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Journal of Geotechnical and Geo Computational Engineering

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GROUND WATER QUALITY ASSESSMENT AROUND EFFLUENT FED BELLANDUR LAKE, BENGALURU

Preeti Jacob[1], Dr. G. S. Dwarakish[2], Bhaskar Bhushan[3], Sudhakar S.[4]

[1, 3, 4]CMR Institute of Technology, AECS Layout, Kundalahalli, ITPL Main Road, Bengaluru, India.

[2]National Institute of Technology, Srinivasnagar, Surathkal, Mangaluru, India.

Abstract

Safe drinking water is a basic necessity for human sustenance. The current infrastructural development ignores the most essence of human life i.e. water. The water resource for urban areas where the surface water is not available is the existing groundwater around the area. The study area of this project is the apartment complex around Bellandur Lake, Bengaluru. This lake is a waste-water paradise, where the industrial waste from factories is discharged into the lake. The lake was in the news recently as the foamed lake caught fire due to the presence of phosphorus and oil slurry from industrial effluents. The polluted lake is surrounded by apartments where the source of water is a mix of ground water of the area and groundwater from nearby areas. The mixing is the layman's concept of purification by dilution method. The above condition has necessitated the requirement of water quality testing from the borewells around Bellandur Lake. Around ten borewells were identified where the following parameters were tested: pH, total dissolved solids (TDS), total hardness, sulphates, chlorides, fluorides, chemical oxygen demand (COD), dissolved oxygen (DO), biological oxygen demand. The parameters were computed by methods prescribed by the methods referred in IS 10500-2012. The parameters were compared with Bureau of Indian Standards (BIS) and World Health Organization (WHO) standards. The statistical analysis of the parameters was done to evaluate the water quality index. There is a significant deviation of TDS, total hardness and fluoride content of the ground water sample. The paper is a *preliminary study of the existing groundwater condition. A database of the parameters is important for suitable purification methods to be implemented for making the water safe for drinking. The chemical analysis is significant in this area as chemically impure water causes irreversible long-term effects on the human body.*

Keywords: *Groundwater Quality, Total Dissolved Solids, BIS*

Introduction

We live in a technology driven society. In the quest for economic development, we compromise the very essence of our life i.e. air and water. The cosmopolitan cities of India where malls and business parks are the highlight of the city, the eye sore are the accumulated solid waste and overflowing drainage network. Sustainability of Urban India in terms of environment is a huge challenge. Each component of environmental pollution has to be taken separately in detail and integrated later to have a very functional environmental solution. The city of Bangalore is a dream city for entrepreneurs due to its good infrastructure but its development has given less importance to the environmental front. In technical terms, the land use-land cover map shows that there is a huge change in the land use pattern of the area. The built area is drastically increased in the area due to rapid urbanization.

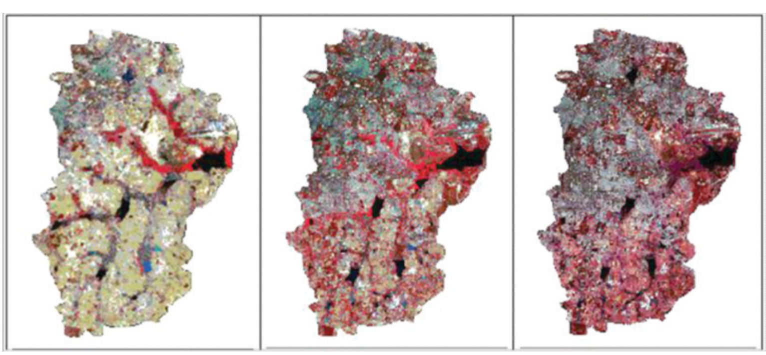


Figure 1 Land Use/ Land Cover of the urban catchment of Bellandur Lake during 1973, 1992, 2000 as reported in praja

1.1 Lakes in Bangalore

Bangalore is a city known for its lakes and parks. The city is located at an altitude of about 920 meters and receives a rainfall of about 800-1000mm (Begum 2008). The nearest river is Cauvery which is about 100kms from Bangalore and it is the main source of water supply. The topography of the city is such that the waters easily drain off from the land surface. The pioneers of the city realized the importance of an effective water supply system since there was no perennial river near the city. Under the reign of King Kempe Gowda, a number of inter-connected man-made lakes were engineered such that an overflow of a lake is transferred to the adjoining lakes causing a cascading effect. The recent boom of real estate saw the conversion of number of lakes to stadiums, apartment complex, bus stations etc. The lake beds which are being filled with soil not only changes the ecology of the area but also blocks the flow of water causing frequent flooding in low–lying areas. The other lakes are dumping zones from domestic as well as small scale industries. Very few lakes in Bangalore are properly maintained. The Lake Development Authority was formed to rejuvenate the lakes in Bangalore.

1.2 Groundwater Resource in Bangalore

The city is heavily dependent on the groundwater resource especially in areas where Cauvery water scheme is not available. Earlier the groundwater level was available at around 60-80 feet deep. Increased urbanization and consequent water demand necessitated the exploitation of groundwater which is at around 1000 feet below the ground surface now. In addition to that the quality of the water is also deteriorating due to influx of untreated sewage.

The objective of the paper is to evaluate the critical groundwater quality parameters around the wetland area of Bellandur Lake. It is 130 year old lake situated in Varthur Hobli, south eastern part of Bangaluru (Samal et al. 2010). The area is a concrete jungle comprising huge apartment complexes and IT parks which necessities the study of quality parameters since a large population is dependent on the resources.

2. Experimental Program

2.1 Sampling

The ground water sample was collected from ten locations between Outer Ring Road and Bellandur Lake. The information about the groundwater level in the vicinity was not very clear from the literature review. So the ground water was taken from the existing deep borewells present in the apartment complexes and from government run borewells in the area. The sample was collected during the pre-monsoon period of Feb - March 2015 from a depth of beyond 1000 feet in all the cases. The volume of the sample taken was 2 litres in sample containers of 1 litre capacity. The figure shows the google map with the location of the sampling points.

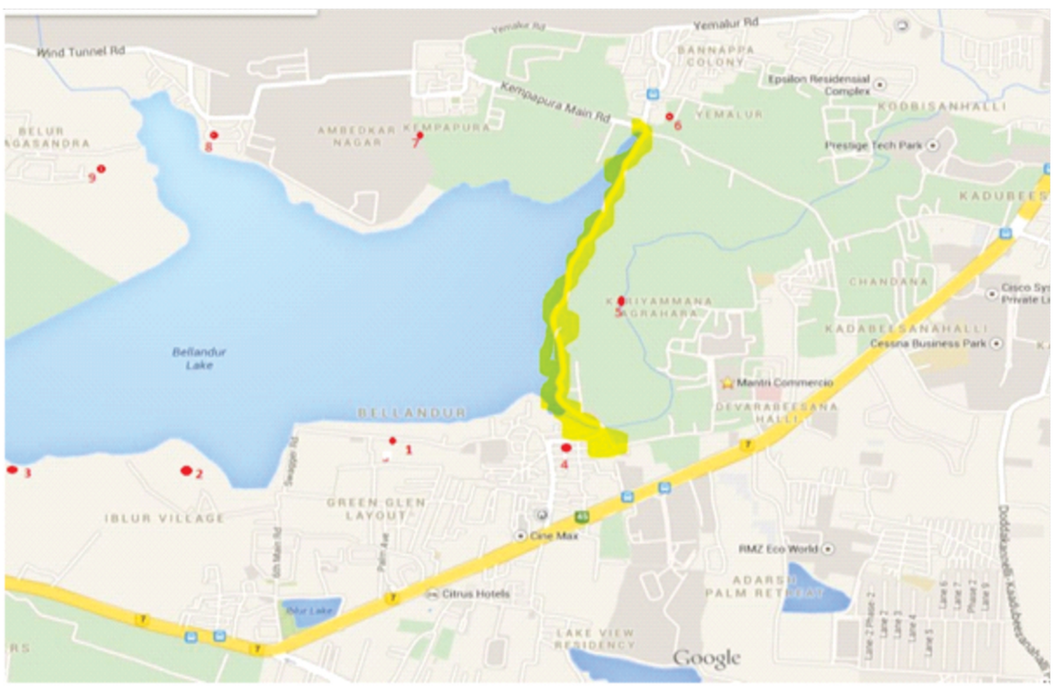


Figure 2 Sample points around Bellandur Lake

The tabular column shows the location of the points along with the distance from the lake. The distance is measured from the boundary of the lake in satellite image using distance measurement tool.

Table 1 Sample Location along with the distance measured from the periphery of the lake

S. No	Location	Distance from
1	Sobha Dahlia - Apartment	128
2	Malibu Rivona- Apartment	335
3	BWSSB, Kempapura	427
4	Srimitra Properties, Yemalur	100
5	Orchid Lake View - Apartment	89
6	Sobha Jasmine- Apartment	295
7	BWSSB, Nagasandra	1260
8	BWSSB, Challghatta	1014
9	Green Glen Layout	502
10	Iblur village	373

The sample was tested within 5 days of sampling to get accurate values. The samples which were beyond the acceptable limit were tested twice for better precision. The lake water quality was not tested as the lake was heavily polluted and requires the expertise of water testing lab for analysis.

2.2 Methodology

The parameters were tested as per IS codes. The IS code procedure for test of the parameters are tabulated below.

Table 2 IS Code reference for procedure

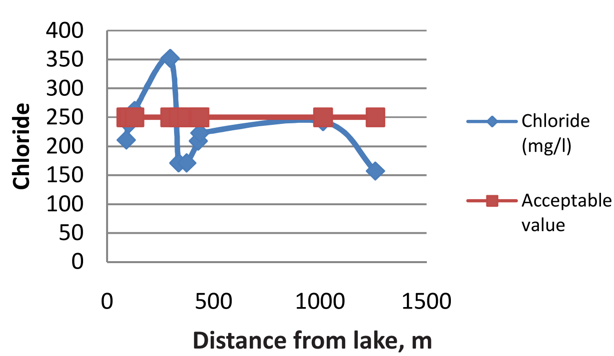
S. No	Parameter	IS code
1	pH	IS: 3025 – Part - 11
2	Total Dissolved Solids (mg/l)	IS: 3025 – Part - 16
3	Chloride (mg/l)	IS: 3025 – Part - 32
4	Fluorides (mg/l)	IS: 3025 – Part - 60
5	Sulphates (mg/l)	IS: 3025 – Part - 24
6	Total Hardness (mg/l as $CaCO_3$)	IS: 3025 – Part - 21
7	Dissolved Oxygen (mg/l)	IS: 3025 – Part - 38
8	Biological Oxygen Demand	IS: 3025 – Part - 44
9	Chemical Oxygen Demand	IS: 3025 – Part - 58

The critical parameters of water quality in this area were only tested. This urban area has issues of frequent refill of RO filters for household purposes. This was the driving force for testing the groundwater samples of this area to gain a preliminary knowledge about the existing groundwater condition.

3 . Results and Discussion

3.1 Spatial Variation of Water Quality Parameters

The groundwater sample points are surrounded between Outer Ring Road and Bellandur Lake. There is spatial variation of the water quality parameters around the wetland area. The highly polluted lake which is filled with foam and oil slurry from small scale industries is a major source of pollution to the surrounding groundwater. The understanding of the geology of the area is important to correctly correlate the amount of pollution which is transferred to the aquifer. Bangalore region is covered with gneiss with intermediate sedimentary layers. The depth of the borewell is beyond 1000 feet where the aquifer is confined. The pollution of confined aquifers is largely due to the sedimentary layers present in between the rocks or due to the fissures present in the rock surface. The high values of some of the parameters indicate that there is seepage of polluted water to the aquifers but the quality and the quantity of the seepage is different as indicated by the variation of the parameters. The graphs of some of the parameters along with the acceptable limit as per IS 10500-2012 is shown in figure 3. The fluctuations in the values of chloride and hardness indicate that the polluted lake has an effect on the surrounding groundwater. The 2nd point in the chloride graph shows the maximum deviation from the acceptable value indicating the lake is a recharge source for the groundwater. The pH of the samples is within range though some of the points are in extreme touching the graph in the lower and upper limit.



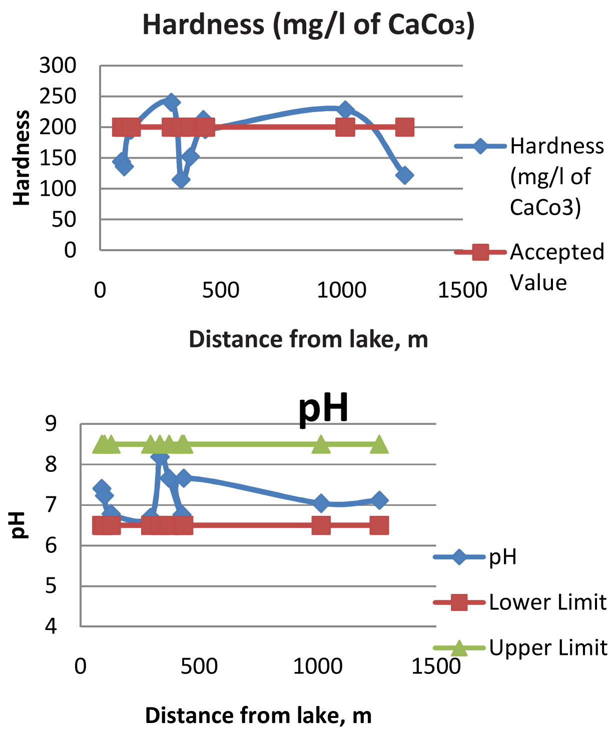


Figure 3 Variation of chlorides, hardness and pH

3.2 Statistical Analysis of the Parameters

The statistical analysis of the parameters exhibits variation within the urban watershed indicating that the physical and chemical constituents are unevenly distributed in the wetland area near the lake. The table shows that standard deviation of pH, dissolved oxygen and sulphates is very less. It indicates that the above mention parameters are fluctuating less in comparison with the parameters like chloride, total dissolved solids (TDS) and total hardness. The variation in hardness is due to both geologic profile of the area and due to pollution. The fluctuation of TDS value is primarily due to the solid waste dumping around the lake and also due to the chemical constituents discharged by small scale industries before the inlet of the lake.

Table 3 Statistical Analysis of the Parameters

S. No	Parameter	Average	Standard
1	pH	7.25	0.48
2	Total Dissolved Solids (mg/l)	680	379.47
3	Chloride (mg/l)	223.92	56.71
4	Fluorides (mg/l)	7.98	1.13
5	Sulphates (mg/l)	2.416	0.98
6	Total Hardness (mg/l as $CaCO_3$)	174	45.52
7	Dissolved Oxygen (mg/l)	5.16	1.22
8	Biological Oxygen Demand	2.17	1.53
9	Chemical Oxygen Demand	54.92	33.90

3.3 Compliance with BIS and WHO Standards

The Bureau of Indian Standards very clearly mentions the acceptable and maximum permissible limit of each of the parameters in IS 10500-2012. The World Health Organization (WHO) is a global organization and the guidelines chartered by the organization are for under developed, developing and developed countries. Each parameter of the water quality analysis is discussed in detail and there are different ranges of values specified for different cases. To select the threshold value for the analysis requires a detailed understanding of the impact of the parameter. The tabular column shows the percent compliance of the parameters with respect to BIS and WHO standards. Both the standards have almost the same acceptable values except in case of hardness and TDS where values show a variation in acceptable limit. Fluoride shows complete non-compliance with both the standards. The sample exhibits min 60% compliance with respect to the other parameters.

Table 4 Percent Compliance with BIS and WHO Standards

Parameter	% Compliance	BIS Standard	% Compliance	WHO Standard
Chlorides (mg/l)	80	250	80	250
Total Hardness (mg/l of $CaCO_3$)	80	300	0	100
pH	100	6.5 - 8.5	100	7 – 8
Fluorides (mg/l)	0	1	0	1
Sulphates (mg/l)	100	200	-	-
TDS (mg/l)	60	500	70	1000

3.4 Fluorides

The fluoride content of certain regions of Bangalore is very high due to the geologic formation of the area. The groundwater sample show high deviation from the acceptable limit of 1mg/l and also from the maximum permissible limit of 1.5mg/l as per IS-10500-2012. None of the samples are within the permissible limit prescribed by the IS code as well as WHO standards. Fluoride enters aquifer through weathering of granite rocks and as it goes deeper the fluoride concentration increases. The geologic profile of the area is mainly gneiss which is formed due to the metamorphosis of granite and sedimentary rocks. The depth of the bore well in this area is more than 1000 feet and this can be one of the reasons for the increased values of fluoride. Short term consumption of water is not harmful but long term effects of fluoride is very toxic and cause irreversible geochemical diseases like fluorosis.

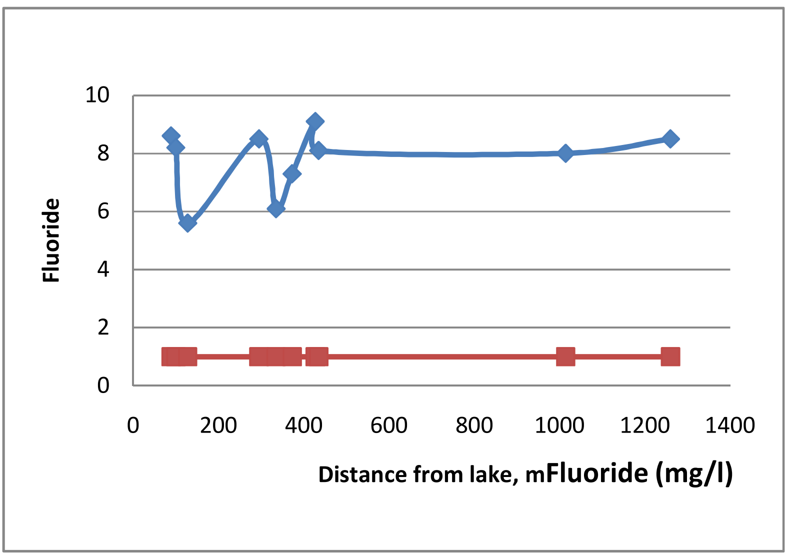


Figure 4 Variations of Fluorides

4. Conclusion

This paper is a preliminary study of the critical water quality parameters around the wetland area of Bellandur Lake. The analysis is done for the pre-monsoon season and shows compliance with the BIS and WHO standards in some percentage of the parameters and total non-compliance with the standards for fluorides. The methods for removal of fluorides should be taken seriously for avoiding long term effects on the human body. The project aims to study the effect of polluted lake on the adjoining wetland areas which has been transformed into built-up area. The primary source of water is the groundwater and the most affected population is the urban poor of the area whose treatment methods are very much limited to boiling water.

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GROUNDWATER SCENARIO IN SOUTH TRIPURA DISTRICT OF NORTH-EAST INDIA

Surajit Murasingh[2], Pawan Wable [1] and Madan Kumar Jha[1]

[1]AgFE Department, Indian Institute of Technology, Kharagpur, India.
[2]CORAL, Indian Institute of Technology, Kharagpur, India.

Abstract:

Despite sufficient rainfall, a large portion of the north-east region of India suffers from water scarcity during dry seasons and during dry periods groundwater acts as the important source of water supply. Therefore, proper assessment of groundwater condition at a district/block level is necessary. In this study, an attempt has been made to present groundwater condition at five sites, viz., Harshumukh, Santir Bazar, Gorjee Bazar, Subroom and Udaipur sites located in the South Tripura district of north-east India. With the available temporal groundwater-level and rainfall data at these five sites for the 2005-2013 period, the 'dynamic groundwater reserve' (DGWR) has been estimated to explore groundwater dynamics in the study area. The results of the study indicated that the maximum groundwater fluctuation was in the range of 0.89 to 3.6 m and minimum -2.91 to 0.19 m in the study area. The trend analysis showed that there is an increasing trend of groundwater level at Gorjee Bazar, Subroom and Udaipur site and a decreasing trend at Harshumukh site. Further, the DGWR results showed that two sites (Harshumukh and Santir Bazar) were overexploited in during 2005-2007 years, and the situation improved in subsequent years due to the occurrence of highest rainfall in the study area in the year 2007. Thus, the results of this study provide a clear picture of spatial and temporal variations of dynamic groundwater resources in the study area, based on which important recommendations are made for managing the scarce groundwater resources of the study area in a sustainable manner.

Keywords: *Groundwater Assessment, groundwater fluctuation, trend analysis, dynamic groundwater reserve, north-east India.*

Introduction

Groundwater is a primary source of freshwater in many parts of the world. Some regions are becoming overly dependent on it, consuming groundwater faster than it is naturally replenished and causing water tables to decline unremittingly (Postel, 1993). Groundwater resource is a finite resource but replenishable. Groundwater has been the mainstay for meeting the domestic needs of more than 80% of rural and 50% of the urban population besides, fulfilling the irrigation needs of around 50% of irrigated agriculture (Debbarma, 2013). The principal source of groundwater recharge is rainfall, though in some areas, canal seepage and return flow from irrigation also contribute significantly to recharge. However, the rapid industrialization, population growth and agricultural activities have resulted in over utilization of freshwater resources, leading to the reduction of groundwater levels. The use of RS and GIS for the evaluation and management of groundwater resources in various terrains plays an important role. (Jha et al., 2007). Estimation of groundwater depletion can be done by using GRACE Satellite (Rodell et al., 2009). The erratic and non-uniform distributions of rainfall over the country have caused floods in some parts, whereas droughts like situations in other parts of the country. Hence, considering heavy dependency on groundwater in several parts of the country its appropriate is highly essential.

With the current knowledge and new emerging techniques, there are various methods to assess the groundwater viz., remote sensing and GIS (Jha et al., 2007), Grace Satellite (Postel, 1993); groundwater modelling (Wycisk, 2015), soft computing (Raghavendra and Deka, 2015), etc. In India, the long-term average annual recharge under maximum groundwater use is expressed in terms of dynamic groundwater reserve (GWREC, 1997). The latest estimates of dynamic resources are based on groundwater resource estimation methodology-1997 (commonly known as GEC-1997). The committee was constituted by the Government of India, drawing members from various Central and State agencies, academic and scientific institutions and NABARD. The basic principle followed in this methodology is the estimation of annual groundwater recharge from rainfall. Due to simplicity, these estimations are widely used in formulating various groundwater development and management plans in India. Considering this importance, the present study has been undertaken with an objective of groundwater assessment based on dynamic groundwater reserve in South Tripura district, Tripura as a case study.

2. Study Area

South Tripura district is situated between North Latitudes 23^{0}0'00” - 23^{0}30'00” and East Longitude 91^{0}20'0” - 91^{0}40'0”. It is bounded by Bangladesh on south, east and west sides, by west Tripura district on the north western sides and by Dhalai district on the northeast side. The total geographical area of the district is 1514.32 km^2. Belonia is the district head quarter. Administratively, the district is divided into 3 nos. of sub–divisions which are in turn sub-divided into 8 RD Blocks, 1 AMC, 2 Nagar Pachayets, 90 GPs and 70 ADC Villages.

2.1 Climate

The climate in the area is characterized by moderate temperature and is highly humid in nature. There are three prominent seasons, summer, rainy and winter. The summer season spans from March to May and is followed by SW monsoon lasting till September. Winter season starts from November and lasts till the end of February. The temperature in the area varies from 5.1^{0}C to 35.6^{0}C. The humidity is generally high throughout the year. In summer seasons, the relative humidity varies between 50 and 90 % and in rainy seasons, the relative humidity varies from greater than 85% to 70%.The district has two rain gauge stations located at Belonia and Sabroom.

The average annual rainfall in the study area is 2055 mm. The average monsoon rainfall for the last 10 years is 1710 mm. The average number of rainy days for the last 5 years is 95. Maximum rainfall of 5900 mm recorded in 1993 at Sabroom. The coefficient of variation of rainfall in the area ranges from 6 to 32%, suggesting a low variability of annual rainfall in the study area.

2.2 Hydrogeology

There are three hydrogeological units

/ water bearing formations identified in the district are Alluvial formation, Dupitila formation and Tipam formation, which are shown in Fig. 2 below. Alluvial formation occurs along the banks of main rivers and its thickness varies from 10 to 15 m (CGWB, 2012). Ground water occurs under unconfined condition. Ground water development in the area has not been very significant because of high clay and sandy clay content. Dupitila formation is nearly horizontal in disposition and its thickness varies from 10 to 30 m (CGWB, 2012). The formation consists of mainly clay and silt with some intercalations of gritty and ferruginous sandstones. It is exposed in the central portion of Udaipur valley. In general, it has low permeability and low storage capacity due to high clay content. Moreover, Tipam formation consists of sub-rounded, fine to medium grained, friable sandstone with intercalated clay. Tipam formation is found in the majority of the valley portion. Sandstone of Tipam formation constitutes the principal aquifer in the area. The permeability of this sandstone is much higher than that of Dupitila sandstone or Surma sandstone. The recharge area of the sandstone is in the anticlinal hills.

3. Methodology

Groundwater level data of five sites for nine years were downloaded from the website of CGWB (Central Ground Water Board), New Delhi.

3.1 Collection of Groundwater Data

Generally, CGWB is monitoring groundwater levels four times in a year, i.e., in January, March, August and November. There are seven observation wells in the district, which are located at Manurmukh, Udaipur, Gaptalli, Gorjee bazaar, Harshumukh, Santirbazar and Sabroom (Fig. 1). However, for the assessment of groundwater condition, only data from five observation wells are available for a scientific analysis. Hence, the water table data of only five observation wells were used in this study purpose.

3.2 Collection of Rainfall Data

Daily rainfall data of two rainfall stations from 2005 to 2013 were downloaded from the website of India Meteorological Department (IMD), Pune.

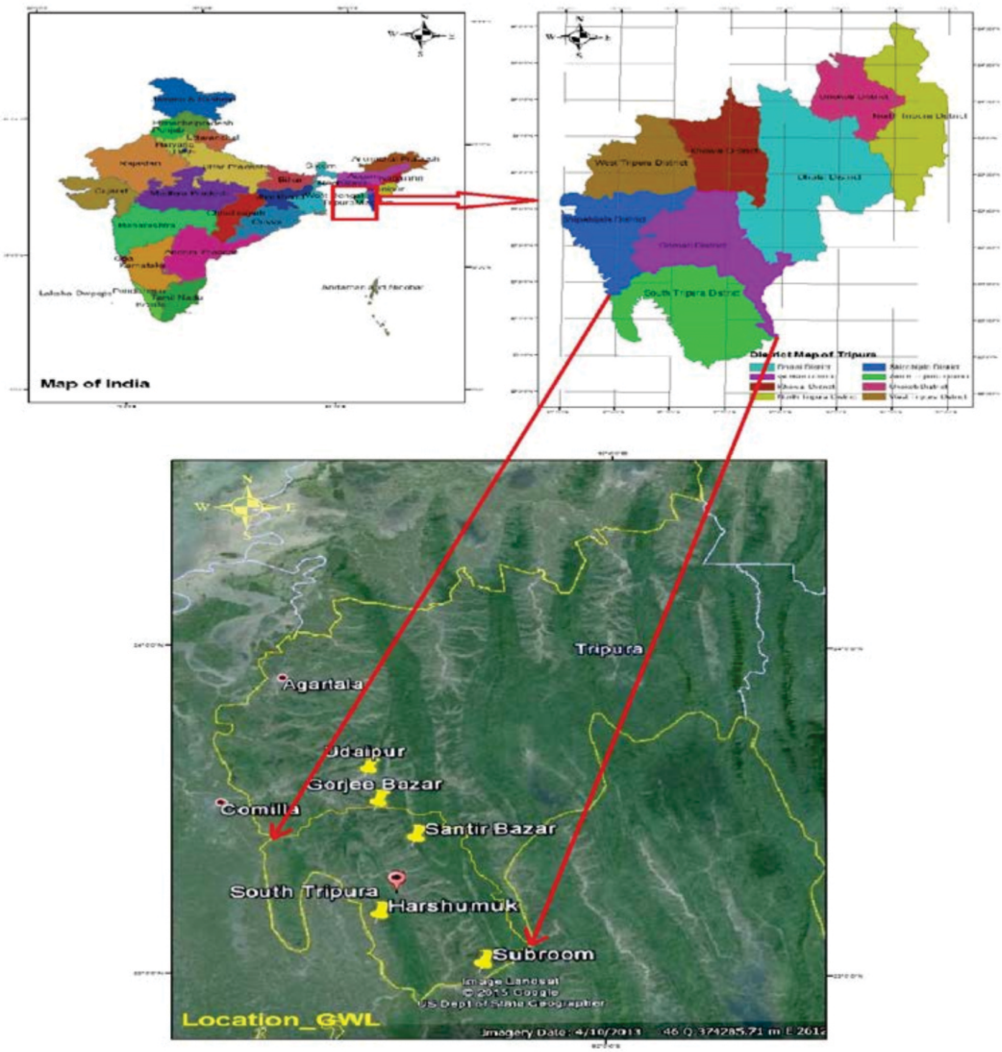

Figure 1 Location map of the study area

3.3 Estimation of Dynamic Groundwater Resource

Dynamic groundwater resources of the states are estimated following the guidelines ofGEC-1997, which are formulated by a committee of groundwater experts. Dynamic groundwater reserve refers to the long-term average annual recharge under conditions of maximum groundwater use (GWREC, 1997). Generally, up to the end of October, the soil is saturated with moisture and no additional groundwater for irrigation is required. Groundwater irrigation usually starts from the beginning of November and continues until May of the next year. Therefore, the dynamic groundwater reserve/resource (DGWR) is estimated as (GWREC, 1997):

$$DGWR = (D_{WTE} - D_{WTO}) \times A \times S_y$$

Where, D_{WTE} = depth towater table in the post-monsoon season of the current year [L], A = aquifer area of influence [L^2], and S_y = specific yield of the aquifer [fraction].

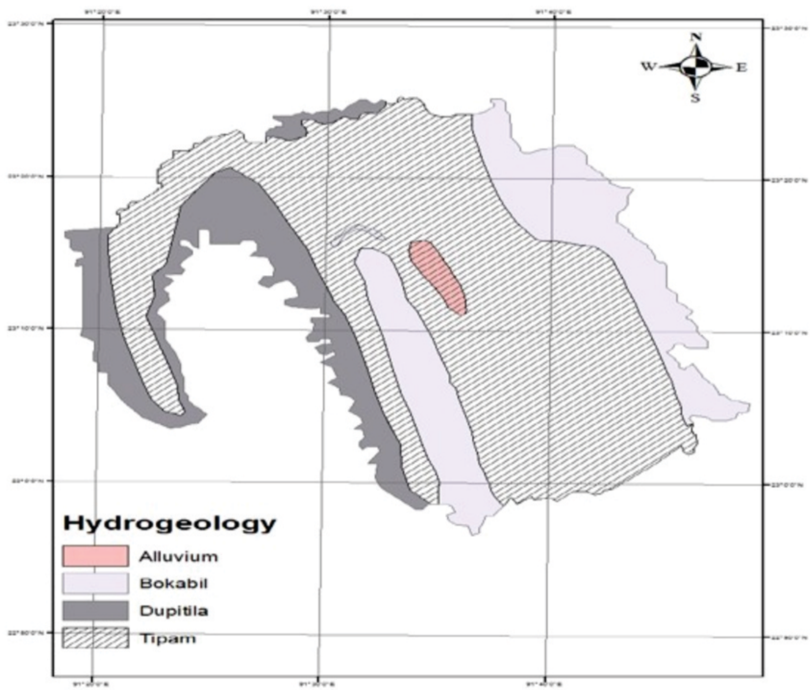

Figure 2 Hydrogeology map of the study area

Dynamic groundwater reserve (DGWR) is also known as 'exploitable groundwater reserve' or 'utilizable groundwater reserve', which clearly indicates that this amount of groundwater (i.e., dynamic groundwater reserve) can be fully extracted/withdrawn to meet annual water demands without causing any detrimental effect on the available groundwater resource and environment. In general, the pre-monsoon season for a particular year refers to the period from October/November of the previous year for the May/June of the particular year, whereas the post-monsoon season for a particular year refers to the period from October/November of that year until May/June of next year. However, for calculating dynamic groundwater reserve using Eqn. (1), the depth to water table in the month of May/June is taken as representative for the pre-monsoon season and the depth to water table in the month of October/November is taken as representative for the post- monsoon season. For the purpose of groundwater assessment in India, the monsoon season can be taken as May/June to September/October for all the areas of India except those areas where predominant rainfall is during the Northeast monsoon season. An additional period of one month after the cessation of the monsoon is taken into account for the base flow or groundwater recession, which occurs immediately after the monsoon season (GWREC, 1997).

3.4 Specific Yield

For the estimation of 'dynamic groundwater reserve' one of the important inputs is the value of Specific yield. Specific yield is defined as the volume of water that an aquifer (unconfined aquifer) releases per unit surface area of the aquifer per unit decline in the hydraulic head (Todd, 1980). This can be determined either from pumping tests on shallow wells tapping the unconfined aquifer or from soil moisture measurements or from groundwater budgeting or water level fluctuations (Healy and Cook, 2002). As the specific yield data of the study area were not available, the specific yield values recommended by the CGWB, New Delhi (GWREC, 1997) were considered for this study according to the geological formations available in the study area. The values of specific yield thus considered are summarized in Table 1 below.

Table 1 Recommended values of the specific yield for different geologic formations

Site	Geological Formation	Specific Yield (Fraction)
(a). Harshumuk	Dupitila	0.06
(b). Santir Bazar	Tipam	0.10
(c). Gorjee Bazar	Tipam	0.10
(d). Subroom	Tipam	0.10
(e). Udaipur	Dupitila	0.06

4. Results and Discussion

Groundwater levels being the only direct indicators of Groundwater development used in the assessment procedure because they can be more accurately sampled as opposed to other parameters like groundwater draft and recharge.

4.1 Response of Groundwater to Rainfall

The effect of rainfall on groundwater levels was studied at five sites of South Tripura district, (Tripura) namely, Harshumukh, Santir Bazar, Gorjee Bazar, Subroom and Udaipur sites for the period of 2005-2013. The range of groundwater level and seasonal fluctuations for these sites are summarized in Table 2. During pre-monsoons the maximum groundwater depth (7.11 m) occurred at Harshumukh site in the year 2005 and minimum (2.11 m) at Gorjee Bazar site in the year 2009. However, in case of post-monsoon, the maximum groundwater depth (5.92 m) was found at Harshumukh site in the year 2006 and minimum (1.35 m) at Gorjee Bazar site in the year 2008. It is also revealed from Table 2 that at the five sites, the minimum seasonal fluctuation range between -2.91 to 0.19 m, whereas the maximum fluctuation is in the range of 0.89 to 3.6 m.

Table 2 Range of groundwater level and seasonal fluctuation at different sites

Site	Range of Groundwater Level (m bgl)		Seasonal Fluctuation (m)	
	Pre-monsoon	Post-monsoon	Minimum	Maximum
(a) Harshumukh	3.01-7.11	2.8-5.92	-2.91	3.6
(b) Santir Bazar	4.28-4.7	3.41-4.89	-0.19	0.89
(c) Gorjee Bazar	2.11-3.78	1.35-2.74	0.19	2.34
(d) Subroom	5.82-6.29	4.51-5.66	0.49	1.71
(e) Udaipur	2.76-4.87	1.94-3.91	0.2	2.49

Moreover, the trends at all five sites were examined for the period 2005-2013. In case of Harshumukh site, both pre-monsoon and post-monsoon groundwater levels have declining trends for the study period as shown in Fig. 3(a). However, at Santir Bazar site showed a different scenario from the above site, in which both the trends were parallel to each other as depicted in Fig. 3(b). It indicates that the variation of water level is almost uniform with less fluctuation for both pre-monsoon and post-monsoon. It is obvious from Fig. 3(c, d, and e) that at Gorjee Bazar, Subroom and Udaipur sites increasing trend exists for both pre-monsoon and post-monsoon seasons.

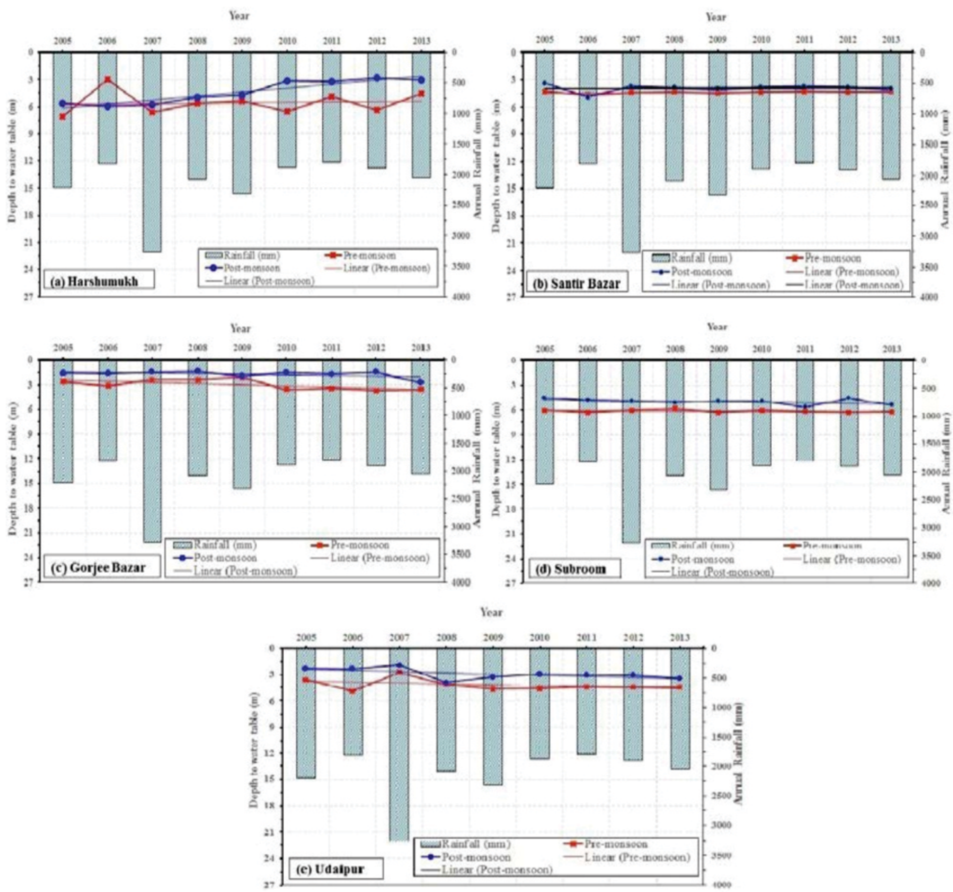

Figure 3(a-e) Variation of depth to water table during pre-monsoon and post monsoon seasons (2005-2013) at (a) Harshumukh, (b) Santir Bazar, (c) Gorjee Bazar, (d) Subroom and (e) Udaipur.

4.2 Status of Dynamic Groundwater Reserve

As mentioned in the methodology, the 'dynamic groundwater reserves' at each site were estimated using the Eqn. (1) and it has been calculated in term of depth because of the lack of the data namely 'area of influence' for individual monitoring well, results are shown in Fig. 4. It is apparent that there was a uniform variation in DGWR at the Udaipur site, indicating that net recharge and groundwater draft were balanced. The maximum DGWR was reported at the Gorjee Bazar site during the year 2012, whereas minimum at the Harshumukh site during the year 2005.

Two sites showed negative values of DGWR indicating that they were over exploited due to pumping in years 2005, 2006 and 2007 (Fig. 4). However, the status of DGWR was further improved after 2007 since the study area received the highest amount of rainfall (3300 mm).

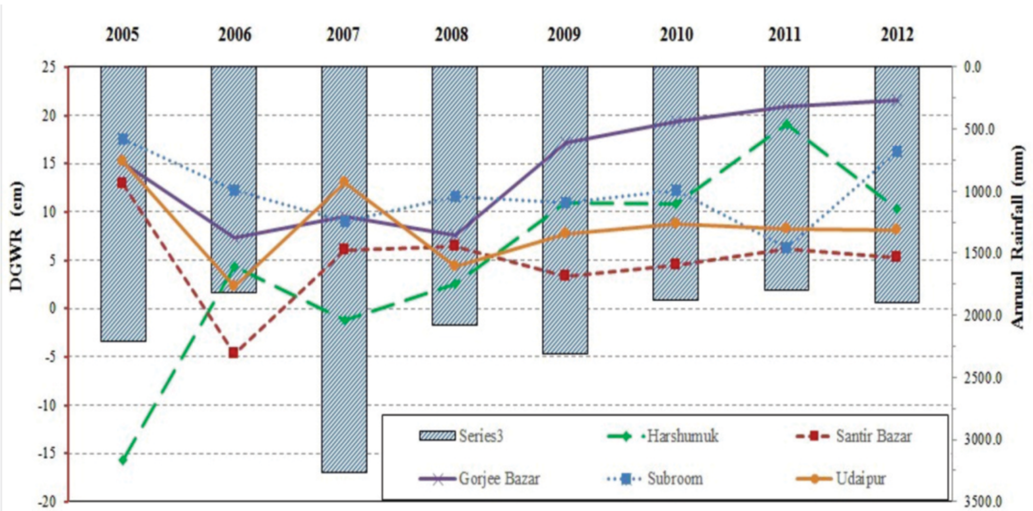

Figure 4 Spatio-temporal variation of 'dynamic groundwater reserve' (DGWR) at five sites during 2005-2013 period.

Conclusions

In the present study, the groundwater assessment was performed on the basis of 'dynamic groundwater reserve' at five sites of South Tripura district, (Tripura) for the period 2005-2013. The guidelines provided by GWREC (1997) were used to estimate the dynamic groundwater reserve. It was found that for both pre-monsoon and post-monsoon the maximum groundwater depths was for Harshumukh site, 7.11 and 5.92 m bgl, respectively. During the study period, minimum seasonal fluctuation was in between -2.91 and 0.19 m, whereas the maximum fluctuation was in the range of 0.89 to 3.6 m. The trend analysis showed that both pre-monsoon and post-monsoon groundwater depths have declining trends at Harshumukh site. Conversely, increasing trend at Gorjee Bazar, Subroom and Udaipur sites and a uniform trend at Santir Bazar site were found. In addition, the status of DGWR indicated that two sites namely, Harshumukh and Santir Bazar, were overexploited due to excess pumping in years 2005,2006 and 2007, but the situation improved due to extreme rainfall events in the year 2007.

Based on the experience gained through this study, it can be recommended that: (i) more number of observations well should be constructed in order to get better assessment of groundwater resources; (ii) spatial and temporal variation of groundwater level should be regularly monitored for improved analysis of groundwater condition in the study area; (iii) groundwater recharge site selection should be done throughout the district and suitable recharge structures should be constructed for proper management of groundwater; and (iv) with the availability of adequate groundwater data, a comprehensive groundwater study should be initiated in the district for efficient management of groundwater resources in the study area.

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FLOOD AND ITS EFFECT ON RIVER AQUIFER INTERACTION

Biswajit Chakravorty,[1] N.G.Pandey [2]

[1]Scientist 'F', CFMS, National Institute of Hydrology, WALMI Complex, Patna, India.
[2]Scientist 'D', CFMS, National Institute of Hydrology, WALMI Complex, Patna., India.

Abstract

During the passage of flood the river stage changes rapidly. The rise in river stages above the aquifer water level in the vicinity of the river leads to groundwater recharge. Consequent to rise in river stage, the upper aquifer is recharged directly through the bed and banks of the river and the lower aquifers are recharged from the top aquifer through the intervening aquitard. The recharge from a river to an aquifer is proportional to the difference in the level of water in the river and in the aquifer in the vicinity of the river. Saturated flow is typically assumed for seepage from a stream underlain by an alluvial aquifer. The water level in the aquifer depends on all the abstractions and recharges including recharge from the river. The present study quantifies the interaction of aquifer and the river during various stages of river. The study area lies between Bhagirathi and Ichamati river in West Bengal. A groundwater flow model under transient state has been employed for the study area using USGS groundwater flow model MODFLOW. The model has been used to compute flow to/from Bhagirathi river to adjacent aquifer. River aquifer interaction relationships have been developed to find the aquifer recharge with rise in river stage for the study area.

Keywords: *Aquitard, saturated flow, groundwater flow model, MODFLOW.*

Introduction

During the passage of flood, the river stage changes rapidly. The rise in river stages above the aquifer water level in the vicinity of the river leads to groundwater recharge. Consequent to rise in river stage, the upper aquifer is recharged directly through the bed and banks of the river and the lower aquifers are recharged from the top aquifer through the intervening aquitard. There are two main aspects of the process of interaction between surface water and groundwater. It is either from groundwater to support river flow or flow from river to groundwater. Recharge may occur whenever the stage in a river is above that of the adjacent groundwater table, provided that the bed comprises of permeable or semi-permeable material. This type of groundwater recharge may be temporary, seasonal or continuous. Also, it may be a natural phenomenon or induced by man. Man can induce groundwater recharge from rivers by lowering the water table adjacent to rivers through groundwater abstraction. The recharge from a river to an aquifer is proportional to a difference in the level of water in the river and in the aquifer in the vicinity of the river (Bouwer, 1969). The coefficient of proportionality recognized as reach transmissivity. The reach transmissivity depends on the stream bed characteristics and the shape of the stream cross-section (Morel, 1964; Bouwer, 1969). The water level in the aquifer depends on all the abstractions and recharges including recharge from the river. Such an implicit and complex stream-aquifer interaction problem has been analyzed by Morel Seytoux & Daly (1975) who have used reach transmissivity and discrete karnel theory for finding an expression for recharge.

The study presented quantifies the interaction of river and the aquifer during changing stages of river Bhagirathi and Ichamati river located in West Bengal. A transient groundwater flow model has been developed for the study area using MODFLOW. The model has been used to compute flow to/from Bhagirathi river to adjacent aquifer at different locations with observed stage of river. River aquifer interaction relationships have been developed to find the aquifer recharge with rise in river stage.

Literature Review

Three fundamentally different analytical solutions for flow to a well besides a stream currently exist. The first solution, obtained by Theis (1941) assumes that the stream completely penetrates the aquifer and the aquifer is in perfect connection with the stream, means the heads at the boundary of river and the aquifer are identical. The second solution, obtained by Hantush (1965) differs from the Theis solution by having a vertical semi-permeable layer at the boundary between the aquifer and stream bank. The third solution, obtained by Hunt (1999), assumes that the stream partially penetrates the top of the aquifer and the stream has a semi-permeable bottom with zero width and that the aquifer extends to infinity in all horizontal directions. The Dupit approximation, which assumes that streamlines are horizontal, is made in all three models. Although these representations depict unconfined aquifers, small drawdown assumption made in all three of these analytical solutions make them equally applicable to either unconfined or confined flow. A single aquifer river interaction problem has been studied analytically by several investigators (Morel-Seytoux 1975, Todd 1955, Cooper & Rorabaugh 1963). Cooper and Rorabaugh (1963) have studied flow into and out of the aquifer of finite length in response to changes in the stream stage by solving one dimensional Boussinesq's equation. Mishra (1987) studied analytically the interaction of river with a system of two aquifers separated by an aquitard and concluded that the quantity of recharge from the upper aquifer is controlled by the storage coefficient of the lower aquifer and the aquitard resistance. It was also inferred that a decrease in river width does not change the recharge rate appreciably. Calver (2001) analyzed a large number of riverbed and bank permeabilities found by researchers through laboratory/field determination and modelling. It was concluded that the riverbed permeabilities vary over eight orders of magnitude. However these information provide a rational starting input value for the models dealing with river aquifer interaction problems. Fox *et al*.(2002) proposed an analytical model of stream/aquifer interaction that predicts drawdown in an aquifer with leakage from a finite-width stream induced by pumping from a well. The model was formulated based on the assumptions of partial penetration of stream, semi-pervious streambed, and distributed recharge across a finite-width stream. Drawdown in the aquifer near a wide stream was found to be less than that predicted by a solution that ignored stream width. It was found that the deviation between the proposed analytical solution and the previous solutions increase as stream width increases. Fox (2003) demonstrated the importance of unsaturated flow in stream/aquifer exchange. He mentioned that the most widely used numerical groundwater-flow model, MODFLOW uses *inappropriate* simplifying assumptions within its RIVER and STREAM packages when the aquifer head drops below the bottom of a semi-pervious streambed. He incorporated the influence of unsaturated stream/aquifer interaction and attempted to improve the modeling capability of MODFLOW by improving its stream/aquifer interaction package. The modified RIVER package can account for saturated flow, a transition regime and also unsaturated flow. The proposed improvement to the RIVER package is based on the use of the Brooks-Corey (1964) relationship. A homogeneous and isotropic streambed is assumed to exist between the stream and underlying aquifer.

Study Area

The study area covers 2-blocks of Nadia district and 7 blocks of north 24-parganas districts lies between latitudes of 2249 and 2303N and longitudes of 8824 and 8851E. For the purpose of analysis and modelling, the study domain has been chosen as 1500 km^2 with a linear length of 50 km. in east-west direction, and width of 30 km. in north-south direction. The river Bhagirathi (also known as Hoogly at the downstream) forms the western boundary and the river Ichamati forms the eastern boundary of the study domain. The river Yamuna although discontinuous is in the middle of the area connects Bhagirathi and Ichamati. Figure 1 represent location map of the study domain. The topography of the area is flat with the surface slope of the order of 1:25000 from North-West to South-East direction. Local ponding in depression exists throughout the year. The area is hot and humid and receives rainfall to the tune of 1,850 mm/year, mostly from the south-west monsoon from May to September. About 80% of the annual rainfall is received during the monsoon months with peaks during June/July. The area has intense agricultural activities, and cultivation of paddy (2-3 times a year) is the main crop in the area. Groundwater is the main sources of water to meet the demand of irrigation and other needs. The rivers Bhagirathi and Ichamati are perennial in nature, and carry considerable water throughout the year. The bed slopes of the Bhagirathi and Ichamati respectively works out to

be 1:15,000 and 1:20,000 respectively. The width of the river Baghirathi and Ichamati varies from section to section due to meandering of rivers. The variation of width of Bhagirathi river is between 400-650m with an average of 500m. The width of Ichamati varies between 300-550m with an average of 400m. Both the rivers experience back-flow due to the tide from Bay of Bengal. The bed materials of rivers is sandy. The river Yamuna has width between 75-150m. The effect of back water flow due to tide from Bay of Bengal is more pronounced.
Fig. 1: Location map showing blocks covered within the study area.The depth to water table in the study area ranges between 2.5-3.0 m (pre-monsoon) and 0.5-2.5 m (monsoon) below ground level. About 29,058 number of shallow tube wells and 197 numbers of heavy duty wells in existence in the study domain. The shallow tubewells operate mostly for irrigation purpose having tapping zones between 18-50m.below ground level and a discharge range of 23-43 m^3/hr. The deep tubewells 60-150m below ground level and discharge of 45-200 m^3/hr meets the demand of domestic and municipal supplies. Out of the yearly withdrawal of 307.264 MCM (conservative estimate), about 10% is withdrawn for Kharif (June-Oct), 30% is for Rabi (Oct-Feb) and 60% is for Bado (Feb-June). In general, top layer consisting of clay followed by fine sand, sand/coarse sand and again clay. The study area thus can be considered as unconfined to semi-confined aquifer system.

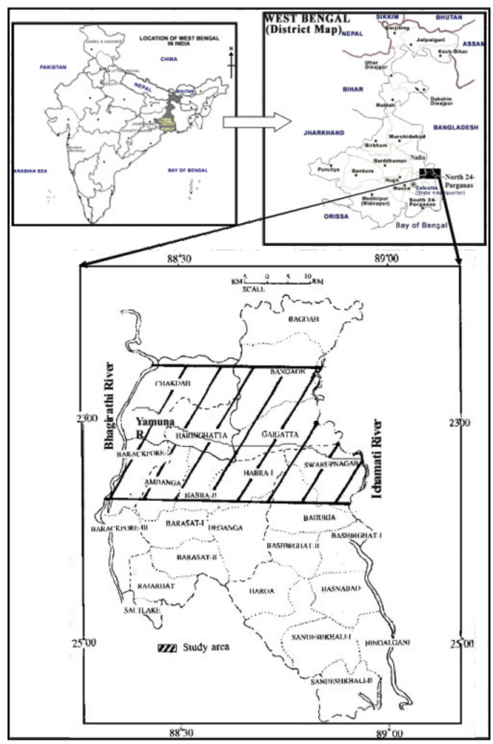

Fig. 1: Location map showing blocks covered within the study area.

Flow Modelling

The USGS 3-D transient groundwater flow model, MODFLOW (McDonald, 1988) as described below has been used for flow modeling.

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-q_s=S_s\frac{\partial h}{\partial t}$$

Where, K_{xx}, K_{yy} & K_{zz} are hydraulic conductivies along major axes [LT^{-1}], H is the potentiometric head [L], q_s is the volumetric flux per unit volume and represents sources and sinks [T^{-1}], S_s is the specific storage of the aquifer [L^{-1}] and t is the time [T]. The model has been employed to compute flow to/from Bhagirathi river to adjacent aquifer. In general, S_s, K_{xx}, K_{yy}, and K_{zz} are function of space and are the aquifer parameters, whereas h and q_s are functions of space and time and are variables. This equation for *flow conditions at the boundaries* of an aquifer system and specification of *initial head conditions* constitutes a mathematical model of the groundwater flow. River aquifer interaction relationships have also been developed to find the aquifer recharge with rise in river stage for the study area.

The study area of 50 km X 30 km has been discretized into 100 X 100 equal sizes gridal network i.e 10,000 cells having a cell dimension of 500 m X 300 m. The discretized area is shown in Figure 2. In order to account the change of lithology in local scales, the vertical depth of 80 m. has been divided into 10 equal layers of each 8 m thick having variable storativities and transmissivities in space. In the study domain, transmissivity and storativity were available at 21 locations. The pump test data represent that the transmissivity values varies from 530 to 4000 m^2/day and storativity between 0.33 x10^{-5} to 1.3 x 10^{-2}. The vertical hydraulic conductivity which is also an input parameter to the model has been taken to be 1/10 times the horizontal hydraulic conductivity uniformly distributed over the area. The porosity has been assumed to be 0.30 for all layers. One year monthly observed water level data for 58 locations were available. The water table data of September'97 (Figure 3) was taken as the initial water table condition for simulation of the flow model. For the sake of convenience all the water table data were transformed with respect to a reference level of 100m above msl.

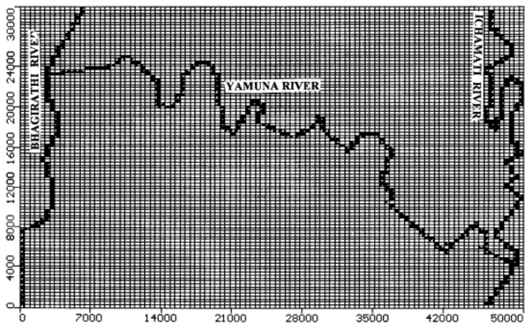

Fig. 2: Discretized map of the study domain showing network of rivers (Grid size: 500mX300m, 100 rows, 100 columns and 10 layers)

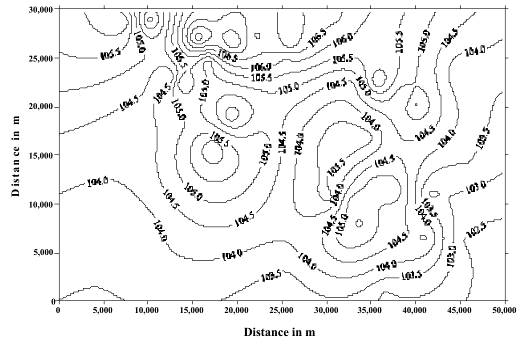

Fig. 3: Contour plot of initial water table elevation (Sept, 97)

Boundary Conditions

The river boundary has been taken in the east and west side of the study domain. In the central part, Yamuna has also been taken as a river. Rivers contribute water to the groundwater system or drain water from the flow domain depending on the head gradient between the stream and the groundwater regime. River package' in the MODFLOW simulates the flow between surface water and groundwater systems. To simulate these effects, three data types are required for each river cell viz. hydraulic conductance of the river bed $[L^2T^{-1}]$, elevation of the river bed bottom [L] and the head in the river. These data are used as input for different stress period in the model. Flow between the stream and the groundwater system is estimated from the following formula:

$$QRIV = CRIV\left(HRIV - h_{i,j,k}\right) \quad CRIV = \frac{k.L.W}{M}$$

Where, QRIV is the flow between the stream and the aquifer $[L^3T^{-1}]$, CRIV is hydraulic conductance of the stream-aquifer interaction $[L^2T^{-1}]$, HRIV is the head in the river [L], $h_{i,j,k}$ is the head at the node in the cell underlying the stream reach [L], k is the hydraulic conductance of river bed $[L\,T^{-1}]$, L is length of the reach contained in the river cell [L], W is the width of the river [L] and M is thickness of the river bed material [L].

Hydraulic conductance value 'k' of river/stream bed material has been assumed as 0.04m/day. This assumption is based on the available exit resistance of water through streambed of rivers. Thickness of the bed material has been taken as 2.0 m for river. The average width 'W'of

Bhagirathi in north(entry) and south (exit) of the study area is 645m and 243m respectively while for Ichamati these values were 128m and 160m. The average width of Yamuna is 15-20m. The cell length 'L' for river Bhagirathi and Ichamati is 300 m while for river Yamuna it is 500m. Values of `QRIV' for other cells have been calculated by linear interpolation method from the slope of the river bed. The river stage data for different months were available. North and south side of the study domain did not have any conventional hydrological boundaries. These two sides were considered as General Head Boundaries (GHB) or flux boundaries or open boundaries. The GHB in the flow model simulates flow into or out of a cell from an external source. Two data types are required for each GHB cells namely; hydraulic conductance [L^2T^{-1}] of the interface between the aquifer cell and the boundary and the head on the boundary. The hydraulic conductance values of GHB are calculated by multiplying the hydraulic conductivity by the layer thickness while heads on the boundaries are estimated from the information of observation wells near the boundary. Since river stage vary from season to season, and so is the GHB.

Estimation of Stresses

Stresses in a groundwater system are usually due to outflow from the aquifer or inflow into the aquifer. Withdrawal from the aquifer and the evapotranspiration have been considered as the discharge components. Evapotranspiration value is assumed to be 100 mm/year from root zone depth of 2.0 metre. Withdrawals from the aquifer are estimated from block-wise groundwater resources data of 1991. The outflow/inflow through boundaries (rivers or general head) are taken care of by the model automatically during simulation depending on the river stages and the head on the boundaries. Areal recharge through rainfall and the irrigation return flow have been considered as the external recharge to the flow domain. Rainfall recharge is considered as 20% of the annual rainfall of 1850 mm distributed over the monsoon period (May to September). For other months no rainfall recharge is considered. The Irrigation Return flow has also been taken as 20% of the net draft in each block in the respective periods.

Calibration of the Model

Initially the model was simulated with

the input values of aquifer parameters and external stresses to/from the model domain. The output i.e the computed water table elevations were compared with the observed water tabe data of observation wells for the different stress periods. In case of mismatch, the aquifer parameters and/or stresses were modified. Comparison of model response is shown for some of the months (Figures 4 and 5). These figures show that the difference between the observed and computed water table elevation is marginal and thus the calibration process was terminated at this stage. The calibrated model was then used to study the river aquifer interaction between Bhagirathi and the adjacent aquifer.

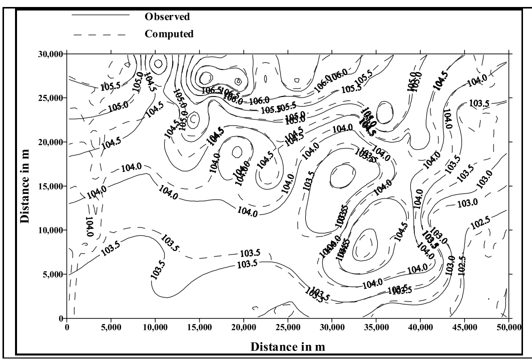

Fig. 4: Comparison of observed and computed water table, October '97.

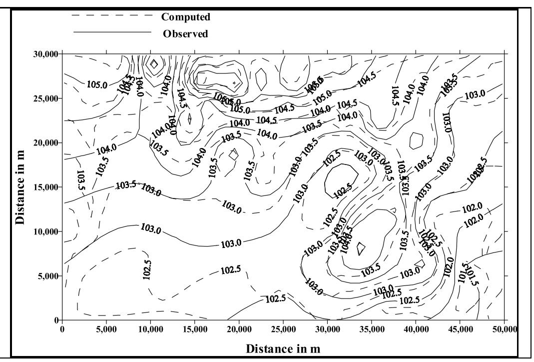

Fig. 5: Comparison of computed and observed water table, February 1998.

Results and Discussions

The calibrated model has been used to study the river aquifer interaction in the study area. For such an analysis 12 different locations from the northern entry point adjacent to Bhagirathi river were selected. The selection of these locations is based on the morphology of the river. Locations are chosen before the bends (at a distance of 15.75 km and 20.25 km), near the bends (at a distance of 0.75 km, 4.05 km, 21.45 km and 22.35 km) and in the straight portion (at a distance of 11.85 km, 26.55 km and 29.55 km) of the river. Two of the locations at 6.15 km and 6.75 km are also chosen where river Yamuna meets Bhagirathi. Two series of simulation and analysis have been done (i) the inflow to aquifer at these locations in different months of the year and (ii) the effect of incremental rise of river stage on the river aquifer interaction relationship for these selected locations and the model area.

Effect of flood on river aquifer interaction

Figures 6 shows that the inflow from Bhagirathi river to the adjacent cell of the aquifer. It is apparent that for different reaches inflow to the aquifer are different depending on the morphology of the river. For instance, the nature of curves for the straight portion at locations of 4.05 km and 6.15 km are similar. In the bend portion, the natures of inflow curves are different. Therefore a definite conclusion of the relation between inflow curves at different locations could not be drawn. Figure 7 represents the inflow to aquifer in the study area from Bhagirathi river in different months of the year. The stage of Bhagirathi river although is minimum in the month of April (from the observed stage data), but the inflow to aquifer during that month is not minimum. This is due to activation of more inflow (recharge) to aquifer from river in response to withdrawal requirement of the area.

River aquifer interaction relationship

In order to arrive at a definite relationship between the river aquifer interactions, each location was individually taken up for analysis. The effect of the incremental rise of the river stage on aquifer recharge was studied adjacent to Bhagirathi river by simulating the model at each location. A relationship has been developed to compute inflow to the aquifer for a unit rise in river stage for 12 locations. One of them are shown in Figures 8 and generalized for the study area in Figure 9. These relationships are in general linear and give the quantum of inflow to aquifer due to unit rise in river stage. If the fitting of the data point does not show perfect correlation which means that the data points are deviating from linearity. The reason may be due to the morphology of the river, geology of the area, bed material of the river, the water table condition and the stress condition of the aquifer adjacent to the river. Figure 9 shows the river aquifer interaction relationship for the study area. The relationship is linear with coefficient of correlation R^2= 0.99.

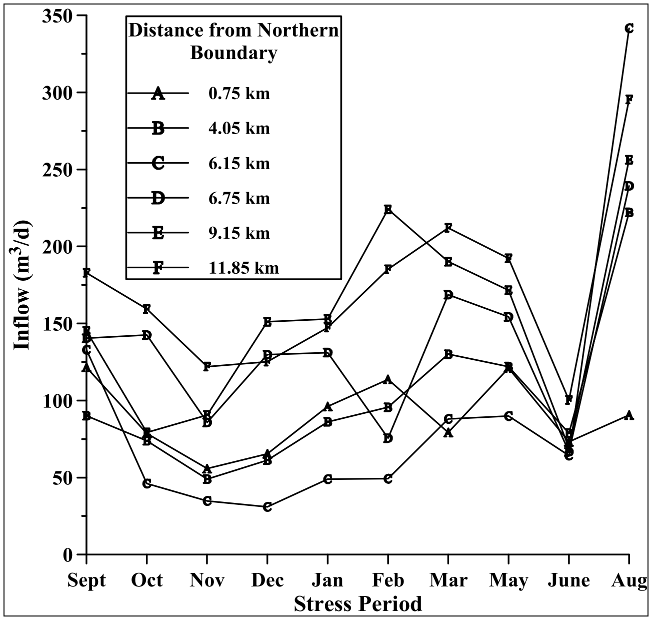

Fig. 6: Inflow to Aquifer for cells at various distances from the north of study area

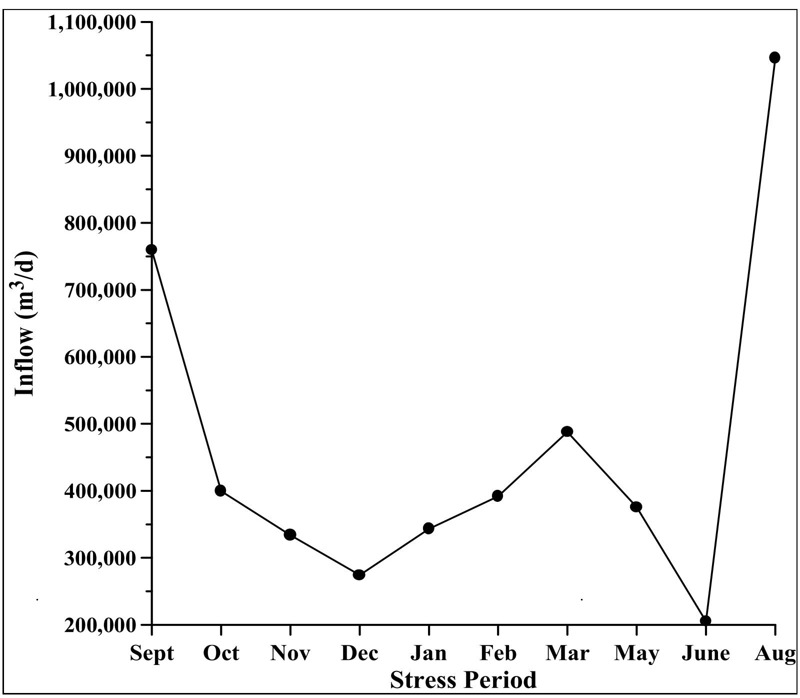

Fig. 7: Inflow to Aquifer in the study area from Bhagirathi River in different months.

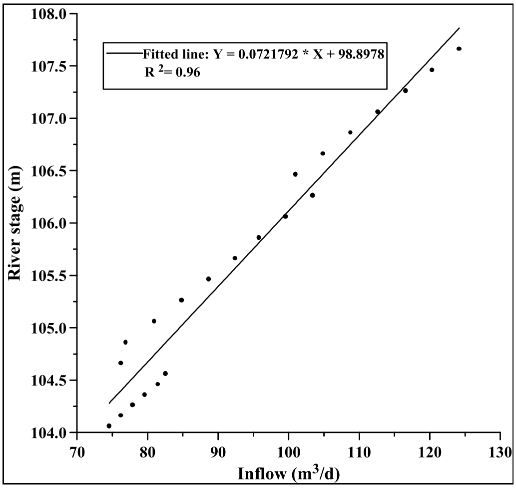

Fig. 8: River aquifer interaction relationship for a cell at a distance of 20.25 km from north.

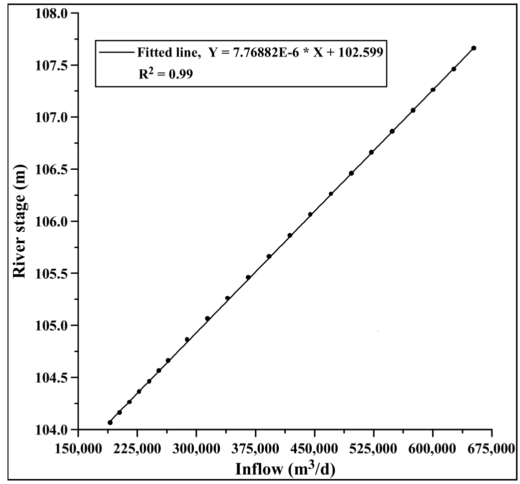

Fig. 9: River aquifer interaction relationship for the study area.

Conclusions

A groundwater flow model for the study area lying between Bhagirathi and Ichamati river in West Bengal have been developed. The model can be used as a prediction tool to find out the response of the aquifer system of the study area due to various stresses. The model has been used to study the river aquifer interaction. From the results and discussions, following conclusions have been drawn.

I) Inflow from Bhagirathi river to aquifer at different reaches for various months of the year starting from September has been quantified.

ii) The inflow from Bhagirathi river to the model domain has also been quantified at different months of the year.

iii) The inflow to aquifer not only depends on the river stage and morphology but also induced due to water table condition and the stresses in the aquifer adjacent to river.

iv) River aquifer interaction relationships for different reaches adjacent to Bhagirathi river due to incremental rise in river stage have been developed. The relationship, in general is linear but the coefficient of regression differs at different reaches. The reason may be attributed to the morphology of the river, water table condition and the stresses in the aquifer.

V. River aquifer interaction relationship for the whole model domain in response to the incremental rise in river stage has also been developed. The regression equation of the river aquifer interaction for the study area has been found to be Y = 7.76882E-6 * X + 102.599. The equation gives the quantum of inflow due to the stage of the river.

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IMPACT OF LAND USE CHANGE ON GROUNDWATER RECHARGE IN HARIDWAR DISTRICT

Nitin Mishra[1], S. Kumar [2]

[1]Assistant Professor, Dept. of Civil Engineering, Graphic Era University, Dehradun
[2]Professor, Civil Engg. Deptt , GEU, Dehradun, India.

Abstract

Over the last century, major changes in land use have occurred locally, regionally and globally. These will continue in the future too. The impact of urbanization on groundwater has a major concern over past few decades, and in particular, to those involved in groundwater quantity and qualitative studies. Increased in impervious area due to urbanization results in decreased infiltration, and finally affecting the groundwater storage. Thus, land use changes have to be assessed with spatial data technologies; especially the application of remotely sensed data and geographical information systems (GIS) has been used. The present study investigates the urban growth of Haridwar District, Uttrakhand using IRS satellite data for the years 1972, 1980, 1992, 2002 and 2011. Unscrupulous population increase, rise in food, fodder and fuel demands combined with industrial activities have led to rapid change in land use patterns. In this study,GIS tool is used to identify different land use classes from remotely sensed data and Groundwater potential of Haridwar District and supervised classification method is used to classify the urban land use and land cover. The analysis of the results show the drastic increase of built up area and reduced green cover within the city boundary limit. Due to increase of settlement area will directly impact the decrease of ground water level. Proper land use planning and Groundwater management is key to socio-economic up-liftment of a region.

Keywords: *Urban, Groundwater, Land use and cover, change detection, Remote Sensing, GIS*

Introduction

Water is essential for sustaining life on earth. The demand of water is increasing year to year with the ever rising population. For masses population water is the basic requirement for drinking and food production. For agriculture sector water supply for irrigation is becomes the difficult task, with limited sources water and uneven distribution pattern of water in space and time (cgwb.gov.in). Depending on a single sources for any purpose is much unreliable and the idea of using water for two or more alternative sources with economic condition is drawing the attention of planners, engineers, and decision makers.. The prospects of practicing conjunctive use of surface and groundwater will be better, provided one understands the hydrological balance cycle the various hydrological components are estimated on a seasonal basis for monsoon, Pre-monsoon and Post-monsoon seasons. For understanding and monitoring the water balance of the system helps in better conjunctive use (cgwb.gov.in).

Groundwater is a major source of drinking water across the world and plays a vital role in maintaining the ecological value of many areas (IPCC, 2001). However, the quantity and quality of groundwater are changing due to human activity (Gehrels et al., 2001) jeopardizing the suitability of the groundwater system as a source of drinking water and affecting natural reserves. Assessing the impact on the groundwater system and predicting the magnitude of change in the future is therefore a major scientific challenge (Tang, 2005). Land-use and land-cover changes are one of the main human induced activities altering the groundwater system (Calder, 1993). Nevertheless, the impact of future land-use changes on the groundwater system has not been investigated extensively. Throughout the entire history of mankind, intense human utilization of land resources has resulted in significant changes of the land-use and land-cover (Bronstert, 2004). Since the era of industrialization and rapid population growth, land-use change phenomena have strongly accelerated in many regions. The impact of land use and land cover changes on the regional water balance is the most vigorous research in the international hydrological fields, and lots of research indicate that large-scale land use and land cover changes are the important factors resulting in the regional climate and hydrological cycle changes (Hutjes *et al,* 1998; Zhang L *et al,* 2001[a]). Therefore, IGBP, IHDP, WCRP, DIVERSITAS, etc. take the relationship between Biosphere Aspects of the Hydrological Cycle (BAHC) and the land use and land cover changes, as well as its climate frangibility, as the core plans (Hoff, 2002; Lambin *et al.,* 2002).

The quantity and quality of groundwater are changing due to human activity which is one of the major scientific task. Since the era of industrialization and rapid population growth, land-use change phenomena have strongly accelerated in many regions (J. Dams, 2008). Management strategies on the development of groundwater resource while the growing demand for water by communities and industries. For example Urban/Land use, Cropping Pattern, Industrialization etc. The demand of water is increased; this demand is meet with groundwater.

The impact of urbanization implicates in groundwater quantity and qualitative studies. Increased in urbanization decreases infiltration. Land use planning and management approaches are key for development. It has been reported that in many parts of the country the water table is declining at the rate of 1–2 m/year (thirdworldcentre.org). The quantity and quality of groundwater are changing due to human activity. Since the era of industrialization and rapid population growth, land-use change phenomena have strongly accelerated in many regions which directly impacting the hydrology of the catchment area (J. Dams, 2008).

The impact of land use and land cover changes on the regional water balance is the most vibrant research in the international hydrological fields. Such work indicates that the regional vegetation ecosystem changes caused by land use and land cover changes remarkably affect the regional hydrological cycle (Wang Genxu, 2005). About 75-80% of human requirements like disposal of urban waste into water bodies cause groundwater contamination (Singh, 1999, 2000). Groundwater pollution has become one of the most vital issues in India. In January 1994 the Central Pollution Control Board (CPCB), Delhi, undertook the first major groundwater quality monitoring exercise (CPCB, 1998).

Many of the critical regions have to depend on groundwater resources for various needs due to scarcity of surface water. In the urban central zones of cities, the subsoil water has already been adulterated by industrial wastes (Sharad K. Jain, 2007).

Moreover, in LUCC established by IGBP and IHDP, one core problem is to understand the impact of the regional land use and land cover changes on hydrological process and water resources (Suzanne Serneels, 2001). Such work indicates that the regional vegetation ecosystem changes caused by land use and land cover changes remarkably affect the regional hydrological cycle (Zhang L *et al.,* 2001[b]). Therefore, the mechanism of land use and land cover changes in the catchment impacting on hydrological process become important fields in the development of hydrology (Hoff, 2002). There in to, actual estimation of the impact of human activities on groundwater system is critical to establish reasonable utilization program of regional groundwater resources (Schwarts et *at.,* 2003; Sato et *at.,* 2003). Previous research of the impact of human activities on groundwater system mainly focused on the aspects of the intensity and reasonability of groundwater utilization, while ignoring the impact of land use changes on the groundwater system in the basin. Actually, as the important part of regional hydrological cycle, groundwater system has strong response to land use and land cover changes (Mtembezeka et *at.,* 1997; Alley et *at.,* 1999).

About 75-80% of human requirements for water are fulfilled by groundwater. Uncontrolled disposal of urban waste into water bodies, open dumps, and poorly designed landfills cause groundwater contamination (Singh, 1999, 2000). Groundwater pollution has become one of the most important toxicological and environmental issues in India. In January 1994 the Central Pollution Control Board (CPCB), Delhi, undertook the first major groundwater quality monitoring exercise. The report, published in December 1995, identified 22 locations in 16 states of India as “critical” sites of groundwater pollution, and the CPCB found industrial effluents to be the primary reason for groundwater pollution (CPCB, 1998). Many of the critical regions have to depend on groundwater resources for various needs due to scarcity of surface water. In the industrial and urban fringe zones of cities, the subsoil water in the area has already been polluted by industrial effluents. Industries release high concentrations of toxic substances. The wells in many residential areas are contaminated with nitrate and detergents. The high fluoride content of groundwater has negative effects and is suspected to be a severe health hazard in the surrounding region.

2. Study Area

Haridwar district, covering an area of about 2360 sq.km. is in the western part of Uttarakhand state of India. It's latitude and longitude are 29.58 degree north and 78.13 degree east respectively. The height from the sea level is 249.7 mts. The district came into existence on 28th Dec. 1988. Prior to its inclusion in the newly created state of Uttarakhand, this district was a part of Saharanpur Divisional Commissionary. The district is ringed by Saharanpur in the west, Dehradun in the north and east, Pauri Garhwal in the east, Muzzaffar Nagar and Bijnor in the south. The district is administratively subdivided into three tehsils i.e. Haridwar, Roorkee and Laksar and six development blocks i.e. Bhagwanpur, Roorkee, Narsan, Bahadrabad, Laksar and Khanpur. Haridwar is one of the first towns where Ganga emerges from the mountains to touch the planes. As per the 2001 census, the population of the district is 14,44,213.

The Land use/cover Map was generated by using satellite image of 1972, 1980, 1992, 2002 and 2011, through ERDAS IMAGINE (version 9.2), which is powerful image processing software.The determination of digital land cover classification is to have a meaningful information class value, which can evaluate the landscape in accurate. Land Cover refers to the cover including vegetation, urban infrastructure, water, barren land, etc. Land cover is a fundamental variable that impacts on and links many parts of the human and physical environments. Land cover is highly affected by human induced activities rather than natural events. Today, mainly agriculture expansion, burning activities or fuel wood consumption, deforestation, some construction works and urbanization cause land cover changes. Consequently, such changes may have great impacts on the catchment by varying hydrological processes such as infiltration, groundwater recharge, and base flow and runoff. Land use change is the main concern for worldwide environment change and is used by town and country planners to design Eco friendly and sustainable economic growth.

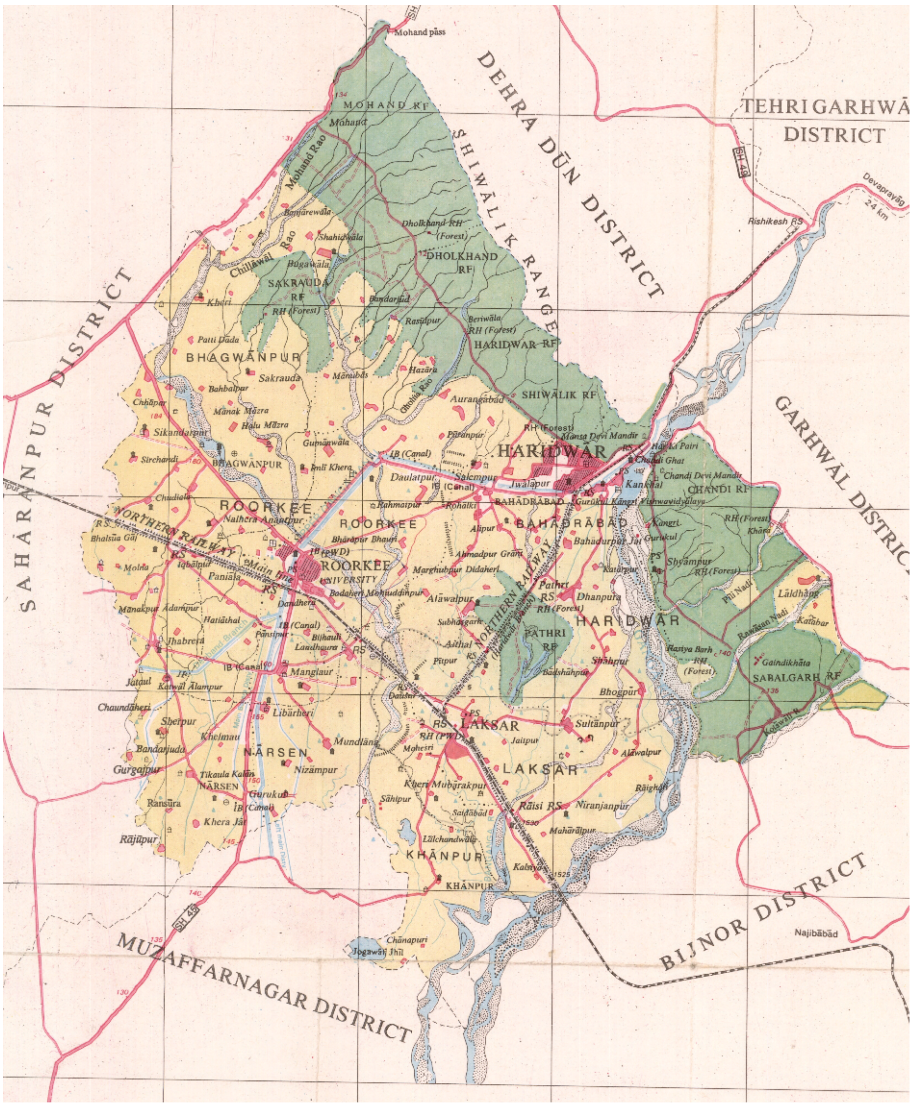

Figure 1: Map of Haridwar District

Table 1. Land-use / land-cover for Haridwar District Area (in sq. km).

Class	1972		1980		1992		2002		2011	
	Area (Km^2)	Area (%)	Area (Km^2)	Area (%)	Area (Km^2)	Area (%)	Area (Km^2)	Area (%)	Area (Km^2)	Area (%)
Urban	11.42	0.59	126.21	6.55	204.33	10.60	493.03	25.57	693.47	35.97
Water	51.96	2.69	49.52	2.57	45.57	2.36	18.65	0.97	9.56	0.50
Vegetation	518.85	26.91	492.48	25.54	486.58	25.24	318.21	16.50	277.70	14.40
Agriculture	1255.88	65.14	1199.47	62.21	1147.84	59.54	1062.56	55.11	935.54	48.52
Barren Land	89.90	4.66	60.32	3.13	43.68	2.27	35.55	1.84	11.74	0.61

3. Groundwater Analysis

Groundwater resources are facing increasing pressure as urbanization is increasing and climatic condition are changing all over the world. The impacts of land-use changes and climate changes are difficult to separate as they partly result in similar changes in the ecosystems. These cause major risks to our most valued water resource and on ecosystems (nks-umwelt.pt-dlr.de).

Demand for groundwater is increasing while the water resources remain almost constant. Therefore, continuous withdrawals of groundwater may result in depletion of water table. It is necessary to maintain the water level fluctuations have to be kept within a particular range over the monsoon and non-monsoon seasons (www.sys.virginia.edu). Inspite of the favorable average availability of groundwater, there are some areas in the country having scarcity of water. From time immemorial, groundwater has played a major role in increasing the food production in India (Dhirendra Kumar Singh, 2002).

For this study, 12 wells have been considered in the study area. The data were collected from Saharanpur Divisions of UP State Groundwater Department. Groundwater storage per year calculated using well data. Both techniques recharge due to rainfall using rainfall infiltration factor and ground water storage equation are utilized in this study to find out storage and recharge of Haridwar district. The Recommended Value for specific yield is 16 % by GEC1997. The soil property is assumed same for whole Haridwar district for this study and in the absence of any pumping test. Study area is having area of 1928 Km^2, a specific yield value of 0.16 (recommended values Geological Estimation Committee, 1997), considering the Sandy Loam soil Alluvium.

3.1 *Storage Equation*

The estimation of groundwater storage has been done by using the storage equation. The specific yield values considered in the computations are to be taken preferably from field tests, in the absence of which, the recommended values of specific yield are 16 % to be considered (Rana Chatterjee 2009) and study area of different districts. Pre and Post monsoon data were collected from Saharanpur and Meerut Divisions of UP State Groundwater Department.

The storage equation used to find out groundwater storage given by GEC1997 is as follow:

$S = \Delta h \times S_y \times A$

Where, *S* = Storage, *Δh* = Well Location Data of Pre Monsoon $(h)_2$-Well Data Location of Post monsoon $(h)_1$, S_y = Specific yield.

In Haridwar district as given in Table 2 and Figure 3 the urban area has increased from 11.42 Km^2 in 1972 to 693.47 Km^2 in 2011 which shows an increment, whereas other like water bodies are decreasing from 51.96 Km^2 in 1972 to 9.56 Km^2 in 2011, Vegetation from 518.85 Km^2 in 1972 to 277.70 Km^2 in 2011, Agriculture from 1255.88 Km^2 in 1972 to 935.54 Km^2 in 2011 and Barren Land from 89.90 Km^2 in 1972 to 11.74 Km^2 in 2011 which led to the decrease in storage from 0.629 Km^3 in 1972 to 0.259 Km^3 in 2011.

Table 2. Year wise Change in Storage w.r.t. Land use of Haridwar

Year	Urban	Water	Vegetation	Agriculture	Barren Land	Change in Storage
1972	11.42	51.96	518.85	1255.88	89.90	0.629
1980	126.21	49.52	492.48	1199.47	60.32	0.562
1992	204.33	45.57	486.58	1147.84	43.68	0.336
2002	493.03	18.65	318.21	1062.56	35.55	0.287
2011	693.47	9.56	277.70	935.54	11.74	0.259

3.1 *Recharge assessment based on Rainfall Infiltration Factor*

Recharge can be estimated based on the rainfall infiltration factor method. Recharge from rainfall in monsoon season is as follow (cgwb.gov.in)

$$R_{rf} = f \times A \times N_r \qquad (2)$$

Where, R_{rf} = Recharge due to Rainfall, A = Area of computation for recharge, Nr = Normal rainfall in monsoon, f = Rainfall Infiltration factor.

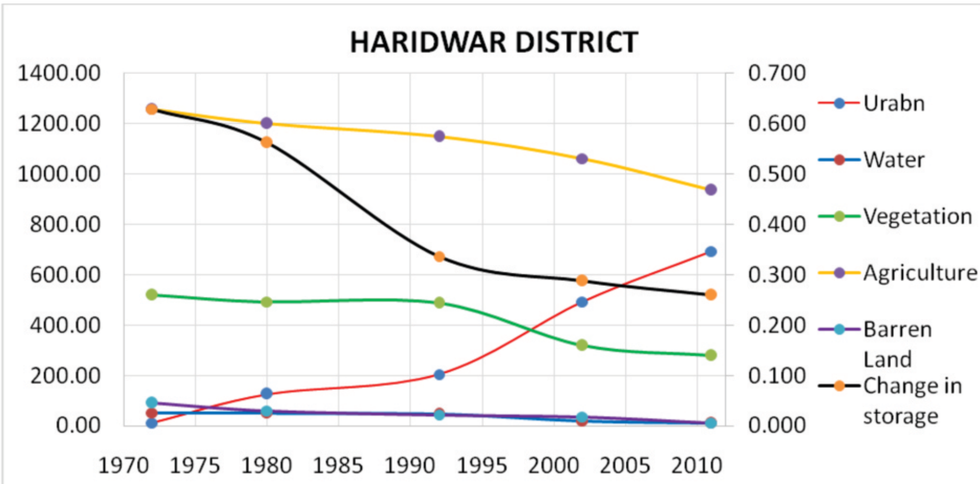

Figure 3. Year wise Change in Storage w.r.t. Land use of Haridwar

The same recharge factor may be used for both monsoon and non-monsoon rainfall, with the condition that the recharge due to non-monsoon rainfall may be taken as zero, if the normal rainfall during the non-monsoon season is less than 10% of normal as by GEC 1997annual rainfall (cgwb.gov.in).The most part of study area considered under alluvial soil series. The Recommended Value for rainfall infiltration factor is 10 % by GEC 1997 (Rana Chatterjee 2009) (cgwb.gov.in).The soil property is assumed same for whole command area for this study. Recharge due to rainfall infiltration factor for study area has been preferred by calculating the average of normal monsoon rainfall data for whole year in the study area.

For Haridwar district the urban area has increased from 11.42 Km^2 in 1972 to 693.47 Km^2 in 2011 is shown in table 3 and illustrated in figure 4 which shows an increment, whereas other like water bodies are decreasing from 51.96 Km^2 in 1972 to 9.56 Km^2 in 2011, Vegetation from 518.85 Km^2 in 1972 to 277.70 Km^2 in 2011, Agriculture from 1255.88 Km^2 in 1972 to 935.54 Km^2 in 2011 and Barren Land from 89.90 Km

Km^2 in 1972 to 11.74 Km^2 in 2011 which led to the decrease in rainfall recharge in monsoon season from 0.000309 Km^3 in 1972 to 0.000227 Km^3 in 2011.

Table 3. Year wise Rainfall Recharge w.r.t. Land use of Haridwar

Year	Urban	Water	Vegetation	Agriculture	Barren Land	Rainfall Recharge
1972	11.42	51.96	518.85	1255.88	89.90	0.000309
1980	126.21	49.52	492.48	1199.47	60.32	0.000295
1992	204.33	45.57	486.58	1147.84	43.68	0.000286
2002	493.03	18.65	318.21	1062.56	35.55	0.000251
2011	693.47	9.56	277.70	935.54	11.74	0.000227

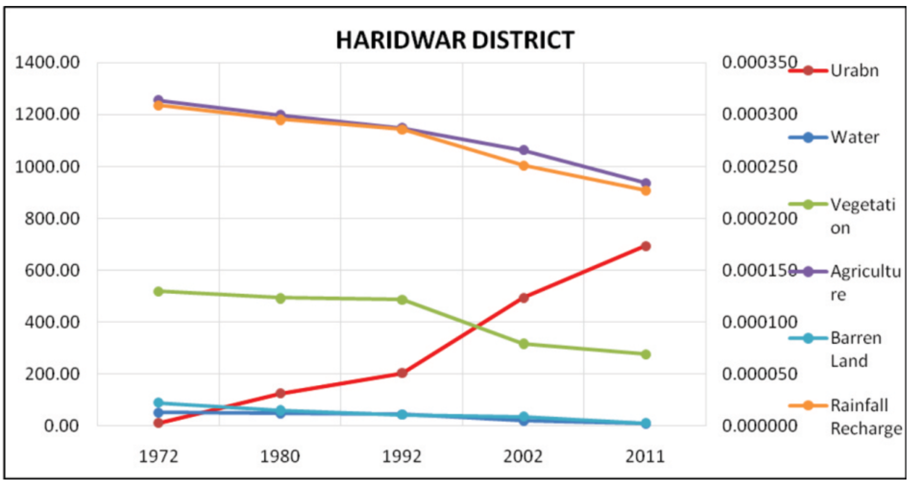

Figure 4 Year wise Rainfall Recharge w.r.t. Land use of Haridwar

Conclusions

During the last five decades there has been sharp increase in water consumption owning to the population explosion, unprecedented rise in standard of living and enormous development. The problem is caused not only by natural factors, but also due to mismanagement and lack of knowledge about existing water resources. Therefore, a proper management plan can only be adopted by knowing the balance of different hydrologic components of hydrological unit. The present study is an attempt to assess the impact of land use change on groundwater storage in Haridwar District with an area of 1928 Km^2 in Uttarakhand. It has been found that the land use profoundly affects the groundwater storage in the region. The current study deals with the use of a physical storage equation of groundwater, remote sensing data, ERDAS IMAGINE 9.2 for Index Map registration and GIS techniques to locate the well location on Shapefile, estimating the water table contour which shows the variation in ground water fluctuation in Pre Monsoon season and Post Monsoon Season.

This result shows an increase in paved area which lead to increase in runoff volume and decrease in time of concentration, which effect the decrease in percolation rate and once the percolation rate get affected, it is obvious the groundwater storage will decline. In addition as per decadal calculation results show groundwater levels are going down due excessive withdrawal of groundwater in Haridwar District area and reduction in natural recharge area.

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APPLICATION OF DATA ENVELOPMENT ANALYSIS FOR RANKING OF IRRIGATION SUBSYSTEMS

K. Srinivasa Raju[1]**, D. Nagesh Kumar** [2]

[1]Department of Civil Engineering, BITS Pilani Hyderabad Campus, Hyderabad, India.

[2]Department of Civil Engineering, Indian Institute of Science, Bangalore, India.

Abstract

Twenty irrigation subsystems of Khadakwasla irrigation project, Maharashtra, India are evaluated and selection of the suitable subsystem(s) is made using CCR based Data Envelopment Analysis (DEA). Five criteria, participation and cooperation, effective water availability, conjunctive use, agricultural education and economic status are evaluated. Out of these, first four are considered as inputs whereas economic status as output for consideration into the DEA methodology. Three weight scenarios are proposed, namely, WS1, WS2, WS3. Average efficiency of irrigation subsystems for WS1, WS2, WS3 are found to be 0.77, 0.7062, 0.8125. Significant difference between the efficiency values and ranking pattern before and after cross efficiency matrix analysis is observed. Comparative analysis of the three weight scenarios indicated that cross efficiency approach is not proved to be useful for discriminating the irrigation subsystems for the present case study, however it is found to be effective for grouping the irrigation subsystems. Kendall rank correlation coefficient between efficiency and cross efficiency approaches for WS1, WS2, and WS3 are found to be 0.701, 0.701, 0.842. It is inferred that the present study can be explored for similar complex situations with appropriate modifications.

Keywords: *Cross efficiency, DEA, Khadakwasla, rank*

1. Introduction

Irrigation systems are expected to be financially and economically attractive to achieve food and production targets. However, this may not be true for most of the irrigation systems in developing countries. Establishing a totally new irrigation system to augment the increasing food and production targets in the present context of environmental awareness and conflicting perspectives of various stakeholders is becoming difficult. This necessitates the improvement of existing irrigation systems which may result in increased efficiency. Factors such as participation and co-operation among farmers, timely water availability, relevant education for farmers, effective utilization of available groundwater, recycled wastewater also contribute to the improved efficiency. Data Envelopment Analysis (DEA) is becoming popular due to its ability to establish relationship simultaneously between inputs and outputs. Numerous researchers had explored DEA with reference to irrigation planning and performance related aspects some of which are as follows: Ntantos and Karpouzos (2010) applied DEA to the case study of Thessaloniki plain, Northern Greece. They concluded that combined use of DEA and performance criteria was useful for efficiency assessment of irrigation systems. Phadnis and Kulshrestha (2012) evaluated the efficiency of water users' associations of Samrat Ashok Sagar irrigation project, India, using DEA and inferred that considerable variations occur amongst the various water users's associations. Umanath and Rajasekar (2013) analyzed the technical and scale efficiency of farms in Periyar-Vaigai irrigation system, India using DEA. It is observed that (a) potential exists for increasing the profit further by 43% in the farm holdings and (b) 47% of the farms were not operating at optimal scale. Borgia et al. (2013) analyzed 17 small and 3 large irrigation schemes located along the River Senegal using DEA and found that large schemes performed similarly to small-scale schemes. Lu et al. (2013) evaluated eco efficiency of water systems of 31 administrative regions in China using DEA and found that there was a significant difference in the eco efficiency of water systems. Ali and Klein (2014) applied DEA to estimate the technical efficiency scores, the Malmquist total factor productivity indices, and their implicit input shadow shares for 12 irrigation districts in Southern Alberta. Irrigation districts were on average

84.3 % technically efficient in their input use.

Poudel et al. (2015) used DEA and Tobit regression to compute the efficiency of conventional and organic coffee growing farmers in Nepal and efficiency was found to be 0.89 and 0.83 respectively. Variation in technical efficiency was related to education, farm experience and training/extension services, and access to credit. Azad et al. (2015) evaluated the economic efficiency of irrigated agriculture of Australian farms using DEA and found that irrigated farms are comparatively more efficient in overall farm activity management and not very efficient in managing water resources. Sayin and Yilmaz (2015) measured the efficiency level of irrigation unions in the Antalya Province of Turkey and found that technical efficiency scores varied between 0.39 and 1.00. Restoration and modernization efforts were suggested to enhance the efficiency level in the long term. Similar studies are reported by Ma and Zheng (2011) for evaluation of degree of harmony between water resources and economic development, Manjunatha et al. (2011) for impact of groundwater markets in India on water use efficiency, Storto (2013) for public and private partnership in water supply efficiency.

Present study is an effort to explore the suitability of DEA as a ranking approach for analyzing the irrigation systems of Khadakwasla irrigation project, Maharashtra, India. Present paper covers description of data envelopment analysis, case study and formulation of payoff matrix, results and discussion followed by conclusions.

2. Data Envelopment Analysis

Mathematical expression of CCR (Charnes Cooper Rhodes) based DEA is as follows (Charnes et al. 1978; Raju and Nagesh Kumar 2014):

Optimal efficiency of irrigation subsystem k is defined as

$$E_k = \underset{u_r, v_i}{Max} \sum_{r=1}^{s} u_r y_{rk} \quad (1)$$

Subject to

$$\sum_{r=1}^{s} u_r y_{rj} - \sum_{i=1}^{m} v_i x_{ij} \leq 0; \quad j = 1,2,..k..,n \quad (2)$$

$$\sum_{i=1}^{m} v_i x_{ik} = 1 \quad ; j = 1,2,..k..,n \quad (3)$$

$$u_r \geq \varepsilon_r \quad ; r = 1,2,..,s \quad (4)$$

$$v_i \geq \varepsilon_i \quad ; i = 1,2,..,m \quad (5)$$

where j = irrigation subsystem index, $j = 1,2,...k,...,n$; r = Output index, $r = 1,2,..,s$; i = Input index, $i = 1,2,..,m$; y_{rk} = Value of r^{th} output for the k^{th} irrigation subsystem; y_{rj} = Value of r^{th} output for the j^{th} irrigation subsystem; x_{ij} = Value of i^{th} input for the j^{th} irrigation subsystem; u_r = Weight of the r^{th} output; v_i = Weight of the i^{th} input; ε_r = Lower limit of weights for output r; ε_i = Lower limit of weights for input i; E_k = Efficiency of irrigation subsystem k.

Irrigation subsystem with efficiency of 1 is considered as the suitable and the weights derived for that irrigation subsystem are termed as optimal weights.

3. Case study and formulation of payoff matrix

The Khadakwasla project is situated in Upper Bhima subbasin of Krishna basin, located in Pune district of Maharashtra State, India. Khadakwasla project supplies irrigation water through New Mutha Right Bank Canal (NMRBC), taking off from Khadakwasla dam through a distributary network. There are 60 distributaries/ irrigation subsystems to irrigate 62,146 ha area. The main canal is 202 km long (Khadakwasla Complex Project Note, 2008; Morankar 2014). In the present study, 20 irrigation subsystems are considered and are named as A1 to A20 for academic purpose.

The questionnaire used for the study was designed after a considerable literature review, consultation with irrigation department officials, local researchers and experts, who are well versed with the project. The field survey was conducted distributarywise. In the present study, evaluation criteria chosen are: participation and cooperation (PC), effective water availability (EWA), conjunctive use (CU), economic status (ES) and agricultural education (AE) (Morankar 2014). Each evaluation criteria for the respective irrigation subsystem was assessed subjectively (based on the perceptions of researcher) i.e., Very Good (VG), Good (G), Moderately Good (MG), Fair (F), Unsatisfactory (UNS). Accordingly, these values are rated as 5, 4, 3, 2, 1 (Morankar 2014).

Table 1 presents payoff matrix consisting of irrigation subsystems considered.

Table 1 Irrigation subsystems and evaluation criteria

Irrigation Subsystems	PC	EWA	CU	AE	ES
A1	MG	F	G	MG	MG
A2	G	F	G	MG	MG
A3	MG	F	MG	MG	F
A4	G	MG	G	MG	MG
A5	G	MG	G	MG	F
A6	MG	F	G	F	F
A7	VG	MG	MG	MG	F
A8	MG	G	VG	MG	MG
A9	MG	MG	MG	MG	MG
A10	MG	F	G	MG	F
A11	F	F	G	F	F
A12	G	F	MG	MG	MG
A13	MG	F	MG	MG	MG
A14	F	F	MG	F	MG
A15	G	MG	MG	MG	MG
A16	G	F	MG	MG	F
A17	MG	MG	G	F	MG
A18	MG	F	MG	F	F
A19	F	F	MG	MG	F
A20	VG	F	G	MG	MG

4. Results and Discussion

In the present study, out of the five criteria, PC, EWA, CU, AE are considered as inputs whereas ES as output for the DEA purpose. Three different weight scenarios are proposed to assess the relative efficiency : weight set 1 (WS1) bounds are (equations 4 and 5: u, v1 to v4 .02; weight set 2 (WS2) bounds are: u0.1; v1 to v4 .05 whereas weight set 3 (WS3) bounds are u, v1 to v4 0.0.

Weight set 1: It is observed from Table 2 that maximum and minimum values of u, v1, v2, v3, v4 respectively are (0.3333, 0.2156), (0.43, 0.02), (0.4,0.02), (0.28,0.02), (0.42,0.02). Note that minimum values of v1 to v4 are same as the chosen lower bound. Contrarily, minimum value of u is much higher than the chosen lower bound. It is observed from Table 3 that lowest efficiency of 0.48 is observed for irrigation system A5 whereas highest efficiency of 1 is observed for A14. Average efficiency value is 0.77. It is observed that irrigation systems (A1, A9, A12, A17), (A2, A15), (A11, A18, A19), (A3, A6), (A10, A16) occupying 3, 4, 7, 9, 10 positions with efficiencies of 0.94, 0.92, 0.6533, 0.64, 0.6267. Tie in the ranking pattern creates uncertainty while prioritizing the irrigation subsystems for possible improvements. In other words, it can be inferred that irrigation systems A1, A9, A12, A17 require similar improvements as they are falling in one cluster of homogeneous irrigation subsystems with similar efficiency.

An effort is also made to understand the impact of cross efficiency for discriminating the irrigation system's (cross efficiency considers not only irrigation system's usual efficiency, but also other irrigation system's efficiencies based on corresponding weights within the payoff matrix). It is observed from Table 3 that irrigation systems are divided into two distinct groups in this process. Irrigation systems, A1, A2, A4, A8, A9, A12, A13, A14, A15, A17, A20 with efficiency value of 0.9093 form one group whereas A3, A5, A6, A7, A10, A11, A16, A18, A19 with efficiency value of 0.6062 form another group which is contrary to the discussion made in the previous paragraph. It can be noticed that cross efficiency approach has not improved the discrimination capacity between the irrigation systems. However, it formulated two distinct groups for possible improvements which clearly show the DEA's simultaneous advantage and disadvantage. Kendal rank correlation value is computed between the ranks obtained from efficiency and cross efficiency approach and found to be 0.701 which is reasonable.

Weight set 2: It is observed from Table 2 that similar trend of variation of weights as that of weight set 1 exists. It is observed from Table 3 that lowest and highest efficiency of 0.45 and 1 is observed for A5 and A14 whereas average efficiency is found to be 0.7062. It is interesting to note that efficiency values of each irrigation system for WS2 are lower than that of WS1. However, ranking pattern of irrigation systems remains same for WS1 and WS2. Cross efficiency in this case also leads to two distinct groups as that of WS1 having efficiency values of 0.8358, 0.5572. Kendall rank correlation value is same as that of Ws1.

Weight set 3: It is observed from Table 2 that weights for most of the input variables are zero which is not representing the realistic situation indicating the necessity of precise estimation of weights of criteria other than zero as proposed in this weight set. Irrigation systems (A1,A2, A9, A12, A13, A14, A15, A17, A20), A4, (A3, A6,A7,A8, A10,A11, A16, A18, A19), A5 are having efficiency values of 1, 0.75, 0.6666, 0.5 with average efficiency of 0.8125; cross efficiency leads to two distinct groups with efficiencies 0.9583, 0.6389. Note that effect of weight is significant in this case as number of irrigation systems having equal efficiency are more as compared to WS1 and WS2. Kendall rank correlation value is 0.842.

Above outcome is based on the views of the surveyed stakeholders, proposed lower bounds and data availability; however, focus of the present paper is on the methodology that can be implemented with minor modifications.

Conclusions

Data Envelopment Analysis is explored for twenty irrigation subsystems of Khadakwasla irrigation project with five criteria. Three weight sets are proposed to assess their relative impact on the ranking. The following conclusions are drawn based on the obtained results:

- Average efficiency of irrigation subsystems for WS1, WS2, WS3 are 0.77, 0.7062, 0.8125.
- It is observed that there is significant difference between the efficiency values and ranking pattern before and after cross efficiency matrix analysis in DEA for three scenarios of weight sets.
- Precise estimation of weights of criteria is essential for meaningful ranking of irrigation systems as evident from the results of three weight sets.
- Comparative analysis of three weight sets indicated that cross

efficiency approach is not proved to be useful for discriminating the irrigation subsystems for the present case study. However, found to be effective for grouping the irrigation subsystems.
- Kendall rank correlation coefficient between efficiency and cross efficiency approaches for WS1, WS2, and WS3 are found to be 0.701, 0.701, 0.842.

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Table 2 Weight values corresponding to inputs and outputs for three weightage scenarios

Irri. System	Weight set 1(W1)					Weight set 2 (W2)					Weight set 3 (W3)				
	u	v1	v2	v3	v4	u	v1	v2	v3	v4	u	v1	v2	v3	v4
A1	0.3133	0.02	0.4	0.02	0.02	0.2833	0.0500	0.2500	0.0500	0.0500	0.3333	0.0000	0.5000	0.0000	0.0000
A2	0.3067	0.02	0.39	0.02	0.02	0.2667	0.0500	0.2250	0.0500	0.0500	0.3333	0.0000	0.5000	0.0000	0.0000
A3	0.32	0.02	0.02	0.28	0.02	0.3000	0.0500	0.0500	0.2000	0.0500	0.3333	0.0000	0.0000	0.3333	0.0000
A4	0.24	0.02	0.02	0.2	0.02	0.2250	0.0500	0.0500	0.1250	0.0500	0.2500	0.0000	0.0000	0.2500	0.0000
A5	0.24	0.02	0.02	0.2	0.02	0.2250	0.0500	0.0500	0.1250	0.0500	0.2500	0.0000	0.0000	0.2500	0.0000
A6	0.32	0.02	0.02	0.02	0.41	0.3000	0.0500	0.0500	0.0500	0.2750	0.3333	0.0000	0.0000	0.0000	0.5000
A7	0.3	0.02	0.02	0.26	0.02	0.2500	0.0500	0.0500	0.1500	0.0500	0.3333	0.0000	0.0000	0.3333	0.0000
A8	0.2156	0.2533	0.02	0.02	0.02	0.2056	0.1333	0.0500	0.0500	0.0500	0.2222	0.3333	0.0000	0.0000	0.0000
A9	0.3133	0.02	0.02	0.2733	0.02	0.2833	0.0500	0.0500	0.1833	0.0500	0.3333	0.0000	0.0000	0.3333	0.0000
A10	0.3133	0.02	0.4	0.02	0.02	0.2833	0.0500	0.2500	0.0500	0.0500	0.3333	0.0000	0.5000	0.0000	0.0000
A11	0.3267	0.42	0.02	0.02	0.02	0.3167	0.3000	0.0500	0.0500	0.0500	0.3333	0.5000	0.0000	0.0000	0.0000
A12	0.3133	0.02	0.02	0.2733	0.02	0.2833	0.0500	0.0500	0.1833	0.0500	0.3333	0.0000	0.0000	0.3333	0.0000
A13	0.32	0.02	0.02	0.28	0.02	0.3000	0.0500	0.0500	0.2000	0.0500	0.3333	0.0000	0.0000	0.3333	0.0000
A14	0.3333	0.43	0.02	0.02	0.02	0.3333	0.3250	0.0500	0.0500	0.0500	0.3333	0.5000	0.0000	0.0000	0.0000
A15	0.3067	0.02	0.02	0.2667	0.02	0.2667	0.0500	0.0500	0.1667	0.0500	0.3333	0.0000	0.0000	0.3333	0.0000
A16	0.3133	0.02	0.02	0.2733	0.02	0.2833	0.0500	0.0500	0.1833	0.0500	0.3333	0.0000	0.0000	0.3333	0.0000
A17	0.3133	0.02	0.02	0.02	0.4	0.2833	0.0500	0.0500	0.0500	0.2500	0.3333	0.0000	0.0000	0.0000	0.5000
A18	0.3267	0.02	0.02	0.02	0.42	0.3167	0.0500	0.0500	0.0500	0.3000	0.3333	0.0000	0.0000	0.0000	0.5000
A19	0.3267	0.42	0.02	0.02	0.02	0.3167	0.3000	0.0500	0.0500	0.0500	0.3333	0.5000	0.0000	0.0000	0.0000
A20	0.3	0.02	0.38	0.02	0.02	0.2500	0.0500	0.2000	0.0500	0.0500	0.3333	0.0000	0.5000	0.0000	0.0000
Max	0.3333	0.43	0.4	0.28	0.42	0.3333	0.325	0.25	0.2	0.3	0.3333	0.5	0.5	0.3333	0.5
Min	0.2156	0.02	0.02	0.02	0.02	0.2056	0.05	0.05	0.05	0.05	0.2222	0	0	0	0

Table 3 Efficiency, cross efficiency and corresponding ranking pattern for three weight scenarios

Irri. System	Weight set 1				Weight set 2				Weight set 3			
	Efficiency	Rank	Cross efficiency	Rank	Efficiency	Rank	Cross Efficiency	Rank	Efficiency	Rank	Cross efficiency	Rank
A1	0.94	3	0.9093	1	0.85	3	0.8358	1	1	1	0.9583	1
A2	0.92	4	0.9093	1	0.8	4	0.8358	1	1	1	0.9583	1
A3	0.64	9	0.6062	2	0.6	9	0.5572	2	0.6666	3	0.6389	2
A4	0.72	6	0.9093	1	0.675	6	0.8358	1	0.75	2	0.9583	1
A5	0.48	12	0.6062	2	0.45	12	0.5572	2	0.5	4	0.6389	2
A6	0.64	9	0.6062	2	0.6	9	0.5572	2	0.6666	3	0.6389	2
A7	0.6	11	0.6062	2	0.5	11	0.5572	2	0.6666	3	0.6389	2
A8	0.6467	8	0.9093	1	0.6166	8	0.8358	1	0.6666	3	0.9583	1
A9	0.94	3	0.9093	1	0.85	3	0.8358	1	1	1	0.9583	1
A10	0.6267	10	0.6062	2	0.5666	10	0.5572	2	0.6666	3	0.6389	2
A11	0.6533	7	0.6062	2	0.6333	7	0.5572	2	0.6666	3	0.6389	2
A12	0.94	3	0.9093	1	0.85	3	0.8358	1	1	1	0.9583	1
A13	0.96	2	0.9093	1	0.9	2	0.8358	1	1	1	0.9583	1
A14	1	1	0.9093	1	1	1	0.8358	1	1	1	0.9583	1
A15	0.92	4	0.9093	1	0.8	4	0.8358	1	1	1	0.9583	1
A16	0.6267	10	0.6062	2	0.5666	10	0.5572	2	0.6666	3	0.6389	2
A17	0.94	3	0.9093	1	0.85	3	0.8358	1	1	1	0.9583	1
A18	0.6533	7	0.6062	2	0.6333	7	0.5572	2	0.6666	3	0.6389	2
A19	0.6533	7	0.6062	2	0.6333	7	0.5572	2	0.6666	3	0.6389	2
A20	0.9	5	0.9093	1	0.75	5	0.8358	1	1	1	0.9583	1
Max	1.0000		0.9093		1.0000		0.8358		1.0000		0.9583	
Min	0.4800		0.6062		0.4500		0.5572		0.5000		0.6389	
Average	0.7700		0.7729		0.7062		0.7104		0.8125		0.8146	

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