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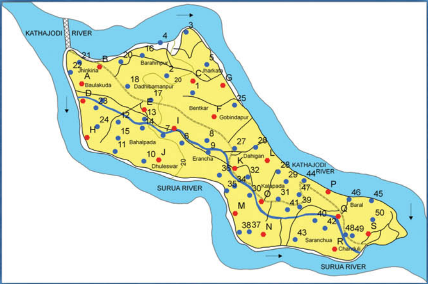

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PREFACE

Water is indispensable for virtually all human activities and for sustaining our ecosystem. Indeed water is the lifeline of the mankind. However, with increase in population and higher living standards, there will be ever increasing demand for good quality water. Almost 97% of the earth's water occurs as salt water in the oceans. About 2% of the water occurs as snow and ice in polar and mountainous regions leaving only 1% of the global water as liquid freshwater. Almost 98% of this liquid freshwater occurs as groundwater, and hence it is the most valuable freshwater resource of the earth.

However, overexploitation and continued mismanagement of groundwater resources to supply ever increasing demand of water has led to water shortages, increased pollution and degraded ecosystems worldwide. Hence the key concern is how to maintain a long term sustainable yield from the aquifer in the face of impending climate change and socio-economic factors. This requires groundwater assessment for development of a sustainable groundwater management plan in river basins. Development of an efficient groundwater management plan requires detailed hydrogeologic investigation in the study area which can help in vulnerability assessment of aquifer system or, assessment of sustainable yield of aquifer.

In the current study, in-depth hydrologic and hydrogeologic investigations were carried out in Kathajodi-Surua Inter-basin within Mahanadi Delta of Odisha to explore the possibility of enhanced and sustainable groundwater supply. The 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. We hope that the results of this study will be helpful for groundwater modeling of the deltaic groundwater system as well as for determining 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.

Authors

CONTENTS

1. INTRODUCTION

Groundwater is a very important and invaluable natural resource on the earth. Its unique qualities that it is easily accessible, generally free from pathogens and suspended particles, and requires no or little treatment has made it the most important and preferred source of water for domestic, agricultural and industrial uses. However, the over-exploitation and the growing pollution of groundwater are depleting the aquifers worldwide and threatening the sustainability of water supply and ecosystems on the earth (Shah *et al.,* 2000; Zektser, 2000; Sophocleous, 2005; Biswas *et al.,* 2009). Hence, the present challenge is how to maintain a long-term sustainable yield from aquifers (e.g., Hiscock *et al.,* 2002; Alley and Leake, 2004) in the face of looming climate change and socio-economic changes.

In India, the demand for water has already increased a multiple times over the years due to increasing population, growing urbanization, agriculture expansion, rapid industrialization and economic development and the water demand has an increasing trend in all the sectors (Kumar *et al.,* 2005; Mall *et al.,* 2006). Total water requirement in India for various activities around the year 2050 has been assessed as 1450 km^3/year (Gupta and Deshpande 2004). This is significantly more than the current estimate of utilizable water resource potential (1086 km^3/year) through conventional development strategies. Already there are several areas of the country that face water scarcity due to intensive groundwater exploitation (CGWB, 2006). 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. In recent studies, the analysis of GRACE satellite data revealed that the groundwater reserves in the states of Rajasthan, Punjab and Haryana are being depleted at a rate of 17.7 ± 4.5 km^3/yr (Rodell *et al.*, 2009). Thus, the depletion of groundwater resources has increased the cost of pumping, caused seawater intrusion in coastal areas and has raised questions about sustainability of groundwater supply and ecological security. Therefore, efficient and judicious utilization of surface and groundwater resources is very much essential to protect vital groundwater resources as part of sustainable land and water management strategies.

The state of Odisha in eastern India is no exception and it 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. Because of uneven nature of rainfall and its capricious distribution, there is an increasing dependence on groundwater resources for meeting the growing water demand of agriculture, industrial and domestic sectors. About 3 million people in the western part of Odisha are facing acute drinking water crisis due to large-scale deforestation, unplanned irrigation and poor management of natural resources. Moreover, the overexploitation of groundwater has resulted in declining groundwater levels in several areas and seawater intrusion in coastal areas (CGWB, 2006). More than 80% of the geographical area of Odisha is underlain by hard rocks and the remaining area by semi-consolidated and unconsolidated subsurface formations. In hard-rock terrains, groundwater is mainly confined to weathered residuum and fractured zones, with limited to moderate groundwater potential. Even though sufficient water is available in coastal areas in the monsoon season, there is a water shortage for irrigation in the post-monsoon season. Therefore, there is a need to develop optimal groundwater management strategies to increase area under post-monsoon season crops and thereby sustain agricultural productivity and livelihoods.

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. Considering the growing water problem in Odisha, the Kathajodi-Surua Inter-basin within the Mahanadi deltaic system of Odisha 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

Kathajodi-Surua Inter-basin which is locally known as Bayalish Mouza, is located in the Cuttack district of Odisha, Eastern India. The basin is a part of the Mahanadi Delta which is located around the confluence of the Mahanadi River with the Bay of Bengal along the eastern coast of India (Fig. 1). The apex of the Mahanadi delta lies at Naraj where Mahanadi River divides into two major branches: Mahanadi to the north and Kathajodi to the south. The Kathajodi River, after the branching out of Kuakhai River, is further divided into two branches, namely Kathajodi to the north and Surua to the south. Both the branches of the Kathajodi River later rejoin and is named as the Debi River afterwards. Bayalish Mouza is the entrapped land mass of about 35 km^2 area surrounded on both sides by the Kathajodi River and its branch Surua.

Agriculture is the major occupation of the inhabitants. Total cultivated area in the study area is 2445 ha, of which 1365 ha is irrigated land. The area under low land is 408 ha, medium land 1081 ha and high land is 956 ha. Paddy is the major crop in the monsoon season, whereas crops like vegetables, potato, groundnut, greengram, blackgram and horsegram are grown in the post-monsoon season. Owing to the lack of irrigation infrastructure for surface water, all the irrigated lands are irrigated by groundwater. At present there are 69 functioning government tubewells in the study area, which are the major sources of groundwater withdrawal. These tubewells were earlier constructed and managed by Orissa Lift Irrigation Corporation (OLIC), Cuttack, Orissa, but now they have been handed over to the water users' associations (WUAs). Although there is no water shortage during the monsoon season (June to October), in the summer season (March to May), the farm ponds dry up and the groundwater supply is not sufficient to meet the entire water demand of the farmers.

During the monsoon season, a problem of waterlogging is encountered in the study area. 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 the main drain and discharged at a single outlet into the river. A sluice gate is provided at the outlet of the area to prevent entry of river water during flood events. During this time period, waterlogging problem is encountered in the downstream side of the study area.

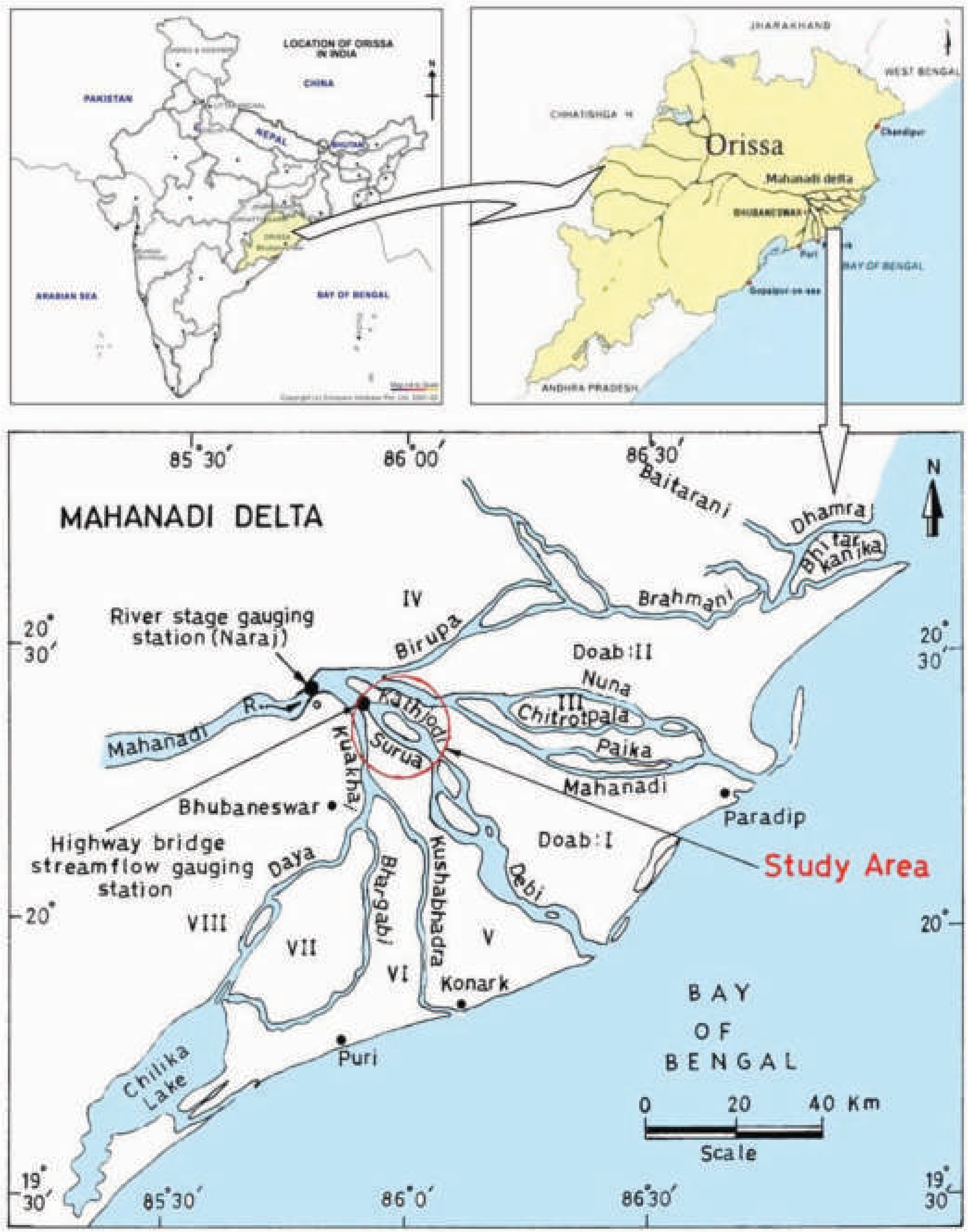


Fig. 1: Location Map of the Kathajodi-Surua Inter-Basin

2.1 Groundwater 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 nineteen monitoring wells are shown as red circles (A to S) in Fig. 2. Groundwater levels were monitored in the 19 tubewells on a weekly basis from February 2004 to October 2007. The geographic locations of the tubewells in the study area were found with the help of a global positioning system (GPS) and the elevations of the tubewell sites were determined by leveling survey.

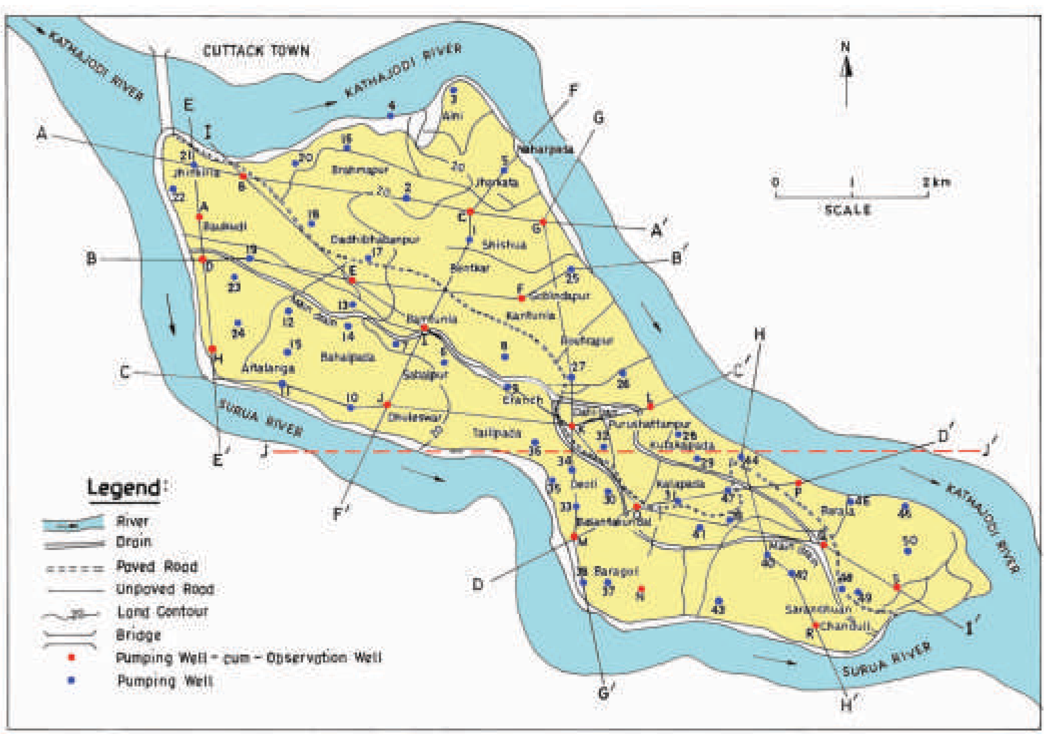


Fig. 2: Base Map of the Study Area Showing Drainage Network and Location of Tubewells

3. HYDROLOGIC ANALYSIS

3.1 Rainfall characteristics

Analysis of 20 years (1990-2009) of rainfall data in the study area indicated that the average annual rainfall is 1649.8 mm with a standard deviation of 375.9 mm. The variation of mean monthly rainfall over the 20-year period along with standard deviation bars is shown in Fig. 3. It is apparent from this figure that the highest mean monthly rainfall (402.8 mm) with a standard deviation of 193.6 mm is observed in the month of August. 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 a 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 them to short periods of a year. As sufficient rainfall is available during July, August and September, groundwater withdrawal is minimum during these months. Relatively large standard deviations in the months of May, June, July, August, September and October indicate that the magnitude of monthly rainfall varies appreciably from year to year.

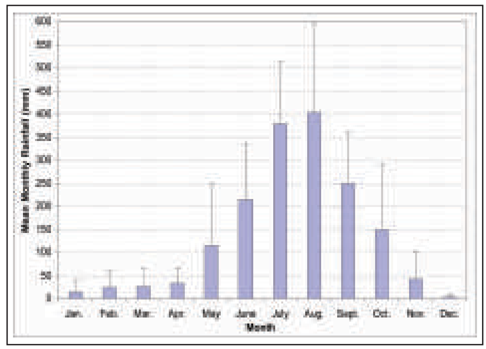


Fig. 3: Variation of Mean Monthly Rainfall in the Study Area

Moreover, Fig. 4 shows the variation of annual rainfall over the basin along with the 20-year mean annual rainfall and 75% of mean annual rainfall lines. It is obvious from this figure that years 1990, 1993, 1995, 1997, 1999, 2001, 2003, 2005, 2006, 2007 and 2008 have received more than the mean annual rainfall and rest of the years have received less than the mean annual rainfall. 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 this criteria, the years1996, 2000 and 2002 can be

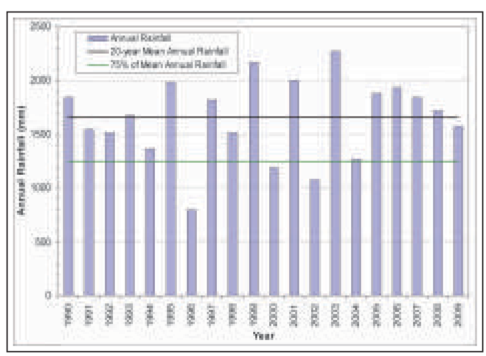


Fig. 4: Variation of Annual Rainfall during the 1990-2009 Period

characterized as drought years, with the year 1996 being the most severe drought year wherein only an annual rainfall of 797 mm was received (Fig. 4). The probability analysis of the monthly rainfall data indicated that Two-Parameter Log Normal distribution was found to be best fit to the rainfall data of January, February, March and December; Pearson Type III distribution for April and November; Log Pearson Type III distribution for May, June, August and October; Gumbel Type 1 Extremal distribution for the month of July and Normal distribution for the month of September. Using the best-fit probability distribution functions for different months, the probabilities of monthly rainfalls at 20%, 50% and 80% exceedence of rainfall were found out which are represented as monthly rainfall under wet, normal and dry scenarios, respectively. Fig. 5 shows the temporal variation of monthly rainfall during wet, normal and dry scenarios which indicates considerable variation in the amount of monthly rainfall during wet and dry scenarios.

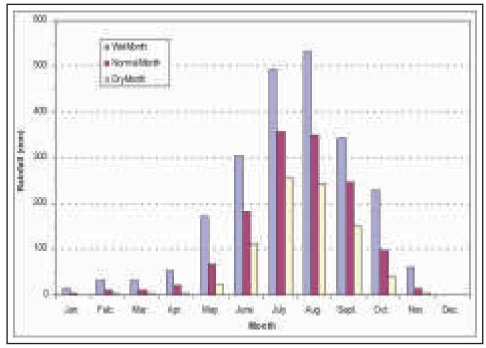


Fig. 5: Monthly Variation of Rainfall during Wet, Normal and Dry Scenarios

3.2 Streamflow characteristics

The daily variation of streamflow in the Kathajodi River for six years (2001-2006) at the highway bridge gauging station is shown in Fig. 6. 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 m^3/s) from December onwards when rainfall events are very less. The streamflow reduces further and varies from 10 to 20 m^3/s during February to May. The streamflow varies appreciably over the six year period, with the minimum streamflow (mean flow = 283 m^3/s) in 2002, which was a meteorological drought year (Fig. 2). In 2002, 2004 and 2005, the mean streamflow was lower than the 6-year average streamflow, whereas it was higher in the remaining years.

The streamflow data of the Kathajodi River 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 daily streamflow data of a given year 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. Table 1 summarizes the flow characteristics for the 6 year period. Lowest maximum streamflow (7557 m^3/s) is observed in 2002, which is significantly less than the six-year mean. Maximum streamflow is observed in 2001 (18380 m^3/s) followed by 2003 (16530 m^3/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 three years (2001, 2002 and 2004), while it is quite low in the remaining three years. This suggests the unavailability of surface water resources in the study area for a considerable time period. Zero streamflow is also detrimental to the river ecosystem. Therefore, a comprehensive investigation is necessary in this direction to find out a suitable low flow in the river during dry seasons in order to protect river ecosystems.

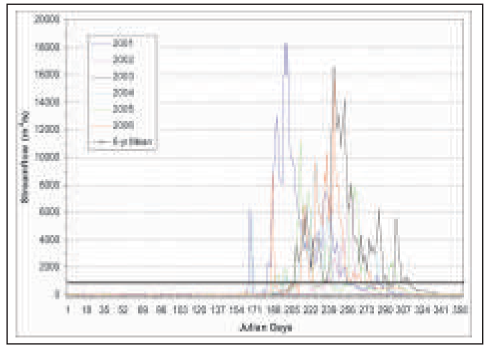


Fig. 6: Annual Discharge Hydrograph of the Kathajodi River at Highway Bridge Gauging Station for the 2001-2006 Period

Table 1: Streamflow Characteristics of the Kathajodi River for 2001-2006 Period

Flow	Streamflow (m^3/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

3.3 Land use/land cover variation

Land use/land cover map of the study area for the wet (*Kharif*) and dry (*Rabi*) seasons were generated using remote sensing imagery. One pre-monsoon IRS P6 MX image (path-101, row-095, LISS-4, and date of pass = 20.03.2004) and another post-monsoon IRS P6 MX image (path-102, row-073, LISS-4, and date of pass = 20.11.2004) of the study area were procured from National Remote Sensing Agency (NRSA), Hyderabad, Andhra Pradesh, India. Both the images were rectified and geometrically corrected with respect to the Survey of India toposheets of the study area namely 73 h/15 and 73 l/3 using ERDAS IMAGINE 8.7 software. The classification of the FCC map of the study area was accomplished by supervised classification method. A number of field visits were made to verify the accuracy of land use classifications obtained from satellite imagery. The, image of 20th March 2004 was used for generation of land use/land cover map of the dry season (*Rabi* season) whereas, the image of 20th November 2004 was used for the land use/land cover map of the wet season (*Kharif* season).

Based on the remote sensing image analysis, land use of the study area was classified into 7 categories, namely settlement, orchard/plantations, water body, wetland, fallow land, paddy area and vegetables/pulses/oilseed area. The land use/land cover maps of the wet season (*Kharif* season) and the dry season (*Rabi* season) are shown in Figs. 7 and 8, respectively. The areas under different land uses/land covers in both the seasons are summarized in Table 2. About 816.42 ha of the study area are 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 *Kharif* season covering an area of 1140.57 ha. In the *Rabi* 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 (1307.04 ha) remains fallow during the *Rabi* season as compared to the *Kharif* season (945.25 ha), which necessitates efficient irrigation water management in the study area.

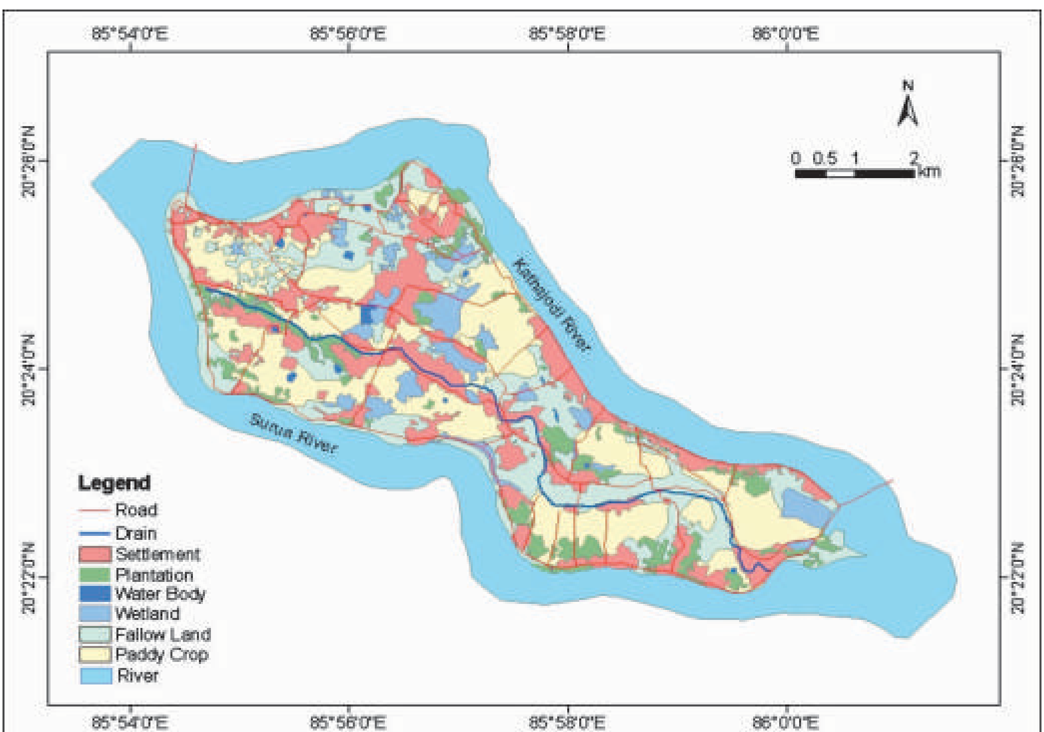


Fig. 7: Land Use/Land Cover Map of Kathajodi-Surua Inter-basin in the *Kharif* Season

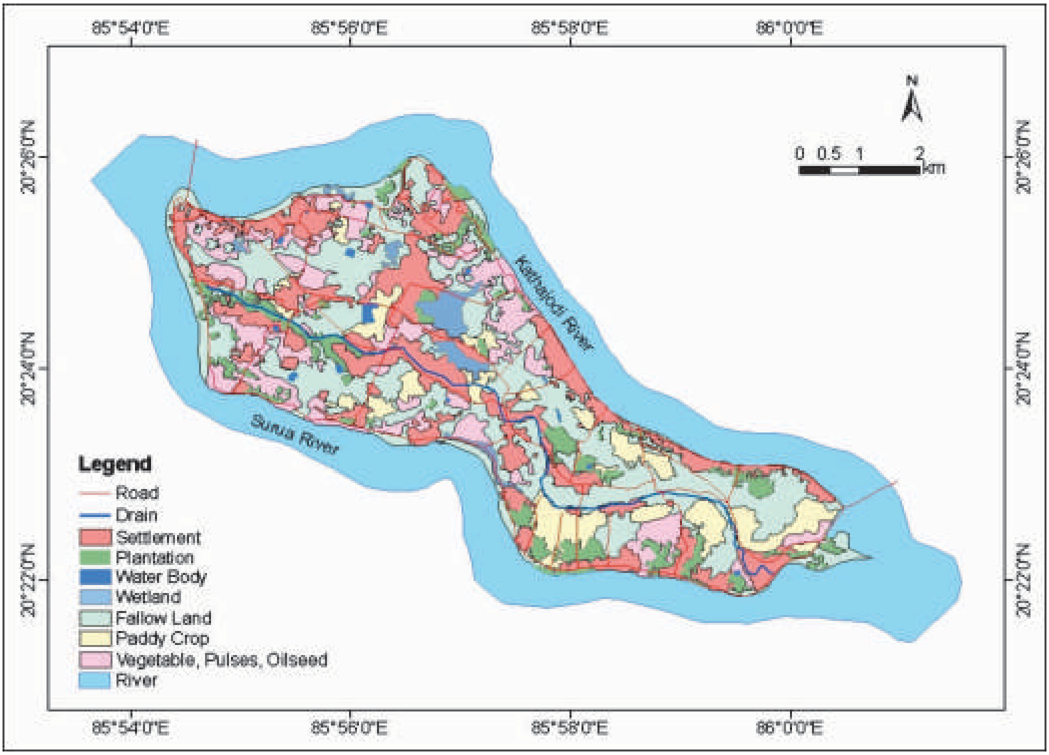


Fig. 8: Land Use/Land Cover Map of Kathajodi-Surua Inter-basin in the *Rabi* Season

Table 2 Land Use/Land Cover in the Study Area during *Kharif* and *Rabi* Seasons

Sl. No.	Land Use	Area (ha)	
		***Kharif* Season**	***Rabi* 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	260.48	98.55
5	Fallow Land	945.25	1307.04
6	Paddy Cultivated Land	1140.57	377.42
7	Land under Vegetables, Pulses or Oilseed in *Rabi* Season	-	563.32
	Total	3502.14	3502.17

3.4 Soil map

The soil map of the study area was prepared in GIS environment with reference to the soil map of the region prepared by Orissa Space Application Centre (ORSAC), Bhubaneswar, India. The soil map was rectified and geometrically corrected as explained above in case of land use/land cover map. The different soil polygons representing different soil taxonomy were delineated using ArcGIS software. The soil map shows that the study area comprises three major soil types, namely (i) Fine loamy, Udic Ustochrepts, (ii) Coarse loamy, Typic Udipsamments and (iii) Fine, Typic Endoaquepts with a majority of the area belonging to type 1 category (Fig. 9).

The soil groups were characterized in different hydrologic soil groups for development of hydrologic soil cover complex of the study area. Based on the characteristics of the soil types present 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 Udipsamments was grouped under hydrologic soil group B (moderately low runoff potential) according to the guidelines of USDA Soil Conservation Service (SCS, 1985).

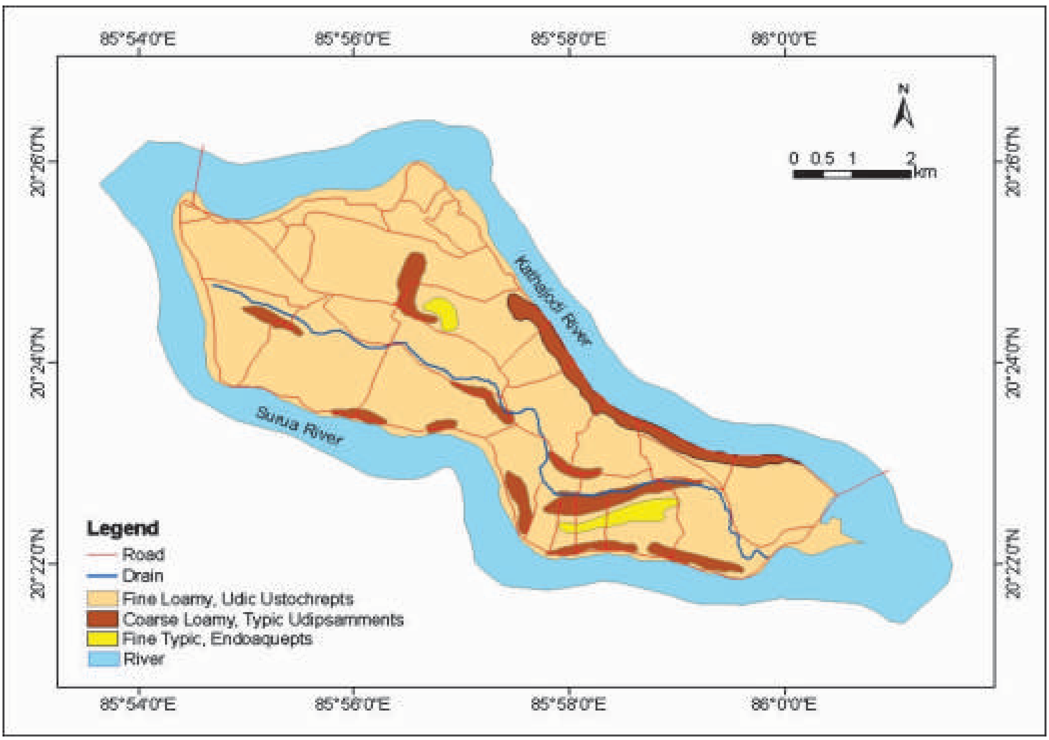


Fig. 9: Soil Map of the Study Area

3.5 Runoff potential in the study area

The curve number technique (SCS, 1985) was used for runoff estimation in the study area. According to characteristics of the soil types in the study area, soils were classified into different hydrologic soil groups. The land use/land cover coverage of the wet season and the soil coverage were merged using ArcGIS software to delineate the curve number coverage of the study area (Subramanya, 2008). All the polygons having a particular land use and a hydrologic soil group were selected and then curve numbers for Antecedent Moisture Condition (AMC) II condition were assigned to these polygons with the help of standard table (SCS, 1985). AMC conditions were determined based on the cumulative previous 5 days rainfall for a particular rainfall event and using standard guidelines. Based on the AMC conditions, i.e., AMC I, AMC II or AMC III, curve numbers were assigned to the polygons using the AMC conversion table (Subramanya, 2008). Composite curve number method was used for runoff estimation.

The curve number (AMC II) map obtained by overlaying the land use map of the wet season and the soil map of the study area in GIS environment is shown in Fig. 10. The areas under different curve numbers are shown in Table 3. It is evident from this table that a majority of the study area (1081.20 ha) falls under paddy on hydrologic soil group C, i.e., curve number equal to 82, while only 41.72 ha falls under orchard/plantation crops in hydrologic soil group B, i.e., curve number 55.

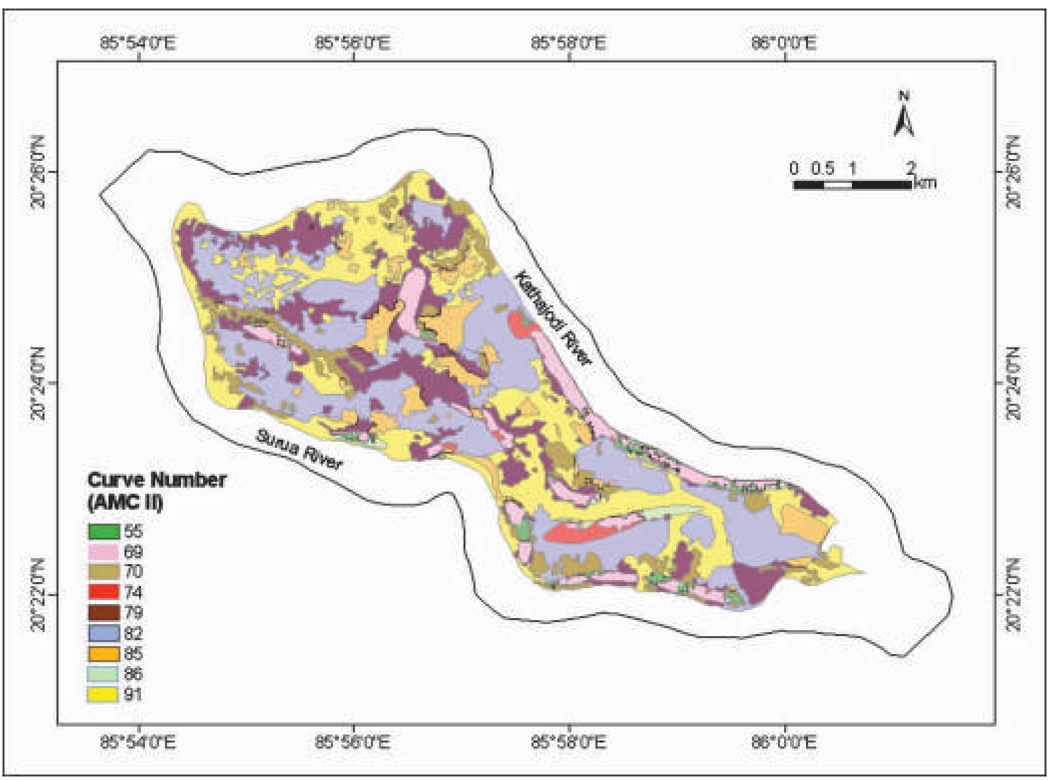


Fig. 10: Spatial Distribution of Curve Number over Kathajodi-Surua Inter-basin

The estimated runoff obtained by composite curve number method along with the total monsoon rainfall for the 1990-2009 period is shown in Fig. 11. The estimated runoffs for the twenty years period (1990-2009) vary 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 varies from a minimum of 10.19% in the year 1995 to a maximum of 43.3% in the year 2003. Incidentally, more of high rainfall events occurred in the years 1993, 1997, 1999, 2001, 2003, 2006 and 2007, and hence more runoffs were generated in these years. 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.

Table 3 Curve Number Distribution (AMC II) in the Study Area during Wet 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/Wetland	85	281.60	8.04
	Total	3502.29	100.00

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). These water harvesting structures will ensure increased and dependable water supply for monsoon and post-monsoon crops as well as will facilitate augmentation of groundwater resources in the study area.

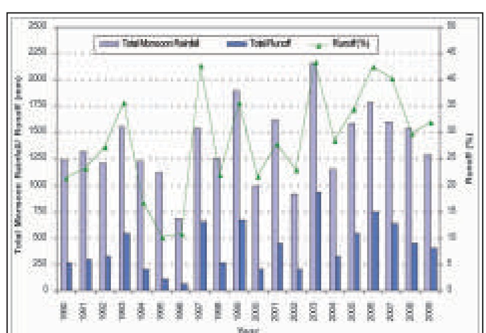


Fig. 11: Total Monsoon Rainfall, Runoff and Percent Runoff during 1990-2009

3.6 Groundwater recharge

The recharge from rainfall in the study area was estimated using the rainfall-recharge relationship in alluvial geological provinces of India, which is given as (Rangarajan and Athavale, 2000):

$$R = 0.147(P) - 6 \quad \ldots (1)$$

Where, P = annual rainfall (mm) and R = annual recharge from rainfall (mm). The formula gives the total annual recharge from rainfall. The monthly recharge from rainfall was estimated by dividing the total annual recharge from rainfall into different monsoon months in proportion to the monthly rainfall.

The total groundwater recharge was estimated by adding the recharge from different sources such as rainfall, return flow from irrigation and water bodies. The recharge from the return flow from irrigation was estimated according to the guidelines of Central Ground Water Board, New Delhi, India (CGWB, 1997). Further, the recharge from water bodies was considered as 1.4 mm/day for the period during which water is present in the water bodies (CGWB, 1997).

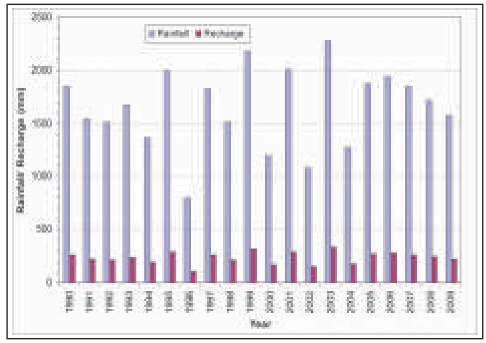


Fig. 12: Total Rainfall and Recharge from Rainfall during 1990-2009

Fig. 12 shows the variation of recharge from rainfall along with the total rainfall during 1990-2009 period. Recharge from rainfall varies from a minimum of 111.2 mm in the year 1996 to a maximum of 328 mm in the year 2003. The recharge as percentage of total rainfall is about 14%, with negligible variation from year to year. Table 4 shows the monthly total groundwater recharge during 2004-2007, which reveals that the recharge is mostly concentrated during monsoon months (June to October). Total groundwater recharge in the years 2004 to 2007 varied from about 288 mm in the year 2004 to 385 mm in the year 2006.

Table 4 Estimated Monthly Groundwater Recharge in the Period 2004-2007

Month	Total Recharge (mm)			
	2004	2005	2006	2007
January	10.4	10.4	10.4	10.4
February	12.5	12.5	12.5	12.5
March	15.6	15.6	15.6	15.6
April	16.9	16.9	16.9	16.9
May	12.5	26.6	12.5	12.5
June	21.4	27.5	29.0	35.2
July	58.1	88.9	57.8	37.5
August	55.6	43.6	156.2	109.5
September	30.0	67.4	52.0	92.3

Month	Total Recharge (mm)			
	2004	2005	2006	2007
October	42.0	50.1	9.8	16.7
November	5.0	9.9	5.0	5.0
December	8.0	8.0	8.0	8.0
Total	**288.1**	**377.4**	**385.7**	**372.1**

3.7 Crop water requirement

The irrigation requirement of the crops in the study area is mostly in the post-monsoon (*Rabi*) season. Paddy, sugarcane, potato, onion, groundnut, vegetables, greengram, blackgram, horsegram and mustard are major crops in the study area during this season. The Department of Agriculture, Government of Orissa has fixed target areas of coverage under these *Rabi* crops, which are summarized in Table 5.

Table 5 Targeted Area of Coverage under Different Post-monsoon Crops

Sl. No.	Crop	Area (ha)
1	Paddy	710
2	Sugarcane	130
3	Potato	200
4	Onion	20
5	Groundnut	82
6	Winter Vegetables	400
8	Summer vegetables	165
8	Greengram	210
9	Blackgram	320
10	Horsegram	150
11	Mustard	36

The water requirements of these crops were computed by the pan evaporation method. The effective rainfall was estimated by the USDA-SCS method (Doorenbos and Pruit, 1977). The total crop water requirements in the months of November, December, January, February, March, April and May were computed as 4.76×10^5, 9.01×10^5, 26.47×10^5, 22.65×10^5, 24.69×10^5, 22.16×10^5 and 8.13×10^5 m^3, respectively. Similarly, the total water requirements for the *rabi* paddy, sugarcane, potato, onion, groundnut, winter vegetables, summer vegetables, greengram, blackgram, horsegram and mustard were computed as 73.85×10^5, 7.47×10^5, 5.78×10^5, 0.59×10^5, 2.21×10^5, 10.65×10^5, 5.03×10^5, 3.27×10^5, 5.24×10^5, 3.0×10^5 and 0.8×10^5 m^3, respectively.

The net irrigation requirements of different crops for the wet, normal and dry scenarios are shown in Table 6(a to c), respectively. The net irrigation requirements of paddy in the wet, normal and dry scenarios are 875.2, 938.2 and 999.2 mm, respectively. It is apparent from Tables 6(a,b) that the values of the difference between the net irrigation requirement in the wet scenario and that in the normal scenario in the months of November and May is more (28 and 62 mm respectively) because effective rainfall in the wet scenario is more in these two months. Similarly, the difference between the net irrigation requirements in the wet scenario and that in the normal scenario is low (3 mm) in the month of December because the effective rainfall in the wet scenario is quite low in this month. Interestingly, the net irrigation requirement in December during normal scenario is the same as that during dry scenario [Tables 6(b,c)], which is due to the fact that the effective rainfall in the normal scenario is zero in December.

Table 6(a): Net Irrigation Requirements of the Crops in the Wet Scenario

Crop	Net Irrigation Requirement (mm)							
	November	December	January	February	March	April	May	Total
Paddy	-	22.0	231.4	181.9	223.5	216.4	0	875.2
Sugarcane	26.5	0	15.4	37.1	64.8	109.6	54.9	308.3
Potato	-	33.7	45.1	64.2	75.9	-	-	218.9
Onion	-	48.4	48.7	56.5	70.4	-	-	224.0
Groundnut	-	26.4	41.6	64.2	67.0	-	-	199.2
Winter Vegetables	11.5	58.0	60.7	54.1	-	-	-	184.3
Summer Vegetables	-	-	-	-	33.9	75.9	8.1	117.9
Greengram	0	58.0	51.5	-	-	-	-	109.5
Blackgram	0	66.8	48.0	-	-	-	-	114.8
Horsegram	-	-	18.2	48.7	65.9	-	-	132.8
Mustard	0	52.1	68.5	33.2	-	-	-	153.8

Table 6(b) Net Irrigation Requirements of the Crops in the Normal Scenario

Crop	Net Irrigation Requirement (mm)							
	November	December	January	February	March	April	May	Total
Paddy	-	25.0	239.4	195.9	240.5	237.4	0	938.2
Sugarcane	54.5	0	23.4	51.1	81.8	130.6	116.9	458.3
Potato	-	36.7	53.1	78.2	92.9	-	-	260.9
Onion	-	51.4	56.7	70.5	87.4	-	-	266.0
Groundnut	-	29.4	49.6	78.2	84.0	-	-	241.2
Winter Vegetables	39.5	61.0	68.7	68.1	-	-	-	237.3
Summer Vegetables	-	-	-	-	50.9	96.9	70.1	217.9
Greengram	17.0	61.0	59.5	-	-	-	-	137.5
Blackgram	20.0	69.8	56.0	-	-	-	-	145.8
Horsegram	-	-	26.2	62.7	82.9	-	-	171.8
Mustard	13.2	55.1	76.5	47.2	-	-	-	192.0

Table 6(c) Net Irrigation Requirements of the Crops in the Dry Scenario

Crop	Net Irrigation Requirement (mm)							
	November	December	January	February	March	April	May	Total
Paddy	-	25.0	242.4	201.9	247.5	252.4	30.0	999.2
Sugarcane	63.5	0	26.4	57.1	88.8	145.6	147.9	529.3
Potato	-	36.7	56.1	84.2	99.9	-	-	276.9
Onion	-	51.4	59.7	76.5	94.4	-	-	282.0
Groundnut	-	29.4	52.6	84.2	91.0	-	-	257.2
Winter Vegetables	48.5	61.0	71.7	74.1	-	-	-	255.3
Summer Vegetables	-	-	-	-	57.9	111.9	101.1	270.9
Greengram	26.0	61.0	62.5	-	-	-	-	149.5
Blackgram	29.0	69.8	59.0	-	-	-	-	157.8
Horsegram	-	-	29.2	68.7	89.9	-	-	187.8
Mustard	22.2	55.1	79.5	53.2	-	-	-	210.0

4. HYDROGEOLOGIC ANALYSIS

4.1 Basin geology

The lithologic data offer unique opportunities to gather information about type, depth and areal extent of subsurface formations (aquifer and confining layers) and groundwater condition in a basin. These information are of immense importance for the design and analysis of pumping tests as well as for the numerical modeling of groundwater systems (Anderson and Woessner, 1992; Fetter, 2000). Using the lithologic data, geologic profiles along four west-east sections (Sections A-A', B-B', C-C' and D-D'), four north-south sections (Sections E-E', F-F', G-G' and H-H') and one central section (Section I-I') as shown in Fig. 2 were prepared. Thereafter, stratigraphic analysis was performed to characterize aquifers and confining layers present in the study area.

The analysis of lithologic data along the four west-east, four north-south and one central cross-sections of the study area [Fig. 13(a to i)] indicated that a confined or leaky confined aquifer exists in the study area, which contributes a major source of groundwater. This aquifer consists of coarse sand, medium to coarse sand and coarse sand with gravel; the coarse sand being the dominant formation. The thickness of the aquifer varies from 20 to 55 m over the basin. The top confining layer comprises clay or sandy clay with isolated patches of coarse sand or medium sand, whereas the bottom confining layer consists of clay. Wherever the confining layer consists of sandy

(a)

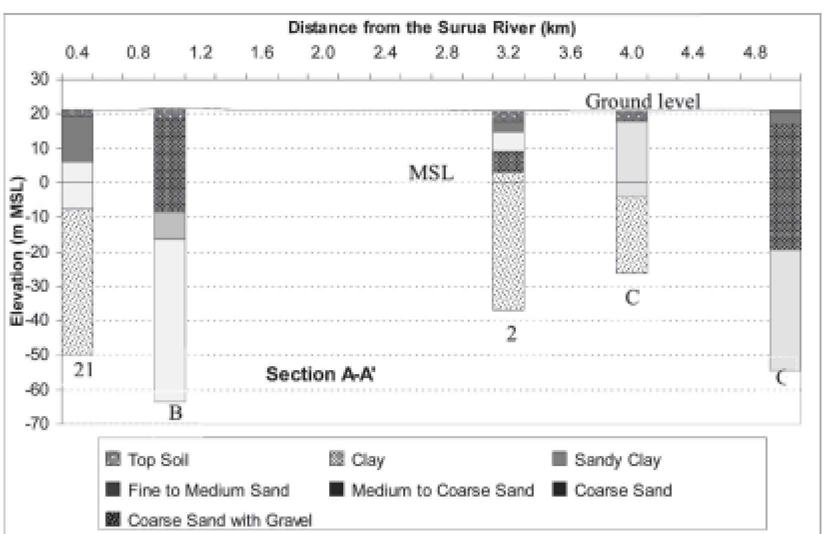
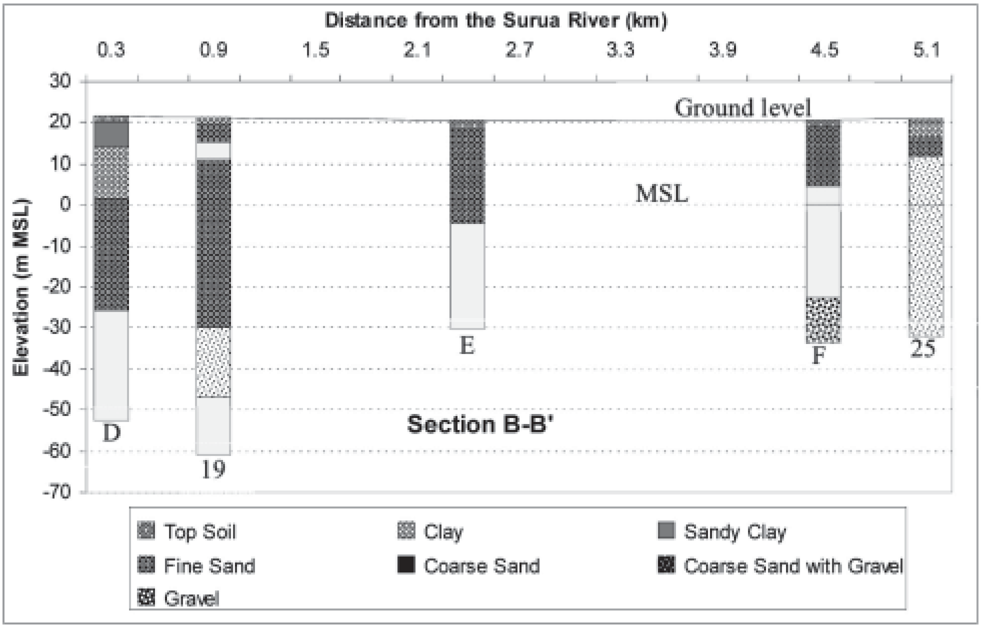


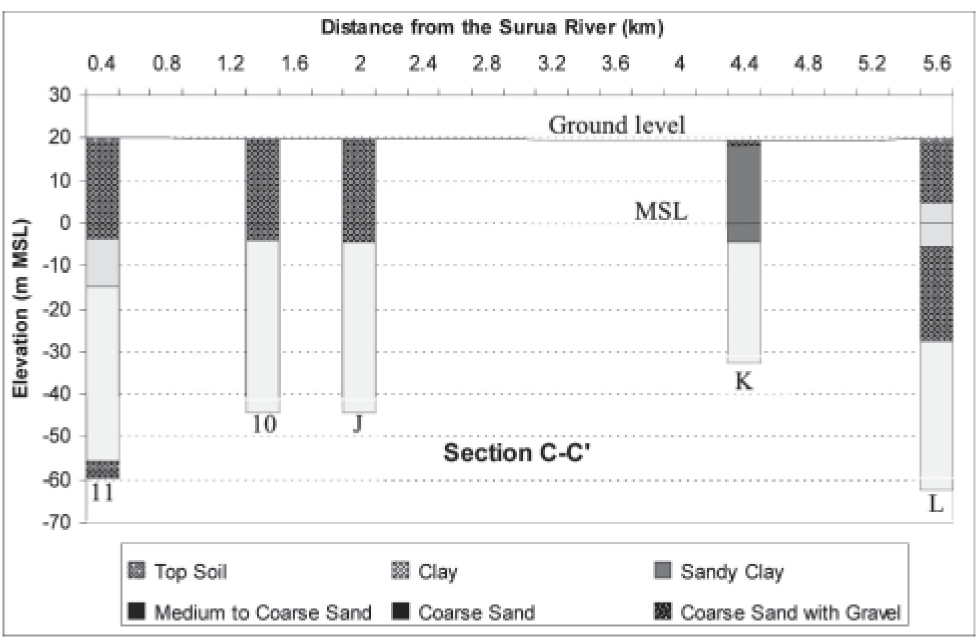
Fig. 13 (a to i): Geologic Profiles along Four West-East, Four North-South and a Central Sections

(b)



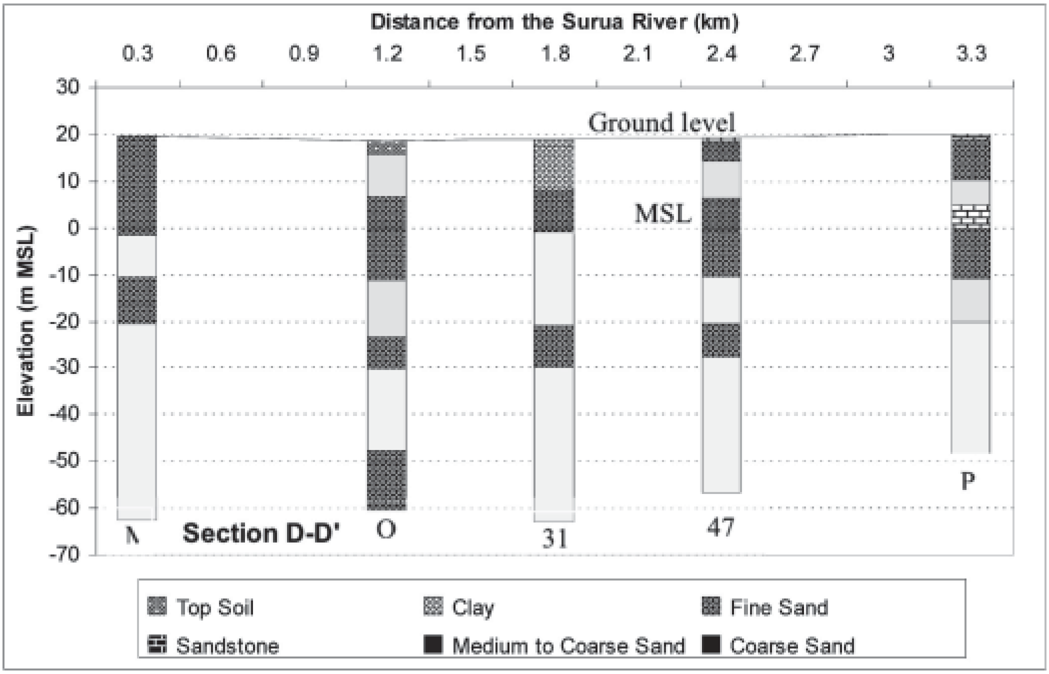
Distance from the Surua River (km)
0.3
0.9
1.5
2.1
2.7
3.3
3.9
4.5
5.1
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
Elevation (m MSL)
Ground level
MSL
D
19
E
F
25
Section B-B'
Top Soil
Clay
Sandy Clay
Fine Sand
Coarse Sand
Coarse Sand with Gravel
Gravel

(c)

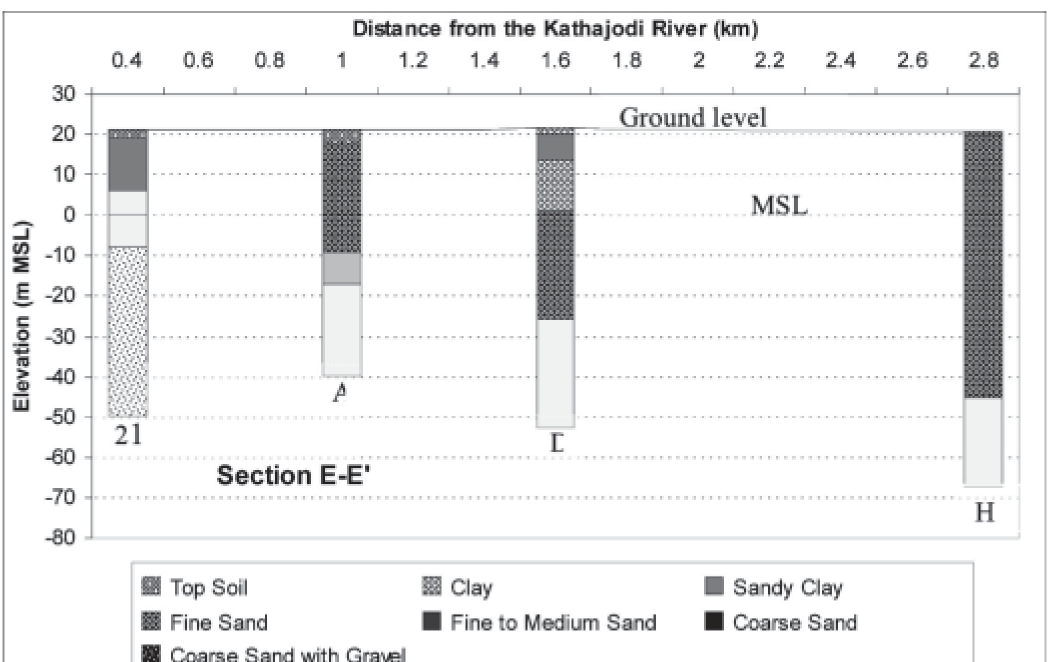


Distance from the Surua River (km)
0.4
0.8
1.2
1.6
2
2.4
2.8
3.2
3.6
4
4.4
4.8
5.2
5.6
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
Elevation (m MSL)
Ground level
MSL
11
10
J
K
L
Section C-C'
Top Soil
Clay
Sandy Clay
Medium to Coarse Sand
Coarse Sand
Coarse Sand with Gravel

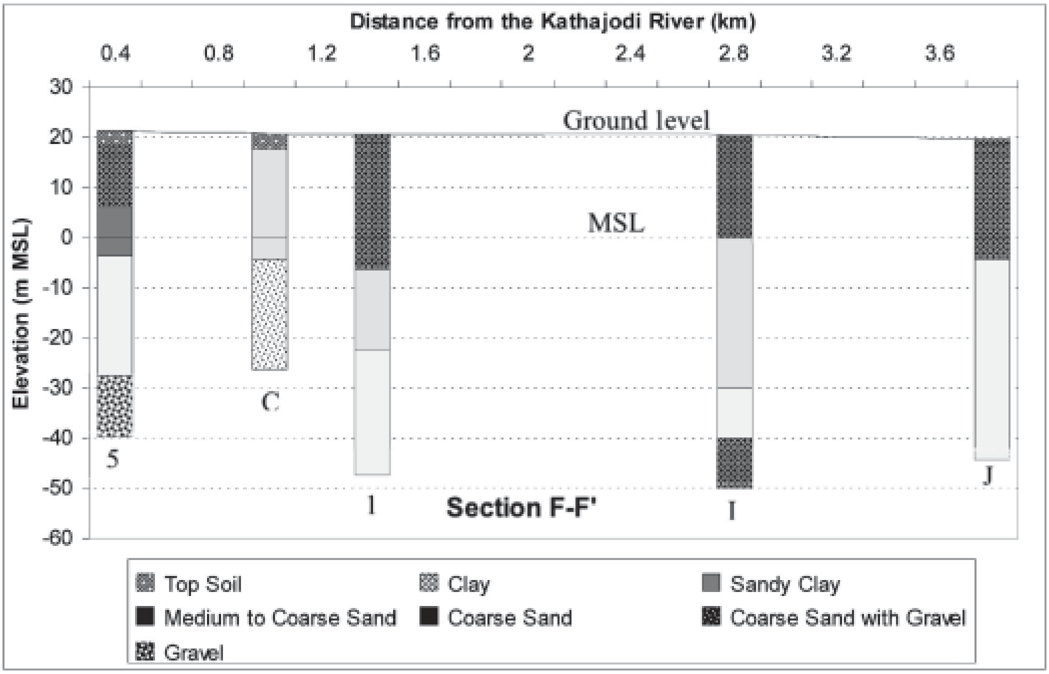
(d)


Distance from the Surua River (km)
0.3
0.6
0.9
1.2
1.5
1.8
2.1
2.4
2.7
3
3.3
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
Elevation (m MSL)
Ground level
MSL
Section D-D'
O
31
47
P
Top Soil
Clay
Fine Sand
Sandstone
Medium to Coarse Sand
Coarse Sand

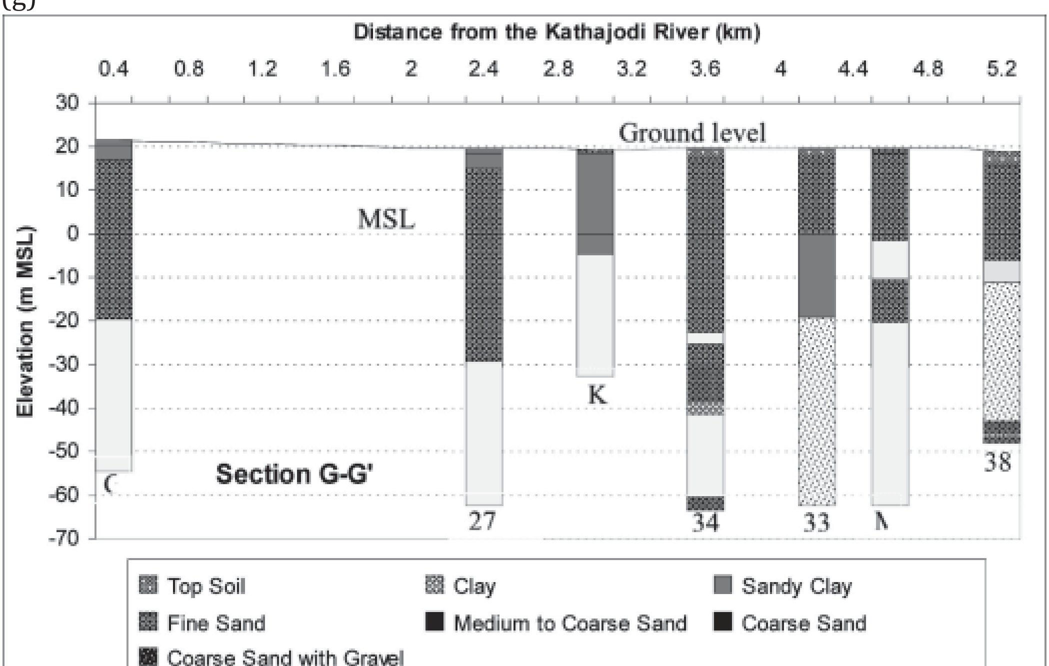
(e)


Distance from the Kathajodi River (km)
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
Elevation (m MSL)
Ground level
MSL
21
Section E-E'
H
Top Soil
Clay
Sandy Clay
Fine Sand
Fine to Medium Sand
Coarse Sand
Coarse Sand with Gravel

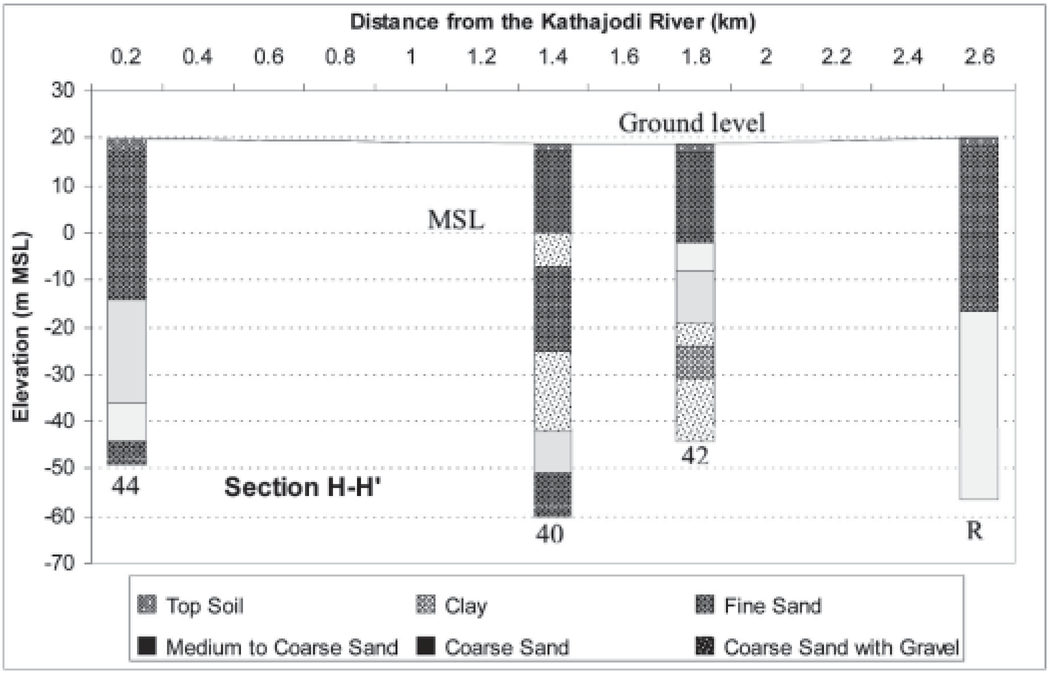
(f)


Distance from the Kathajodi River (km)
0.4
0.8
1.2
1.6
2
2.4
2.8
3.2
3.6
30
20
10
0
-10
-20
-30
-40
-50
-60
Elevation (m MSL)
Ground level
MSL
5
C
1
I
J
Section F-F'
Top Soil
Clay
Sandy Clay
Medium to Coarse Sand
Coarse Sand
Coarse Sand with Gravel
Gravel

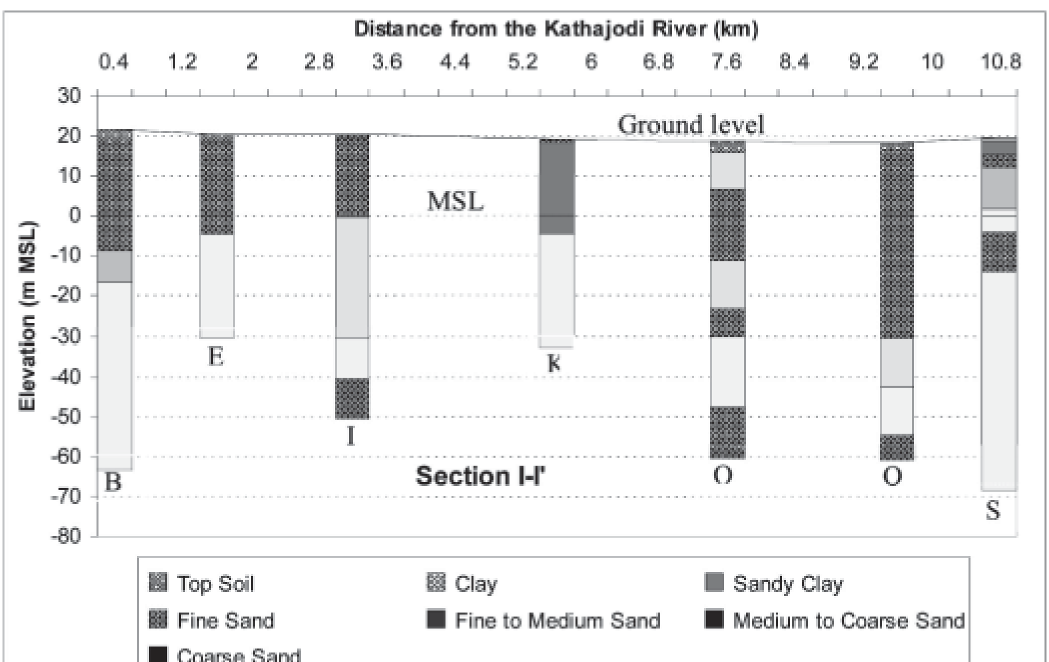
(g)


Distance from the Kathajodi River (km)
0.4
0.8
1.2
1.6
2
2.4
2.8
3.2
3.6
4
4.4
4.8
5.2
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
Elevation (m MSL)
Ground level
MSL
Section G-G'
K
27
34
33
38
Top Soil
Clay
Sandy Clay
Fine Sand
Medium to Coarse Sand
Coarse Sand
Coarse Sand with Gravel

(h)


Distance from the Kathajodi River (km)
0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6
30 20 10 0 -10 -20 -30 -40 -50 -60 -70
Elevation (m MSL)
Ground level
MSL
44
40
42
R
Section H-H'
Top Soil
Clay
Fine Sand
Medium to Coarse Sand
Coarse Sand
Coarse Sand with Gravel

(i)


Distance from the Kathajodi River (km)
0.4 1.2 2 2.8 3.6 4.4 5.2 6 6.8 7.6 8.4 9.2 10 10.8
30 20 10 0 -10 -20 -30 -40 -50 -60 -70 -80
Elevation (m MSL)
Ground level
MSL
B
E
I
K
O
O
S
Section I-I'
Top Soil
Clay
Sandy Clay
Fine Sand
Fine to Medium Sand
Medium to Coarse Sand
Coarse Sand

clay or has patches of coarse sand or medium sand, it can contribute leakage into or from the aquifer depending on hydraulic conditions. The thickness of the top confining layer varies from 15 to 50 m, except at Site C where the aquifer is available at a shallower depth and at Site H where the clay layer is extended up to a depth of 66 m [Fig. 13(e)]. The depth of the impermeable layer below the aquifer (i.e., bottom confining layer) ranges between 47 m and 88 m.

The geologic profile along the section D-D' [Fig. 13(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 the 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 the ground level and at Site 31, the aquifers are available at depths of 20-40 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 geologic profile along the section I-I' [Fig. 13(i)] shows the presence of aquifer at a deeper depth towards the south-east side of the basin. Based on this discussion, it can be concluded that a confined or leaky confined aquifer of 20-55 m thickness exists at depths of 15 to 50 m in the study area. The aquifer slopes from north-west to south-east direction in the basin

4.2 Hydraulic parameters of aquifer system

In order to measure the hydraulic parameters like transmissivity and storage coefficient of the aquifer system, time-drawdown pumping tests were conducted at 9 sites, i.e., B, C, H, I, J, K, O, S and 42 (Fig. 2) in the study area during January to April 2006 using existing infrastructure in the area. Drawdowns in the observation wells were measured with time during pumping. Wherever observation wells were not available, single-well pumping test was conducted by measuring the water level in the pumped well itself during pumping as well as recovery. These field measured time-drawdown data of 7 sites (B, C, H, I, K, O, and 42) were analyzed to determine aquifer parameters transmissivity (T) and storage coefficient (S) by the graphical method using widely used Aquifer-Test software (WHI, 2002).

The hydraulic parameters of the aquifer system, viz., transmissivity, hydraulic conductivity and storage coefficient at 9 sites were determined by pumping tests and are presented in Table 7. The analysis of time-drawdown pumping test data at sites B and H by Aquifer-Test Software is illustrated in Figs. 14(a) and 14(b), respectively as an example. The hydraulic conductivity values were obtained by dividing transmissivity values with corresponding aquifer thickness values obtained from the lithologic data. It should be noted that, storage coefficient values could not be obtained at sites J and S because of single-well pumping tests at these two sites. Table 7 reveals that the aquifer hydraulic conductivity (K) varies from site to site with a maximum value of 96.8 m/day at Site O and a minimum value of 11.3 m/day at Site B, indicating a large spatial variation of K over the basin (i.e., strong heterogeneity of the aquifer system). This finding is reasonable as the hydraulic properties of alluvial formations can change within short distances (Anderson and Woessner, 1992). Further, it can be seen that the downstream region of the study area usually has a higher hydraulic conductivity than the upstream region. Qualitatively, the hydraulic conductivity of the basin could be classified as 'high' (Todd, 1980), suggesting fast groundwater movement in the study area. On the other hand, the aquifer transmissivity varies from about 3485 m^2/day (Site O) to 529 m^2/day (Site B) with an average value of 1779 m^2/day. The values of storage coefficient range between 1.43×10^{-4} (Site H) and 9.9×10^{-4} (Site O), which also suggest a significant variation of storage coefficient over the basin.

Table 7: Hydraulic Parameters of the Aquifer System

Site	Transmissivity (m^2/day)	Storage Coefficient	Aquifer Thickness (m)	Hydraulic Conductivity (m/day)
Site B	528.5	2.04 10^{-4}	47	11.3
Site C	1521.2	2.34 10^{-4}	44	34.6
Site H	833.8	1.43 10^{-4}	22	37.9
Site I	1071.4	9.30 10^{-4}	40	26.8
Site J	3212.0	-	40	80.3
Site K	2463.0	3.24 10^{-4}	28	88.0
Site O	3484.8	9.9 10^{-4}	36	96.8
Site S	3148.4	-	54	58.3
Site 42	2861.0	4.02 10^{-4}	48	59.6

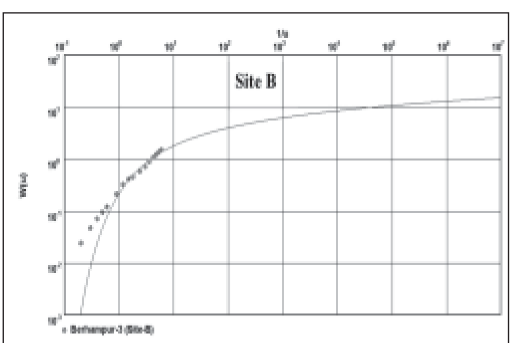


Fig. 14(a): Pumping Test Analysis at Site B by Aquifer-Test Software

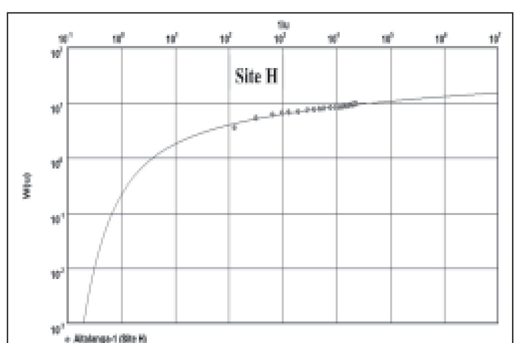


Fig. 14(b): Pumping Test Analysis at Site H by Aquifer-Test Software

4.3 Rainfall-groundwater dynamics

Well hydrographs of different tubewells were plotted along with the bar graphs of rainfall to study rainfall-groundwater dynamics in the study area. Weekly variation of groundwater levels at sites A to S during the period February 2004 to October 2007 are shown in Figs. 15(a to d), respectively along with the weekly rainfalls. The groundwater-level fluctuation at Site N has not been shown because the monitoring of groundwater at this site was discontinued after 7th May 2006. These figures suggest that groundwater levels at all the sites are generally higher in the rainy season (July to September). Groundwater level rises in the month of June (week no. 22 to 25) with the onset of monsoon and reaches its peak during August to September (week no. 33 to 38). From October onwards, it starts declining with the minimum groundwater level in the months of April/May. The difference in the minimum and maximum groundwater level varies from 3 to 6.5 m. In the year 2005, there was a delay in monsoon and hence the minimum groundwater 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 and/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 8). Clearly, the correlation between the weekly rainfall and weekly groundwater level in the upstream portion of the study area is 'poor' (r =0.333 to 0.398), while it is 'fair' (r = 0.562 to 0.659) in the downstream portion of the study

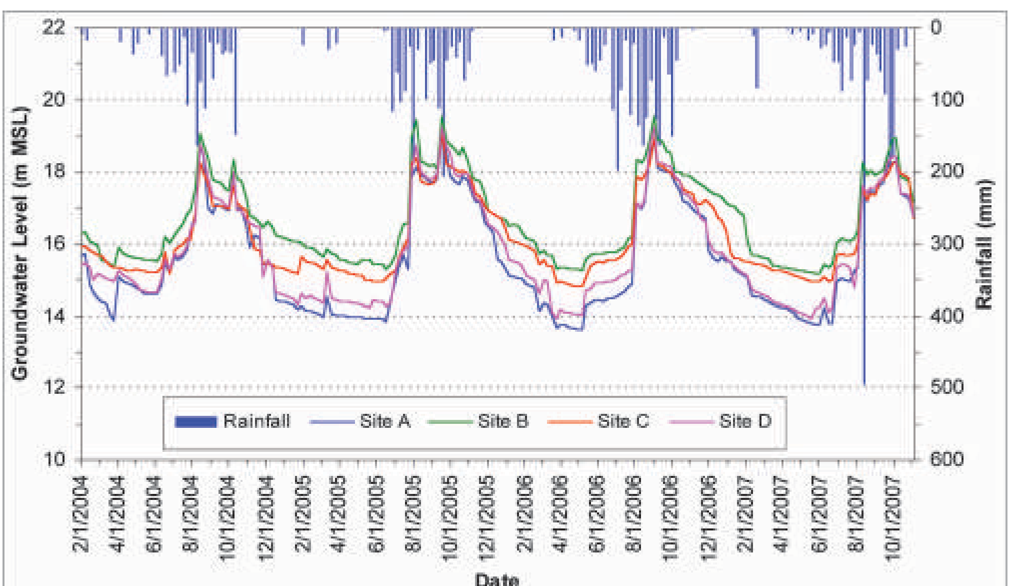


Fig. 15(a): Groundwater-Level Fluctuations at Sites A to D with Bar Graphs of Rainfall

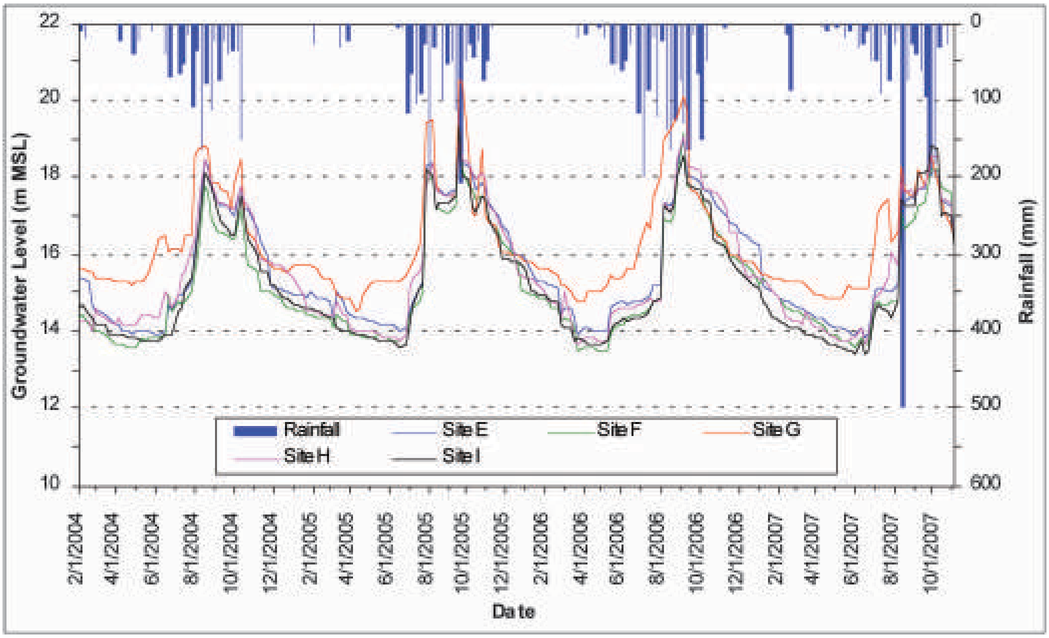


Fig. 15(b): Groundwater-Level Fluctuations at Sites E to I with Bar Graphs of Rainfall

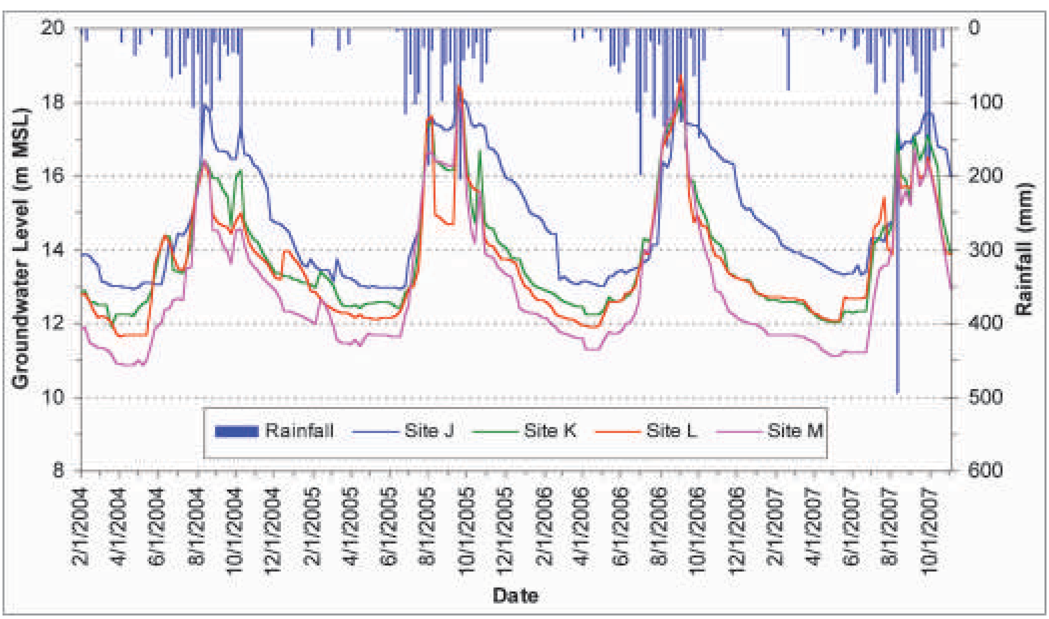


Fig. 15(c): Groundwater-Level Fluctuations at Sites J to M with Bar Graphs of Rainfall

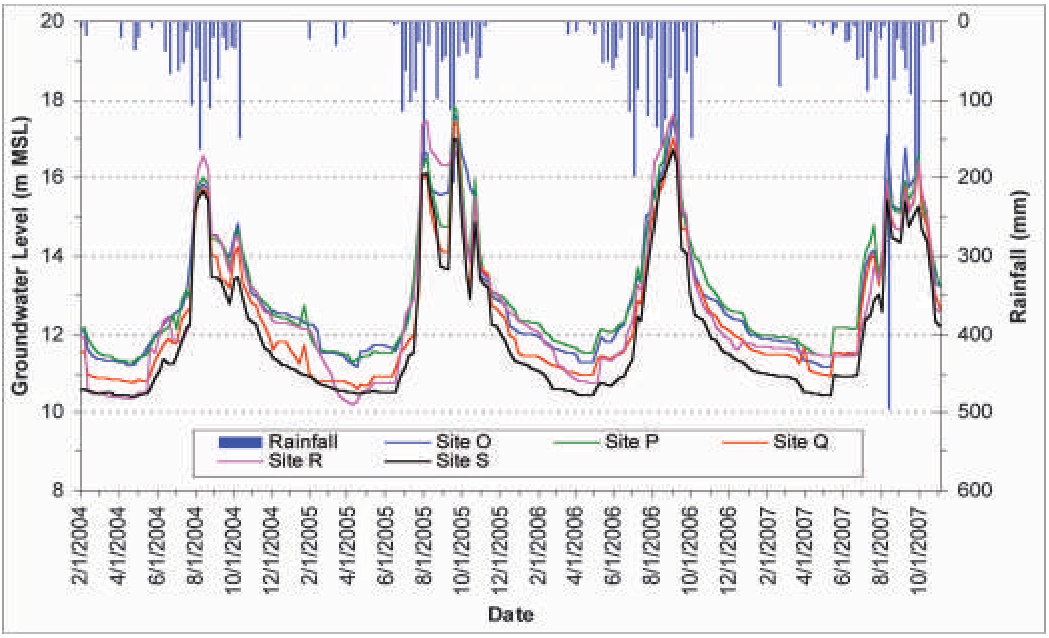


Fig. 15(d): Groundwater-Level Fluctuations at Sites O to S with Bar Graphs of Rainfall

area. However, 'good' (r > 0.8) correlation exists between groundwater level and river stage at sites G, K, L, M, N, O, P, Q, R and S. It is apparent from Table 8 that the river stage has a greater influence on groundwater levels than the direct rainfall; this finding suggests that the aquifer is not a perfectly confined aquifer, rather it is a semi-confined (leaky) aquifer. It confirms the finding of lithologic investigation.

Table 8 Correlation of Weekly Groundwater Levels with Weekly Rainfall and Weekly River Stage

Site	Correlation Coefficient (r) for Groundwater Level versus Rainfall	Remarks	Correlation Coefficient (r) for Groundwater Level versus River Stage	Remarks
Site A	0.382	Poor	0.728	Fair
Site B	0.381	Poor	0.729	Fair
Site C	0.375	Poor	0.720	Fair
Site D	0.376	Poor	0.737	Fair
Site E	0.358	Poor	0.703	Fair
Site F	0.379	Poor	0.722	Fair
Site G	0.589	Fair	0.886	Good
Site H	0.380	Poor	0.725	Fair
Site I	0.398	Poor	0.741	Fair
Site J	0.333	Poor	0.686	Fair

Site	Correlation Coefficient (r) for Groundwater Level versus Rainfall	Remarks	Correlation Coefficient (r) for Groundwater Level versus River Stage	Remarks
Site K	0.578	Fair	0.857	Good
Site L	0.581	Fair	0.867	Good
Site M	0.585	Fair	0.860	Good
Site N	0.659	Fair	0.812	Good
Site O	0.627	Fair	0.878	Good
Site P	0.582	Fair	0.891	Good
Site Q	0.586	Fair	0.887	Good
Site R	0.562	Fair	0.844	Good
Site S	0.581	Fair	0.879	Good

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

In order to assess the extent and frequency of water level fluctuations at a particular site during a month, the mean groundwater level and range of groundwater level fluctuation in that particular month along with their standard deviations were calculated. Tables 9(a) and 9(b) show the mean groundwater level and its range along with their standard deviation values at sites A to S for all the months. In the upstream portion of the study area, highest mean monthly groundwater level is observed in the month of September, whereas it is observed in the month of August in the downstream portion. This variation can be attributed to difference in recharge potential, cropping preferences, pumping schedule and extent of stream-aquifer interaction. Higher variation of water level is discernable in the monsoon season than in the dry season. This can be due to recharge from direct rainfall and increased river stage during the monsoon season. Maximum range (1.25±1.25 m at Site C to 2.88±2.05 m at Site S) of groundwater level fluctuation is observed in the month of July at almost all the sites, except for sites A, D, F, H where the range of groundwater fluctuation is maximum (1.40±0.98 m at Site A to 1.63±0.71 m at Site D) in the month of August and Site L where the range was maximum (2.68±2.07 m) in the month of September. As the groundwater level suddenly increases from a minimum in the month of June due to increase in river water levels and significant rainfalls, a higher deviation of groundwater level data is observed in July.

4.4 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 aquifer. However, no information was available about the stream-aquifer interaction in the study area, though it plays an important role in the integrated management of surface water and groundwater resources. To study stream-aquifer interaction based on available field data, well hydrographs at 18 sites were plotted along with the river stage hydrograph

Table 9(a): Monthly Groundwater Level and Range of Fluctuation at Sites A to J

Month	Statistic (m)	Groundwater Level (m MSL) and Range of Fluctuation (m) at Different Sites									
		A	B	C	D	E	F	G	H	I	J
January	Range±S.D.	0.29±0.07	0.24±0.12	0.35±0.14	0.37±0.14	0.33±0.24	0.26±0.12	0.12±0.07	0.52±0.33	0.42±0.30	0.49±0.19
	Mean±S.D.	14.88±0.53	16.49±0.43	15.65±0.41	15.10±0.56	15.18±0.27	14.86±0.34	15.61±0.18	15.11±0.19	14.77±0.30	14.45±0.63
February	Range±S.D.	0.67±0.47	0.38±0.13	0.24±0.19	0.40±0.19	0.45±0.40	0.32±0.19	0.24±0.16	0.45±0.27	0.36±0.25	0.56±0.56
	Mean±S.D.	14.57±0.35	15.91±0.14	15.59±0.19	14.84±0.31	14.90±0.10	14.45±0.20	15.45±0.09	14.46±0.13	14.43±0.20	13.85±0.33
March	Range±S.D.	0.49±0.21	0.30±0.16	0.35±0.22	0.57±0.47	0.48±0.27	0.41±0.32	0.27±0.14	0.58±0.51	0.29±0.09	0.27±0.21
	Mean±S.D.	14.17±0.12	15.55±0.12	15.34±0.09	14.63±0.27	14.49±0.14	14.14±0.24	15.13±0.19	14.32±0.15	14.02±0.08	13.34±0.36
April	Range±S.D.	0.17±0.10	0.12±0.09	0.12±0.03	0.16±0.08	0.17±0.09	0.16±0.14	0.21±0.21	0.17±0.08	0.11±0.09	0.17±0.09
	Mean±S.D.	14.17±0.54	15.44±0.20	15.11±0.18	14.43±0.46	14.17±0.16	13.79±0.24	14.96±0.23	14.01±0.17	13.81±0.11	13.16±0.28
May	Range±S.D.	0.27±0.27	0.18±0.18	0.24±0.24	0.39±0.33	0.28±0.28	0.30±0.29	0.35±0.29	0.33±0.33	0.22±0.22	0.16±0.15
	Mean±S.D.	14.13±0.37	15.44±0.17	15.09±0.12	14.39±0.29	14.18±0.25	13.83±0.08	15.30±0.21	14.10±0.29	13.78±0.21	13.14±0.17
June	Range±S.D.	0.51±0.34	0.28±0.28	0.26±0.24	0.37±0.37	0.30±0.30	0.43±0.46	0.31±0.23	0.33±0.26	0.20±0.11	0.42±0.42
	Mean±S.D.	14.33±0.51	15.56±0.26	15.20±0.25	14.65±0.43	14.28±0.36	14.03±0.34	15.61±0.50	14.27±0.47	13.85±0.36	13.35±0.30
July	Range±S.D.	1.16±1.16	**1.43±1.43**	**1.25±1.25**	1.13±1.13	**1.49±1.49**	1.37±1.37	1.94±1.69	1.34±1.30	**1.78±1.78**	**1.58±1.58**
	Mean±S.D.	15.38±0.62	16.39±0.41	15.96±0.23	15.64±0.48	15.22±0.32	14.93±0.38	16.75±0.40	15.41±0.58	14.99±0.43	14.42±0.55
August	Range±S.D.	**1.40±0.98**	1.34±0.75	1.11±0.92	**1.63±0.71**	1.41±0.83	**1.46±0.73**	1.18±0.70	**1.43±0.58**	1.33±0.78	1.53±1.11
	Mean±S.D.	17.57±0.26	18.35±0.22	17.71±0.31	17.73±0.31	17.61±0.19	17.11±0.30	**18.65±0.61**	17.66±0.13	17.39±0.11	16.96±0.35
September	Range±S.D.	0.78±0.50	0.89±0.60	0.76±0.68	0.90±0.61	0.95±0.67	1.25±1.03	**2.04±1.21**	0.79±0.61	1.12±0.73	0.73±0.46
	Mean±S.D.	**17.81±0.73**	**18.42±0.67**	**17.84±0.72**	**18.02±0.71**	**17.90±0.59**	**17.52±0.89**	18.46±0.76	**17.96±0.60**	**17.60±0.72**	**17.30±0.62**
October	Range±S.D.	0.86±0.60	0.72±0.30	0.48±0.25	0.96±0.34	0.72±0.16	1.04±0.59	1.57±0.57	0.68±0.24	1.23±0.31	0.81±0.25
	Mean±S.D.	17.43±0.37	18.10±0.43	17.60±0.47	17.60±0.48	17.56±0.35	16.96±0.64	17.31±0.35	17.72±0.40	17.07±0.38	17.01±0.41
November	Range±S.D.	0.62±0.31	0.38±0.15	0.65±0.31	0.91±0.51	0.79±0.58	0.53±0.05	0.59±0.13	0.52±0.36	0.78±0.21	0.72±0.65
	Mean±S.D.	16.59±0.60	17.31±0.62	16.80±0.82	16.73±0.54	16.67±0.56	15.98±0.75	16.21±0.27	16.58±0.63	16.02±0.45	16.19±0.48
December	Range±S.D.	0.79±0.41	0.33±0.09	0.36±0.35	0.61±0.33	0.36±0.25	0.66±0.40	0.17±0.14	0.58±0.37	0.31±0.17	0.47±0.33
	Mean±S.D.	15.48±0.53	16.81±0.48	16.30±0.82	15.71±0.67	15.89±0.71	15.38±0.52	15.79±0.20	15.70±0.18	15.36±0.42	15.18±0.59

Table 9(b): Monthly Groundwater Level and Range of Fluctuation at Sites K to S

Month	Statistic (m)	Groundwater Level (m MSL) and Range of Fluctuation (m) at Different Sites								
		K	L	M	N	O	P	Q	R	S
January	Range±S.D.	0.24±0.16	0.45±0.38	0.18±0.05	0.25±0.10	0.12±0.07	0.30±0.30	0.30±0.30	0.15±0.10	0.17±0.05
	Mean±S.D.	12.95±0.25	12.95±0.36	12.04±0.26	11.63±0.16	12.07±0.23	12.19±0.18	11.45±0.08	12.01±0.28	11.05±0.09
February	Range±S.D.	0.29±0.17	0.46±0.14	0.39±0.27	0.47±0.30	0.43±0.33	0.33±0.26	0.26±0.26	0.68±0.60	0.21±0.17
	Mean±S.D.	12.79±0.28	12.52±0.14	11.86±0.37	11.19±0.27	11.75±0.11	11.84±0.16	11.15±0.28	11.44±0.41	10.75±0.17
March	Range±S.D.	0.38±0.24	0.24±0.17	0.29±0.19	0.18±0.10	0.11±0.10	0.12±0.04	0.11±0.10	0.30±0.29	0.10±0.06
	Mean±S.D.	12.47±0.16	12.23±0.25	11.49±0.23	10.87±0.19	11.51±0.17	11.62±0.19	11.01±0.27	10.92±0.52	10.60±0.16
April	Range±S.D.	0.15±0.10	0.05±0.03	0.23±0.14	0.10±0.05	0.22±0.13	0.14±0.07	0.24±0.30	0.13±0.13	0.06±0.02
	Mean±S.D.	12.25±0.14	11.97±0.25	11.22±0.26	10.79±0.11	11.28±0.04	11.43±0.12	10.88±0.21	10.72±0.55	10.44±0.03
May	Range±S.D.	0.40±0.37	0.79±0.79	0.36±0.36	0.72±0.72	0.50±0.47	0.38±0.29	0.37±0.23	0.50±0.49	0.27±0.24
	Mean±S.D.	12.49±0.25	12.29±0.16	11.42±0.28	11.13±0.03	11.69±0.30	11.72±0.24	11.08±0.26	11.05±0.33	10.60±0.09
June	Range±S.D.	0.49±0.39	0.36±0.24	0.43±0.28	0.32±0.13	0.46±0.37	0.34±0.22	0.32±0.24	0.51±0.33	0.28±0.17
	Mean±S.D.	12.92±0.79	12.97±0.79	11.82±0.49	11.92±1.00	12.22±0.92	12.06±0.28	11.46±0.26	11.53±0.51	10.90±0.25
July	Range±S.D.	**2.54±1.79**	2.65±1.69	**2.60±1.59**	**2.55±2.55**	**2.56±1.63**	**2.51±1.57**	**2.66±1.70**	**2.77±2.22**	**2.88±2.05**
	Mean±S.D.	14.20±0.49	14.13±0.29	13.89±0.77	12.98±0.36	13.58±0.47	13.47±0.65	12.81±0.46	13.13±1.04	12.44±0.47
August	Range±S.D.	0.91±0.30	1.76±1.02	1.04±0.80	2.41±0.43	1.60±0.63	1.69±0.09	1.63±0.28	1.33±0.59	2.03±0.46
	Mean±S.D.	**16.64±0.61**	**16.13±0.89**	**16.51±0.86**	**14.76±0.35**	**15.47±0.65**	**15.81±0.49**	**15.31±0.41**	**16.45±0.56**	**15.28±0.41**
September	Range±S.D.	1.90±0.54	**2.68±2.07**	1.78±0.92	2.08±1.95	2.17±1.44	2.22±1.35	2.15±1.25	1.27±1.16	2.22±1.37
	Mean±S.D.	16.49±0.97	15.95±1.19	16.00±1.71	14.24±1.63	15.42±1.05	15.55±1.22	14.97±1.31	15.60±1.31	14.59±1.25
October	Range±S.D.	1.66±0.45	1.29±0.37	1.57±0.48	1.25±0.32	1.63±0.39	1.49±0.39	1.64±0.52	1.56±0.29	1..37±0.55
	Mean±S.D.	15.13±0.39	14.78±0.56	14.20±0.44	13.38±0.35	13.89±0.53	14.20±0.56	13.64±0.55	13.80±0.71	13.08±0.74
November	Range±S.D.	0.63±0.18	0.43±0.08	0.47±0.11	0.41±0.06	0.44±0.07	0.48±0.10	0.72±0.29	0.53±0.05	0.73±0.35
	Mean±S.D.	13.95±0.36	13.69±0.22	13.10±0.57	12.48±0.20	12.86±0.23	13.02±0.23	12.58±0.46	12.70±0.56	12.08±0.55
December	Range±S.D.	0.25±0.15	0.52±0.20	0.54±0.37	0.18±0.06	0.39±0.30	0.29±0.21	0.40±0.20	0.22±0.17	0.39±0.22
	Mean±S.D.	13.40±0.37	13.40±0.28	12.49±0.45	12.11±0.22	12.43±0.12	12.56±0.20	11.92±0.21	12.20±0.45	11.41±0.21

at Naraj. The weekly river stage data near the study area was not available, and hence the river-stage data available at an upstream gauging station at Naraj (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 were considered representative for the study area. In addition, correlation analysis was performed between the weekly groundwater levels at 19 sites and the weekly river stage using the data from February 2004 to October 2007. Correlation analysis was also performed between river stage lags and the groundwater levels at 19 sites considering 2-day to 10-day lags of the river stage.

Figs. 16(a to d) show the well hydrograph at different sites along with the river stage hydrograph at Naraj. These figures show similarity in trends of groundwater levels at all the sites with the river stage at Naraj. The regression analysis between river stage and groundwater level (Table 8) shows that there is a reasonably high correlation of weekly river stage (r = 0.686 to 0.891) with the weekly groundwater level compared to the weekly rainfall (r = 0.333 to 0.659). Thus, the increase in groundwater levels at all the sites in the monsoon season is more due to increase in river stage than the direct 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 a stronger stream-aquifer

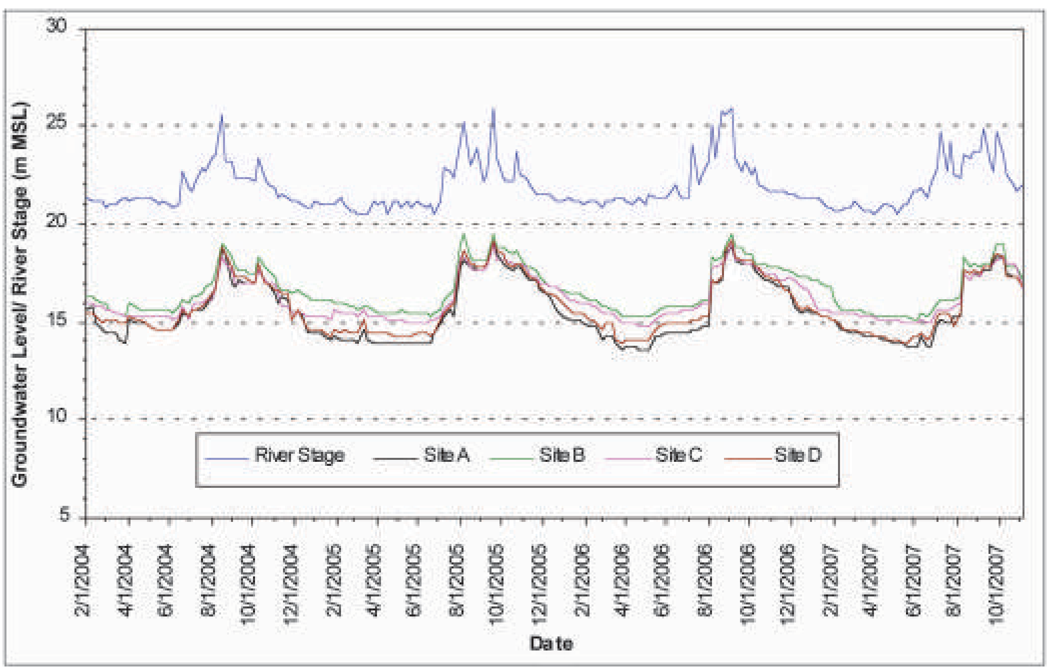


Fig. 16(a): Well Hydrographs at Sites A to D with River Stage Hydrograph at Naraj

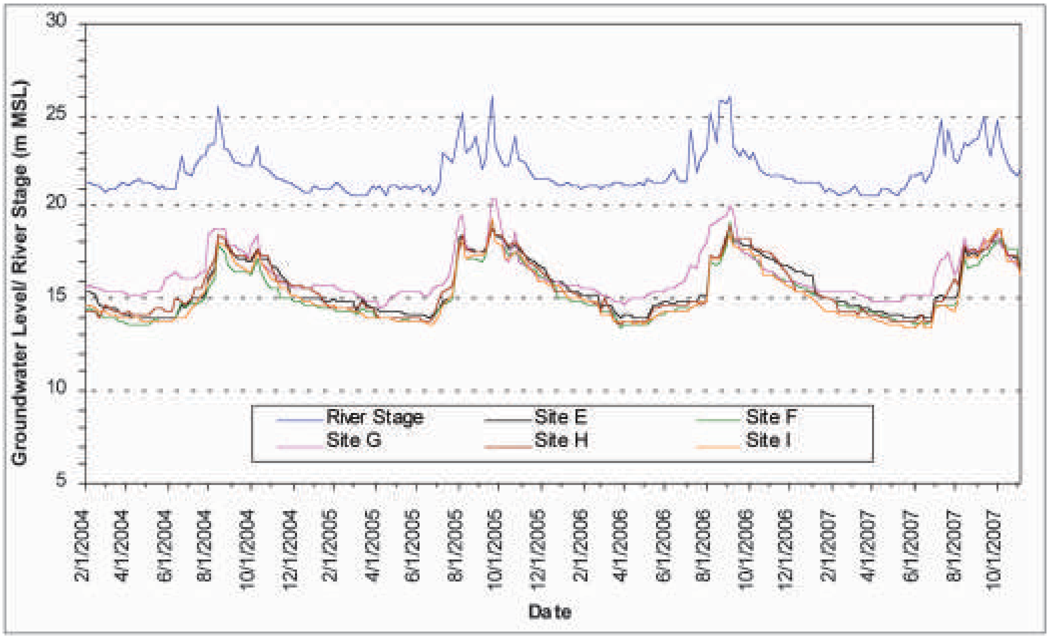


Fig. 16(b): Well Hydrographs at Sites E to I with River Stage Hydrograph at Naraj

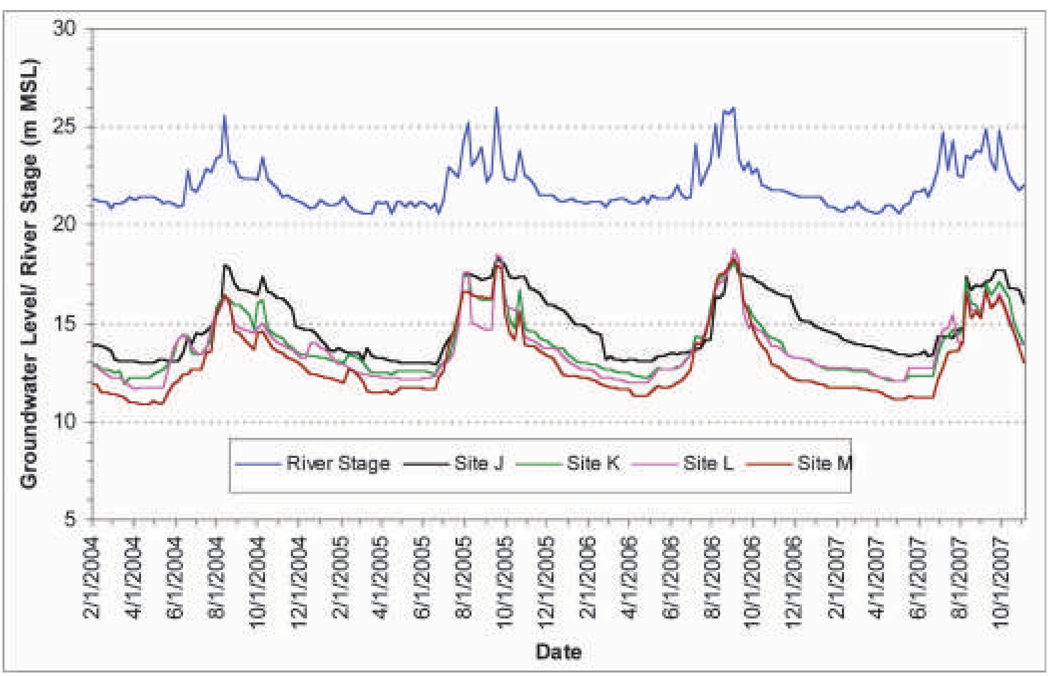


Fig. 16(c): Well Hydrographs at Sites J to M with River Stage Hydrograph at Naraj

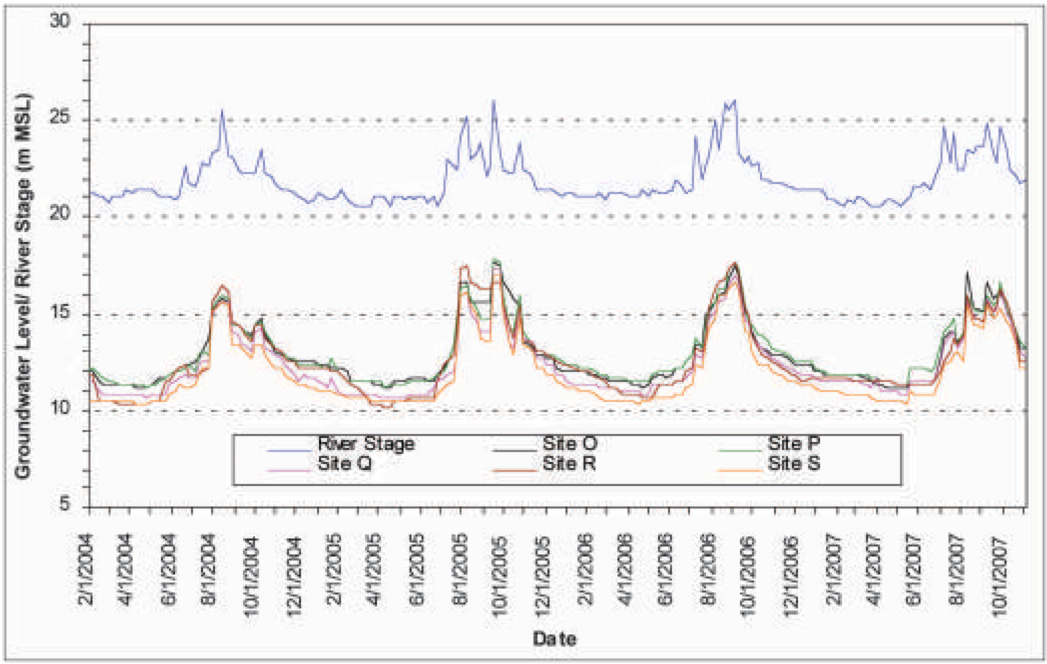


Fig. 16(d): Well Hydrographs at Sites O to S with River Stage Hydrograph at Naraj

interaction in the downstream portion of the study area compared to the upstream portion. This finding is in agreement with relatively large hydraulic conductivity in the downstream region of the study area as discussed earlier.

Moreover, the correlation of groundwater level with river stages of 1 to 10 days lag is shown in Table 10. Clearly, there is a better correlation between groundwater level and river stage in the downstream portion of the basin than the upstream portion at all the lag times. In the upstream side of the basin, the highest correlation is observed at 9-day lag time (r = 0.733 to 0.769). In the downstream side of the basin, though the highest correlation is observed at 2-day lag time (r = 0.855 to 0.894), significantly good correlation between groundwater level and river stage (r = 0.726 to 0.891) is observed up to 10-day lag time. Thus, it can be inferred that there is a significant influence of river stage on groundwater levels up to 10-day lag time. This finding suggests that proper streamflow management is necessary for enhanced and sustainable groundwater supply, especially during dry periods.

4.5 Hydraulic connectivity in the study area

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, which was analyzed to explore the hydraulic connectivity between individual sites. For this, 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. Correlation matrices were also developed considering only wet-period (June to September) as well as only dry-period (October to May) groundwater level data in order to check the suitability of datasets for investigating hydraulic connectivity in the study area.

Table 10: Results of Correlation Analysis of Groundwater Levels and River Stages of Different Lag Times

Site	Correlation Coefficient (r) for Different Lags of River Stage									
	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	0.728	0.730	0.705	0.692	0.740	0.721	0.751	0.765	0.767	0.741
B	0.729	0.735	0.709	0.692	0.738	0.724	0.746	0.753	0.756	0.729
C	0.720	0.723	0.698	0.684	0.726	0.711	0.733	0.744	0.746	0.716
D	0.737	0.740	0.713	0.701	0.749	0.730	0.754	0.767	0.769	0.744
E	0.703	0.707	0.682	0.668	0.715	0.701	0.726	0.738	0.742	0.717
F	0.722	0.725	0.699	0.684	0.730	0.715	0.737	0.749	0.752	0.724
G	0.886	0.883	0.862	0.855	0.849	0.846	0.858	0.847	0.831	0.806
H	0.725	0.730	0.704	0.697	0.743	0.725	0.752	0.764	0.767	0.740
I	0.741	0.744	0.713	0.701	0.747	0.736	0.755	0.766	0.768	0.739
J	0.686	0.688	0.664	0.657	0.709	0.692	0.718	0.733	0.733	0.708
K	0.857	0.867	0.851	0.839	0.833	0.830	0.845	0.842	0.838	0.812
L	0.867	0.874	0.851	0.838	0.825	0.829	0.839	0.831	0.819	0.793
M	0.860	0.873	0.853	0.838	0.834	0.830	0.852	0.851	0.847	0.822
N	0.812	0.870	0.764	0.726	0.822	0.805	0.816	0.812	0.794	0.765
O	0.878	0.889	0.867	0.849	0.828	0.831	0.845	0.838	0.831	0.804
P	0.891	0.894	0.871	0.863	0.865	0.862	0.876	0.870	0.857	0.830
Q	0.887	0.893	0.869	0.861	0.861	0.858	0.872	0.867	0.855	0.828
R	0.844	0.855	0.833	0.822	0.821	0.815	0.834	0.828	0.824	0.800
S	0.879	0.890	0.867	0.852	0.851	0.852	0.872	0.866	0.860	0.832

The correlation matrix of groundwater levels of 10 selected sites over the study area is shown in Table 11. It can be seen from this table that except the highlighted correlation coefficient (r) values, all the other correlation coefficient values are appreciably high (r ≥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 sites are either in the upstream side of the basin or in the downstream side of the basin, then the correlation is stronger. However, the correlation between a well in the upstream side of the basin and a well in the downstream side of the basin is relatively poor, with r values ranging from 0.827 (between sites J and L) to 0.872 (between sites F and S). This indicates that the hydraulic connectivity of the sites is very good in both upstream and downstream parts of the basin, but the hydraulic connectivity between the upstream part of the basin and the downstream part is relatively poor. This could be attributed to the distance between the sites, pumping pattern, and/or presence of a less permeable layer in between upstream and downstream ends of the basin.

Table 11 Correlation Matrix of Groundwater Levels at 10 Observation Sites for the Whole Year

Correlation Coefficient (r)										
Site →↓	**A**	**C**	**F**	**H**	**J**	**L**	**M**	**P**	**R**	**S**
A		1								
C	0.966	1								
F	0.967	0.979	1							
H	0.974	0.959	0.972	1						
J	0.971	0.964	0.975	0.974	1					
L	**0.835**	**0.829**	**0.855**	**0.858**	**0.827**	1				
M	**0.853**	**0.847**	**0.866**	**0.869**	**0.840**	0.948	1			
P	**0.856**	**0.852**	**0.871**	**0.871**	**0.849**	0.968	0.970	1		
R	**0.851**	**0.839**	**0.865**	**0.864**	**0.852**	0.942	0.972	0.966	1	
S	**0.860**	**0.836**	**0.872**	**0.871**	**0.847**	0.961	0.973	0.986	0.969	1

Moreover, Tables 12 and 13 show the correlation matrices of groundwater levels at 10 sites for the wet season (June to October) and dry season (November to May), respectively. Except the highlighted correlation coefficient values, all the other correlation coefficient values are higher than or equal to 0.90, which range from 0.907 to 0.996 for the wet season and 0.900 to 0.957 for the dry season. Tables 12 and 13 also indicate that when both the sites are either in the upstream side of the basin or in the downstream side of the basin, then the correlation is generally better. In contrast, the correlation of groundwater levels between a site in the upstream portion of the basin and a site in the downstream portion of the basin is relatively poor. Based on the above discussion, it can be inferred that either the wet season's data of groundwater levels or the entire year's data could be used to explore the hydraulic connectivity in the study area. This finding is very useful for the areas where, there are well distinct wet and dry seasons like monsoon dominated regions.

Table 12 Correlation Matrix of Groundwater Levels at 10 Observation Sites for the Wet Season

Correlation Coefficient (r)										
Site	A	C	F	H	J	L	M	P	R	S
A	1									
C	0.975	1								
F	0.978	0.996	1							
H	0.985	0.976	0.971	1						
J	0.988	0.977	0.976	0.987	1					
L	**0.765**	**0.783**	**0.785**	**0.763**	**0.749**	1				
M	**0.811**	**0.820**	**0.814**	**0.799**	**0.793**	0.907	1			
P	**0.794**	**0.813**	**0.816**	**0.796**	**0.796**	0.946	0.952	1		
R	**0.805**	**0.813**	**0.807**	**0.797**	**0.799**	**0.896**	0.966	0.947	1	
S	**0.802**	**0.813**	**0.814**	**0.798**	**0.796**	0.943	0.957	0.979	0.961	1

Table 13 Correlation Matrix of Groundwater Levels at 10 Observation Sites for the Dry Season

Correlation Coefficient (r)										
Site	A	C	F	H	J	L	M	P	R	S
A	1									
C	0.903	1								
F	**0.899**	0.921	1							
H	0.907	**0.872**	0.934	1						
J	0.906	**0.897**	0.957	0.930	1					
L	**0.712**	**0.681**	**0.823**	**0.836**	**0.827**	1				
M	**0.729**	**0.706**	**0.834**	**0.836**	**0.830**	**0.878**	1			
P	**0.831**	**0.802**	**0.892**	**0.889**	0.914	0.913	**0.880**	1		
R	**0.700**	**0.650**	**0.806**	**0.775**	**0.838**	**0.879**	**0.866**	**0.896**	1	
S	**0.852**	**0.818**	0.911	0.908	0.919	**0.872**	0.900	0.943	**0.857**	1

4.6 Groundwater quality

Groundwater samples were collected from 8 tubewells spread over the basin in the month of May 2005 (representative for the pre-monsoon season) and November 2005 (representative for the post-monsoon season) for assessing temporal variation in the water quality. The groundwater samples were analyzed for pH, EC, Na^{+}, Ca^{2+},

Mg^{2+}, Cl^{-}, CO_3^{2-} and HCO_3^{-} by following standard methods (APHA, 1989; Richards, 1968). Sodium Adsorption Ratio (SAR) and Residual Sodium Carbonate (RSC) of the water samples were also computed using standard procedure (Richards, 1968; Ayers and Westcot, 1989).

The results of the detailed groundwater quality analysis at 8 sites in the pre-monsoon and post-monsoon seasons of the year 2005 are summarized in Tables 14(a) and 14(b), respectively. The pH of the groundwater samples in the pre-monsoon season ranges from 6.8 to 7.3, which is considered normal according to WHO guidelines (WHO, 1971). The corresponding values for the post-monsoon season range from 5.3 to 6.3, which indicate that the groundwater is slightly acidic. The groundwater EC ranges from 0.16 to 0.26 dS/m in the pre-monsoon season and 0.12 to 0.21 dS/m in the post-monsoon season, which is within the prescribed limit of drinking water. 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 the study area can be characterized as of low salinity, and hence suitable for the irrigation purpose. The relative abundance of Na^{+} with respective to Ca^{2+} plus Mg^{2+}, influences the suitability of water for irrigation purpose and is represented by SAR. 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 of groundwater in the study area range from 0.09 to 0.39 in the pre-monsoon season and 0.07 to 1.80 in the post-monsoon season, there is no sodium hazard both in pre-monsoon and post-monsoon seasons. The groundwater does not contain carbonate, but it contains bicarbonate varying from 0.2 to 0.6 me/L in the pre-monsoon season and 0.19 to 0.42 me/L in the post-monsoon season.

Table 14(a): Groundwater Quality in the Study Area in Pre-monsoon Season (2005)

Site	pH	EC (dS/m)	Ca^{2+} (me/L)	Mg^{2+} (me/L)	Na^{+} (me/L)	Cl^{-} (mg/L)	HCO_3^{-} (me/L)	SAR	Mg^{2+}/Ca^{2+}
Site A	6.99	0.20	1.2	0.7	0.20	35.5	0.30	0.31	0.58
Site B	7.10	0.19	1.4	0.5	0.20	32.0	0.20	0.21	0.36
Site G	6.85	0.22	1.2	0.7	0.10	35.5	0.20	0.10	0.58
Site I	6.80	0.26	1.6	0.9	0.30	42.6	0.30	0.27	0.56
Site N	7.30	0.17	1.0	0.2	0.30	42.6	0.60	0.39	0.20
Site O	6.99	0.20	2.0	0.4	0.10	63.9	0.20	0.09	0.20
Site Q	7.03	0.16	0.8	0.3	0.20	24.8	0.40	0.27	0.38
Site S	6.79	0.24	1.6	0.8	0.10	31.9	0.20	0.09	0.50

Table 14(b):Groundwater Quality in the Study Area in Post-monsoon Season (2005)

Site	pH	EC (dS/m)	Ca^{2+} (me/L)	Mg^{2+} (me/L)	Na^{+} (me/L)	Cl^{-} (mg/L)	HCO_3^{-} (me/L)	SAR	Mg^{2+}/ Ca^{2+}
Site A	5.90	0.19	1.8	1.9	0.93	55.8	0.29	0.68	1.05
Site B	6.10	0.13	1.4	1.3	2.10	58.3	0.41	1.80	0.93
Site G	5.30	0.14	1.7	2.3	1.24	60.4	0.19	0.88	1.35
Site I	6.30	0.20	2.0	1.3	0.85	67.7	0.36	0.66	0.65
Site N	6.00	0.12	2.1	1.5	1.73	62.9	0.31	1.29	0.71
Site O	6.20	0.20	1.6	2.4	0.10	68.6	nil	0.07	1.50
Site Q	5.80	0.20	3.2	1.2	1.23	58.7	nil	0.83	0.37
Site S	5.90	0.21	1.9	1.6	1.63	60.0	0.42	1.23	0.84

Waters containing carbonate and bicarbonate ions in excess of Ca^{2+} plus Mg^{2+} often lead to much greater alkali formation than is indicated by their SAR values and this excess is denoted by Residual Sodium Carbonate (RSC) (Richards, 1968). In the study area, RSC values in both the seasons were found nil in all the samples, which suggests that the water is suitable for the irrigation purpose. Ca^{2+} and Mg^{2+} do not behave equally in the soil system, and Mg^{2+} deteriorates soil structures particularly when irrigation water is sodium dominated and highly saline. Therefore, the Mg^{2+} and Ca^{2+} ratio is also used as a useful index for water quality assessment. The Mg^{2+}/ Ca^{2+}ratio of the groundwater samples varies from 0.2 to 0.58 in the pre-monsoon season and 0.37 to 1.5 in the post-monsoon season, which is within the allowable safe limit of 1.5. Further, the chloride content of the groundwater samples ranges from 24.8 to 63.9 mg/L in the pre-monsoon season and 55.8 to 68.6 mg/L in the post-monsoon season. As the chloride contents of all the groundwater samples are less than 70 mg/L, they are generally safe for all the plants (Ayers and Westcot, 1989). As far as potable water is concerned, the values of EC, Cl^{-}, and Mg^{2+} are within the permissible limits for drinking 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 recommended suites of water quality parameters so as to have a better understanding of groundwater chemistry and degree of pollution, if any. Such a comprehensive and long-term groundwater quality monitoring is of great importance for protecting vital groundwater resources from point and non-point sources of pollution.

5. CONCLUSION

The detailed hydrologic and hydrogeologic analysis were carried out in the Kathajodi-Surua Inter-basin of Mahanadi Delta 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 a 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 1.43×10^{-4} and 9.9×10^{-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. The majority of the study area exhibits a strong river-aquifer interaction, and 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 non-point sources of pollution. Based on the results of this study, development of a groundwater flow simulation model and simulation of management scenarios in essential for sustainable utilization of water resources in the study area.

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