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Groundwater flow modelling of a micro-watershed in the upland area of East Godavari district, Andhra Pradesh, India

Yellapu Siva Prasad[1] · Yellamelli Ramji Satyaji Rao[1]

Abstract

In view of the progressive decline of groundwater levels in the majority of non-command upland area in the East Godavari district, Andhra Pradesh state, India, there is an urgency to augment groundwater in the non-command upland areas. Groundwater flow model is constructed for a micro-watershed of 50 km^2 namely 'Konda Kalava watershed' of 'Suddegedda river basin' located in the non-command upland area of East Godavari district. The steady state groundwater flow model simulated to seven observation wells and calibrated for the month of April, 2018. The objective of the model is to assess input and output stresses and to identify the over-stressed areas within the basin. The water budget analysis has revealed that the total groundwater extraction by pumping wells is 83.3% and evapotranspiration loss is 5.7% of the total groundwater recharge in the basin. The groundwater flow following the topography and is towards the mainstream with a maximum velocity of 0.4 m/day. The results revealed that the southern part of the basin is experiencing huge aquifer stress due to over-dependence on deep bore wells. It is recommended that, for at least one season, the most affected dry areas which are under paddy cultivation are to be promoted irrigated dry crops such as maize and jowar. It is also suggested that, due to local high salinity in and around Vannepudi village at the central part of the basin, the horticulture cultivation is to be promoted by increasing the surface water resources. The artificial recharge structures have to be constructed at suitable areas in and around Vannepudi village in order to improve the groundwater quality in terms of high salinity and also to rise the groundwater table in the southern part of the basin.

Keywords Groundwater · Suddegedda · Recharge · Salinity · Khondalite

Introduction

East Godavari district is one of the most important agrarian districts of Andhra Pradesh state, India. It is situated on the North-East of Andhra Pradesh. The district can be broadly classified into three natural zones viz., the River Godavari delta in the southern zone, Upland in the central zone and Agency Tracts in the northern zone of the district. The Godavari delta region is endowed by thick alluvium and vast potential of surface water resources whereas the upland region consists of hard granitic and khondalitic suit of formations with less surface water resources (Bhaskara Rao 2013). Since surface water resources are limited for the irrigation, groundwater is the major source in the uplands

of the district. Even though the normal annual rainfall of the district (1050 mm) is higher than the State (940 mm), the groundwater levels in many parts of the upland in the district have dropped to alarming levels. In the majority of upland part during the offset of monsoon, the groundwater levels are declining to 20–70 m (below ground level) deep which is very high when compared to the other parts of the district as well as the State. According to the Central Ground Water Board (CGWB 2016) report during the last two decades, the decline of groundwater levels is reporting continuously in all basins of the upland in view of heavy pumping in the recent years. As a result, annual groundwater fluctuations of more than 4 m are a common scenario for the last 10 years in the upland of East Godavari district (Dinesh Kumar et al. 2011). This is reflected in hydrograph analysis of long term historical water level data. Due to deficit rainfall of 24% during the year 2014–2015 as compared to 2013–2014, water level fluctuations during May-2015 with respect to decadal mean of May 2005–2014, shows a fall in water levels in 73%

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of the geographic area of the State (CGWB 2015). Ground Water Department (GWD 2002) of Government of Andhra Pradesh has reported that during last 3 decades, the well population in Andhra Pradesh state is increased from 8 to 22 lakhs resulting in increase of groundwater exploitation from 16 to 43%. In command areas which cover only 5% of the state geographical area, the stage of groundwater development is 16% as against 56% in the Non-command areas. Hence, there is an urgency to augment groundwater in the non-command upland areas in the state as well as in the East Godavari district (GWD 2002).

The occurrence and movement of groundwater in any basin depends on the geological setting, climate, rainfall, drainage, topography and extent of surface water bodies. As groundwater basin follows the drainage basin, the groundwater studies in the basin level are very important for accounting the groundwater budget within the basin (Takounjou et al. 2009). For the present study, the 'Suddagedda River' basin in the Non-command upland of East Godavari district is selected. The total catchment area of the basin is 658 km² (NIH 2000). However, generally the development of groundwater is not uniform throughout the groundwater basin. There are micro basins of very high draft and relatively low draft even in the over exploited basins (GWD 2002). According to the Groundwater Estimation Committee (GEC 1997), for detailed micro level investigations the micro basins of extent ranging between 30 and 60 km² can be considered. To study the input and output stresses in micro level and to address the groundwater prospects in village level, a micro watershed namely 'Konda Kalava' of 50 km² in the Suddagedda river basin is delineated for the current study. A steady state groundwater flow model is constructed for 'Konda Kalava' watershed. In general, the groundwater flow models have great importance to know the groundwater potential for any basin in judicial manner. Moreover, the sustainable development and management of groundwater resources requires precise quantitative assessment based on valid scientific principles (Khadri and Pande 2016).

The study area, 'Suddegadda river sub basin' or 'Konda Kalava basin' or 'Konda Kalava watershed' is covering the area of 50 km² and underlain by khondalitic suit of rocks in

Fig. 1 Location map of Konda Kalava basin in the Suddagedda river basin
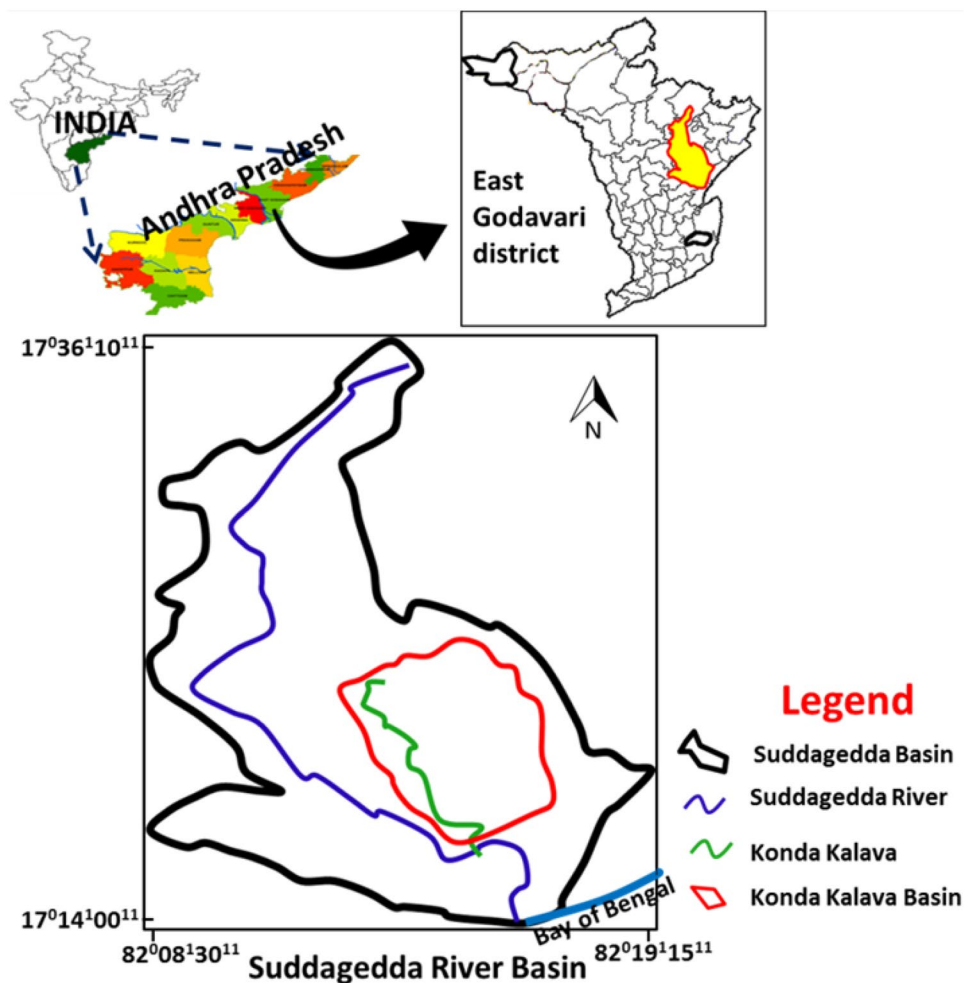
the northern part and Tirupati sandstones in the southern part. A steady state groundwater flow model is developed in the basin to estimate the aquifer characteristics, groundwater flow velocities, and input and output stresses. The main aim of this study is to build the conceptual two dimensional groundwater flow model and thereby to know the aquifer response under various input and output stresses. After complete assessment of the Konda Kalava watershed, groundwater flow model is constructed by the Visual MODFLOW 2011.1 software (Ahmed and Umar 2009; Surinaidu et al. 2014). Groundwater flow modeling has become an invaluable tool for assessing the impact of existing and future activities on groundwater resources (Lachaal and Gana 2016; Jackson 2007; Sathish and Elango 2015; Mayer et al. 2007). In accordance with the model results, the remedial measures have to be adopted where the places groundwater depletion is found.

Study area

Suddegedda river basin

The Suddegedda basin lies in between latitudes $17^\circ14'0''$ and $17^\circ36'10''$ and longitudes $82^\circ08'30''$ and $82^\circ19'15''$ over the catchment area of 658 km^2 up to the river mouth at Uppada village near Kakinada town. The basin slopes south to south-east. The location map of the Suddegadda river basin is shown in Fig. 1.

Drainage

The main stream originates from Gundalamma konda in Vatangi reserved forest area in Rajavommangi mandal of East Godavari district of Andhra Pradesh at an elevation of about 813 m. It is joined by many rivulets on its way. It flows southwards and it is joined on its left bank by its rivulet namely 'Konda Kalava' near Gollaprolu village. The drainage pattern in the basin is dendritic in the upstream of the basin. However, the drainage pattern is not clear in the downstream side. Being plain terrain in the coastal zone, the exact demarcation of catchment boundary is very difficult.

Hydrogeology

Khondalites, Granites and Charnokites underlie a major portion of the basin. The central and western parts of the basin are underlain by alluvium of the streams. The southern part of the basin is underlain by Khondalite suit of rocks, basaltic formation or Deccan trap and Tirupathi sandstones (Vijaya Kumar et al. 1994). Groundwater in the crystalline rock is restricted to weathered and fractured zones and is being exploited mostly by dug wells and dug-cum bore wells (Satyaji Rao et al. 1997).

Fig. 2 Drainage and digital elevation map of the Konda Kalava basin
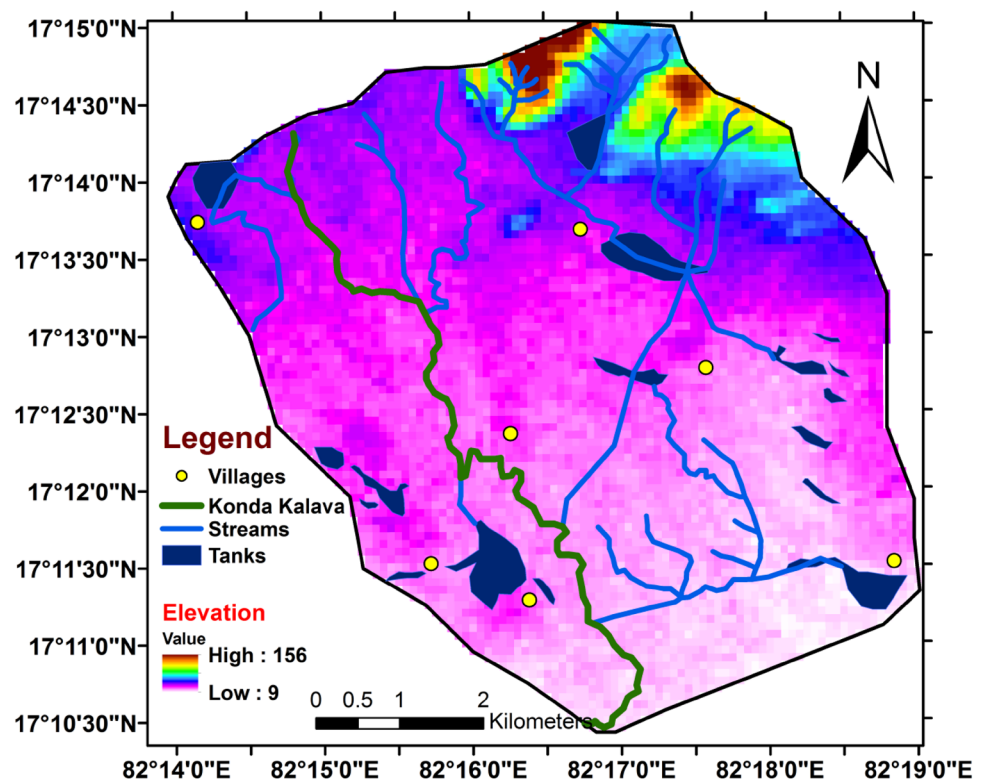
Suddegedda river sub basin or Konda Kalava basin

'Konda Kalava' stream in the east is a main rivulet of the Suddagedda river. As Konda Kalava is main stream, a micro-watershed namely 'Konda Kalava basin' (Fig. 1) is delineated in the Suddagedda river basin. The Suddegedda river sub basin or Konda Kalava basin lies between north latitudes $17°10'30''$ and $17°15'00''$ and east longitudes $82°14'00''$ and $82°19'00''$ occupying an area of 50 km². The area falls in the Survey of India (SoI) topographical sheet No. 65K/8. The basin covers part of Gollaprolu mandal (an administrative unit within the district). The average annual rainfall of the basin area is 1059 mm. The basin area represents almost upland terrain of East Godavari district with the elevation range of 9–156 m. The basin has a general slope towards south-southeast. The main stream 'Konda Kalava' flows southwards and joins in the Suddagedda river at Gollaprolu village. The basin area enjoys tropical climate with hot summers and cold winters. About 80% of the rainfall is received during monsoon season (June–November). The north portion of the Konda Kalava basin is underlain by khondalite suit of rocks and south portion of the basin

is covered with the Tirupathi sandstones (NIH 1993). The drainage network and the digital elevation model of the Konda Kalava basin is shown in the Fig. 2.

## Groundwater flow modelling

Base map and refining of model area

The base map of the study area is delineated from Survey of India toposheet no. 65K/8 and it is digitized in three themes viz., boundary, drainage network and well locations using Arc GIS and imported to the Visual MODFLOW. The model area is divided into cells which are containing 70 rows and 70 columns. The size of the each grid cell is 100 m × 100 m. Figure 3 shows the grid map of the study area with observation wells.

Elevation data to the layers

For the elevation database, Global Positioning System (GPS) survey is conducted in the basin. Lithological data

Fig. 3 Grid map of the Konda Kalava Basin
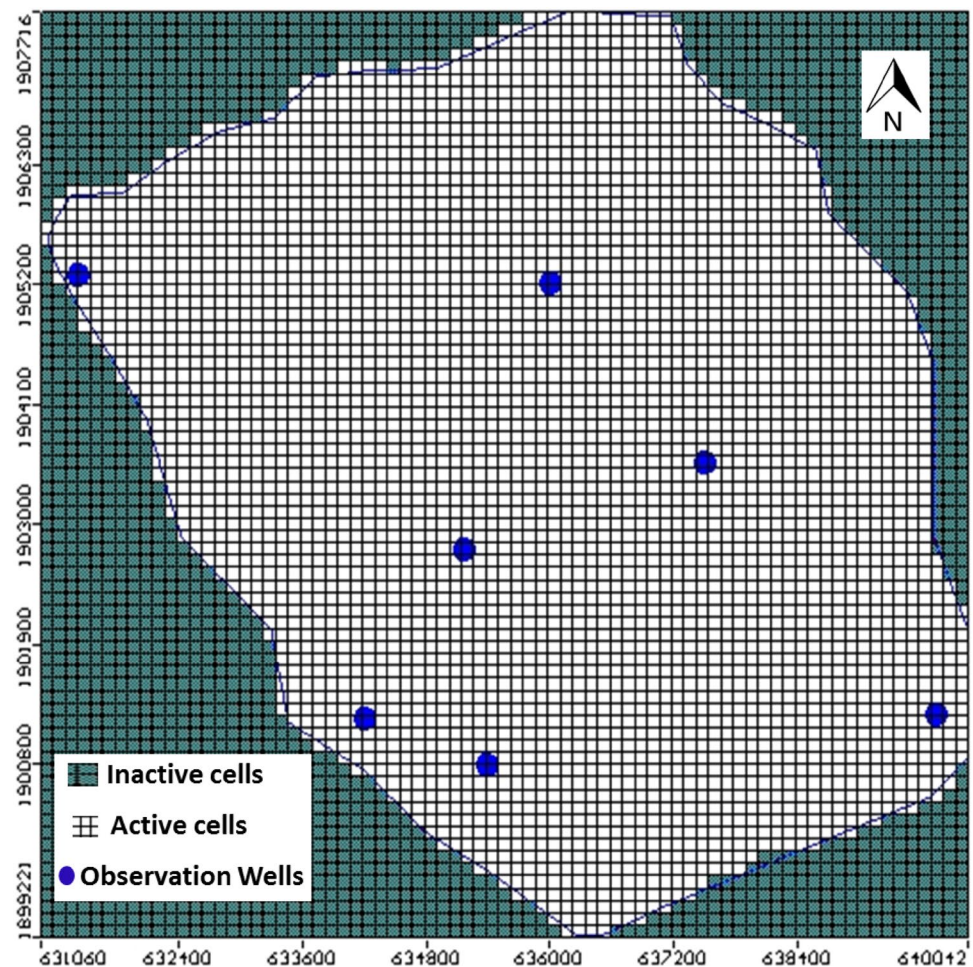
of the basin is taken from the DRC (1993). In all villages the information of the lithologs, depth of the bore wells in the villages and their yield information at different depths during drilling is collected from the local villagers and the owners of the bore wells. This information is very much useful for construction of elevation of different layers more accurately.

Based on the lithological data and field observations, geologically Konda Kalava basin has two divisions. The north portion of the basin is covered with the khondalitic suit of rocks and the south portion is mainly underlain by the Tirupathi sandstones. In the north portion, the basin has three distinct sub surface layers. i.e., (1) highly weathered khondalite (2) semi weathered and fractured khondalite which is the principal aquifer layer and (3) hard granitic gneiss. In this terrain, generally groundwater is available only in weathered and fractured zones under unconfined to semi confined conditions. In the southern portion, the basin has three layers i.e., (1) thin Rajahmundry sandstones (2) thick Tirupathi sandstones (3) hard basement rocks. Based on the litho units, the two layer model has been constructed for the basin since only highly weathered khondalite and fractured khondalitic

layer in the northern part and Rajahmundry sandstones followed by Tirupathi sandstones in the southern part of the basin are the saturated water columns. The thickness of first layer consists of 15–25 m underlain by 30–120 m second layer. The simulated vertical section has a total thickness of about 55–145 m. Figure 4 shows the lithological formation map of row 38 and column 29 respectively.

Initial heads

The pre-monsoon groundwater levels of seven observation wells on the month of April 2018 have been collected from the basin. These water levels are used as initial heads to the model. The hydraulic heads are varying from 3 to 20 m below ground level in the basin. The locations of hydraulic heads are shown in Fig. 3.

Pumping wells

Pumping wells census data is collected from the field work carried out in the basin. At each village, the pumping rate or discharge rate (Q) of bore wells is calculated. The pumping rates are estimated by collecting the quantity of water pumped
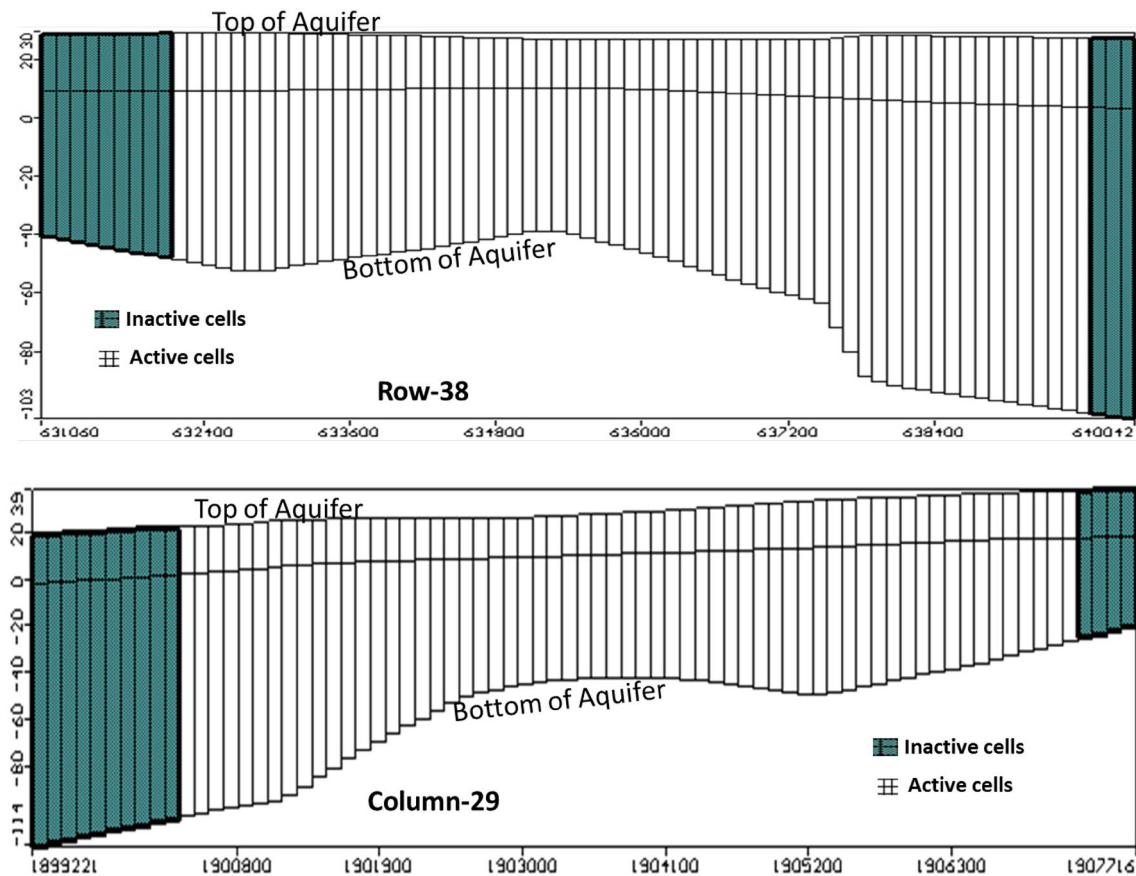

Fig. 4 Vertical cross section of row 38 and column 29 in the model grid

Table 1 Obtained pumping rates in the Konda Kalava basin

Location	Number of pumping wells nearly	Depth of bore wells (m)	DTW (m)	Yield (lps)	Discharge rate (m³/day)
Tatiparthi	40	140	22	8.62	744
China Jaggampeta	40	140	20	8.00	691
Chebrolu	100	170	22	7.00	604
Vannepudi	0	60	9	–	–
Chendurthi	20	80	3	5.82	502
Kodavali	14	90	4	4.91	424
Dharmavaram	20	60	8	4.00	345

Fig. 5 Pumping wells distribution in the basin
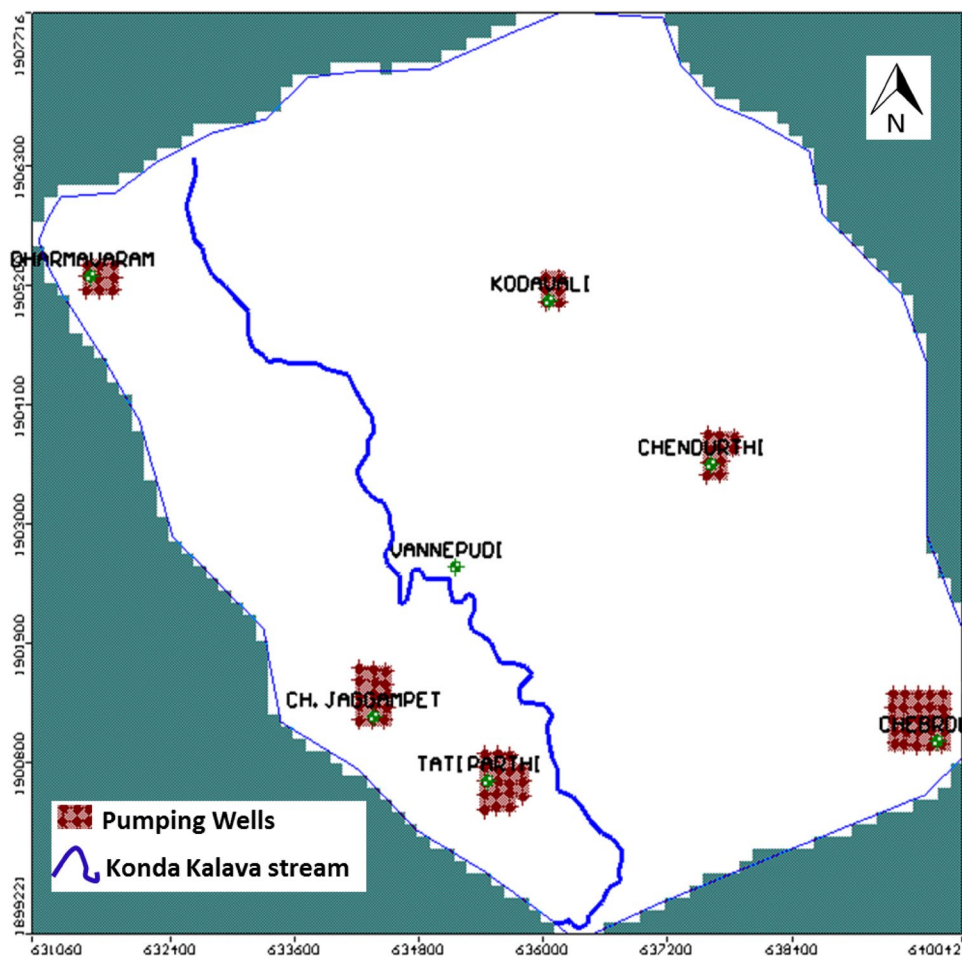
in litre per second (lps). The wells are being pumpedat the average local pumping duration of 7 h in a day. The pumping rates are then estimated in m³/day at every village. Table 1 shows the pumping rate obtained in seven villages in the basin.

The DRC (2000) reported that the quality is very poor in and around Vannepudi and Dharmavaram villages. These areas affected with high amounts of total dissolved solids, chloride, sodium or potassium, magnesium and bicarbonate. The groundwater of these villages indicate end product water

and is of NaCl or KCl type indicating the presence of trapped sea water. Due to very high salinity (TDS: 3648 mg/L; Cl: 740 mg/L; Na: 400 mg/L; K: 1100 mg/L, Total Hardness: 6620 mg/L, SAR: 6.99) locally (DRC 2000) in groundwater which is detrimental to the crops, no wells are being pumped for agricultural activities in and around Vannepudi village. Hence, pumping rate is considered as zero in the central part of the basin. The distribution of pumping wells in the model is shown in the Fig. 5.

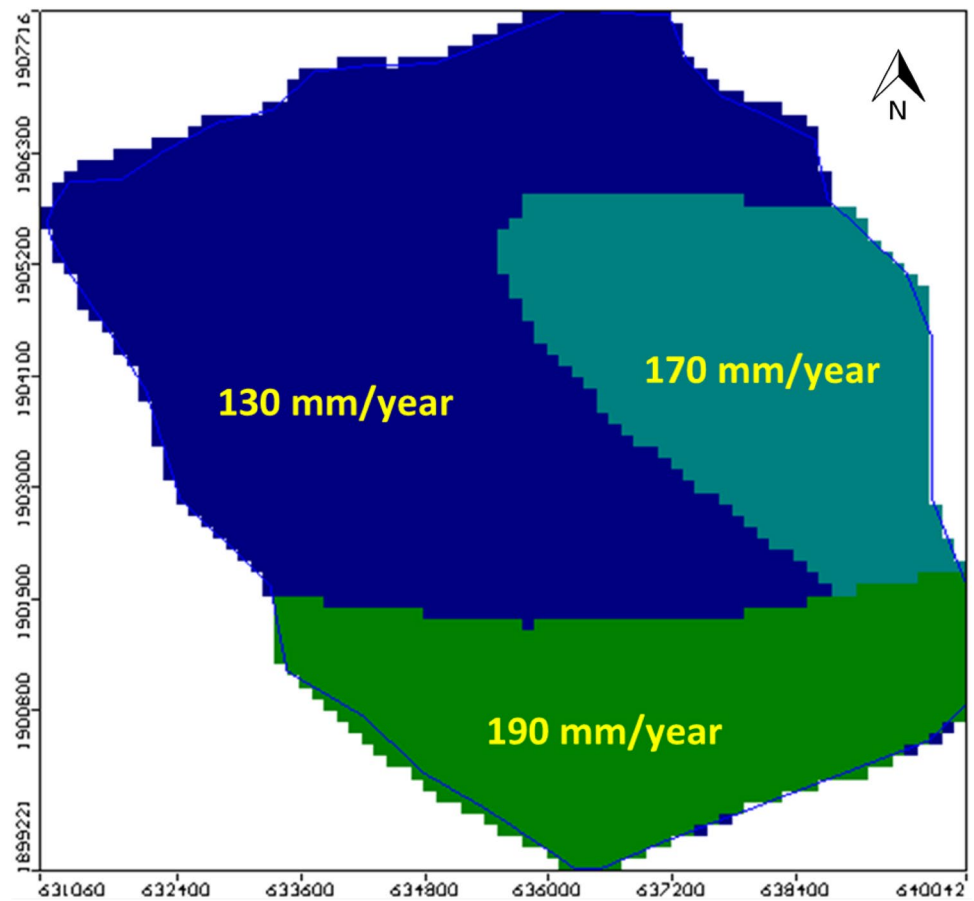**Fig. 6** Recharge distribution in the Konda Kalava basin

Table 2 Calibrated Hydraulic conductivity values in the basin

Region in the basin	Age	Geological formation	Hydraulic conductivity values calibrated by model (m/day)
Northern part	Archaean	Highly weathered Khondalite in the first layer	3
		Semi weathered with Fractured Khondalite in the second layer	3.9
Southern part	Mio-Pliocene	Rajahmundry sandstones in the first layer	0.8
	Lower Cretaceous to Lower Triassic	Tirupathi sandstones in the second layer	1.3

Recharge

Recharge to the groundwater regime due to monsoon rainfall forms the main input to the aquifer. Irrigation return flows and seepage from surface water bodies through the beds of tanks and canals contribute as additional input stress to the flow regime. Even though the precipitation is the main source of recharge in the study area, irrigation return flows mainly from canals also contribute to the total groundwater recharge in the southern and eastern parts of the basin. NIH (1993) has conducted the water balance studies in the Suddegadda river basin and calculated the annual groundwater recharge from the rainfall is of 5 MCM. This is equals to 10% of total annual rainfall of 50.4 MCM. The same percent of recharge is taken for the Konda Kalava basin. Based on the irrigation pattern, command area from canals, type of crops and vegetation cover, three recharge zones are identified in the study area. Initially 10% of annual rainfall applied as rainfall recharge to all the zones in the model. Based on GEC (1997) norms, higher recharge values have been applied for the zones having with higher return flows (Mondal et al. 2011). After calibration, the model is
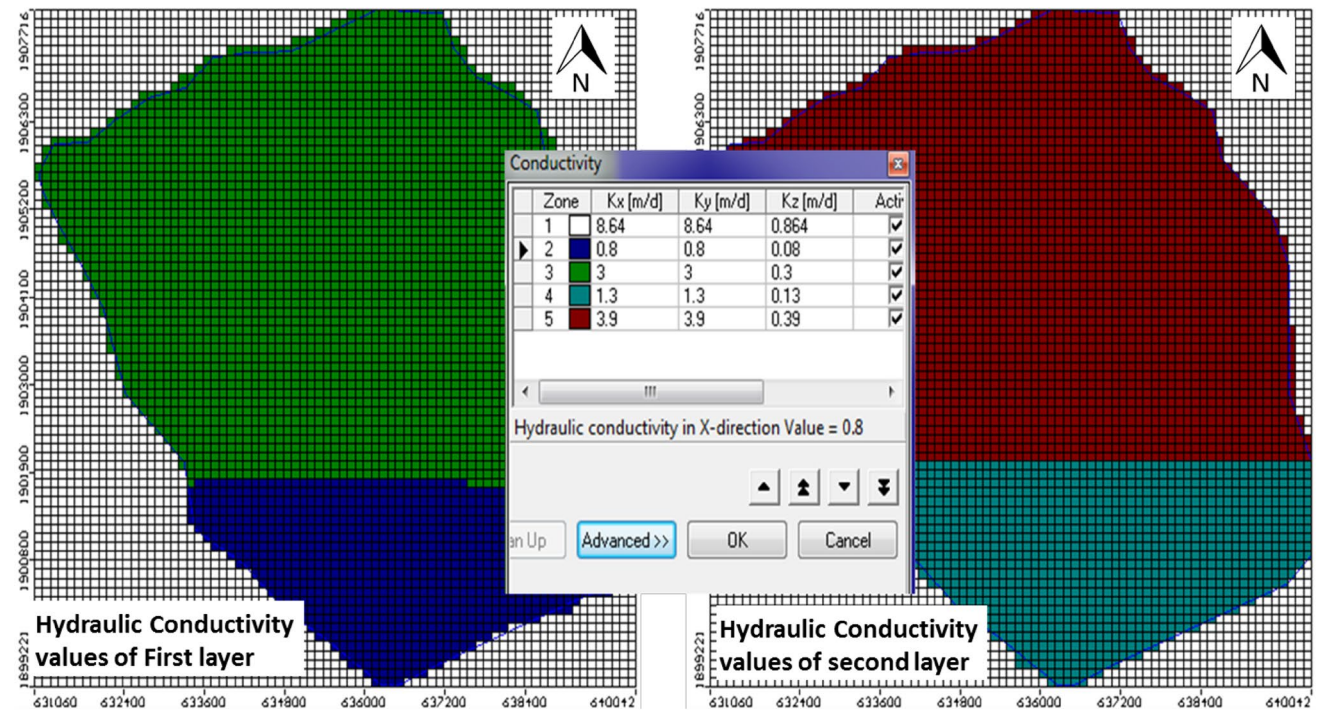
Fig. 7 Distribution of hydraulic conductivity values for both first and second layers

simulated the total recharge values for the three zones as 130, 190 and 170 mm/year (Fig. 6). However, the effect of recharge is considered over the first layer in the basin.

Evapotranspiration

As the evapotranspiration is a function of evaporation, at actual field condition it can be less than Potential Evapotranspiration (PET) (Kumar et al. 2017). For calculation of the PET in the basin, the Thornthwaite (1948) method is used. The PET is estimated in the basin as 200 mm/year. The actual evapotranspiration (AET) is estimated from the PET. The average AET value of 120 mm/year for a depth of 1 m based on type of soil, plants and crops is applied to entire basin. That means, 1 m below the ground surface no evapotranspiration rate takes place and it is 120 mm/year at the ground surface.

Hydraulic conductivity

According to the local hydrogeological conditions, the study area is divided into two parts. The northern part is underlain by crystalline khondalitic suit of rocks and southern part is covered with the sandstone formations. Since the hydraulic conductivity varies with the different aquifer zones of saturated strata, the different conductivity values are applied to different geologic formations of two layers (Table 2).

The higher conductivity values are assigned for the second layer than the first layer (Fig. 7) since the fractured environment of khondalites in the second layer of north part of the basin and more thickness and saturation conditions of Tirupathi sandstones in the second layer of southern part of the basin. After trial and error method within narrow adjustment, the southern part is simulated the conductivity values of 0.8 and 1.3 m/day for the first and second layers respectively. The conductivity values of 3 and 3.9 m/day are simulated for the first and second layers of northern part. The best fit is obtained between calculated and observed heads with these conductivity values.

Constant head and river head

Every model requires an appropriate set of boundary conditions to represent the system's relationship with the surrounding area. The boundary conditions are a key component of the conceptualization of a groundwater flow system. The north western and southern boundaries of the modeled area are simulated through a constant head boundary (Fig. 8) in order to represent the groundwater inflow and outflow through nearby sub-watersheds. Constant head boundary conditions of 22 and 7 m are simulated at the inflow and outflow regions respectively. The main stream 'Konda Kalava' has been simulated with river boundary condition (Fig. 8) varying from +20 to +7 m. The elevation difference of 0.5 m is assigned to River

Fig. 8 Constant head and river boundary condition in the model
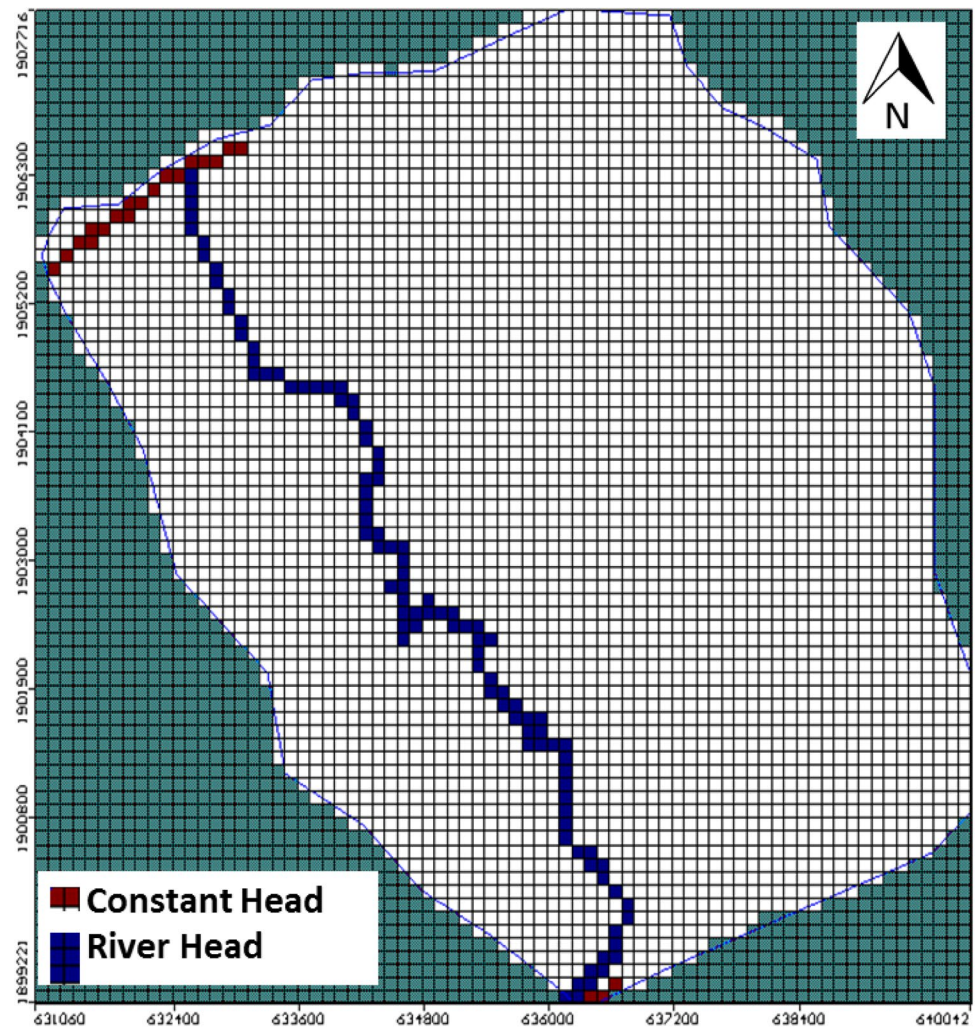
stage and river bed bottom elevation for all appropriate grids. Figure 8 shows the Constant Head and River boundary conditions in the model.

Model calibration

Model calibration refers to changing values of model input parameters to match field conditions within an acceptable criterion. In this study, the trial and error calibration is carried out. Model calibration requires that field conditions be properly specified. The calibration parameters in the model are the recharge, horizontal and vertical hydraulic conductivities and evapotranspiration. Then these parameters are adjusted sequentially to match the calibration targets. After a number of trial runs, computed heads are matched fairly with observed heads. The sensitivity analysis is also carried out in order to find the most sensible parameter in the model.

Steady state calibration

The calibration has been carried out using seven observation wells monitored during April, 2018. The model is calibrated against the recharge, constant head boundary, hydraulic conductivity and evapotranspiration values by trial and error method during many sequential runs until the best match between the observed and calculated water level contours were obtained. The model is run for 365 days. The calibrated water levels are varying from 4 to 26 m (a.m.s.l.). The plot between computed and observed heads with statistical analysis of the steady state calibration results are shown in Fig. 9.

Observation well at Chebrolu village is showing the high residual error of 4.985 (Fig. 9) as this well is being controlled by higher abstractions. The minimum residual error of − 0.521 m is obtained at Chendurthi. The lowest RMS error of 3.52 m and NRMS error of 12.139% is achieved in the steady state calibration. The observed
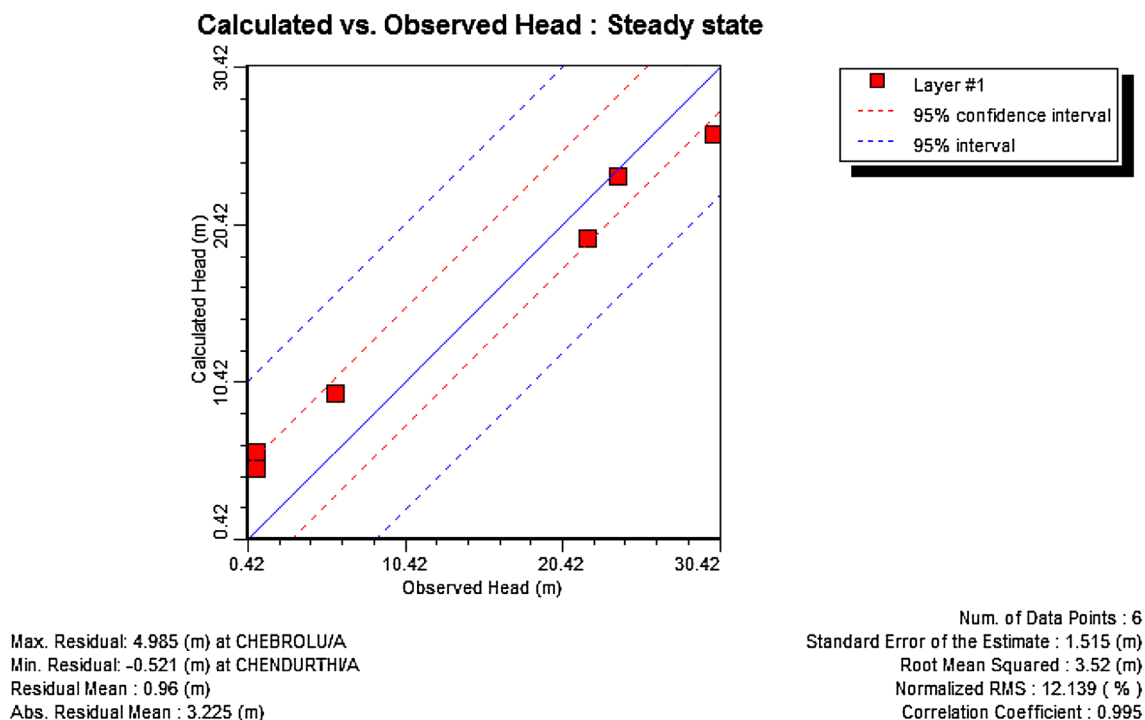
Calculated vs. Observed Head : Steady state

Max. Residual: 4.985 (m) at CHEBROLU/A
Min. Residual: –0.521 (m) at CHENDURTHI/A
Residual Mean : 0.96 (m)
Abs. Residual Mean : 3.225 (m)

Num. of Data Points : 6
Standard Error of the Estimate : 1.515 (m)
Root Mean Squared : 3.52 (m)
Normalized RMS : 12.139 (%)
Correlation Coefficient : 0.995

Fig. 9 Plot of calculated and observed heads during steady state calibration

and calculated heads are matched closely (Fig. 10). From Fig. 10, it is observed that the direction of groundwater flow is towards the main stream.

Results and discussion

The steady state calibration has been carried out during April, 2018 (pre-monsoon season of 2018). The computed groundwater level contours for the basin are following the trend of observed groundwater levels during steady state calibration. In the steady state condition, the minimum and maximum groundwater velocities are calibrated as 0.043 and 0.400 m/day with a mean of 0.220 m/day. The groundwater velocity vectors are indicating that the flow is towards Konda Kalava stream. It is also observed that the route of groundwater circulation from high elevation areas to low lying areas. From the zone budget analysis, the total inflow of the basin 26,405.60 m³/day and the total outflow of the basin is 26,406.50 m³/day. Hence the basin has the deficit of 0.90 m³/day. In accordance with the groundwater flow directions (Siva Prasad and Venkateswara Rao 2018) of the basin, the artificial recharge structures have to be constructed at suitable areas in and around Vannepudi village in order to improve the groundwater quality in terms of high salinity and to also rise the groundwater table in the southern part of the basin. The detailed zone budget analysis and sensitivity analysis are presented in the following subsequent sections.

Zone budget analysis

Groundwater flow models produce zone budget for the model area and it is useful establishing the water budget for a specific region of the model area. The detailed zone budget analysis is shown in the Table 3. Table 3 shows that groundwater abstraction in the basin is 83.3% of annual groundwater recharge and the evapotranspiration losses are 5.7% of the annual recharge. The inflow of river leakage is less than the outflow of river leakage. The outflow of river leakage is 2.1% of the annual groundwater recharge. The minimum numerical error or difference between inflow and outflow of 0.01% is occurred in the model as shown in Table 3.

Sensitivity analysis

Sensitivity analysis brings out and helps understand significant role played by individual parameters in the computation of the model simulation output and also aids determine which data must be defined most accurately (Konikow and Bredehoeft 1974; Varni and Usunoff 1999). During the sensitivity analysis, it is observed that model is highly sensitive to both recharge and hydraulic conductivity than evapotranspiration.

Initially the hydraulic conductivity values are taken for the sensitivity analysis. During the first sensitivity run by keeping the recharge values unchanged, the conductivity

Fig. 10 Contour map of calculated and observed heads during steady state calibration
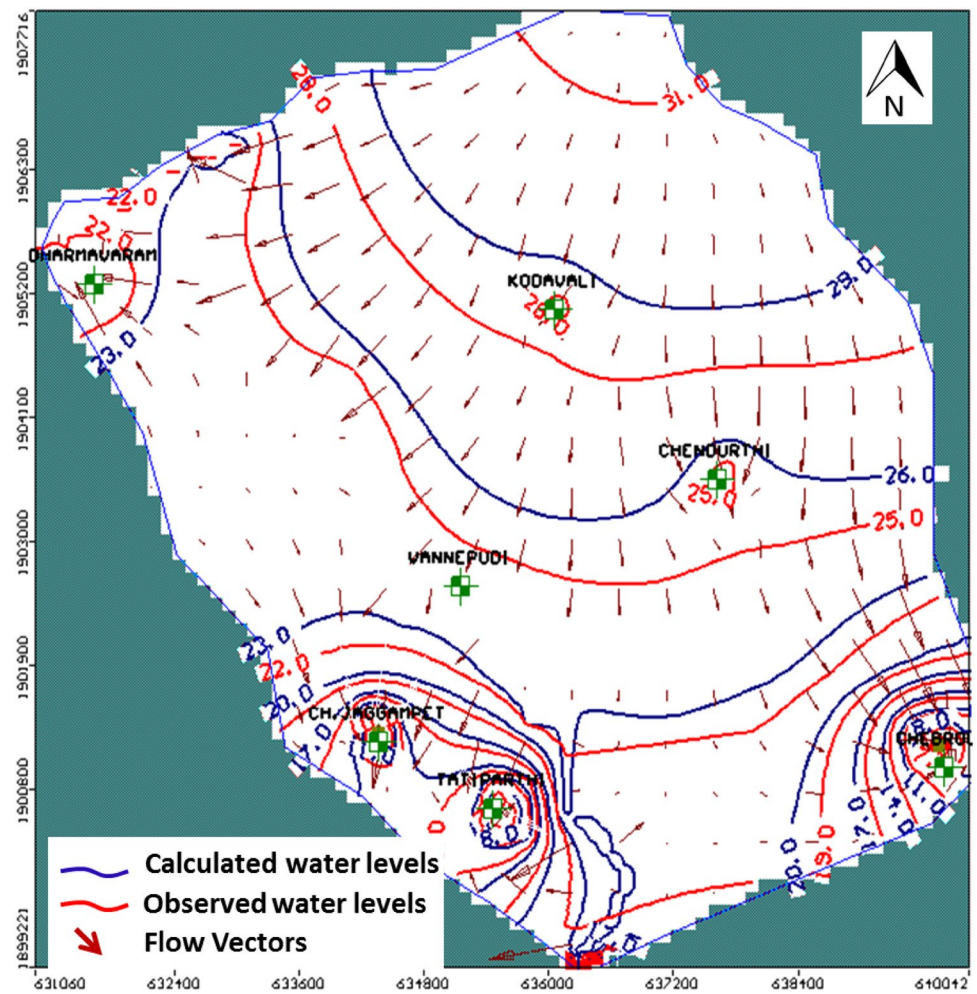

Table 3 Zone budget results during the steady state calibration

Parameters	Inflow (m^3/day)	Outflow (m^3/day)	Outflow as a percentage of recharge (%)
Recharge	21,728.873	0	0
Constant Head	291.2213	− 2231.9517	8.9
Evapotranspiration	0	− 1235.7797	5.7
River Leakage	4385.4995	− 4836.6274	2.1
Pumping	0	− 18,102.1406	83.3
Total	26,405.5938	− 26,406.498	–
Inflow-Outflow	− 0.9043		

values are increased by 10% of the initial calibrated model. For this modification, the NRMS error has increased from 11.4 to 14.4%. Further in the second sensitivity run, the conductivity values are decreased by 10%. It resulted again increasing of NRMS value to 14.8%. The Recharge is the second parameter changed while keeping conductivity value unchanged. Recharge value is lowered by 10 mm/year in the entire watershed. Then the NRMS value changed from 11.3

to 11.0%. Further reduction of recharge by 10 mm/year in the basin resulted dry cells (Fig. 11) at Chinna Jaggampeta and Chebrolu villages which are in the southern part of the basin. It is evidenced from the field work that the bore wells in the Chinna Jaggampeta, Tatiparthi and Chebrolu are being pumped out with the 25 Horse Power submergible motors from the deeper depths. This excessive pumping of bore-wells has led to over-usage of groundwater at higher rates

Fig. 11 Dry cells during the sensitivity analysis
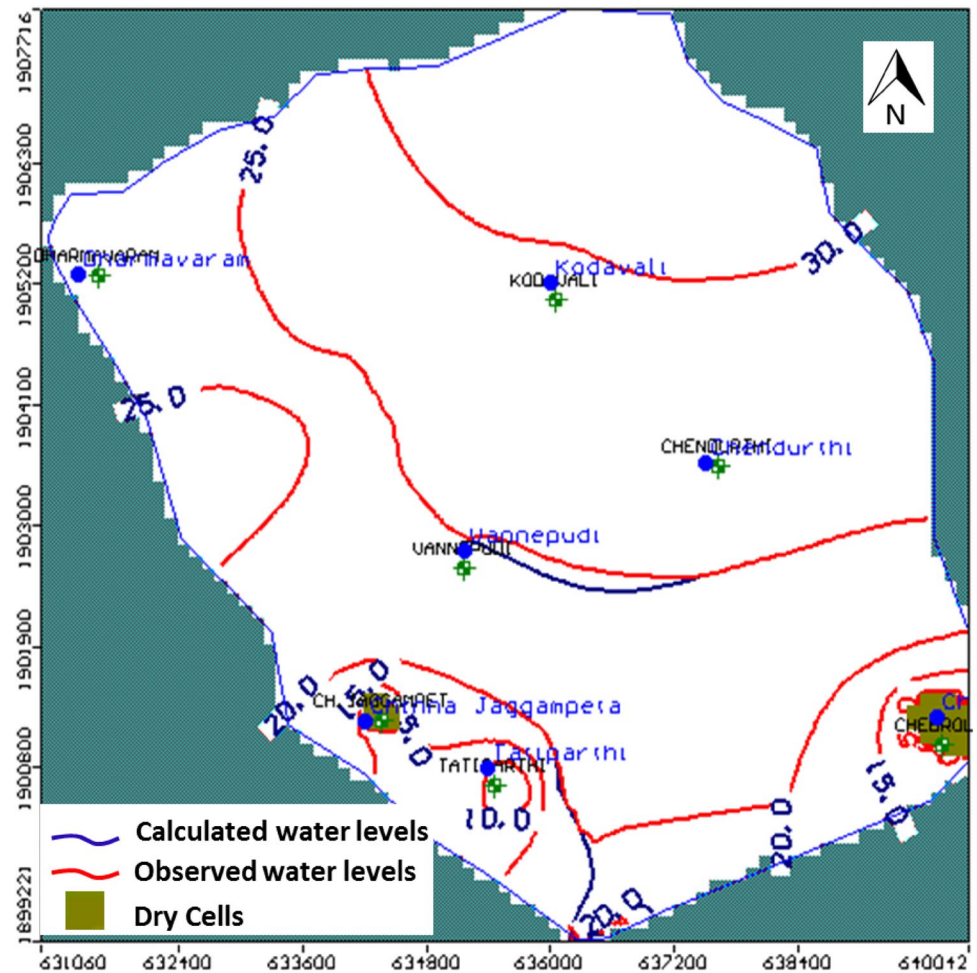
than the rate of groundwater recharge and caused depletion of the groundwater levels in these villages. As a consequence at these villages, the dug wells and shallow tube wells are already dried up. Due to higher abstraction rates at both Chinna Jaggampeta and Chebrolu villages which are under sandstone aquifers, the model is producing dry cells even small reductions of recharge. At these locations, any additional increase of withdrawal from this aquifer results a progressive decline of water level.

Conclusions

Groundwater flow model is simulated for the micro watershed namely 'Konda Kalava basin' having the geographic area of 50 km^2 of Suddegedda river basin, East Godavari, Andhra Pradesh, India. The estimated maximum groundwater velocity is 0.4 m/day in the basin. The input and output stresses of the Konda Kalava watershed are indicating that the total volume of water entering the basin is 26,405.59 m^3/day and leaving the basin is 26,406.49 m^3/day. The total groundwater abstraction by pumping wells is about 83.3%

of total groundwater recharge and the evapotranspiration losses are 5.7% of groundwater recharge. For the khondalitic aquifers, the model estimated the hydraulic conductivity values of 3.0 and 3.9 m/day; and for the sandstone aquifer, the hydraulic conductivity values of 0.8 and 1.3 m/day for first and second layers respectively. Groundwater recharge and hydraulic conductivity values are the most sensitive parameters than other input parameters in the basin. The southern part of the basin is experiencing huge aquifer stress due to over-dependence on deep bore wells. At Chinna Jaggampeta and Chebrolu villages, additional increase of withdrawal and reduction in recharge resulting groundwater decline in shallow aquifers progressively. The groundwater abstractions can be minimized by increasing irrigation tanks, canal network and revival of ponds in the southern part of the basin. It is recommended that, for at least one season, the most affected dry areas which are under paddy cultivation are to be promoted Irrigated Dry crops such as maize and jowar. It is also suggested that, due to local high salinity in and around Vannepudi village at the central part of the basin, the horticulture cultivation is to be promoted by increasing the surface water resources. The artificial recharge structures

have to be constructed at suitable areas in and around Vannepudi village in order to improve the groundwater quality in terms of high salinity and also to rise the groundwater table in the southern part of the basin.

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