

## Hydrologic and Hydrogeologic Characterization of a Deltaic Aquifer System in Orissa, Eastern India

S. Mohanty · Madan K. Jha · Ashwani Kumar · S. K. Jena

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**Abstract** The present study focuses on the in-depth hydrologic and hydrogeologic analyses of Kathajodi-Surua Inter-basin within the Mahanadi deltaic system of Orissa, eastern India to explore the possibility of enhanced and sustainable groundwater supply. The results of 6 years (2001–2006) streamflow analysis indicated that the river flow is highly seasonal and it reduces to almost no flow during summer seasons. Land use map of the study area for the monsoon (*Kharif*) and post-monsoon (*Rabi*) seasons was developed by remote sensing technique and runoff estimation was done by curve number method. The runoff estimated for the 20-year period (1990–2009) varied from a minimum of 10.2% of the total monsoon rainfall in 1995 to a maximum of 43.3% in 2003. The stratigraphy analysis indicated that a leaky confined aquifer comprising medium to coarse sand exists at depths of 15 to 50 m and has a thickness of 20 to 55 m. The analysis of pumping test data at 9 sites by Aquifer-Test software indicated that the aquifer hydraulic conductivity ranges from 11.3 to 96.8 m/day, suggesting significant aquifer heterogeneity. Overall groundwater flow is from north-west to south-east direction. There is a 5 to 6 m temporal variation and 3 to 4 m spatial variation of groundwater levels over the basin. The rainfall-groundwater dynamics and stream-aquifer interaction in the river basin were studied by correlation analysis of groundwater level with weekly rainfall and river stage. The correlation between the weekly rainfall and weekly groundwater level was found to vary from ‘poor’ to ‘fair’ ( $r=0.333$  to  $0.659$ ). In contrast, the weekly groundwater level was found to be strongly correlated with the weekly river stage ( $r=0.686$  to  $0.891$ ). The groundwater quality was found suitable for both irrigation and drinking purposes. It is recommended that a simulation-cum-optimization modeling following an integrated approach is essential for efficient utilization of groundwater resources in the study area.

**Keywords** Hydrologic and hydrogeologic characterization · Runoff potential · River-aquifer interaction · Pumping test · Groundwater quality · Deltaic aquifer system · Groundwater management

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## 1 Introduction

Total water requirement in India for various activities around the year 2050 has been assessed as 1,450 km<sup>3</sup>/year (Gupta and Deshpande 2004). Therefore, when compared to the availability of 500 km<sup>3</sup>/year at present, the water availability around 2,050 needs to be trebled. According to another estimate, the supply–demand gap for water in India is projected to rise to about 50% by 2030, with demands doubling from the present level of 700 billion cubic meters (Yojana 2010). Besides the water quantity, the quality of water is another serious concern for India owing to ever-increasing population and rapid industrialization. The experiences in the field of water management in India have shown that the indiscriminate uses of water resources have either lowered groundwater levels or caused waterlogging and salinity in different parts of the country (Jha et al. 2001). Particularly, in the canal-dominated regions of North India (the regions having extensive network of canal systems for irrigation), there has been an increase in groundwater levels due to seepage from the canals. Excessive groundwater development, on the other hand, has led to alarming decrease in groundwater levels in some parts of states like Tamil Nadu, Gujarat, Rajasthan, Punjab and Haryana (Romani 2006). This in turn has increased the cost of pumping, caused seawater intrusion into coastal aquifers and has raised questions about the sustainability of groundwater. On the top of it, global climate change, as evidenced by receding glaciers of the Himalayas and fluctuating pattern of the monsoon, is aggravating the water problem. Thus, the water management system of India is not sustainable. Undoubtedly, there is an urgent need for efficient management of water resources by adopting modern water management concepts, tools and techniques so as to ensure water security as well as environmental security on a long-term basis.

The state of Orissa in eastern India has its own share of water problem with diverse situation in different parts like the recurrence of drought in western parts, pockets of saline water in the coastal tract and acute water scarcity in many other parts. About 3 million people in the western part of Orissa are facing acute drinking water crisis due to large-scale deforestation, unplanned use of irrigation water, and low participation by people in the management of natural resources (Rejani et al. 2003). Moreover, overexploitation of groundwater in certain parts of the densely populated coastal Orissa has resulted in declining groundwater levels and seawater intrusion (Panda et al. 2007). Now, Orissa is passing through a phase of rapid industrialization where many mineral based industries have either come up or are envisaged. Water being the primary infrastructure need, there is already sign of conflict arising out of use of water by agriculture and mineral based industries in the state (Pati 2009). This is progressively adding to the stress on groundwater system. In coastal Orissa, rainfall occurs during mid-June to 1<sup>st</sup> week of October and remaining period remains almost dry. Therefore, there is an excess water situation during monsoon and scarcity of irrigation water during post-monsoon. This leads to *Kharif* paddy followed by fallow in the post-monsoon season. Thus, there is a need to develop an efficient groundwater management plan so that more area can be covered under irrigation in the post-monsoon season.

Development of an efficient groundwater management plan requires detailed hydrogeologic investigation in the river basin. The hydrogeologic investigations along with use of modeling techniques can help in vulnerability assessment of aquifer system or, assessment of sustainable yield of aquifer or, identifying alternate source of irrigation and drinking water. Al-Amoush et al. (2010) assessed the intrinsic vulnerability of the alluvial aquifer system of the Northern Jordan valley using SINTACS model and Geographic Information System (GIS) technique, taking into account different hydrological and hydrogeological impacts. The results showed that about 40% of the investigated area was highly or very highly vulnerable to groundwater pollution. Yin et al. (2011) assessed the sustainable yield in the

Huaibei Karst water area of Anhui province, China based on hydrogeologic investigations and artificial neural network modeling. Sustainable yield was calculated by the pumping rate when the critical water level can be maintained. The estimated sustainable yield provided a sound scientific foundation for the Huaibei karst groundwater development and management programme. Hilberg and Schneider (2011) investigated aquifer characteristics of the dolomite formation in the northern calcareous Alps region in Germany and Austria for identifying alternate source of drinking water. The study indicated that the dolomite formation aquifers provide a steady discharge of water in comparison to karst springs and is minimally influenced by precipitation and seasonal effects.

Considering the growing water problem in Orissa, the Kathajodi-Surua Inter-basin within the Mahanadi deltaic system of Orissa was selected as a study area for in-depth hydrologic and hydrogeologic investigations to explore the possibility of enhanced and sustainable groundwater supply. Needless to mention that detailed knowledge of hydrology and hydrogeology of the study area is crucial for the efficient planning and management of scarce water resources in a basin. The present study is first of its kind in the study area. The results of this study will be helpful for groundwater modeling of the deltaic groundwater system as well as for determining an optimal cropping pattern and optimal pumping rates so as to ensure efficient groundwater utilization in the study area. The results of the study will also be useful for other river basins of India in general and eastern India in particular.

## 2 Study Area

The study area is located in the Mahanadi deltaic system of Orissa, eastern India (Figs. 1 and 2) and is a typical river island surrounded by the Kathajodi River and its branch Surua. It is located between  $85^{\circ} 54' 21''$  to  $86^{\circ} 00' 41''$  E longitude and  $20^{\circ} 21' 48''$  to  $20^{\circ} 26' 00''$  N latitude. The altitude of the area varies from 18 to 23 m MSL. The total area of the river island is  $35 \text{ km}^2$  and agriculture is the major occupation of the inhabitants. Total cultivated area in the region is 2,445 ha of which 1,365 ha (55.83%) is irrigated land. Total low lands in the region are 408 ha, medium lands are 1,081 ha and high lands are 956 ha. All the low lands, medium lands and 618 ha of total high lands are used for paddy cultivation in the monsoon season (June to October). In the post-monsoon season, majority of the low lands are used for paddy cultivation and a substantial portion of the total area is under vegetable cultivation. Owing to the lack of irrigation infrastructure for surface water, all the irrigated lands are irrigated by groundwater. There are about 100 government tubewells in the area, which are the major source of groundwater withdrawal for irrigation. These have been constructed and managed by the Orissa Lift Irrigation Corporation, Cuttack, but are gradually being handed over to the water users' associations (WUAs). Out of the hundred tubewells, at present 69 tubewells are operating in the study area. Besides the government tubewells, there are some private dug wells, which are mainly used for drinking purpose. However, some of these dug wells get dry during dry periods (March-May), and thereby creating drinking water scarcity in the area.

Even though the Kathajodi River and Surua River flow on both sides of the study area, there is water shortage during dry periods. Embankments have been provided on the banks of the rivers to prevent the entry of river water into the inhabited area during flood events. Therefore, entire rainwater of the region is drained through a main drain and discharged at a single outlet into the River (Fig. 2). A sluice gate is provided at the outlet of the study area to prevent river water inflow into the area during flood events. During this time surface waterlogging problem is often encountered in the downstream portion of the study area.

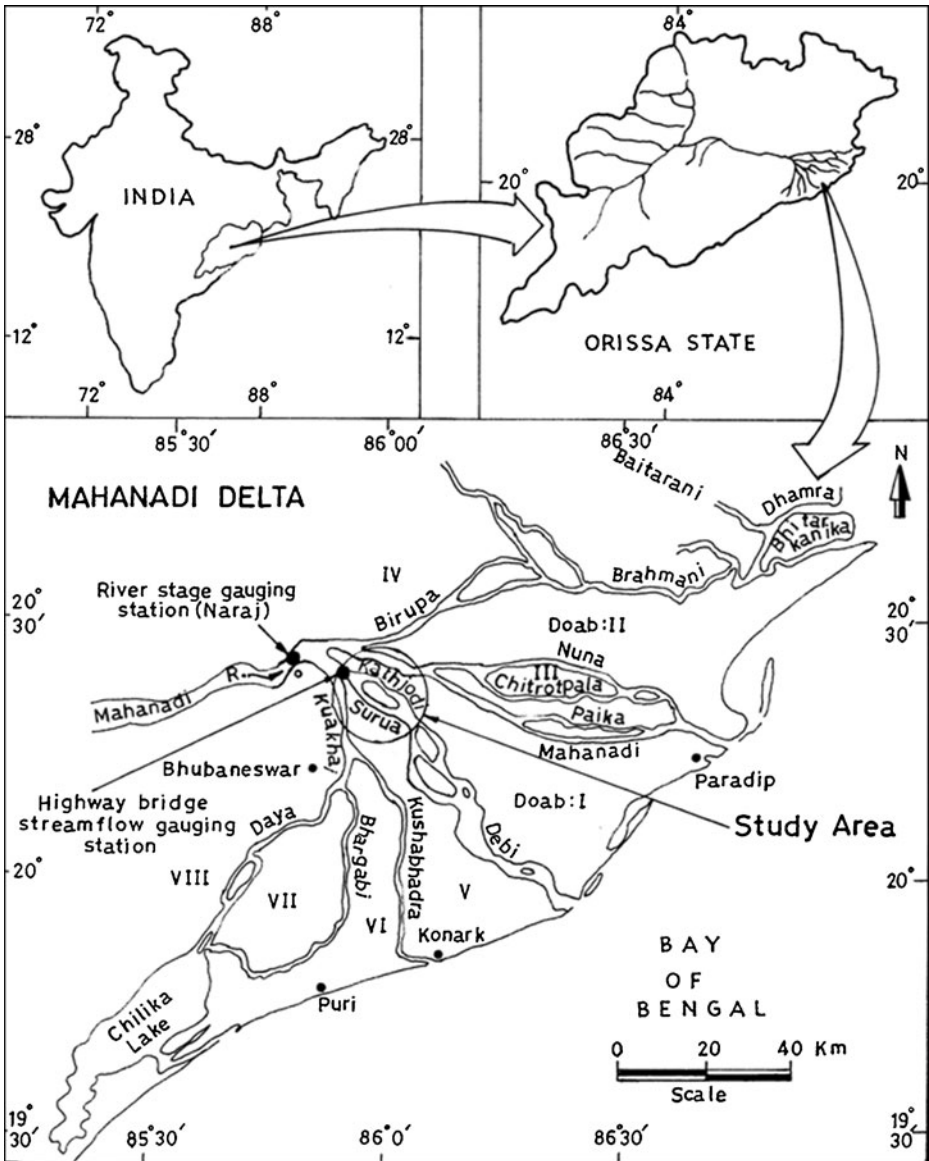
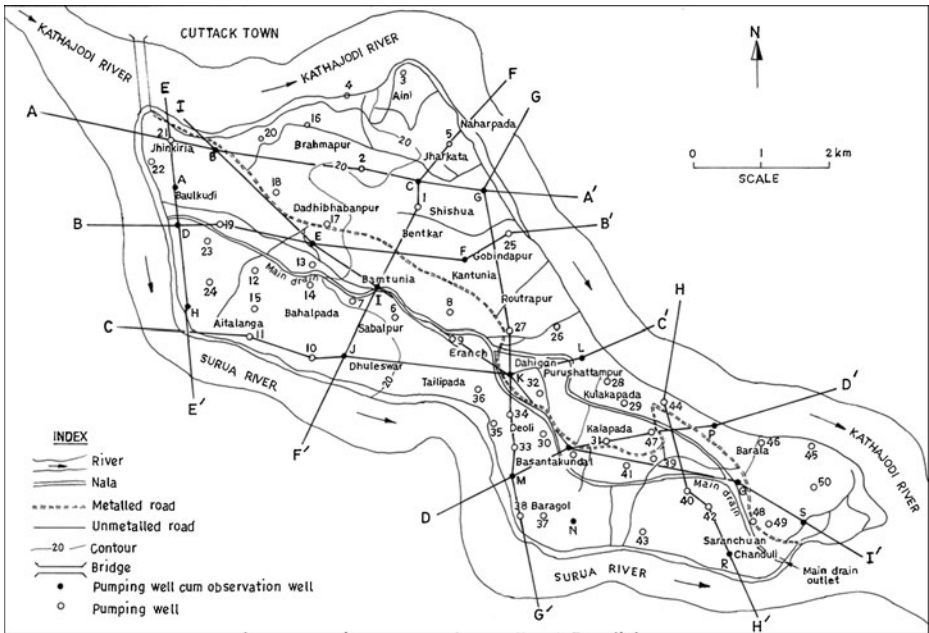


Fig. 1 Location map of the study area

### 3 Materials and Methods

#### 3.1 Database

Daily rainfall data of 20 years (1990–2009) were collected from a nearby meteorological observatory at Central Rice Research Institute (CRRI), Cuttack, Orissa located at about 2 km from the study area. The rainfall data were used for studying annual and seasonal variations of rainfall in the river basin as well as for investigating rainfall-groundwater dynamics and runoff



**Fig. 2** Location of observation and pumping wells and geologic cross sections in the study area

potential. The daily streamflow data of Kathajodi River at the highway bridge gauging station (Fig. 1) were obtained for 6 years (2001–2006) from the Department of Hydrometry, Government of Orissa, India and were used for detailed streamflow analysis. As the weekly river stage data near the study area were not available, the river stage data available at an upstream site named Naraj (Fig. 1) were collected from the office of Central Water Commission (CWC), Bhubaneswar, Orissa. Furthermore, Stratigraphic analysis of the study area was done based on lithological data of 70 exploration sites obtained from Orissa Lift Irrigation Corporation (OLIC), Cuttack.

**3.2 Groundwater Level Monitoring**

Since no groundwater data were available in the study area, a groundwater monitoring program was initiated in February 2004. For the monitoring of groundwater levels, nineteen tubewells were selected in the study area in such a way that they represent approximately four west–east and four north–south cross-sections of the study area. The locations of the 19 monitoring wells are shown as filled circles (A to S) in Fig. 2. The groundwater levels were monitored in the selected tubewells on a weekly basis from February 2004 to October 2007. The location of different tubewells in the study area was found with the help of global positioning system (GPS) and the reduced levels of the tubewell sites (in terms of heights above mean sea level) were obtained by detailed leveling survey with respect to existing benchmark points.

**3.3 Analysis of Streamflow**

The analysis of streamflow data is required to understand the characteristics of streamflow and its temporal variation in the river basin. The streamflow data of six-years period (2001–2006) were analyzed to calculate annual maximum discharge, minimum discharge, 95-day

discharge, ordinary discharge, low discharge, droughty discharge and mean discharge using the method reported by Jha et al. (1999). After arranging the annual daily streamflow data in a descending order, the 95/96th day (96th day for a leap year), the 185/186th day, the 275/276th day, and the 355/356th day discharges are respectively known as 95-day, ordinary, low, and droughty discharges (Jha et al. 1999). The annual and seasonal variation of streamflow over the 6 year period was studied.

### 3.4 Mapping of Land Use and Soil Types

The land use map and the soil map of the study area were used for creating hydrologic soil cover complex map for runoff estimation by curve number method. Land use maps for the monsoon (*Kharif*) and post-monsoon (*Rabi*) seasons were created using remote sensing image analysis. Two cloud-free Indian Remote Sensing satellite (IRS) P6 MX images of the study area, one of pre-monsoon season (20 March 2004) and another of post-monsoon season (20 November 2004) were procured from National Remote Sensing Agency (NRSA), Hyderabad, India. Both the images were rectified and geometrically corrected with respect to survey of India toposheets namely 73 H/15 and 73 L/3 using ERDAS IMAGINE 8.7 software. The images were analyzed to create land use map of the study area for monsoon and post-monsoon seasons, respectively. The November image was used for the creation of land use map of the monsoon season, whereas the March image was used for land use map of the post-monsoon season. Based on the reflectance of the images, the entire area was classified into different land uses. A number of field visits were conducted to verify the correctness of land use classification. GPS was also used during the ground truth verification. Based on the field verification and reflectance of the images, the land use maps were prepared for both monsoon and post-monsoon seasons using ArcGIS software. In addition, the soil map of the study area was extracted in the GIS environment from the soil map developed by Orissa Space Application Centre (ORSAC), Bhubaneswar, India.

### 3.5 Estimation of Runoff Potential

Composite curve number technique (USDA Soil Conservation Service 1985) was used for runoff estimation in the study area. Based on the characteristics of the soil types in the study area, soils were classified into different hydrologic soil groups. By overlaying the monsoon season land use map on the soil map in GIS environment, the hydrologic soil cover complexes or curve number distribution in the study area were delineated, from which composite (weighted) curve number was estimated. The event-based daily runoffs were computed for the monsoon months (June to October) of 20 years (1990–2009) period with the help of MS-Excel software using the following equations:

$$S = \frac{25400}{CN_w} - 254 \quad (1)$$

$$Q = \frac{(P-0.2S)^2}{(P+0.8S)} \quad (Q = 0 \text{ for } P \leq 0.2S) \quad (2)$$

where,  $S$  = potential maximum retention or infiltration (mm),  $CN_w$  = weighted curve number,  $Q$  = direct runoff (mm), and  $P$  = total precipitation (mm).

### 3.6 Lithologic Investigation

The lithologic data offer unique opportunities to gather information about the subsurface formations, aquifer and its spatial extent and groundwater condition in a basin. Using the lithologic data, geologic profiles along the four east–west sections, four north–south sections and one central section (section A–A' to section I–I') as shown in Fig. 2 were prepared and stratigraphic analysis was performed to characterize aquifers and confining layers present in the study area.

### 3.7 Determination of Aquifer Parameters

Time-drawdown pumping tests were conducted at 9 sites in the study area during January to April 2006. The duration of the pumping tests varied from 4 to 6 h and the discharge of the wells varied from 12 to 23 lit/s. Drawdowns in the observation wells were measured with time during pumping as well as during recovery. Wherever observation wells were not available, single well pumping test was done by measuring the water level in the pumped well during pumping as well as during recovery. These field measured time-drawdown data were used to determine aquifer parameters (transmissivity and storage coefficient) by the graphical method using Aquifer-Test software (WHI 2002). It is worth mentioning that the single well test data could yield only transmissivity values.

### 3.8 Investigation of Groundwater Characteristics

From the monitored groundwater level data, groundwater elevation contour maps were prepared using Surfer software for representative dry and wet periods in order to study the spatial and temporal variation of groundwater over the study area. The groundwater levels of 19 June 2005; one of the lowest in the particular year was used for the preparation of dry period groundwater level contour map. In the period 2004 to 2007, when groundwater level data was recorded, minimum groundwater levels were mostly observed during the period of April–May month. As monsoon was delayed in the year 2005, one of the lowest groundwater levels was observed in the month of June. Similarly the groundwater levels of 18 September 2005 were used for the preparation of wet period groundwater level contour map.

In order to study rainfall–groundwater dynamics in the study area, well hydrographs of different tubewells were plotted along with the bar graphs of rainfall. A correlation analysis was also performed between groundwater levels of different locations and rainfall.

### 3.9 Analysis of Stream–Aquifer Interaction

As the underlying aquifer in the study area is alluvial, it is likely that there will be hydraulic connection between the Kathajodi River and the underlying aquifer. However, little is known about stream–aquifer interaction, though it is important for efficient management of water resources. To study stream–aquifer interaction, well hydrographs were plotted along with the river stage hydrograph for the view of pattern. The weekly river stage data near the study area was not available, and hence the river stage data available at an upstream site called Naraj, (located at 15 km upstream of the study area) (Fig. 1) were used in this study. As the river water level at Naraj controls the river water level around the study area, the river stage data of Naraj could be representative for the area. Correlation analysis was performed between the weekly groundwater levels at 19 sites and the weekly river stage at 1 day lag period using the data from February 2004 to October 2007. A lag time correlation analysis was also performed between the river stage and the groundwater levels by considering 2-day to 10-day lags of river stage.

### 3.10 Determination of Hydraulic Connectivity

The groundwater level data were further used to explore the hydraulic connectivity in the study area. Weekly groundwater level data from 10 selected wells distributed over the study area, for the period of 3 years and 9 months were used to develop a correlation matrix to study the hydraulic connectivity between individual wells. Ten sites were selected randomly with 5 sites (i.e., sites A, C, F, H and J) from the upstream portion of the basin and 5 sites (i.e., sites L, M, P, R and S) from the downstream portion.

### 3.11 Assessment of Groundwater Quality

Groundwater samples were collected from 8 tubewells spread over the basin in the month of May 2005 for exploring water quality analysis. The locations of these tubewells are A, B, G, I, N, O, Q and S as shown in Fig. 2. Soon after collection, pH and EC (electrical conductivity) of water samples were measured using portable water quality meters. The groundwater samples were also analyzed in the laboratory for  $\text{Ca}^{++}$ ,  $\text{Mg}^{++}$ ,  $\text{Cl}^-$ ,  $\text{CO}_3^-$  and  $\text{HCO}_3^-$  by following standard methods (APHA 1989; Richards 1968).  $\text{Na}^+$  concentrations in the samples were determined by flame photometry. Sodium Adsorption Ratio (SAR) of the water samples was determined as (Richards 1968; Ayers and Westcot 1989):

$$\text{SAR} = \frac{\text{Na}^+}{\sqrt{\frac{\text{Ca}^{++} + \text{Mg}^{++}}{2}}} \quad (3)$$

Where, concentrations of the ions are expressed in milliequivalents per litre.

Furthermore, the Residual Sodium Carbonate (RSC) of the water samples was determined from the following formula (Richards 1968):

$$\text{RSC} = \{[\text{HCO}_3^-] + [\text{CO}_3^{2-}]\} - \{[\text{Ca}^{2+}] + [\text{Mg}^{2+}]\} \quad (4)$$

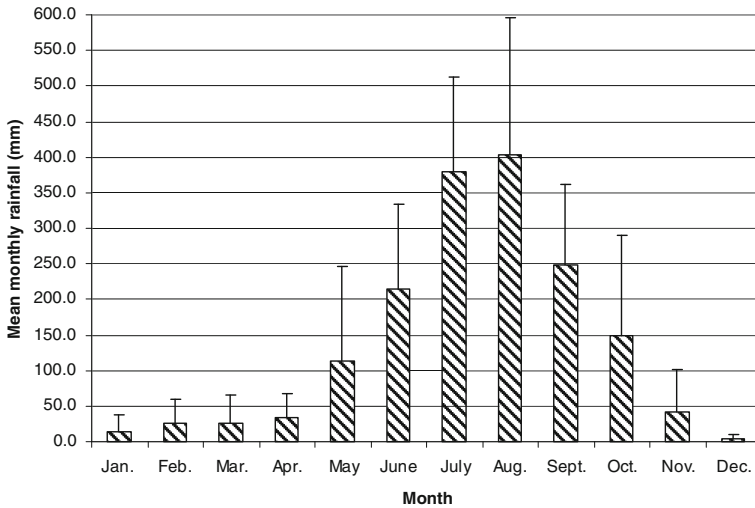
Where the concentrations are expressed in milliequivalents per litre. Additionally, Mg/Ca ratios of the water samples were also determined. Based on the water quality parameters obtained, the suitability of groundwater for irrigation was evaluated following standard guidelines (Richards 1968; Ayers and Westcot 1989). Moreover, the suitability of groundwater for drinking was evaluated following the WHO guidelines (WHO 1971).

## 4 Results and Discussion

### 4.1 Rainfall Characteristics

Analysis of 20 years (1990–2009) of rainfall data in the study area showed an average annual rainfall of 1649.8 mm with a standard deviation of 375.9 mm. The highest average monthly rainfall (402.8 mm) and standard deviation (193.6 mm) were observed in the month of August. Highest annual rainfall was observed in the year 2003 (2272.4 mm), whereas the lowest annual rainfall was observed in the year 1996 (797.3 mm). According to India Meteorological Department (IMD), the meteorological drought year is defined as a year in which less than 75% of the average annual rainfall is received. Based upon these criteria, the years 1996, 2000 and 2002 can be characterized as drought years. Monthly variation of rainfall over the 20-year period along with standard deviation bars is shown in Fig. 3.

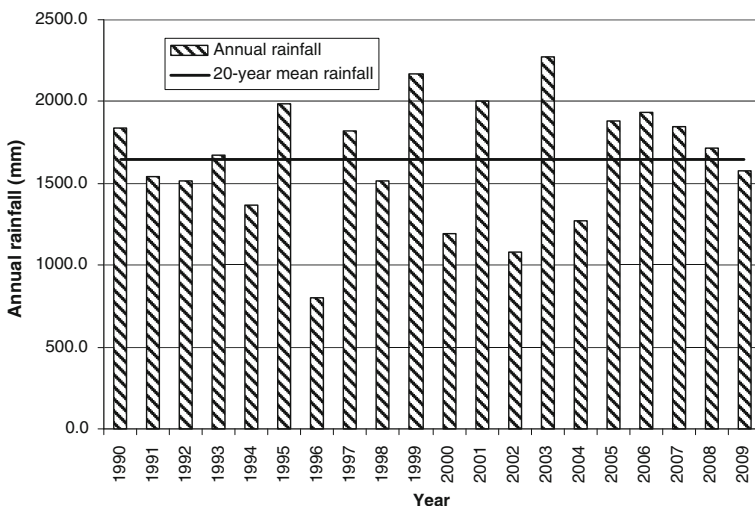




**Fig. 3** Monthly variation of average rainfall in the study area along with standard deviation bars

Though the rainfall events are distributed throughout the year, the rainy season usually starts from mid-June and lasts up to mid-October. November through May is usually characterized as dry period. The most reliable months for rainfall are July, August and September. Thus, the bulk of the rainfall is concentrated in a relatively short time span, which increases the potential for both surface runoff and recharge to the aquifer, but limits it to short periods of a year. As sufficient rainfall is available during July, August and September, there is not much need of groundwater withdrawal for irrigation during these months. Relatively large standard deviations in the months of May, June, July, August, September and October indicate that the magnitude of rainfall varies appreciably from year to year.

Moreover, Fig. 4 shows the variation of annual rainfall over the basin together with 20-year mean annual rainfall. It is apparent from the figure that years 1990, 1993, 1995, 1997,



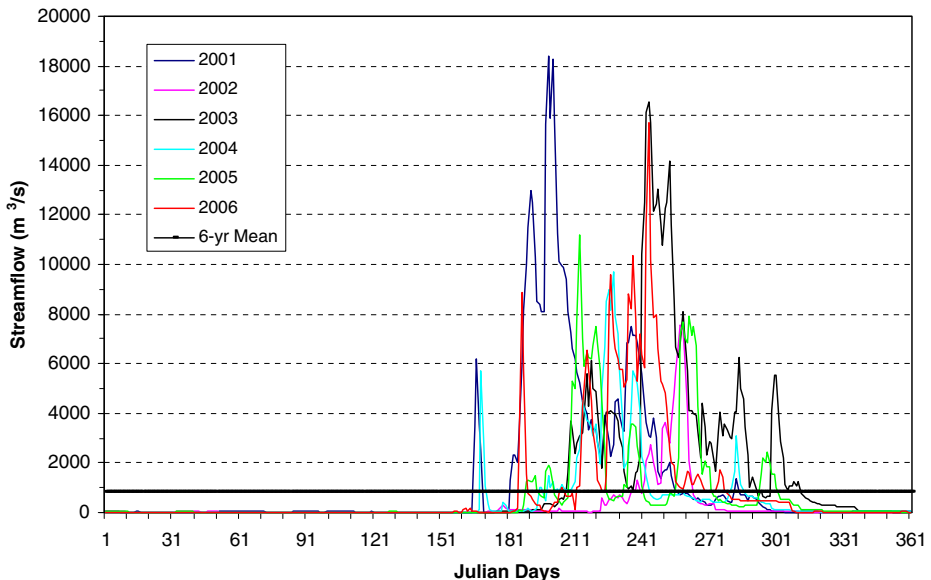
**Fig. 4** Variation of annual rainfall during the period 1990–2008

1999, 2001, 2003, 2005, 2006, 2007 and 2008 are wetter than normal rainfall while other years were drier than normal with the year 1996 being the driest year.

#### 4.2 Streamflow Characteristics

The daily variation of streamflow in the Kathajodi River for 6 years (2001–2006) at highway bridge gauging station is shown in Fig. 5. It is clear from this figure that the streamflow reaches the peak value during the period July to September when most of the rainfall occurs. It starts decreasing from the month of October and becomes very low ( $<50 \text{ m}^3/\text{s}$ ) from December onwards when rainfall events are scanty. The streamflow reduces further and varies between  $10$  and  $20 \text{ m}^3/\text{s}$  during February to May. The streamflow varies appreciably over the 6 year period, with the minimum streamflow (mean flow= $283 \text{ m}^3/\text{s}$ ) in 2002 which was a meteorological drought year. In 2002, 2004 and 2005, the mean streamflow was lower than the 6-year average streamflow, whereas it was higher in the remaining years.

Moreover, Table 1 summarizes some important flow characteristics for the 2001–2006 periods. Lowest maximum streamflow ( $7557 \text{ m}^3/\text{s}$ ) is observed during 2002 which is significantly less than the 6 year mean. Maximum streamflow is observed in 2001 ( $18380.0 \text{ m}^3/\text{s}$ ) followed by 2003 ( $16530.0 \text{ m}^3/\text{s}$ ). Although the years 2001, 2003 and 2006 experienced relatively high streamflows, minimum flows were lower. The 95-day flow in 2002 is significantly less than the 6 year mean whereas the ordinary flow, low flow and droughty flow are comparable over different years. The minimum flow is zero in 3 years (2001, 2002 and 2004) out of the 6 years and is quite low in other 3 years. This shows the unavailability of surface water resources in the study area for a considerable period. Zero streamflow is also detrimental to the river ecosystem. Therefore, a comprehensive investigation is necessary in this direction to ensure a suitable low flow in the river during dry seasons in order to protect river ecosystem.



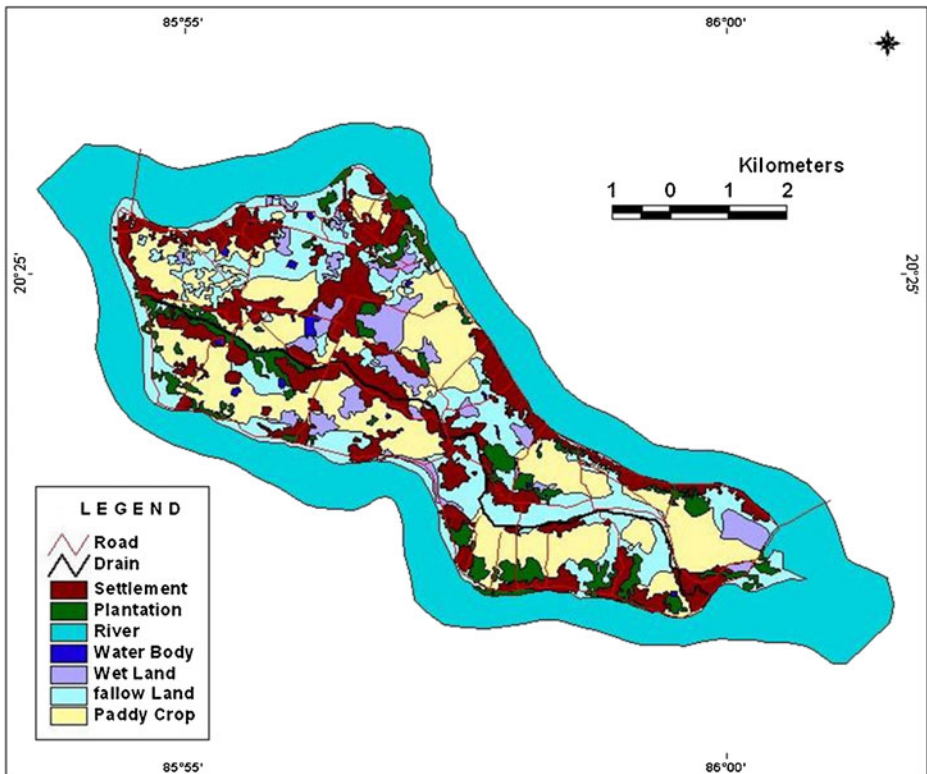
**Fig. 5** Annual discharge hydrograph of the Kathajodi River at Highway Bridge gauging station

**Table 1** Streamflow characteristics of the Kathajodi River for the 2001–2006 period

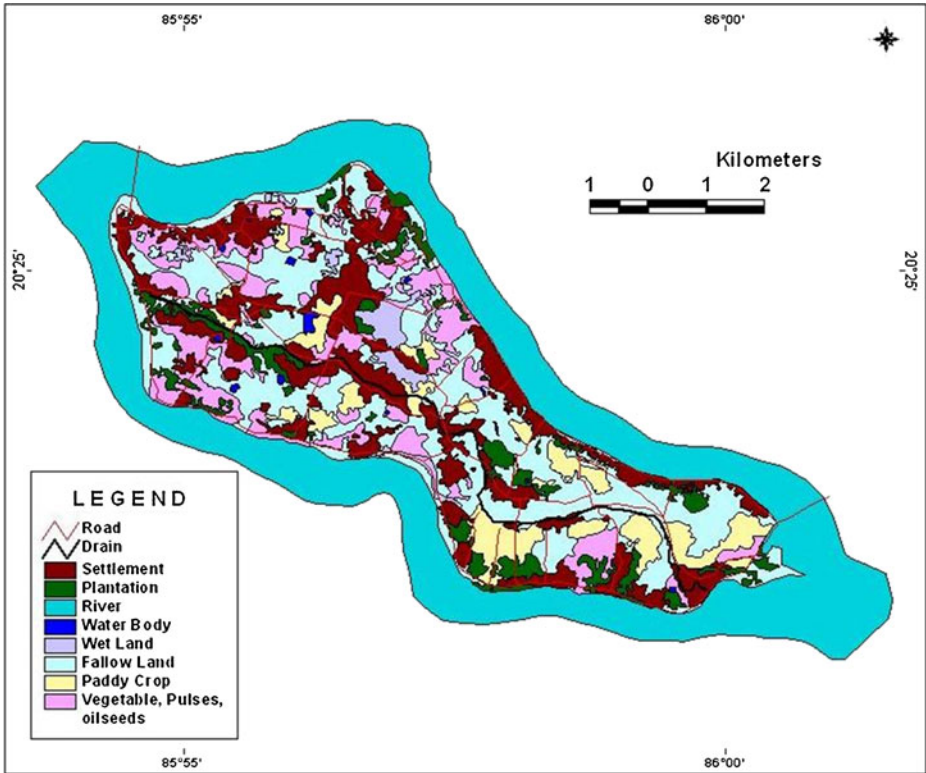
Description	Streamflow (m <sup>3</sup> /s)						
	2001	2002	2003	2004	2005	2006	6-yr mean
Maximum flow	18380.0	7557.0	16530.0	9727.0	11184.0	15719.0	13182.8
95-day flow	643.7	59.0	959.1	431.9	410.5	467.9	495.3
Ordinary flow	33.3	20.7	24.9	20.9	35.4	25.0	26.7
Low flow	17.1	13.2	17.5	3.4	17.2	6.7	12.5
Droughty flow	0.0	0.0	17.0	0.0	2.4	3.0	3.7
Minimum flow	0.0	0.0	12.1	0.0	1.2	0.9	2.4
Mean flow	1345.2	283.0	1338.1	587.9	712.5	873.6	856.7

### 4.3 Land Use/Land Cover Variation

Based on the remote sensing image analysis of the study area, land use was classified into 7 to 8 categories namely settlement, orchard/plantations, water body, wetland, river, fallow land, paddy area and vegetables/pulses/oilseed area. The land use maps of monsoon and post-monsoon season are shown in Figs. 6 and 7, respectively. The areas under different land uses in both the seasons are summarized in Table 2. About 816.42 ha of the study area are



**Fig. 6** Land use map of the study area in the monsoon (*Kharif*) season



**Fig. 7** Land use map of the study area in the post-monsoon (*Rabi*) season

covered under settlements or built up lands, whereas 318.33 ha are covered under orchard/plantation crops. Paddy is the most dominant crop in the monsoon season covering 1,140.57 ha of the total land. In the post-monsoon season, vegetables, pulses and oilseeds covering an area of 563.32 ha are grown along with paddy cultivation in an area of 377.42 ha. Clearly, larger area (1,307.04 ha) remains fallow during the post-monsoon season

**Table 2** Land use/land cover in the study area in March 2004 and November 2004

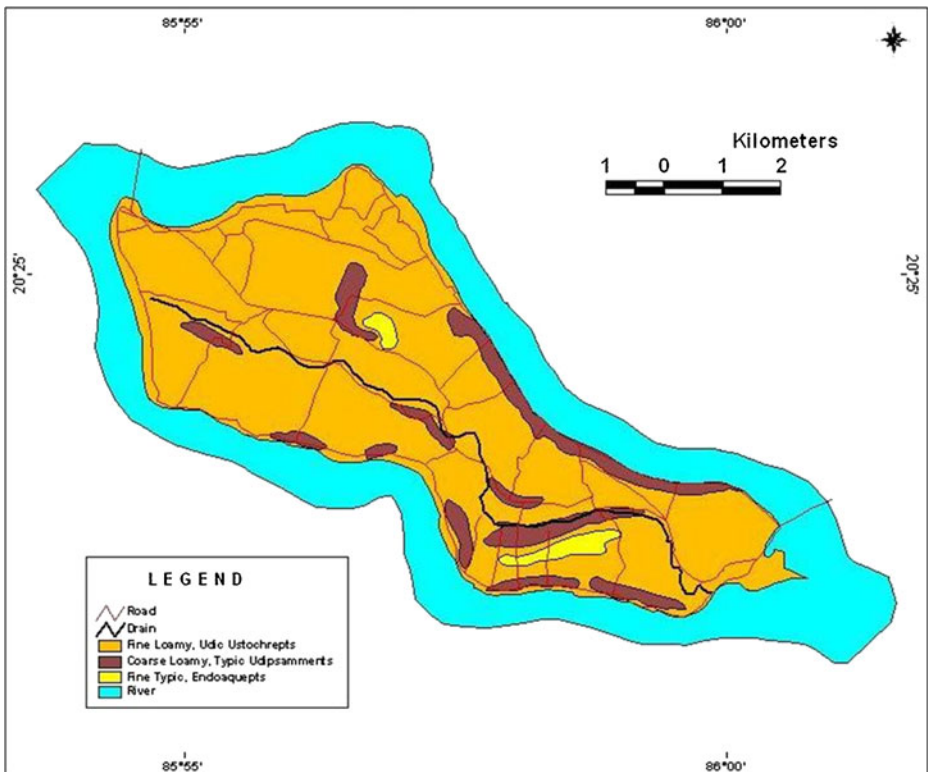
Sl. No.	Land use	Area (ha)	
		<i>Rabi</i> season	<i>Kharif</i> season
1	Built-up Land	816.42	816.42
2	Orchard/plantations	318.33	318.33
3	Water body	21.09	21.09
4	Wetland	98.55	260.48
5	Fallow Land	1307.04	945.25
6	Paddy Cultivated Land	377.42	1140.57
7	Land under Vegetables, Pulses or Oilseed in <i>Rabi</i> season	563.32	–
Total		3502.17	3502.14

as compared to the monsoon season (945.25 ha), which necessitates efficient irrigation water management in the study area.

#### 4.4 Soil Map

The extracted soil map of the study area has been shown in Fig. 8. The region comprises of three major soil types, namely (i) Fine loamy, Udic Ustochrepts, (ii) Coarse loamy, Typic Udipsaments and (iii) Fine, Typic Endoaquepts with the majority of area belonging to type 1 category. A brief description of these soil types are given below.

- (i) **Fine loamy, Udic Ustochrepts:** The soil belongs to the inceptisol order which has an ochric epipedon with ustic water regime indicating soil will remain wet for more than 60 days in a year. The soil has loam to clay loam texture with smectitic clay minerals.
- (ii) **Coarse loamy, Typic Udipsaments:** The soil belongs to entisol order with udic nature of clay water interactions. The soil has all the characters of typical entisols with medium to shallow depths and sandy loam to loamy sand texture with dominance of kaolinitic/illitic clay minerals.
- (iii) **Fine, Typic Endoaquepts:** The soil belongs to inceptisol order with aquic water regime indicating soil remains wet for about 100 days in a year. The soil has medium to fine texture ranging between clay and clay loam with high fertility.



**Fig. 8** Soil map of the study area

Based on the characteristics of the soil types in the study area, the soil types Fine loamy, Udic Ustochrepts and Fine, Typic Endoaquepts were grouped under hydrologic soil group C (moderately high runoff potential) and the soil type Coarse loamy, Typic Udipsaments was grouped under hydrologic soil group B (moderately low runoff potential) as per the guidelines of USDA Soil Conservation Service (1985).

#### 4.5 Runoff Potential in the Study Area

The areas under different hydrologic soil cover complexes (i.e., curve numbers) obtained by overlapping the monsoon season land use map and the soil map are summarized in Table 3. It is evident from this table that a majority of the study area falls under paddy in hydrologic soil group C, i.e., curve number 82 zone (1081.20 ha), while only 41.72 ha falls under orchard/plantation in hydrologic soil group B, i.e., curve number 55 zone. Figure 9 shows the estimated runoff obtained by composite curve number method along with total monsoon rainfall for the 1990 to 2009 period. It is worth mentioning that this estimated runoff is not included in the above mentioned streamflow which is measured at an upstream location of the basin, whereas the runoff is discharged at the downstream end of the basin. The estimated runoffs for the 20 years period (1990–2009) varied from a minimum of 76.15 mm in the year 1996 to a maximum of 935.29 mm in the year 2003. Further, the runoff as percentage of total monsoon rainfall varied from a minimum of 10.19% in the year 1995 to a maximum of 43.3% in the year 2003. Incidentally, more of peak rainfall events had occurred in the years 1993, 1997, 1999, 2001, 2003, 2006 and 2007, and hence percentage of runoff were relatively more in those years.

Based on the above discussion, it can be inferred that the study area has sufficient runoff potential which can be stored through water harvesting structures such as farm ponds at suitable locations and check dams across the main drain (Fig. 2).

#### 4.6 Aquifer Characteristics

The plots of geologic profiles along the four west–east, four north–south and one central cross-section of the study area are shown in Fig. 10(a to i). The water bearing formation (i.e. aquifer) mostly consists of coarse sand, medium to coarse sand and pebbles with coarse sand being the dominant formation. The thickness of the aquifer varies from 20 to 55 m over the

**Table 3** Hydrologic soil cover complex distribution (AMC II condition) in the study area during monsoon season

Hydrologic soil cover complex	Curve number (AMC II)	Area (ha)	Area (%)
Settlement on hydrologic soil group B	69	235.82	6.73
Settlement on hydrologic soil group C	79	580.64	16.58
Orchard/plantation on hydrologic soil group B	55	41.72	1.19
Orchard/plantation on hydrologic soil group C	70	276.66	7.90
Paddy on hydrologic soil group B	74	59.39	1.70
Paddy on hydrologic soil group C	82	1081.20	30.87
Fallow land on hydrologic soil group B	86	45.65	1.30
Fallow land on hydrologic soil group C	91	899.61	25.69
Water body/wet land	85	281.60	8.04
	Total	3502.29	100.00

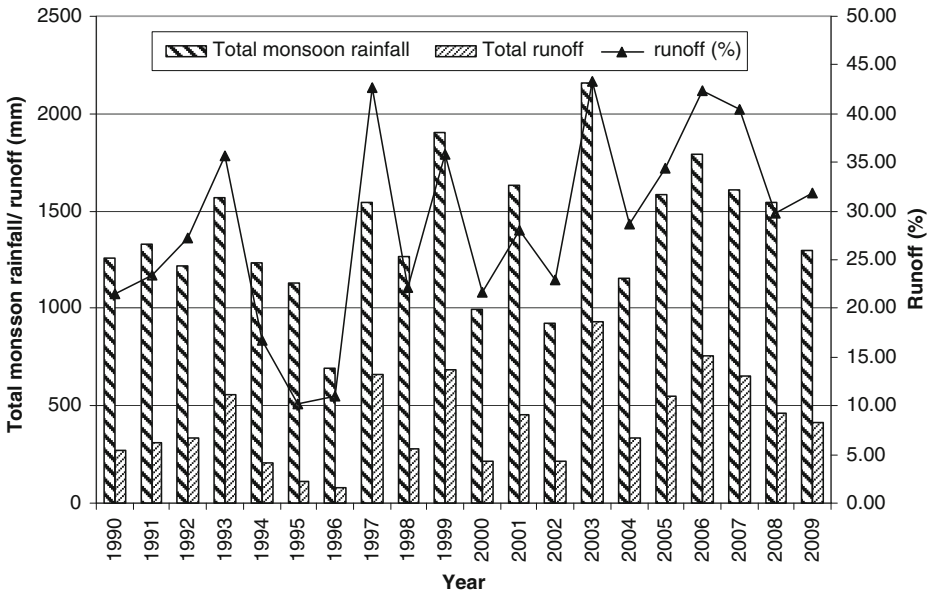


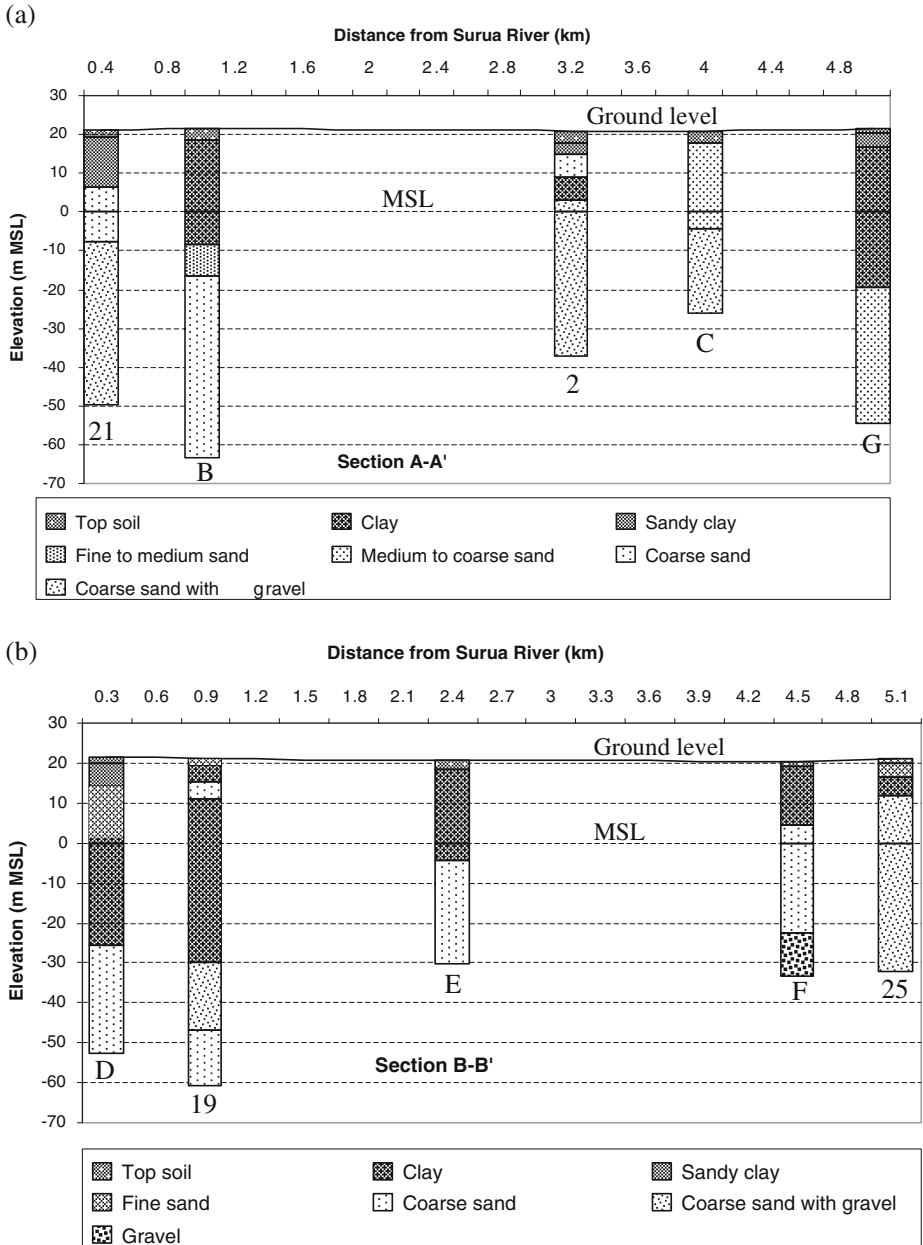
Fig. 9 Total monsoon rainfall, runoff and percent runoff in the years 1990 to 2009

basin. The top confining layer comprises clay or sandy clay with isolated patches of coarse sand or medium sand in between, whereas the bottom confining layer consists of clay. Wherever the confining layer consists of sandy clay or has patches of coarse sand or medium sand, it can contribute leakage into or from aquifer depending on hydraulic conditions. The thickness of the top confining layer varies from 15 to 50 m, except at Site C where aquifer is available at a shallower depth and Site H, where the clay layer is extended up to a deeper depth of 66 m [Fig. 10(e)]. The depth of the impermeable clay layer below the aquifer varies between 47 m and 88 m.

The lithologic data along the section D-D' [Fig. 10(d)] shows the presence of multiple aquifers towards the downstream side of the basin. At Site M, first aquifer is available at a depth of 21–30 m and second aquifer at a depth of 40–82 m below ground level. Similarly, at site O, the aquifers are available at depths of 3–12 m, 30–42 m and 49–66.5 m below ground level and at site 31, the aquifers are available at depths of 20–40 m and 49–82 m. However, as the lithology of many nearby sites do not show a multi-aquifer system, the patches of coarse sand or medium sand to coarse sand can be considered as isolated patches within the clay bed. The lithology along the section I-I' [Fig. 10(i)] shows the presence of aquifer at a deeper depth towards the south-east side of the basin. It shows that the aquifer slopes from north-west to south-east direction in the basin. Based on this discussion, it can be concluded that a confined or leaky confined aquifer exists in the study area.

#### 4.7 Hydraulic Parameters of the Aquifer System

The aquifer parameters transmissivity and storage coefficient at 9 sites were found out by conducting pumping tests and are presented in Table 4. The analysis of time-drawdown pumping test data at two sites C and I by Aquifer-Test Software is illustrated in Fig. 11(a) and (b), respectively as an example. The hydraulic conductivity values were obtained by dividing transmissivity values with corresponding aquifer thickness values obtained from



**Fig. 10** a to i. Variation of lithology along the four west–east and north–south sections and one central section

lithologic data. At Sites J and S, storage coefficient values could not be obtained because of single well pumping tests at these sites. Table 4 reveals that the aquifer hydraulic conductivity (K) varies from site to site with a maximum value of 96.80 m/day at Site O and a minimum value of 11.25 m/day at Site B, indicating a large spatial variation of K over the basin (i.e., large heterogeneity of the aquifer system). Figure 12 shows the spatial variation



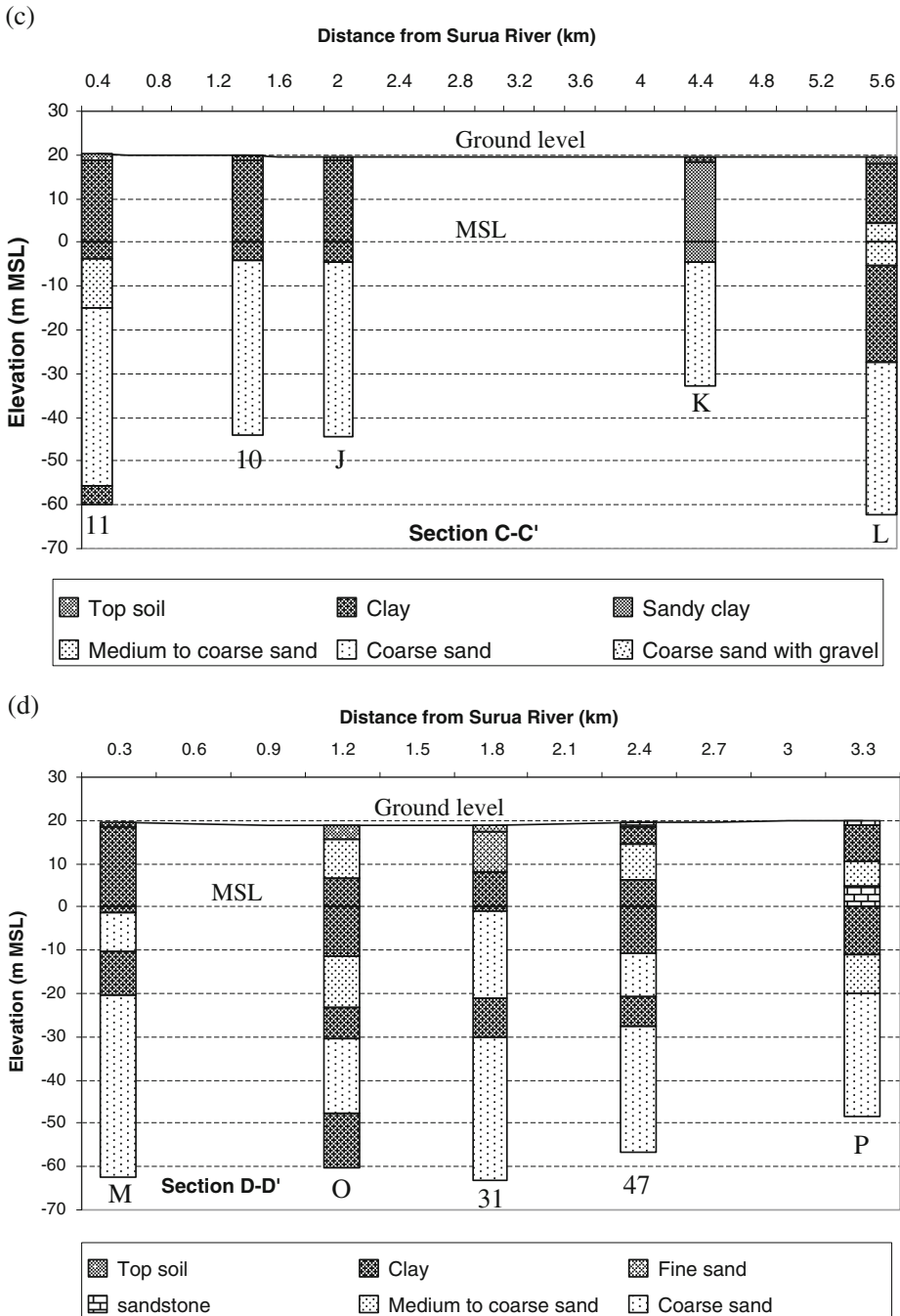


Fig. 10 (continued)

of hydraulic conductivity over the study area. It is observed from the figure that the downstream region of the study area usually has higher hydraulic conductivity than the

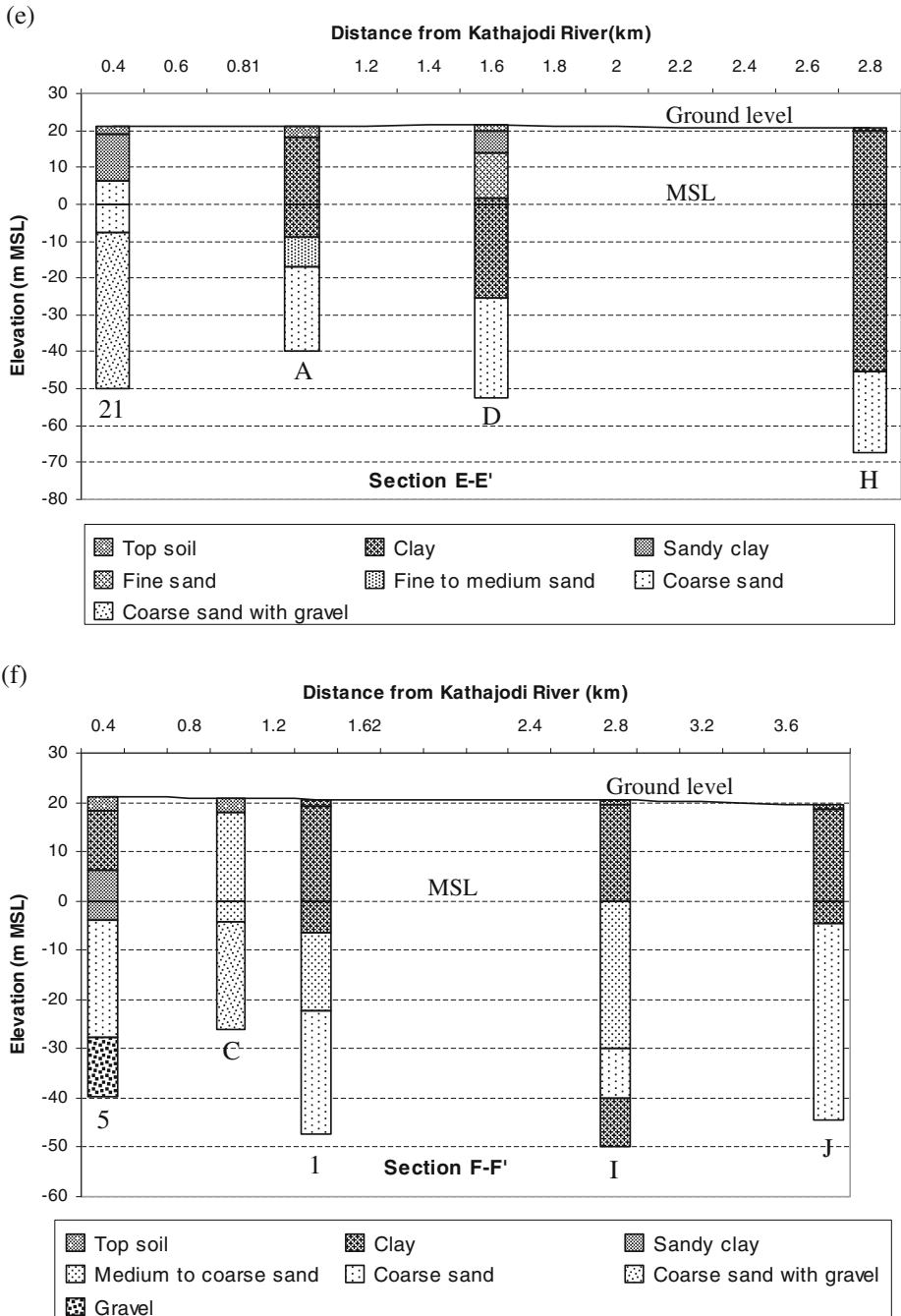
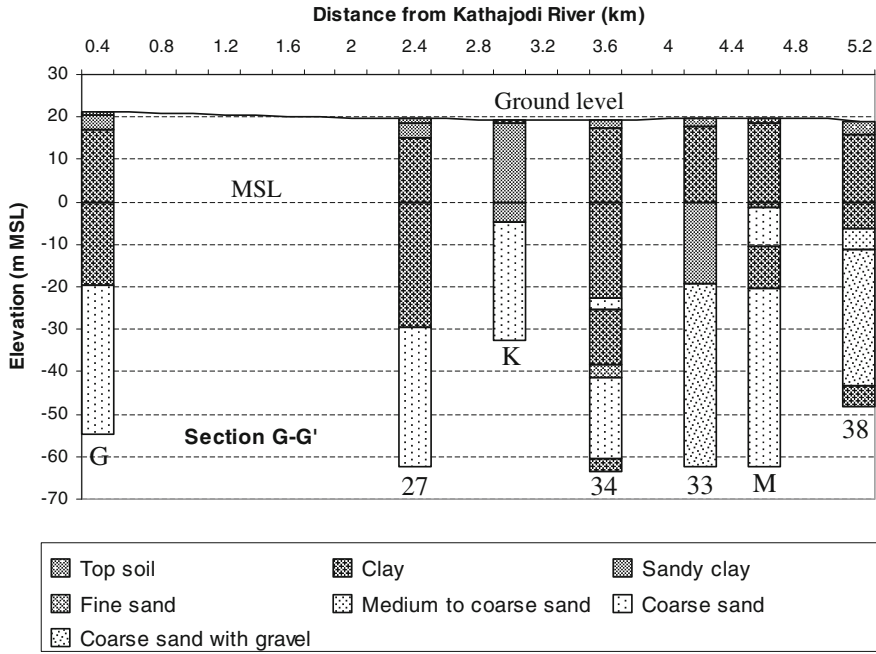


Fig. 10 (continued)

upstream region. Quantitatively, the hydraulic conductivity of the basin could be classified as ‘high’ (Todd 1980), suggesting fast groundwater movement in the study area. The aquifer

(g)



(h)

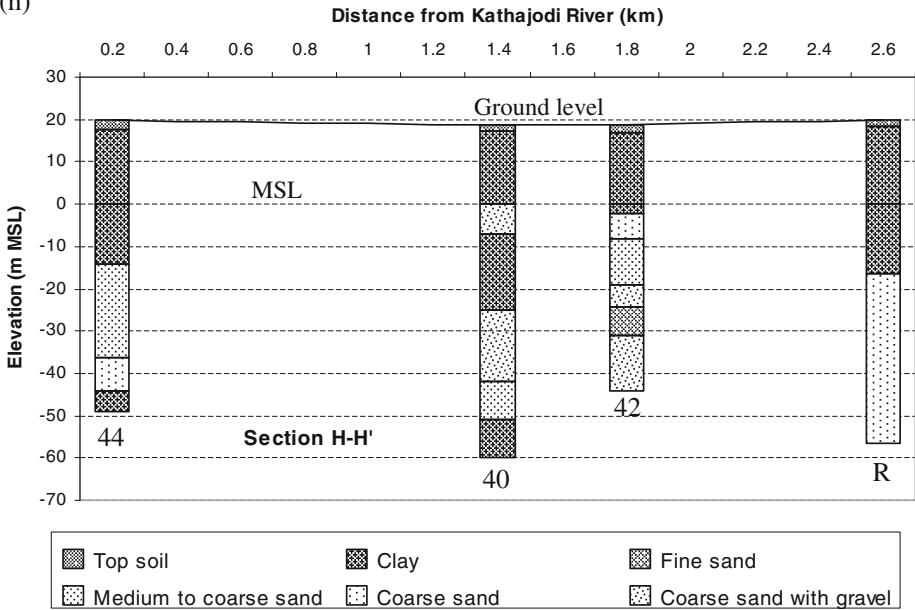


Fig. 10 (continued)

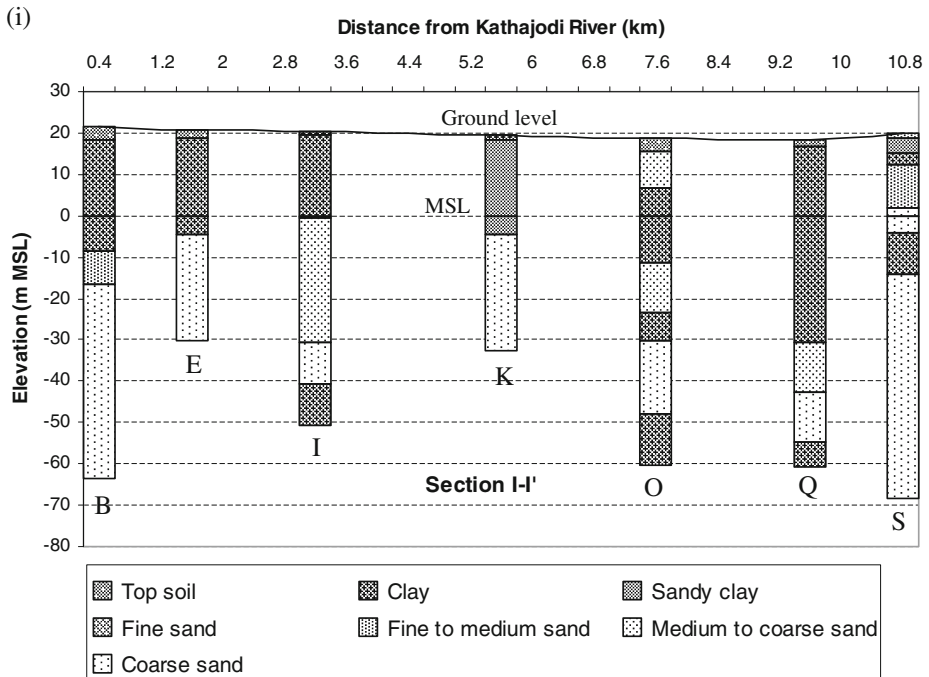


Fig. 10 (continued)

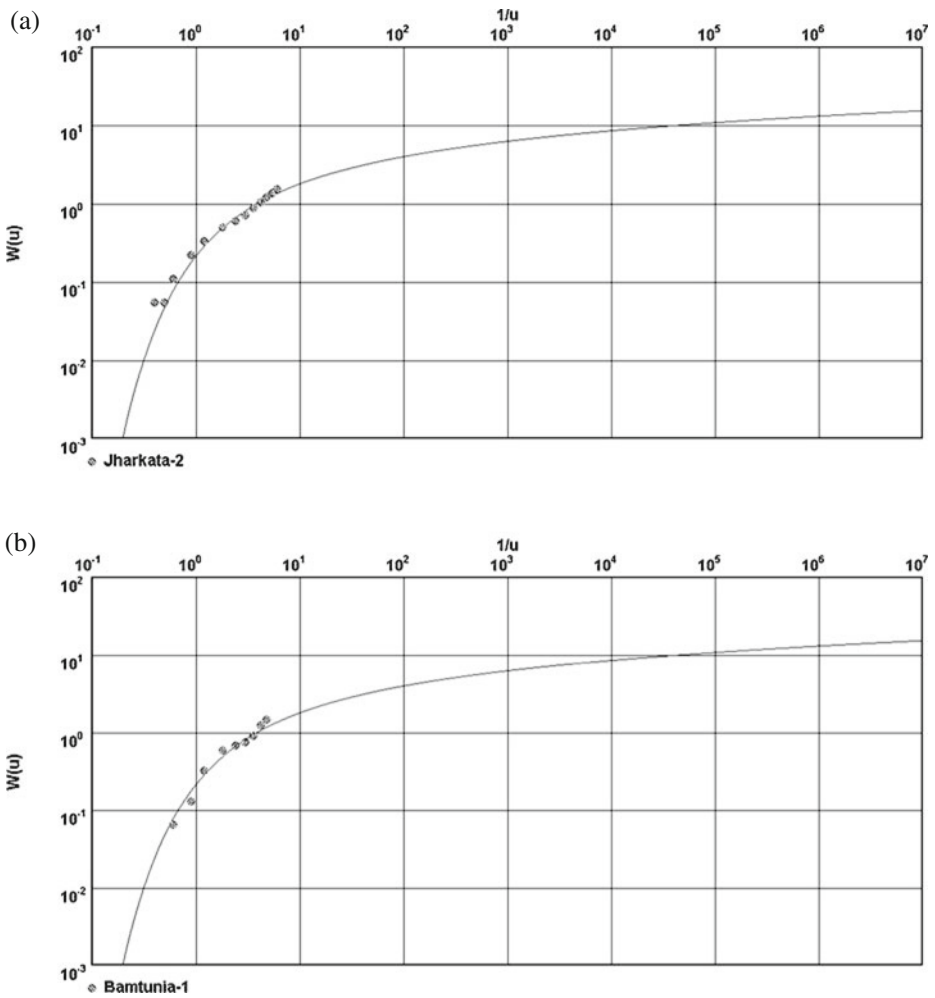
transmissivity varies from 3484.8 m<sup>2</sup>/day (Site O) to 528.5 m<sup>2</sup>/day (Site B) with an average value of 1778.86 m<sup>2</sup>/day. The values of storage coefficient ranges between 1.43 × 10<sup>-4</sup> (Site H) and 9.9 × 10<sup>-4</sup> (Site O), which indicate a significant variation of storage coefficient over the basin.

#### 4.8 Groundwater Flow Pattern

Figure 13(a) and (b) show the groundwater elevation contour map of the representative dry period and wet period, respectively. In the dry season, the water level varies from 15 m in the

Table 4 Aquifer parameters of the river basin from pumping test

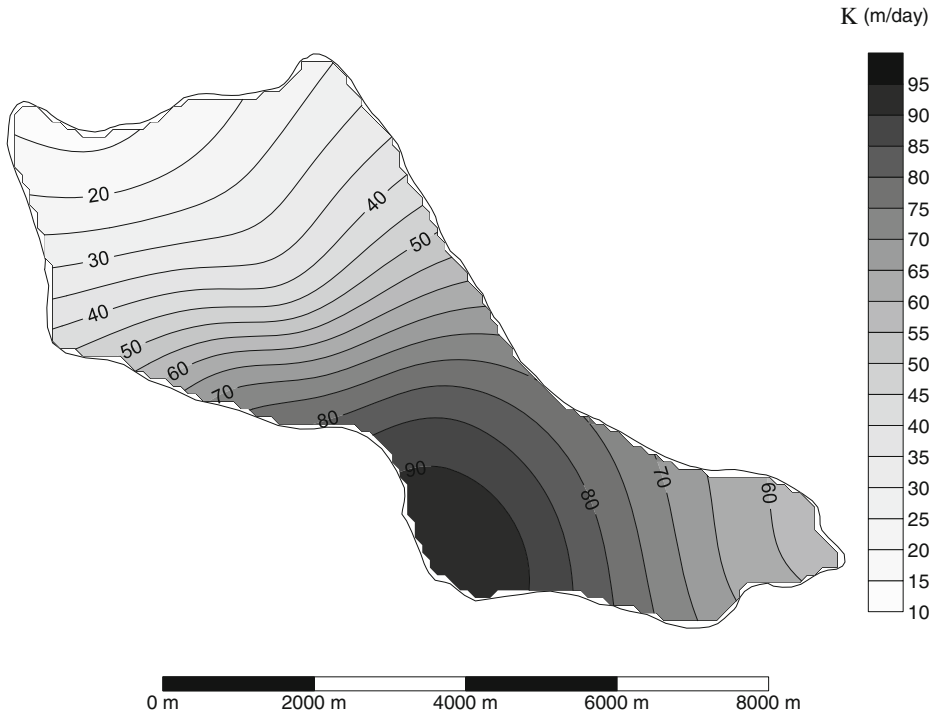
Site	Transmissivity (m <sup>2</sup> /day)	Storage coefficient	Aquifer thickness (m)	Hydraulic conductivity (m/day)
Site B	528.5	2.04 × 10 <sup>-4</sup>	47	11.25
Site C	1521.2	2.34 × 10 <sup>-4</sup>	44	34.57
Site H	833.8	1.43 × 10 <sup>-4</sup>	22	37.90
Site I	1071.4	9.30 × 10 <sup>-4</sup>	40	26.78
Site J	3212.0	–	40	80.30
Site K	2463.0	3.24 × 10 <sup>-4</sup>	28	87.96
Site O	3484.8	9.9 × 10 <sup>-4</sup>	36	96.80
Site S	3148.4	–	54	58.30
Site 42	2861.0	4.02 × 10 <sup>-4</sup>	48	59.60



**Fig. 11** a: Pumping test analysis at Site C by Aquifer-Test software. b: Pumping test analysis at Site I by Aquifer-Test software

north-west portion to 11 m in the south-east portion [Fig. (13a)], whereas in the wet season, the water level varies from 20 m in the north-west portion to 17 m in the south-east portion [Fig. (13b)]. It is apparent that there is a variation of 4 m of groundwater level across the basin during dry season and 3 m variation of groundwater level during wet season. Thus, a variation of 3 to 4 m in groundwater level over about 10 km distance shows a low hydraulic gradient in the study area.

Moreover, it can be seen from Fig. 13(a-b) that in the north-west portion of the study area, there is a 5 m temporal variation of groundwater level whereas in the south-east portion of the area, the temporal variation is 6 m. The higher temporal variation of groundwater level in the downstream side can be attributed to either better interaction of river with the aquifer and/or higher pumping rates in this region. In the dry season contour map, the flow vectors show groundwater flow from north-west to south-east direction. In the wet season also, the flow direction is mostly from north-west to south-east direction. As evident from the flow

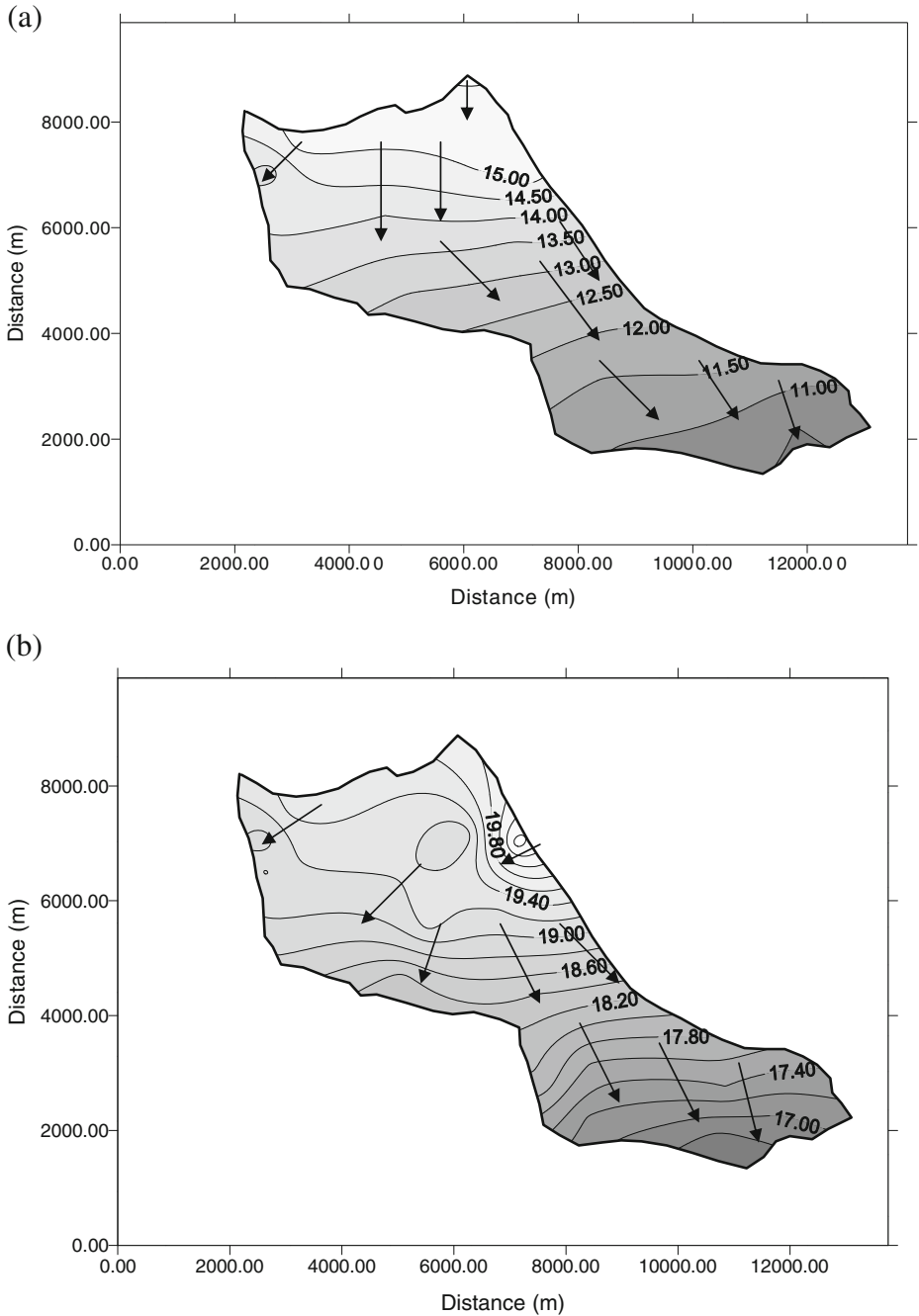


**Fig. 12** Hydraulic conductivity variation in the study area

vectors in the wet season, there is a flow from the Kathajodi River to the aquifer (i.e., losing river condition), but there is a flow of water from the aquifer to the Surua River in the form of baseflow (i.e., gaining river condition).

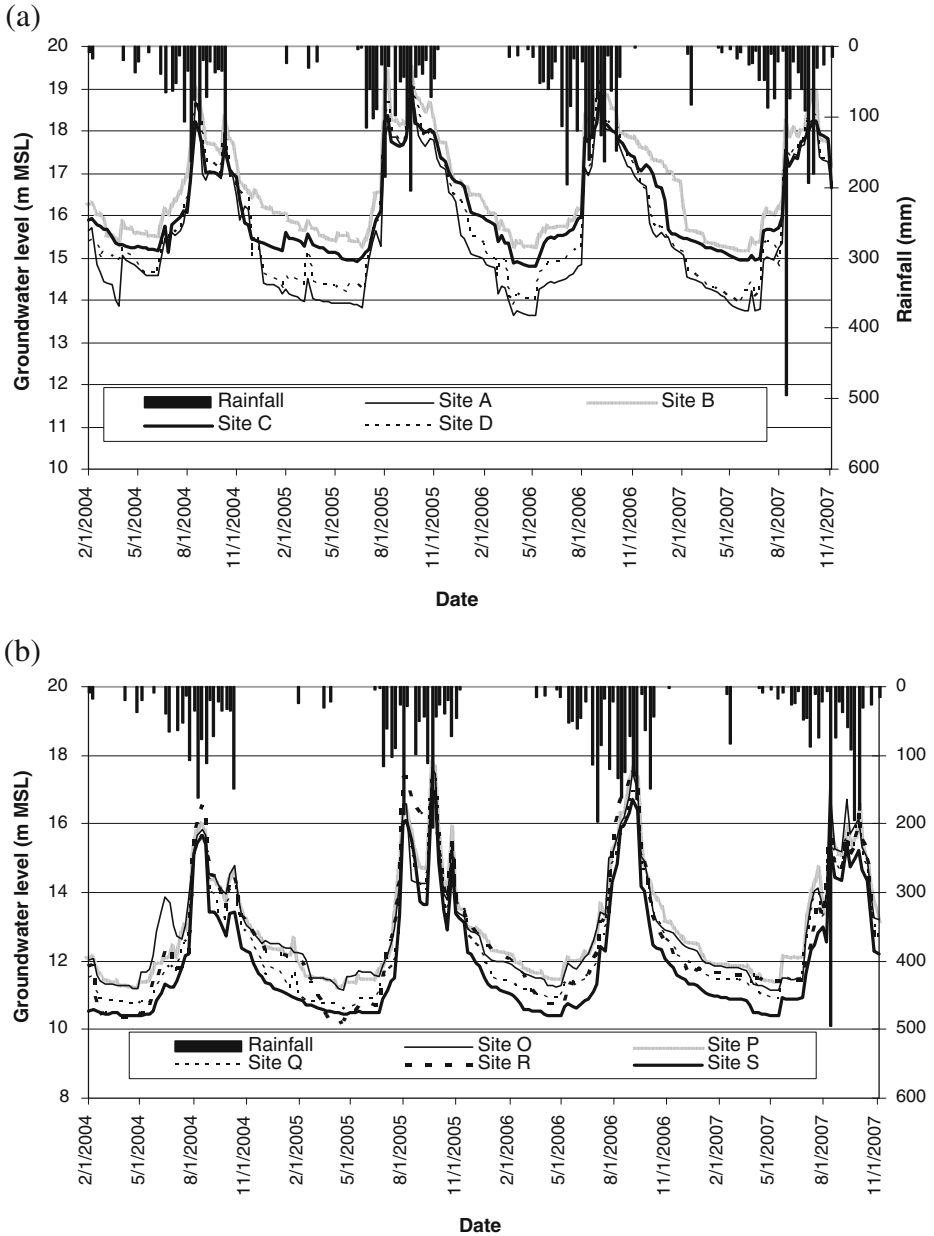
#### 4.9 Rainfall-Groundwater Dynamics

Weekly variation of groundwater levels at sites A to D and sites O to S during the period February 2004 to October 2007 are shown in Fig. 14(a) and (b), respectively along with the weekly rainfall values. It is observed that groundwater levels at all sites is generally higher in the rainy season (mainly July to September). Water level rises in the month of June (week no. 22 to 25) with onset of monsoon and reaches its peak during August to September (week no. 33 to 38). From October onwards it starts declining with minimum groundwater level in the months of April and May. The difference in minimum and maximum water level varies from 3 to 6.5 m. In the year 2005, there was a delay in monsoon and hence minimum water level was observed in the month of June instead of April/May. The higher groundwater level in the rainy season can be attributed to either direct recharge from rainfall or inflow from the river as the river water level is also maintained at a higher level during the rainy season. The influence of rainfall and river stage on groundwater is evident from the results of correlation analysis (Table 5). Clearly, the correlation between the rainfall and weekly groundwater level in the upstream portion of the study area is poor [correlation coefficient ( $r$ ) varies from 0.333 to 0.398] and it is fair (correlation coefficient varies from 0.562 to 0.659) in the downstream portion of the study area. It is apparent from Table 5 that the river stage has a greater influence on groundwater levels than the direct rainfall, which in turn suggests that the



**Fig. 13** a. Groundwater elevation contour map of the study area during dry period (19 June 2005). b. Groundwater elevation contour map of the study area during wet period (18 September 2005)

aquifer is not a perfectly confined aquifer, rather a semi-confined aquifer. It confirms the finding of lithologic investigation.



**Fig. 14** a. Weekly groundwater level fluctuations at sites A to D with bargraphs of rainfall. b. Weekly groundwater level fluctuations at sites O to S with bar graphs of rainfall

#### 4.10 Stream-Aquifer Interaction

The groundwater levels data at sites A to D and sites O to S have been plotted along with the river stage data at Naraj and are presented in Fig. 15(a) and (b), respectively. These figures show similarity in trends of groundwater levels at all the sites with the river stage at Naraj.



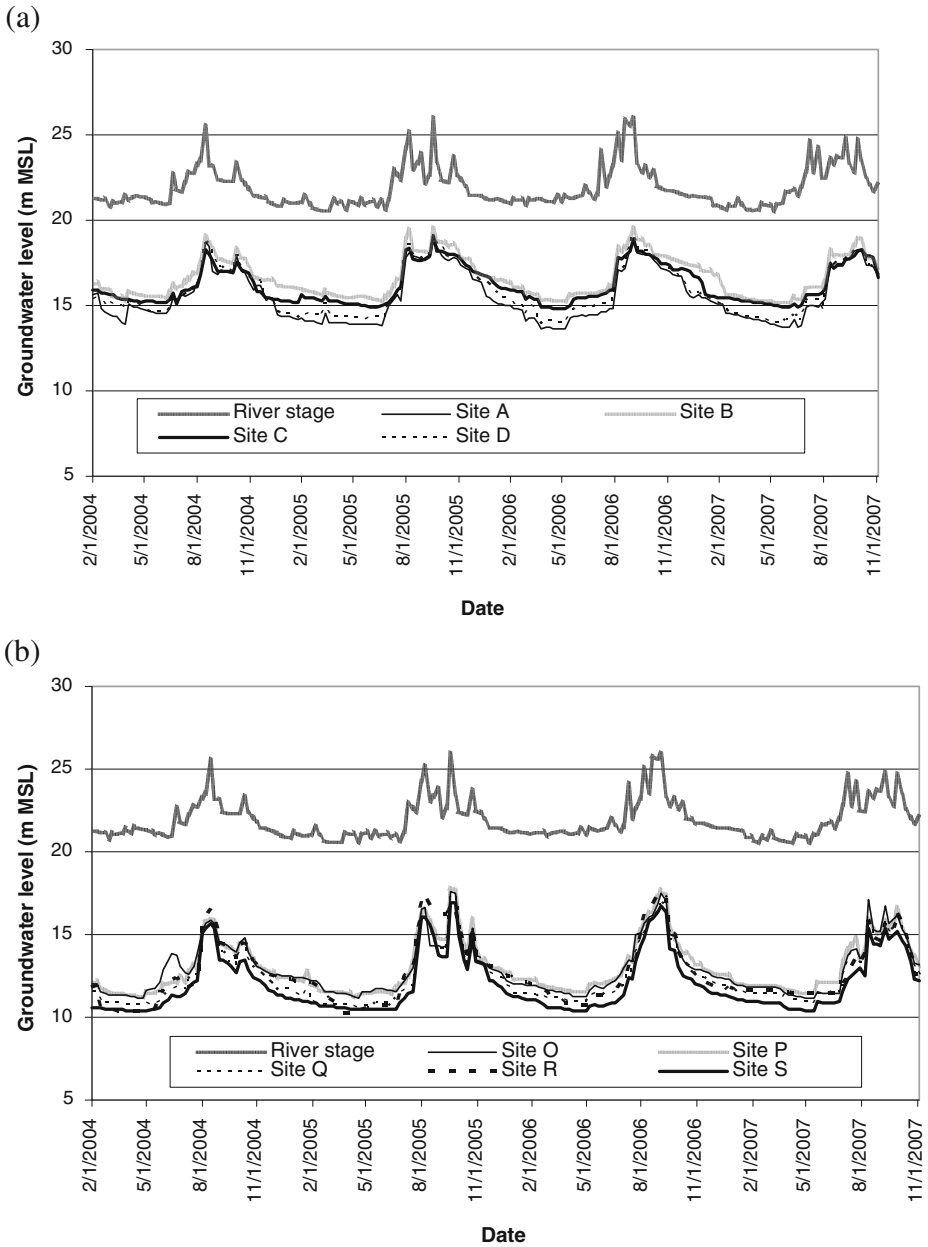
**Table 5** Correlation of weekly groundwater levels with weekly rainfall and river stage

Site	Correlation coefficient (r) for groundwater level vs. weekly rainfall	Remarks	Correlation coefficient (r) for groundwater level versus river stage	Remarks
Site A	0.3820	Poor	0.7284	Fair
Site B	0.3807	Poor	0.7294	Fair
Site C	0.3754	Poor	0.7200	Fair
Site D	0.3764	Poor	0.7367	Fair
Site E	0.3585	Poor	0.7031	Fair
Site F	0.3795	Poor	0.7216	Fair
Site G	0.5893	Fair	0.8861	Good
Site H	0.3800	Poor	0.7250	Fair
Site I	0.3981	Poor	0.7414	Fair
Site J	0.3333	Poor	0.6859	Fair
Site K	0.5779	Fair	0.8574	Good
Site L	0.5806	Fair	0.8668	Good
Site M	0.5851	Fair	0.8599	Good
Site N	0.6592	Fair	0.8119	Good
Site O	0.6272	Fair	0.8784	Good
Site P	0.5822	Fair	0.8906	Good
Site Q	0.5860	Fair	0.8874	Good
Site R	0.5622	Fair	0.8442	Good
Site S	0.5809	Fair	0.8795	Good

Poor:  $r < 0.50$ , Fair:  $r = 0.50 - 0.80$ , Good:  $r > 0.80$

The regression analysis between river stage and groundwater level (Table 5) shows that there is better correlation of river stage ( $r = 0.686$  to  $0.891$ ) with groundwater level than the weekly rainfall ( $r = 0.333$  to  $0.659$ ). Thus, the increase in groundwater level at all the sites in the monsoon season is more due to increase in river stage than rainfall and it can be inferred that there exists good stream-aquifer interaction in the Kathajodi-Surua Inter-basin. In the downstream portion of the study area, there is a better correlation between groundwater level and river stage ( $r = 0.812$  to  $0.891$ ) than the upstream portion ( $r = 0.686$  to  $0.741$ ), suggesting stronger stream-aquifer interaction in the downstream portion of the study area compared to the upstream portion. This finding is in agreement with relatively larger hydraulic conductivity in the downstream region of the study area as discussed earlier.

Moreover, Table 6 shows the correlation values of groundwater level with river stage at 1 to 10 days lag time period. There is a better correlation of groundwater level with river stage at downstream side of the basin than the upstream side at all the lag times. In the upstream side of the basin, best correlation is observed at 9-day lag time ( $r$  varied from  $0.733$  to  $0.769$ ). In the downstream side of the basin, even though best correlation is observed at 2-day lag time ( $r$  varied from  $0.855$  to  $0.894$ ), significantly good correlation between groundwater level and river stage is observed up to 9-day lag time. Thus, it can be inferred that there is a significant influence of river stage on groundwater levels up to 9-day lag time. This finding suggests that ensuring adequate streamflow during dry periods is necessary for enhanced and sustainable groundwater supply.



**Fig. 15** a. Well hydrographs at sites A to D with the river stage hydrograph at Naraj. b. Well hydrographs at sites O to S with the river stage hydrograph at Naraj

#### 4.11 Hydraulic Connectivity in the Study Area

The correlation matrix of the groundwater level data from 10 selected sites over the study area is shown in Table 7. It can be seen from this table that except the highlighted correlation

**Table 6** Correlation of groundwater levels with river stage at different lag times

Site Correlation coefficient (r) values for different lag times										
	1-day lag	2-day lag	3-day lag	4-day lag	5-day lag	6-day lag	7-day lag	8-day lag	9-day lag	10-day lag
A	0.7284	0.7299	0.7048	0.6920	0.7399	0.7215	0.7511	0.7649	0.7667	0.7412
B	0.7294	0.7350	0.7092	0.6919	0.7382	0.7238	0.7462	0.7535	0.7565	0.7293
C	0.7200	0.7234	0.6979	0.6838	0.7260	0.7108	0.7328	0.7444	0.7464	0.7162
D	0.7367	0.7401	0.7128	0.7006	0.7495	0.7298	0.7544	0.7666	0.7694	0.7438
E	0.7031	0.7074	0.6820	0.6682	0.7151	0.7015	0.7257	0.7379	0.7418	0.7169
F	0.7216	0.7252	0.6992	0.6844	0.7296	0.7146	0.7366	0.7488	0.7523	0.7244
G	0.8861	0.8835	0.8618	0.8549	0.8487	0.8463	0.8580	0.8470	0.8312	0.8065
H	0.7250	0.7303	0.7039	0.6966	0.7427	0.7249	0.7517	0.7643	0.7669	0.7401
I	0.7414	0.7444	0.7132	0.7009	0.7475	0.7357	0.7546	0.7657	0.7684	0.7391
J	0.6859	0.6883	0.6636	0.6568	0.7086	0.6924	0.7176	0.7330	0.7328	0.7080
K	0.8574	0.8674	0.8508	0.8395	0.8331	0.8298	0.8447	0.8419	0.8379	0.8125
L	0.8668	0.8742	0.8508	0.8382	0.8252	0.8288	0.8387	0.8308	0.8192	0.7927
M	0.8599	0.8730	0.8529	0.8379	0.8343	0.8300	0.8523	0.8508	0.8468	0.8222
N	0.8119	0.8703	0.7643	0.7256	0.8219	0.8049	0.8162	0.8122	0.7939	0.7646
O	0.8784	0.8893	0.8672	0.8489	0.8284	0.8310	0.8446	0.8385	0.8314	0.8042
P	0.8906	0.8940	0.8711	0.8637	0.8652	0.8621	0.8756	0.8701	0.8573	0.8296
Q	0.8874	0.8926	0.8691	0.8612	0.8611	0.8577	0.8720	0.8671	0.8552	0.8276
R	0.8442	0.8549	0.8332	0.8221	0.8209	0.8150	0.8341	0.8280	0.8243	0.8004
S	0.8795	0.8902	0.8674	0.8516	0.8514	0.8522	0.8718	0.8660	0.8601	0.8322

coefficient (r) values, all the other correlation coefficient values are quite high ( $r \geq 0.90$ ) and range from 0.942 (between Sites L and R) to 0.986 (between Sites P and S). This suggests that when both the wells are either in the upstream side of the basin or in the downstream side of the basin, then correlation of groundwater levels is better. But correlation of groundwater level between a well from the upstream side of the basin and other from the

**Table 7** Correlation matrix of groundwater levels for 10 observation wells

Values of correlation coefficient (r) for different pairs of observation wells										
Site →	A	C	F	H	J	L	M	P	R	S
A ↓	1									
C	0.9661	1								
F	0.9672	0.9788	1							
H	0.9738	0.9595	0.9719	1						
J	0.9707	0.9639	0.9753	0.9745	1					
L	0.8347	0.8289	0.8553	0.8577	0.8273	1				
M	0.8535	0.8470	0.8665	0.8686	0.8402	0.9476	1			
P	0.8564	0.8525	0.8712	0.8709	0.8489	0.9679	0.9699	1		
R	0.8506	0.8390	0.8646	0.8637	0.8523	0.9422	0.9722	0.9660	1	
S	0.8600	0.8357	0.8717	0.8711	0.8475	0.9610	0.9728	0.9861	0.9686	1

downstream side of the basin is relatively poor and ranges from 0.827 (between Sites J and L) to 0.872 (between Sites F and S). This indicates that there is a good hydraulic connectivity among the wells both in the upstream and downstream parts of the basin. However, the hydraulic connectivity between the upstream part of the basin and the downstream part is relatively poor. This could be attributed to the likely presence of a less permeable layer in between upstream and downstream ends of the basin.

#### 4.12 Groundwater Quality

The results of the detailed groundwater quality analysis at 8 sites are summarized in Table 8. The pH of the water samples ranges from 6.8 to 7.3 which are considered normal. The groundwater EC ranges from 0.16 to 0.26 dS/m. According to Palmar (1993), irrigation water is classified into four groups based on salinity: low salinity (<0.25 dS/m); medium salinity (0.25–0.75 dS/m); high salinity (0.75–2.25 dS/m); and very high salinity (>2.25 dS/m). Following this classification, the groundwater of Kathjodi-Surua Inter-basin can be characterized as of low salinity, and hence suitable for the irrigation purpose. The relative abundance of  $\text{Na}^+$  with respect to  $\text{Ca}^{++}$  plus  $\text{Mg}^{++}$ , influence the suitability of water for irrigation purpose and is represented by SAR value. According to Richards (1968), water with SAR values less than 10 can be used for irrigation on almost all types of soils. As the SAR values in the study area range from 0.09 to 0.39, they do not indicate any sodium hazards. The water samples had no carbonate, but contained bicarbonate varying from 0.2 to 0.6 me/L. Waters containing carbonate and bicarbonate ions in excess of  $\text{Ca}^{++}$  plus  $\text{Mg}^{++}$  often lead to much greater alkali formation than is indicated by their SAR values and this excess is denoted by RSC (Richards 1968). As RSC is non-existent in all the samples, the water is suitable for irrigation purpose.  $\text{Ca}^{++}$  and  $\text{Mg}^{++}$  do not behave equally in the soil system, and  $\text{Mg}^{++}$  deteriorates soil structures particularly when irrigation water is sodium dominated and highly saline.  $\text{Mg}^{++}/\text{Ca}^{++}$  ratio of the samples varies from 0.2 to 0.58, which is within the allowable safe limit of 1.5. The chloride content of the water samples ranges from 24.8 to 63.9 mg/L. As the chloride contents of all the water samples are less than 70 mg/L, they are generally safe for all the plants (Ayers and Westcot 1989). Moreover, the values of EC,  $\text{Cl}^-$ ,  $\text{Mg}^{++}$  and pH are within the permissible limits for potable water as prescribed by WHO (1971).

Since the above water quality assessment is based upon short-term and limited number of water quality parameters, there is a need to monitor water quality in the study area at least seasonally on a long-term basis considering adequate water quality parameters so as to have better understanding of groundwater chemistry and degree of pollution, if any. Such a

**Table 8** Groundwater quality in the study area during the pre-monsoon (*Rabi*) season

Site	pH	EC (dS/m)	$\text{Ca}^{++}$ (me/L)	$\text{Mg}^{++}$ (me/L)	$\text{Na}^+$ (me/L)	$\text{Cl}^-$ (mg/L)	$\text{HCO}_3^-$ (me/L)	SAR	Mg/Ca
Site A	6.99	0.20	1.2	0.7	0.2	35.5	0.3	0.31	0.58
Site B	7.10	0.19	1.4	0.5	0.2	32.0	0.2	0.21	0.36
Site G	6.85	0.22	1.2	0.7	0.1	35.5	0.2	0.10	0.58
Site I	6.80	0.26	1.6	0.9	0.3	42.6	0.3	0.27	0.56
Site N	7.30	0.17	1.0	0.2	0.3	42.6	0.6	0.39	0.20
Site O	6.99	0.20	2.0	0.4	0.1	63.9	0.2	0.09	0.20
Site Q	7.03	0.16	0.8	0.3	0.2	24.8	0.4	0.27	0.38
Site S	6.79	0.24	1.6	0.8	0.1	31.9	0.2	0.09	0.50

comprehensive and long-term water quality monitoring is of great importance for protecting vital groundwater resources from point and nonpoint sources of pollution.

## 5 Conclusions

In-depth hydrologic and hydrogeologic investigations were carried out in the Kathajodi-Surua Inter-basin of Orissa, eastern India for the efficient planning and management of water resources. Analysis of streamflow data indicated that maximum streamflow in the Kathajodi River is most likely during July to September, while the streamflow is significantly reduced during dry periods (February to May). The runoff estimates for the study area were found to range from 10.2% to 43.3% of the total monsoon rainfall, which indicated good potential for rainwater harvesting. The geologic investigation indicated that the study area is underlain by both shallow and deep confined or leaky confined aquifers of 20 to 55 m thickness. The aquifer comprises coarse sand, medium to coarse sand and pebbles, with coarse sand being dominant formation. Based on pumping tests, the aquifer hydraulic conductivity varies from 11.3 m/day to 96.8 m/day with a mean value of 46.1 m/day, which is characterized as 'high'. The storage coefficient of the aquifer system was found to range between  $1.43 \times 10^{-4}$  and  $9.9 \times 10^{-4}$ . These findings indicate significant aquifer heterogeneity in the study area.

Moreover, the groundwater level attains its peak during August-September, with April-May-June being the critical period. Overall groundwater flow is from north-west to south-east direction and there is a 5 to 6 m temporal variation and 3 to 4 m spatial variation of groundwater levels over the basin. The majority of the study area exhibits a strong river-aquifer interaction, and hence the river stage influences groundwater levels much more than direct rainfall. Also, there is a good hydraulic connectivity among the wells in the upstream and downstream regions of the basin, but the hydraulic connectivity was found to be relatively 'poor' in between the upstream and downstream regions. Although the quality of groundwater was found suitable for both irrigation and drinking purposes based on short-term data, a comprehensive and long-term water quality monitoring is recommended for protecting vital groundwater resources from point and nonpoint sources of pollution. Based on the results of this study, a simulation-cum-optimization modeling following an integrated water management approach is essential in the study area for sustainable utilization of water resources in general and groundwater resources in particular.

## References

- Al-Amoush H, Hammouri NA, Zunic F, Salameh E (2010) Intrinsic vulnerability assessment for the alluvial aquifer in the northern part of Jordan valley. *Water Resour Manag* 24(13):3461–3485
- APHA (1989) Standard methods for the examination of water and wastewater. American Public Health Association, Port City Press, Baltimore
- Ayers RS, Westcot DW (1989) Water quality for agriculture. FAO irrigation and drainage paper 29 (Rev. 1). Food and Agriculture Organization (FAO), Rome, p 174
- Gupta SK, Deshpande RD (2004) Water for India in 2050: first-order assessment of available options. *Curr Sci* 86(9):1216–1224
- Hilberg S, Schneider JF (2011) The aquifer characteristics of the dolomite formation a new approach for providing drinking water in the northern calcareous Alps region in Germany and Austria. *Water Resour Manag* 25(11):2705–2729
- Jha MK, Chikamori K, Kamii Y, Yamasaki Y (1999) Field investigations for sustainable groundwater utilization in Konan basin. *Water Resour Manag* 13:443–470
- Jha MK, Kamii Y, Chikamori K (2001) Irrigation and water management: an Indian perspective. *Rural Environ Eng* 40(2):46–66

- Palmar DB (1993) Irrigation. In: Ziparo VJ, Hasen H (eds) *Davis' handbook of applied hydraulics*. McGraw-Hill, New York, pp 24.1–24.36
- Panda DK, Mishra A, Jena SK, James BK, Kumar A (2007) The influence of drought and anthropogenic effects on groundwater levels in Orissa, India. *J Hydrol* 343:140–153
- Pati GC (2009) Groundwater resource scenario of Orissa. *Proceedings of the Workshop on Groundwater Scenario and Quality in Orissa, 6–7 March 2009, Bhubaneswar, Orissa, India*, pp. 1–8
- Rejani R, Jha MK, Panda SN, Mull R (2003) Hydrologic and hydrogeologic analysis in a coastal groundwater basin, Orissa. *Appl Eng Agric* 19:177–184
- Richards LA (1968) *Diagnosis and improvement of saline and alkali soils*. Handbook no. 60. US Salinity Laboratory Staff, USA, p 160
- Romani S (2006) Economic sustainability of groundwater resources: need for scientific management. Keynote address in the All India Seminar on Role of Groundwater in National Economy held on 18 January 2006 at Bangalore, India
- USDA Soil Conservation Service (1985) *National engineering handbook*. Section-4, Hydrology, Washington D.C
- Todd DK (1980) *Groundwater hydrology*. Wiley, New York, pp 64–110
- WHI (2002) *AquiferTest user's manual*. Waterloo Hydrogeologic Inc., Ontario, p 270
- WHO (1971) *International standards for drinking water*. World Health Organization, Geneva
- Yin D, Shu L, Chen X, Wang Z, Mohammed ME (2011) Assessment of sustainable yield of karst water of Huaibei, China. *Water Resour Manag* 28(1):287–300
- Yojana (2010) *Yojana: water resource management*. Yojana Bhavan, New Delhi, p 52