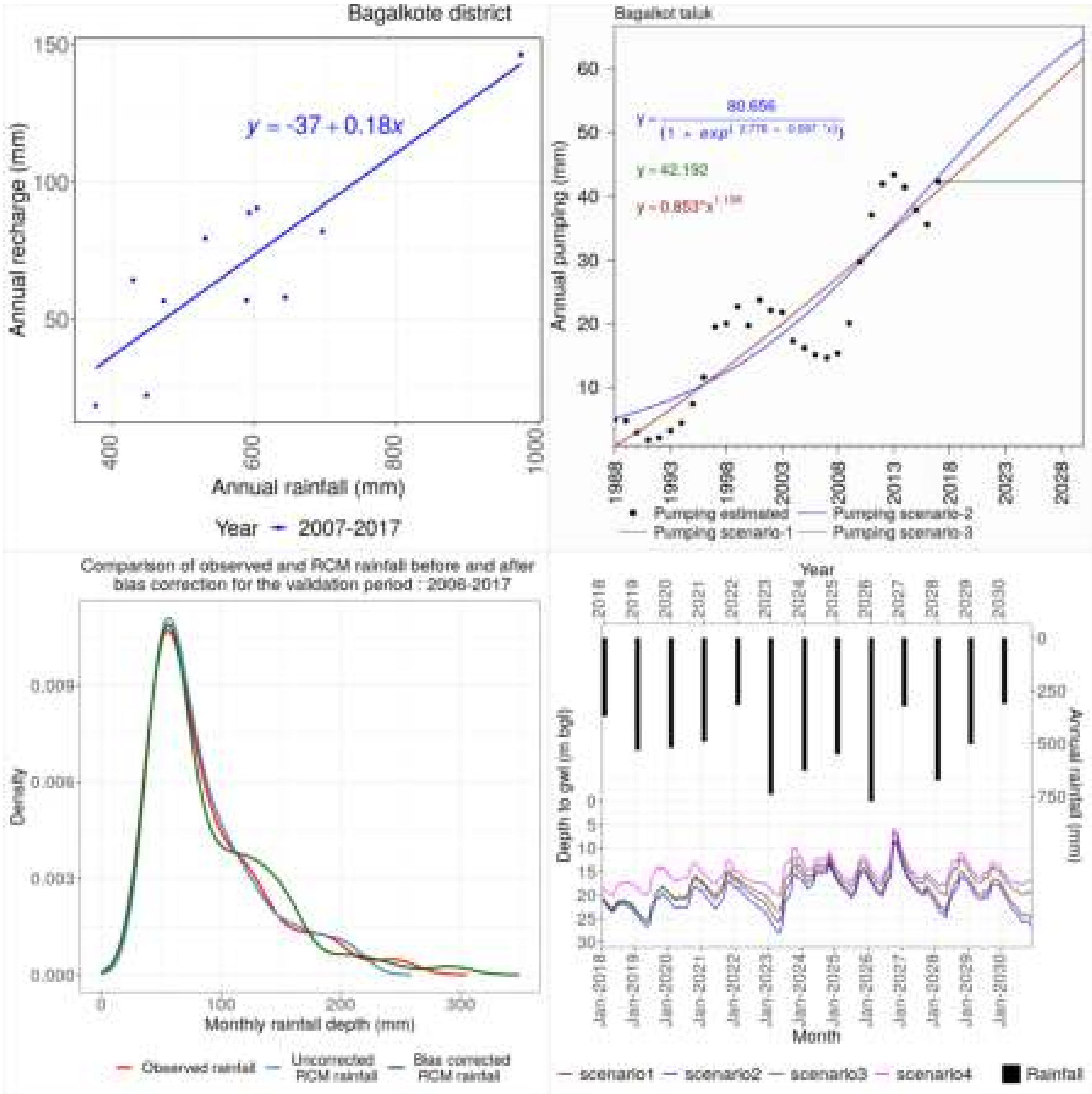


Figure 181: Simulation of future groundwater levels with four pumping scenarios for Bagalkot taluk.

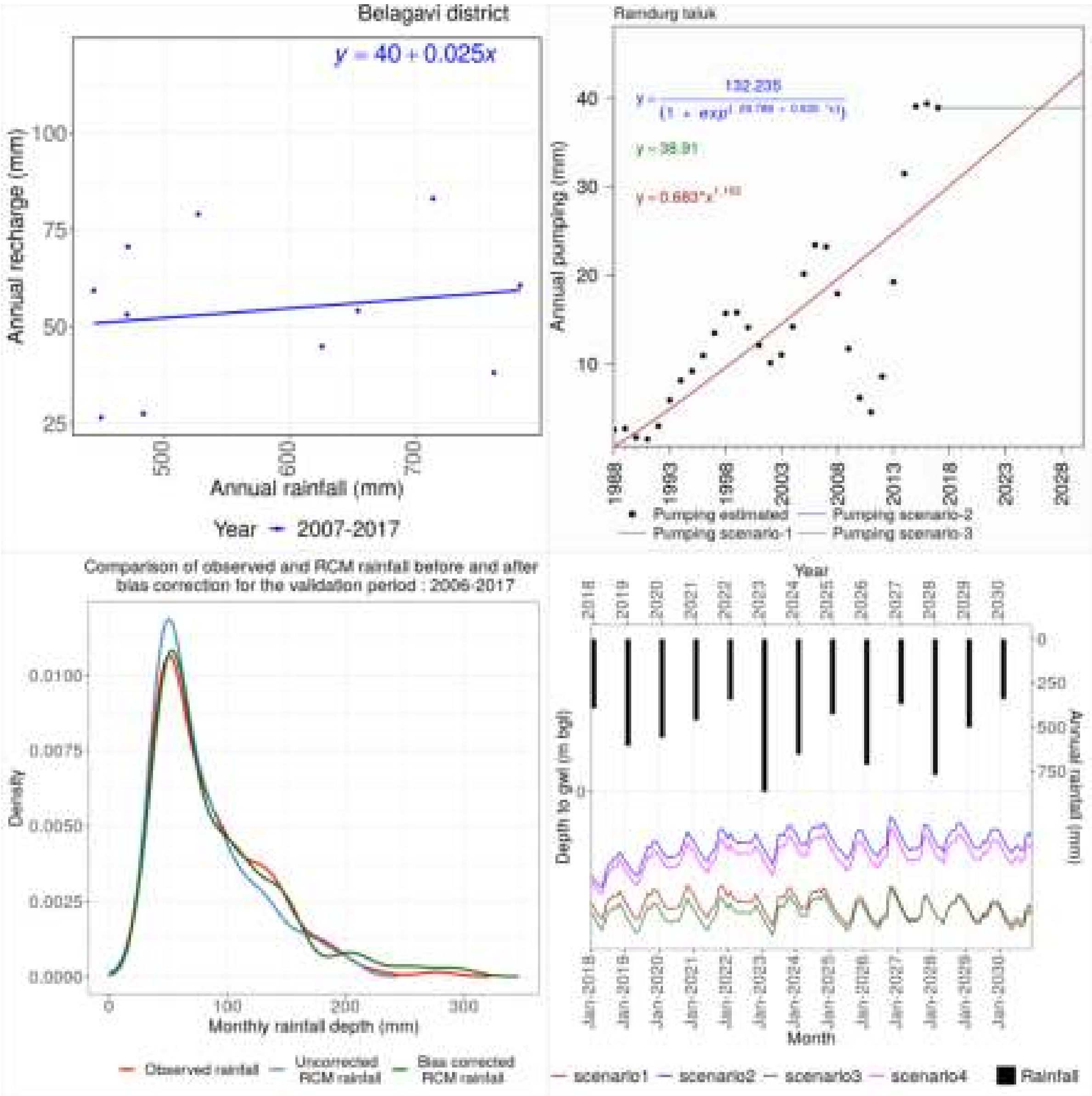


Figure 182: Simulation of future groundwater levels with four pumping scenarios for Ramdurg taluk.

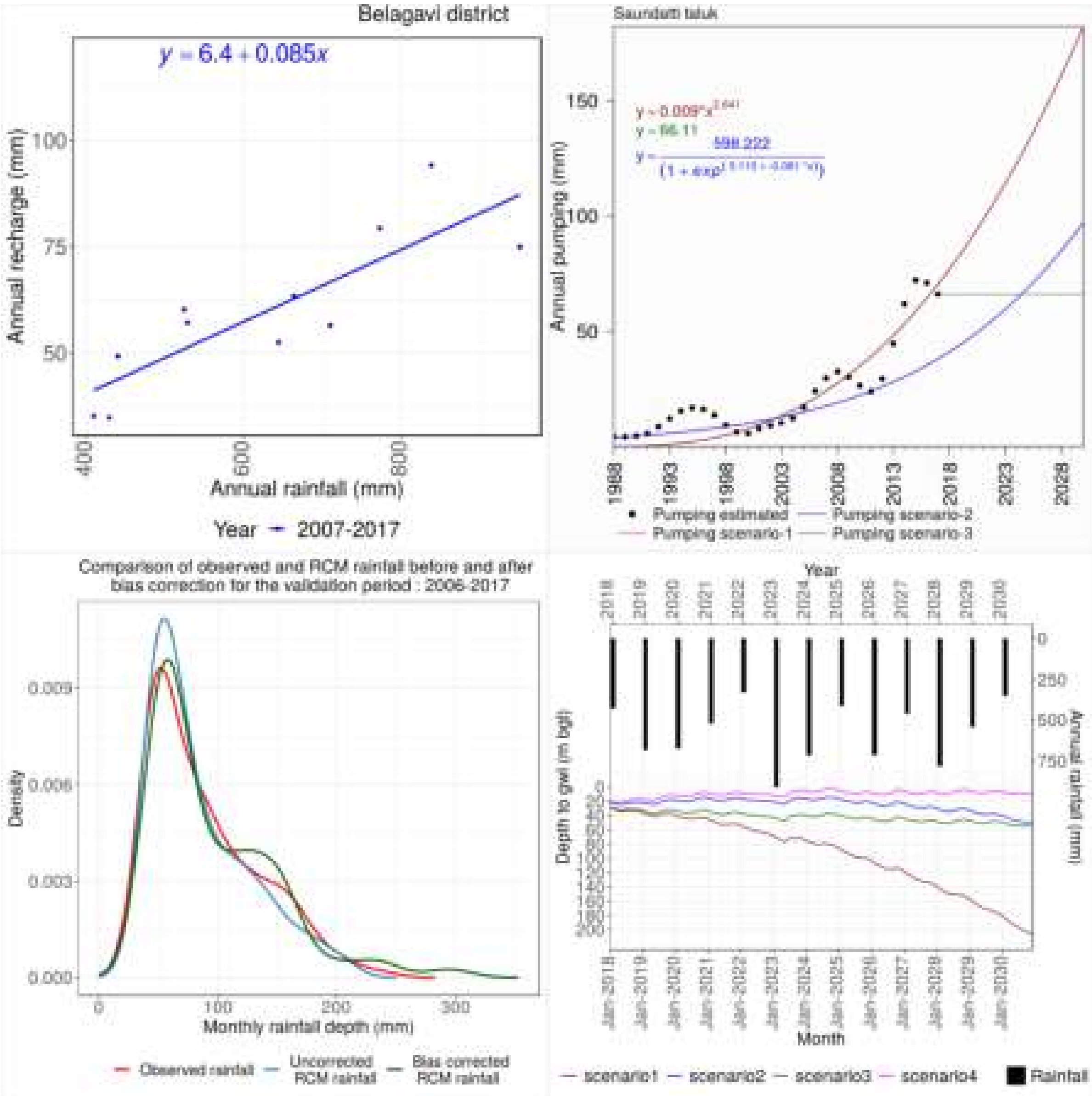


Figure 183: Simulation of future groundwater levels with four pumping scenarios for Saundatti taluk.

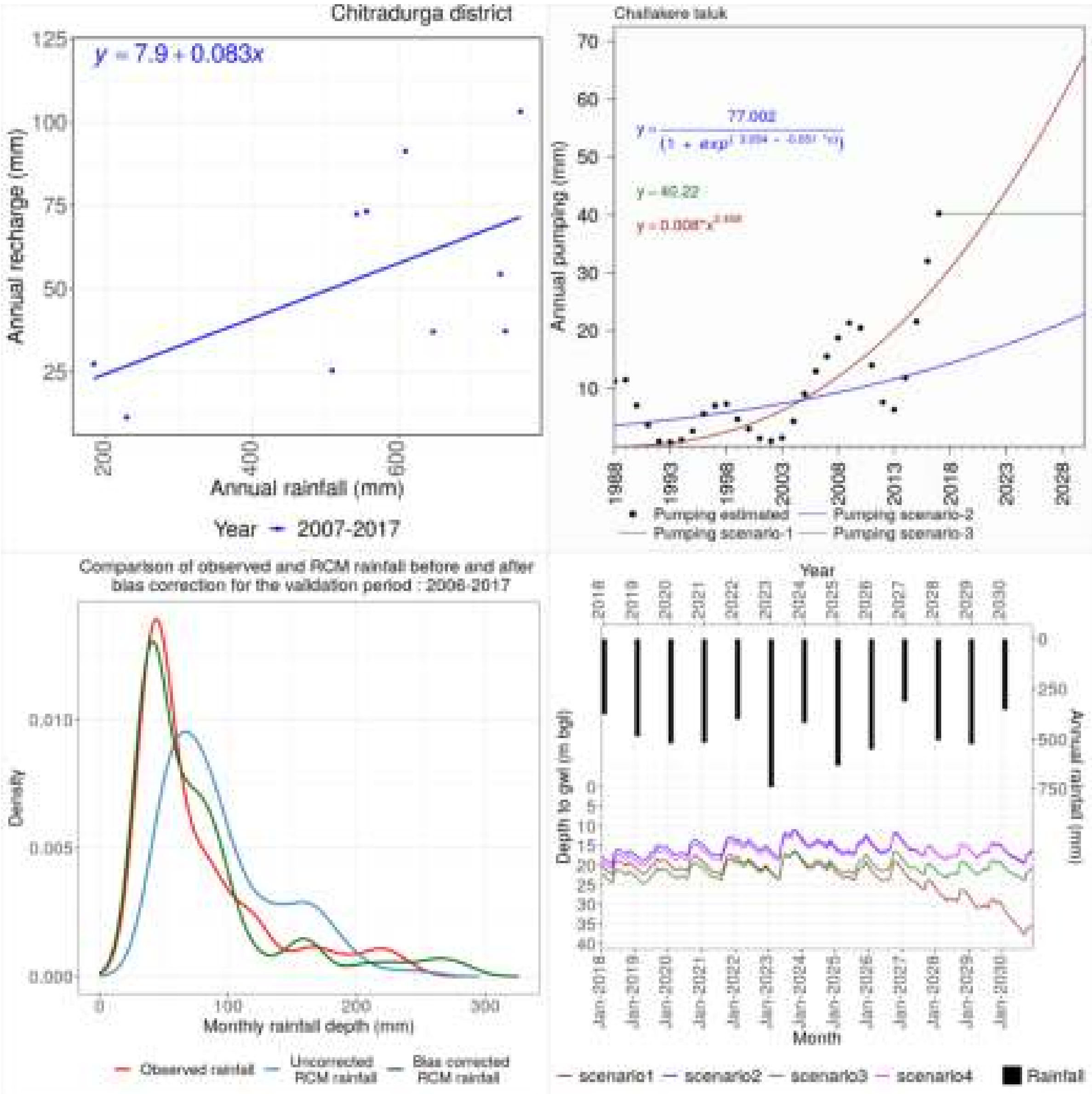


Figure 184: Simulation of future groundwater levels with four pumping scenarios for Challakere taluk.

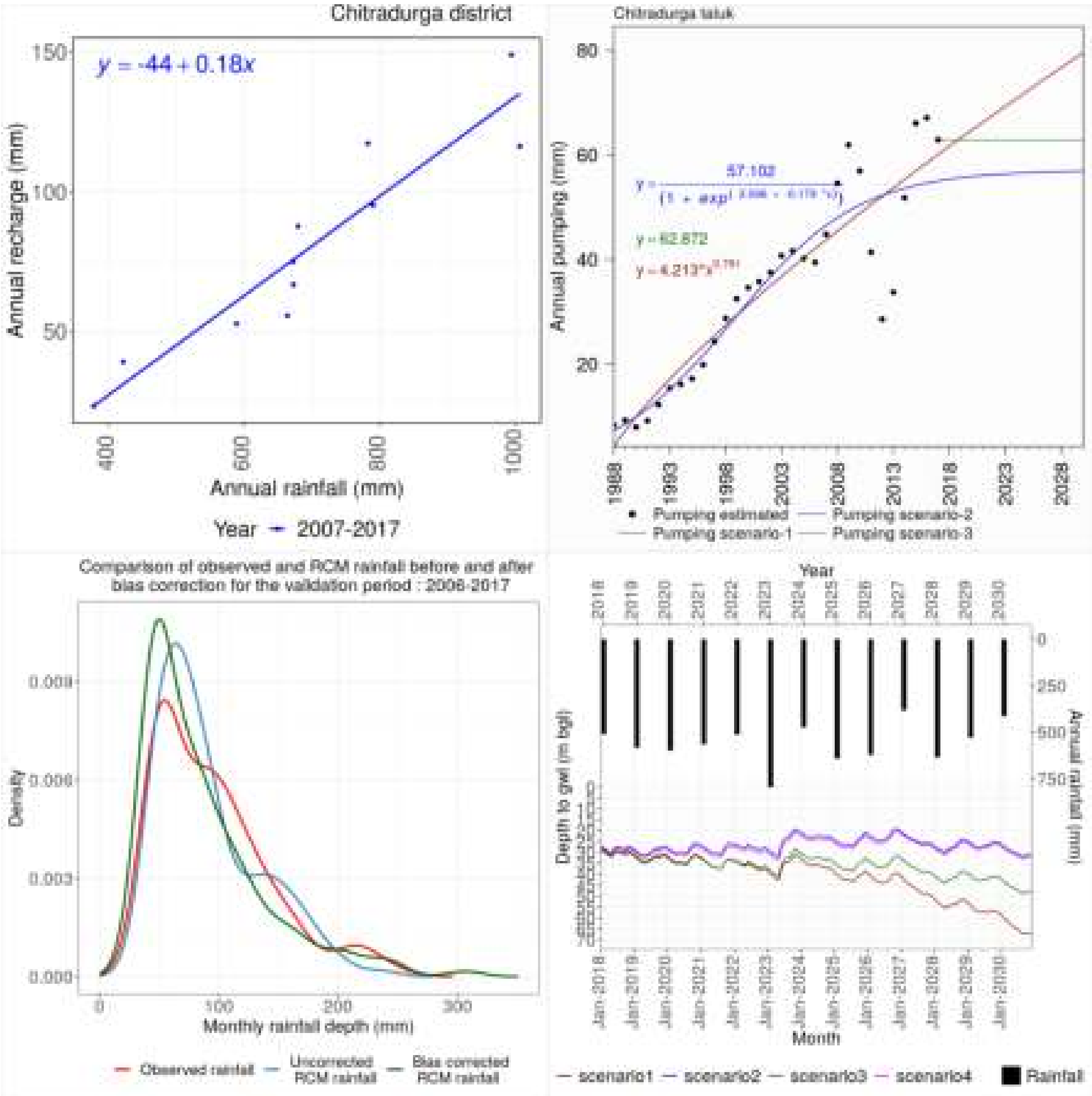


Figure 185: Simulation of future groundwater levels with four pumping scenarios for Chitradurga taluk.

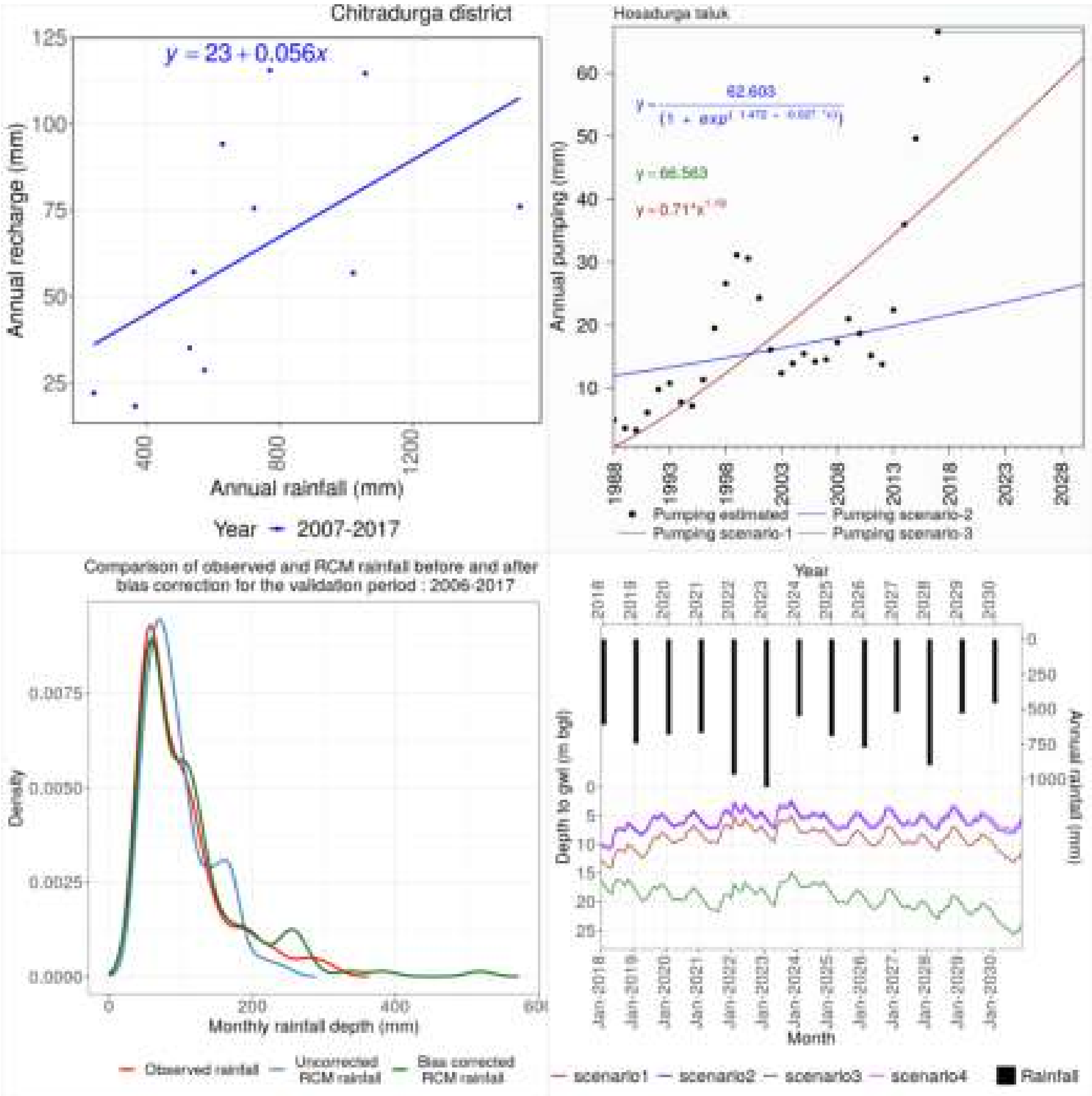


Figure 186: Simulation of future groundwater levels with four pumping scenarios for Hosadurga taluk.

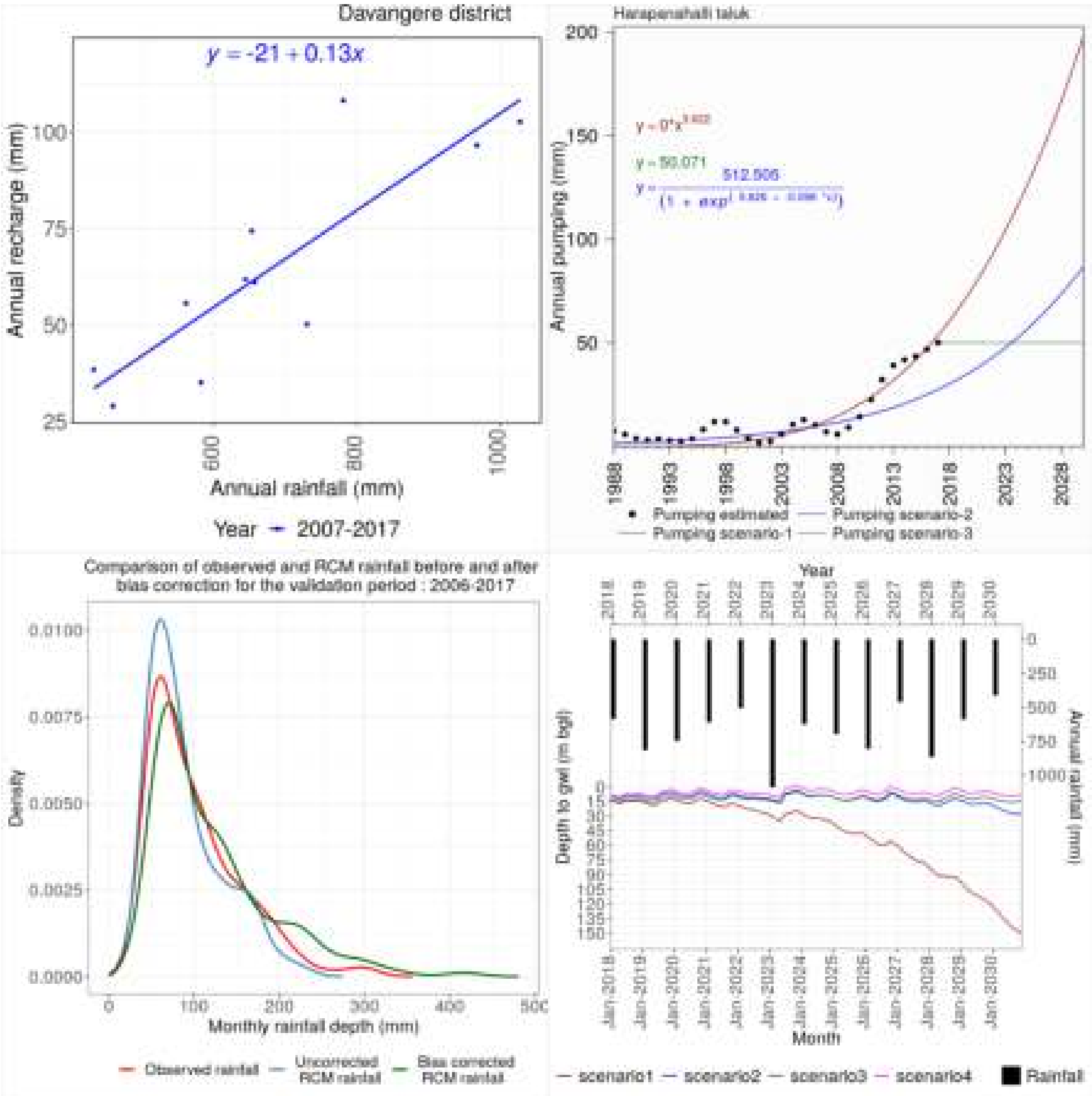


Figure 187: Simulation of future groundwater levels with four pumping scenarios for Harapanahalli taluk.

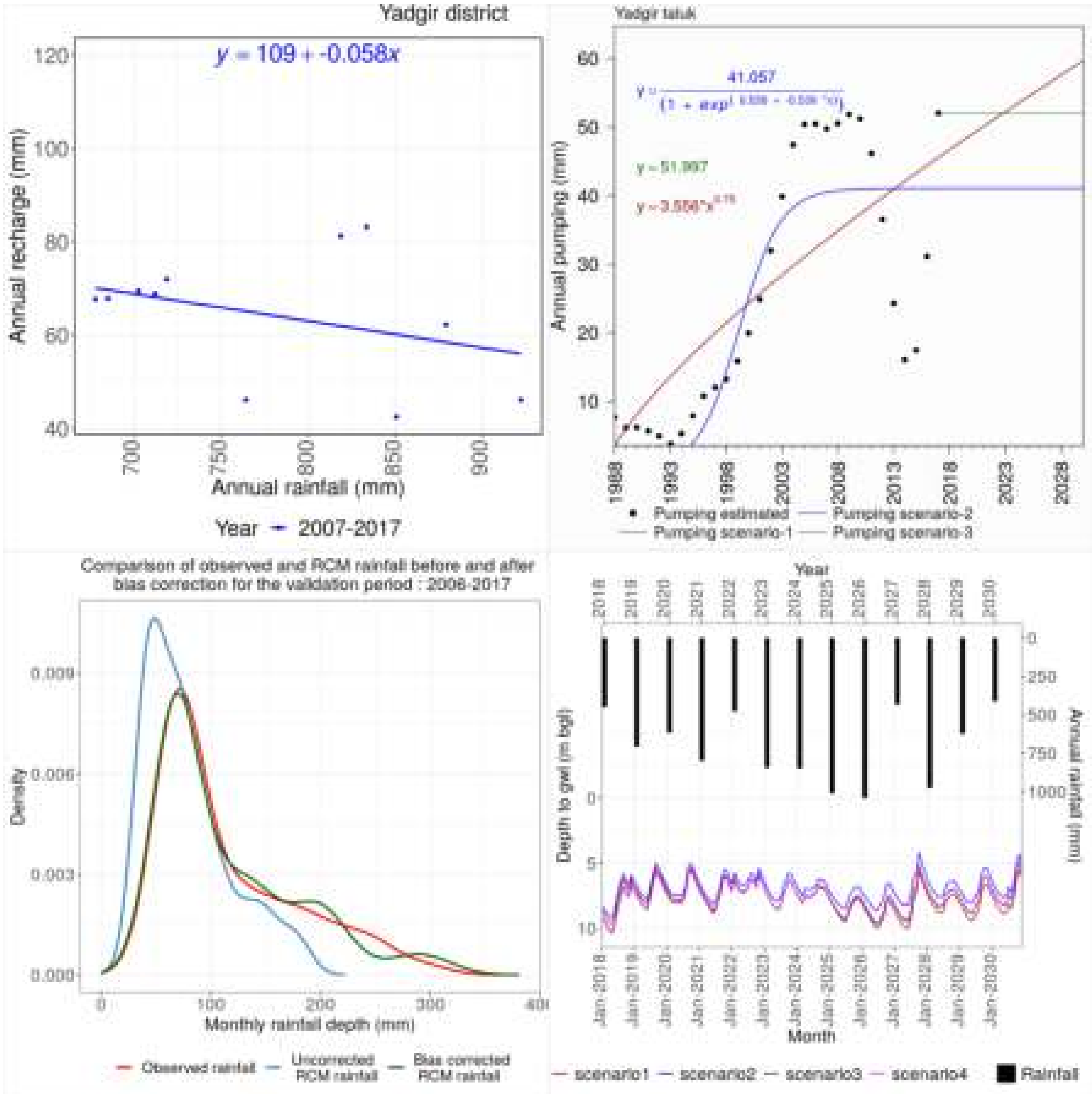


Figure 188: Simulation of future groundwater levels with four pumping scenarios for Yadgir taluk.

Table 5: Summary of the best water management plan that is required to be adopted for achieving acceptable groundwater conditions and satisfying sustainability criterion by 2030.

No	Taluk Name	District Name	Status based on draft alone in the stage of development (refer Column F of Table 2)	Suggested Management plan/ option
1	Afzalpur	Bengaluru Rural	Safe	No action required; (Annual draft increased from 2017 to 2030 and ok from the sustainability condition)
2	Athni	Belagavi	Safe	No action required; (Annual draft increased from 2017 to 2030 and ok from the sustainability condition)
3	Yadgir	Yadgir	Semi-critical	Annual draft to be maintained below 51 mm (8797 Ham)
4	Raybag	Belagavi	Safe	No action required; (Annual draft increased from 2017 to 2030 and ok from the sustainability condition)
5	Hukeri	Belagavi	Safe	No action required; (Annual draft increased from 2017 to 2030 and ok from the sustainability condition)
6	Lingsugur	Raichur	Safe	No action required; (Annual draft increased from 2017 to 2030 and ok from the sustainability condition)
7	Bagalkot	Bagalkot	Semi-critical	Annual draft to be maintained below 30 mm (2778 Ham)

8	Ramdurg	Belagavi	Semi-critical	Annual draft to be maintained below 6 mm (730 Ham)
9	Saundatti	Belagavi	Semi-critical	Annual draft to be maintained below 26 mm (4088 Ham)
10	Badami	Bagalkote	Semi-critical	Annual draft to be maintained below 8 mm (1115 Ham)
11	Nargund	Gadag	Critical	Annual draft to be maintained below 21 mm (915 Ham)
12	Ron	Gadag	OE	Annual draft to be maintained below 64 mm (8249 Ham)
13	Yelbarga	Koppal	Critical	Significant reduction in draft to below 59 mm (8833 Ham) annually with augmentation of recharge
14	Gadag	Gadag	Semi-critical	Annual draft to be reduced to below 52 mm (5687 Ham)
15	Hagaribomman ahalli	Bellary	Critical	Annual draft to be reduced to below 31 mm (3061 Ham)
16	Hadagalli	Bellary	Safe	No action required; (Annual draft increased from 2017 to 2030 and ok from the sustainability condition)
17	Harapanahalli	Davangere	Semi-critical	Annual draft to be reduced to below 7 mm (1004 Ham)
18	Ranibennur	Haveri	Safe	No action required; (Annual draft increased from 2017 to 2030 and ok from the sustainability condition)
19	Jagalur	Davangere	Semi-critical	No action required.

20	Challakere	Chitradurga	Semi-critical	Annual draft to be reduced to below 20 mm (4143 Ham)
21	Davanagere	Davangere	Safe	No action required; (Annual draft increased from 2017 to 2030 and ok from the sustainability condition)
22	Chitradurga	Chitradurga	Semi-critical	Annual draft to be reduced to below 57 mm (7889 Ham)
23	Channagiri	Davangere	Safe	No action required; (Annual draft increased from 2017 to 2030 and ok from the sustainability condition)
24	Holalkere	Chitradurga	Safe	No action required; (Annual draft increased from 2017 to 2030 and ok from the sustainability condition)
25	Hiriyur	Chitradurga	Critical	Annual draft to be reduced to below 37 mm (6304 Ham)
26	Sira	Tumkur	Critical	Annual draft to be reduced to below 45 mm (6985 Ham)
27	Hosadurga	Chitradurga	Semi-critical	Annual draft to be reduced to below 19 mm (2729 Ham)
28	Bagepalli	Chikkaballapura	OE	Annual draft to be reduced to below 40 mm (3719 Ham)
29	Madhugiri	Tumkur	Critical	Annual draft to be reduced to below 49 mm (5449 Ham)
30	Gauribidanur	Chikkaballapura	OE	Annual draft to be reduced to below 51 mm (4538 Ham)
31	Gudibanda	Chikkaballapura	Semi-critical	Annual draft to be reduced to below 11 mm (250 Ham)

32	Chikkanayakan ahalli	Tumkur	Critical	Annual draft to be reduced to below 60 mm (6772 Ham) with augmentation of recharge
33	Chinthamani	Chikkaballapura	OE	Annual draft to be reduced to below 42 mm (3736 Ham)
34	Sidlaghatta	Chikkaballapura	OE	Annual draft to be reduced to below 56 mm (3753 Ham)
35	Chikballapur	Chikkaballapura	Semi-critical	Annual draft to be reduced to below 51 mm (3255 Ham) with augmentation of recharge
36	Koratagere	Tumkur	Critical	Annual draft to be reduced to below 44 mm (2845 Ham)
37	Srinivasapura	Kolar	OE	Annual draft to be reduced to below 41 mm (3533 Ham)
38	Arasikere	Hassan	OE	Annual draft to be reduced to below 44 mm (5572 Ham)
39	Doddaballapur	Bengaluru Rural	Semi-critical	Annual draft to be reduced to below 58 mm (4624 Ham)
40	Tiptur	Tumkur	Critical	Annual draft to be reduced to below 42 mm (3319 Ham)
41	Devanhalli	Bengaluru Rural	Critical	Annual draft to be reduced to below 27 mm (1228 Ham)
42	Mulabagal	Kolar	OE	Annual draft to be reduced to below 26 mm (2137 Ham)

43	Kolar	Kolar	OE	Annual draft to be reduced to below 81 mm (6425 Ham) with augmentation of recharge
44	Malur	Kolar	OE	Annual draft to be reduced to below 50 mm (3224 Ham)
45	Bangarpet	Kolar	OE	Annual draft to be reduced to below 52 mm (4479 Ham)

NOTE : The prescribed annual draft for each taluk indicated in the table above in Hectare metre (Ham) should be applied in 2021 to achieve sustainable conditions by 2030.

Table 6: Summary of mean annual (2007-2017) lateral fluxes for all taluks.

No	Taluk Name	District Name	Recharge (mm/yr)	Lateral flux (mm/yr)	Ratio of Lateral flux to Recharge (%)
1	Afzalpur	Bengaluru Rural	66.8	27.2	40.72
2	Athni	Belagavi	50.5	16.1	31.88
3	Yadgir	Yadgir	64.3	11.0	17.11
4	Raybag	Belagavi	51.1	20.8	40.7
5	Hukeri	Belagavi	75.3	34.1	45.29
6	Lingsugur	Raichur	54.2	19.8	36.53
7	Bagalkot	Bagalkot	69.6	13.6	19.54
8	Ramdurg	Belagavi	54.3	20.1	37.02
9	Saundatti	Belagavi	59.7	12.2	20.44
10	Badami	Bagalkote	60.9	20.8	34.15
11	Nargund	Gadag	60.1	12.9	21.46
12	Ron	Gadag	56.6	0.8	1.41
13	Yelbarga	Koppal	65.9	-0.8	-1.21
14	Gadag	Gadag	54.7	12.4	22.67
15	Hagaribommanahalli	Bellary	55.7	6.5	11.67
16	Hadagalli	Bellary	63.4	28.2	44.48
17	Harapanahalli	Davangere	64.9	19.6	30.2
18	Ranibennur	Haveri	86.9	36.0	41.43
19	Jagalur	Davangere	59.3	7.6	12.82

20	Challakere	Chitradurga	51.0	12.7	24.9
21	Davanagere	Davangere	91.0	36.6	40.22
22	Chitradurga	Chitradurga	79.8	18.0	22.56
23	Channagiri	Davangere	74.7	29.7	39.76
24	Holalkere	Chitradurga	71.7	23.9	33.33
25	Hiriyur	Chitradurga	56.9	2.3	4.04
26	Sira	Tumkur	69.9	8.0	11.44
27	Hosadurga	Chitradurga	63.1	15.7	24.88
28	Bagepalli	Chikkaballapura	49.8	6.8	13.65
29	Madhugiri	Tumkur	62.8	10.9	17.36
30	Gauribidanur	Chikkaballapura	68.5	-3.6	-5.26
31	Gudibanda	Chikkaballapura	60.5	26.8	44.3
32	Chikkanayakanahalli	Tumkur	70.0	3.5	5
33	Chinthamani	Chikkaballapura	65.0	15.8	24.31
34	Sidlaghatta	Chikkaballapura	63.2	6.6	10.44
35	Chikballapur	Chikkaballapura	48.0	15.8	32.92
36	Koratagere	Tumkur	61.6	8.6	13.96
37	Srinivasapura	Kolar	48.6	7.1	14.61
38	Arasikere	Hassan	63.3	7.5	11.85
39	Doddaballapur	Bengaluru Rural	76.4	17.7	23.17
40	Tiptur	Tumkur	68.6	9.2	13.41
41	Devanhalli	Bengaluru Rural	61.4	19.3	31.43
42	Mulabagal	Kolar	41.6	14.8	35.58
43	Kolar	Kolar	41.0	-2.1	-5.12

44	Malur	Kolar	45.7	12.8	28.01
45	Bangarpet	Kolar	46.2	0.3	0.65

NOTE:
negative (-) value indicates inflow
positive (+) value indicates outflow