Methodology for the estimation of groundwater flux across simplified boundary using GIS and groundwater levels

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Accurate estimation of the groundwater budget requires good estimate of flux across the boundary of a region. Different methods and techniques are available to estimate recharge to groundwater however methods for estimation of flux across boundaries are not available. The present article represents a GIS-based methodology to estimate the groundwater flow rate and volume of water flux across the boundary. Groundwater level data (pre-monsoon and post-monsoon) are used to derive detailed maps like flow direction, hydraulic gradient and velocity component perpendicular to the boundary. For the study area, the calculated flux through the simplified boundary average 6.63×10^5 m^3 for monsoon period, 13.75×10^5 m^3 for non-monsoon period and 20.38×10^5 m^3 annually. Flux of monsoon period varies from maximum of 11.41×10^5 m^3 in 2003 to minimum of 0.83×10^5 m^3 in the year 2013 and for annual period it varies from maximum 38.8×10^5 m^3 in 2003–04 to minimum -7.94×10^5 m^3 in 2012–13.

Keywords: Darcy’s law, geographical information system, groundwater flux, simplified boundary.

GROUNDWATER is one of the most important but poorly managed resources. It is considered the major portion of the world’s freshwater resources. Groundwater accounts for 26% of global renewable fresh water resources[1]. Increasing population, expanding areas of irrigated agriculture and economic development are the causes for an ever increasing demand for water worldwide[2]. Although theoretically and globally, such demand can be met by using groundwater aquifer system and surface water, regional variations are large, leading to water stress in several parts of the world. In water stressed areas, groundwater aquifer system is often used as a main source of water. In India, according to one estimate[3], agriculture accounts for about 85% of total annual draft. According to another estimate[4,5], groundwater fulfils about 60% irrigation and 80% drinking water requirements.

The term ‘groundwater’ is used to denote all the water found beneath the ground surface. Groundwater exists in geological formations through which it can be penetrated, transmitted and stored[6]. Many factors affect the occurrence and movement of groundwater in a region, including surface and sub-surface hydrological features such as lithology, geological structure, drainage density, ground water flow and boundary conditions, topography, depth of weathering, extent of fractures, primary porosity, secondary porosity, slope, drainage patterns, landform, land use/cover and climate[7,8].

Groundwater level represents the theoretical surface which is approximated by the elevation of water surfaces in the wells which penetrate only a short distance into the saturated zone[9]. The continuous depletion of groundwater levels is not a new story in India as farmers in many areas of the country are using groundwater faster than nature is replenishing it[3]. Overexploitation or persistent groundwater depletion can occur if the groundwater extraction for agricultural and industrial activities exceeds the groundwater recharge[2,7,8]. To protect the ecosystem, it is one of the most important aspects to understand the relationship between groundwater recharge and extraction. Therefore, knowledge of groundwater aquifer systems is very essential in integrated water resources management[10].

Below the ground level, groundwater flux through boundary refers to the entry of water into the saturated zone below the water table surface, together with the associated flow away from the water table within the saturated zone[8]. Estimation of groundwater recharge as well as flux through boundary is extremely important for water budgeting of a study area. Many different approaches exist for estimating groundwater recharge. Water-level fluctuation method[11,12] and soil moisture budget method[12,13] have been established to estimate the infiltration, runoff, evapotranspiration and groundwater recharge in the watershed.

In this study a new geographical information system (GIS)-based methodology is developed to estimate the groundwater flux flowing through a simplified boundary of the region. GIS is a widely used software system for storing, managing, analysing and visual expressing of hydro-geological data as well as their spatial locations in relational database to improve the groundwater management[7]. GIS tools have been used along with spatial varied data for rainfall, groundwater table variations, hydro-geological zones to estimate spatially distributed values

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of groundwater recharge[14]. GIS has also been extensively used for groundwater modelling[15–17]. Remote sensing, GIS and other assessment techniques have been used for a long time to study groundwater in terms of its movement, quantity, and quality throughout the world[18]. GIS-based methodology along with Darcy's law has been used for groundwater flow estimation across the boundary in ground water flow modelling[19].

GIS-based method is used to estimate the groundwater flux using groundwater mapping which depends on several variables and needs a computationally consistent manipulation of georeferenced information and hydrogeological data at different spatial scales. In absence of hydrogeological data or where the measurements are not made or not feasible to measure due to economic or other various considerations, geostatistical methods can be used to determine the required value using spatial interpolation[20]. This study is useful in identifying the groundwater flux flowing through a boundary of the region on the cell basis analysis using GIS technique.

Study area

The study area covers Khushkhera–Bhiwadi–Neemrana Investment Region (KBNIR) identified by Delhi–Mumbai Industrial Corridor (DMIC), located in the Alwar district, Rajasthan, India (Figure 1). The KBNIR area is situated in north-east of Rajasthan from 27°54′33″ to 28°03′20″N lat. and from 76°24′06″ to 76°35′40″E long. covering a geographical area of about 162.4 km^2. Western part of the study area lies in Neemrana block and eastern part in Mundawar block. Out of the total area, Neemrana block covers 130 km^2 and remaining 32.4 km^2 is covered by Mundawar block.

Climate of the KBNIR is semi-arid and very hot in summer and extremely cold in winter. The monsoon season is of very short duration. Winter season starts by the middle of November and continues up to the beginning of March. Summer season follows the winter season and

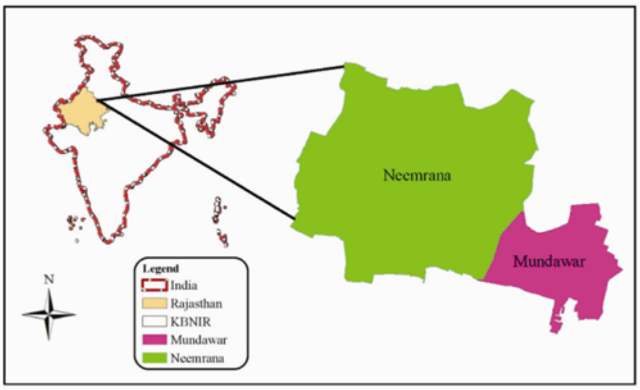

Figure 1. Location of study area.

extends up to the end of the June. The south-west monsoon continues from July to mid-September. The period from mid-September to mid-November forms the post-monsoon season. The annual average rainfall is 588.7 mm. The rainfall during the south-west monsoons constitutes about 82% of the average annual rainfall. The mean monthly air temperature ranges from 12°C in January up to 35°C in June, with a mean annual air temperature of 25°C. Water level data of 16 wells from 2003 to 2013 and borelog data of 5 wells was obtained from Central Ground Water Board (CGWB), Jaipur. Tables 1 and 2 show the borelog data of 5 wells and water level data of 16 wells, respectively, for the study area, in 2012.

The area is covered by unconsolidated formations consisting of sandy clay, clay, silt, kankar and sand, etc. of Quaternary age underlain by Delhi and pre-Delhi group of rocks comprising quartzite, phyllites, schists, etc. Pre-Delhi (pre-Aravalli) is the major group of rocks. The soils of the region can broadly be divided into two classes, viz., Older Alluvial Soils and Red Gravelly Soils. Older Alluvial Soils are found in major part of the KBNIR region including full part of Mundawar tehsil and large part of Neemrana tehsil. Red Gravelly Soils are found in some parts of Neemrana tehsil.

Methodology

The methodology for estimation of the groundwater flux through the boundary is developed using GIS-based spatial analysis of groundwater levels and hydrogeology data of the region. Figure 2 shows the flow chart of the methodology.

Data and information required by hydrogeological studies is complex. Information concerning geology, hydrology, geomorphology, soil, climate, land use, topography and man-made (anthropogenic) features need to be analysed and combined[21]. Methodology is applied assuming that the hydrogeological layers within the region are hydraulically interconnected and the groundwater level gradients do not change significantly for different seasons[19]. It is also assumed that monsoon period starts from 1 June and continues up to 15 September and non-monsoon period starts from 16 September and continues up to 31 May of the next year.

Typically, the boundary taken for groundwater analysis is complex and contains many small curves. It is difficult to calculate normal direction to boundary at different locations. Therefore, in the first step boundary of the study area is simplified into only horizontal and vertical lines. Figure 3 shows both original and simplified boundaries of the study area. This simplification is not likely to introduce major errors in estimation but would significantly reduce the complexity of solution. It may be noted here that some of the area gets excluded from the boundary and another portion is included from outside boundary.

Table 1. Borelog data

Coordinate (UTM)					
Latitude	Longitude	Village	Ground elevation (m)	Bedrock elevation (m)	Permeability (m/day)
3087760.6	656781.0	Khanpur Ahir	280.74	219.24	01.99
3094968.4	628676.3	Gandala	302.32	194.63	00.73
3102704.2	637905.6	Ghilot	310.92	233.42	17.01
3082770.6	638927.7	Sodawas	284.00	224.90	04.11
3100280.2	648832.4	Sakatpura Bawad	276.83	172.00	04.11

Table 2. Water levels during pre- and post-monsoon, 2012

Location coordinate (UTM)				Depth of water level (m)	
Latitude	Longitude	Village	Elevation (m)	Pre-monsoon	Post-monsoon
3086879.3	634833.3	Barrod	234.00	51.20	49.70
3094570.0	628844.5	Gandala	307.50	41.80	42.10
3090159.6	630860.0	Hamzapur	318.50	56.90	52.70
3083855.9	659485.3	Harsauli D/W	285.00	24.50	24.35
3082735.0	658515.2	Harsauli P/W	285.00	23.60	22.90
3097218.1	664226.9	Kheri	271.00	19.80	18.15
3101718.51	669082.16	Kotkasim	260.00	20.00	18.80
3091651.29	662334.61	Nagal Saliya	269.00	16.90	14.90
3093750.98	653450.44	Ajarka	279.00	22.45	21.85
3092486.54	640674.30	Jat Behror	294.00	27.80	26.90
3100361.49	650415.74	Manka	270.00	28.80	28.25
3082573.60	645714.16	Pipli	303.50	38.30	38.20
3104595.14	633651.54	Kanhawas	273.00	51.10	52.70
3110156.98	635554.39	Mandhan	281.00	54.50	54.30
3097980.80	636675.86	Neemrana	315.00	47.80	48.20
3098061.19	643559.63	Shahjahanpur	286.50	30.90	30.90

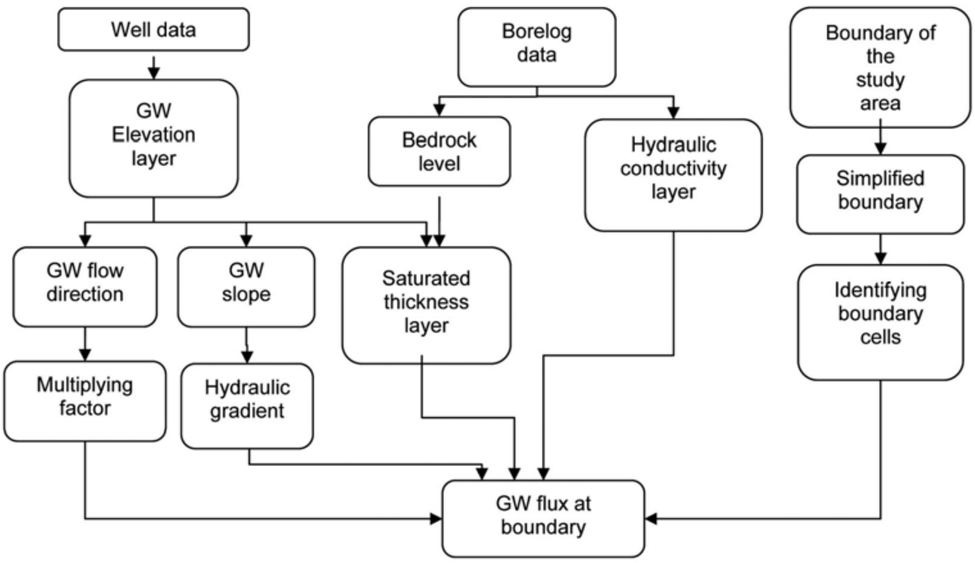

Figure 2. Flow chart showing methodology for estimation of groundwater flux.

Normally, both balance each other and so net effect to this change in shape of boundary shall be negligible.

This GIS-based methodology requires groundwater levels for pre-monsoon and post-monsoon period, lithology information, permeability, transmissivity and saturated thickness of the boundary. The groundwater levels during the pre-monsoon month (June) and post-monsoon month (December) for 2003 to 2013 are observed at 16 wells located surrounding the study area. Ordinary Kriging method is used to calculate the missing values in the database.

A geodatabase is created by point interpolation method and inverse distance weighted (IDW) technique has been used to obtain raster maps of elevation of pre-monsoon and post-monsoon water levels for the study area. A resolution of 100 m is adopted to construct the maps and same resolution is applied to all other raster maps in the GIS database. Also, all the maps are snapped to the same grid so that cells of different maps exactly overlap each other and calculations are easily performed using multiple layers. Simplified boundary of the study area is enclosed only by horizontal (top and bottom) and vertical (left and right) boundaries and includes 708 cells.

In aquifer system, hydraulic gradient can be defined as the change in water depth per unit flow length of water. From groundwater elevation map, the groundwater percentage slope maps are constructed and by multiplying it by 100 using raster calculator, converted to magnitude of hydraulic gradient at each cell. Direction of the hydraulic gradient map could be calculated using 'flow direction' GIS tool. Direction maps are constructed using groundwater level elevation map and extracted at simplified boundary of the study area having horizontal and vertical line segments only.

There are eight valid output directions in a flow direction map related to the eight adjacent cells into which groundwater flow can travel. This approach is commonly referred to as an eight-direction (D8) flow model as shown in Figure 4 and follows an approach presented by Jenson and Domingue[22]. Since the direction of hydraulic gradient could be parallel, perpendicular or at 45° angle to the boundary and could be facing inward (positive flow) or outward (negative flow), a multiplication factor is required to convert it to velocity perpendicular to the boundary. Table 3 shows the multiplying factor for different position of boundary cell and direction of hydraulic gradient.

From borelog geodatabase, spatial distribution of permeability of the aquifer formation and bed rock elevation has been carried out using IDW interpolation method.

Darcy's law is applied to construct velocity map using permeability and slope map at simplified boundary. According to Darcy's law[23], the velocity of groundwater flow is given by eq. (1)

$$v_{\mathrm{d}} = \frac{Q}{A} = -\frac{k\mathrm{d}h}{\mathrm{d}l} = -Ki, \tag{1}$$

$$i = \frac{\mathrm{d}h}{\mathrm{d}l} = \phi, \tag{2}$$

where v_{d} is the Darcy's velocity in the groundwater slope direction, also known as specific discharge; K the hydraulic conductivity which is defined as a constant that serves as a measure of the permeability of the porous medium; Q groundwater flux through area A, $\mathrm{d}h/\mathrm{d}l$ is the hydraulic gradient which is defined as change in hydraulic head per unit change in length (eq. (2)); l is the direction of groundwater flow at the point under consideration and ϕ is slope.

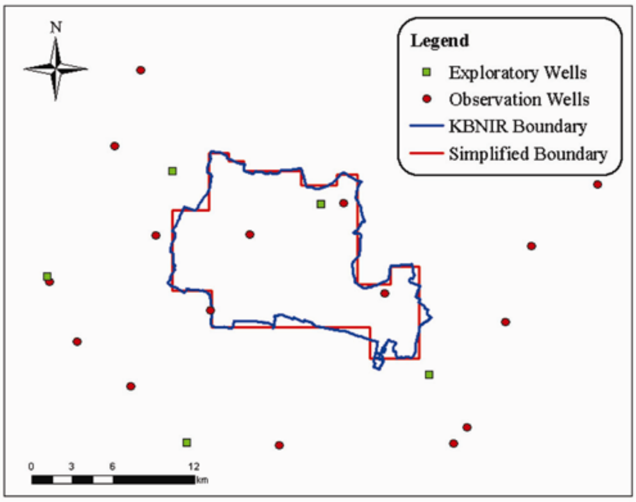

Figure 3. Location of wells.

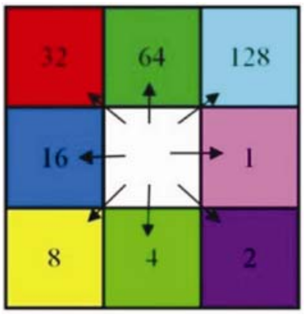

Figure 4. D8 flow model.

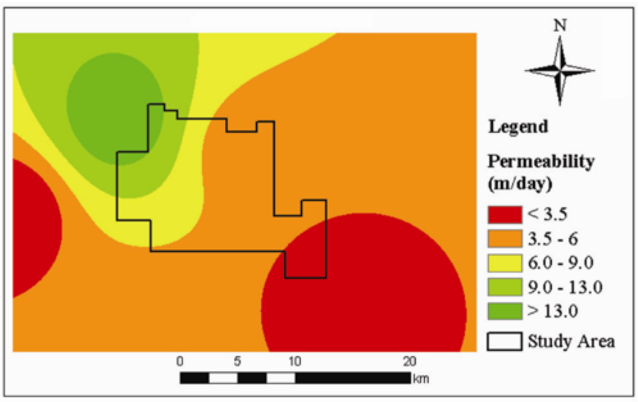

Figure 5. Permeability map.

Table 3. Conversion table for flow direction values to multiplying factors

	Horizontal top boundary segment			Horizontal bottom boundary segment		
Cell value	GW flow direction	Velocity component	Multiplying factor	GW flow direction	Velocity component	Multiplying factor
1	Parallel to boundary	0	0	Parallel to boundary	0	0
2	Inward at 45°	Sin 45°	0.71	Outward at 45°	–Sin 45°	–0.71
4	Inward	1	1	Outward	–1	–1
8	Inward at 45°	Sin 45°	0.71	Outward at 45°	–Sin 45°	–0.71
16	Parallel to boundary	0	0	Parallel to boundary	0	0
32	Outward at 45°	–Sin 45°	–0.71	Inward at 45°	Sin 45°	0.71
64	Outward	–1	–1	Inward	1	1
128	Outward at 45°	–Sin 45°	–0.71	Inward at 45°	Sin 45°	0.71
	Vertical left boundary segment			Vertical right boundary segment		
Cell value	GW flow direction	Velocity component	Multiplying factor	GW flow direction	Velocity component	Multiplying factor
1	Inward	1	1	Outward	–1	–1
2	Inward at 45°	Sin 45°	0.71	Outward at 45°	–Sin 45°	–0.71
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8	Outward at 45°	–Sin 45°	–0.71	Inward at 45°	Sin 45°	0.71
16	Outward	–1	–1	Inward	1	1
32	Outward at 45°	–Sin 45°	–0.71	Inward at 45°	Sin 45°	0.71
64	Parallel to boundary	0	0	Parallel to boundary	0	0
128	Inward at 45°	Sin 45°	0.71	Outward at 45°	–Sin 45°	–0.71

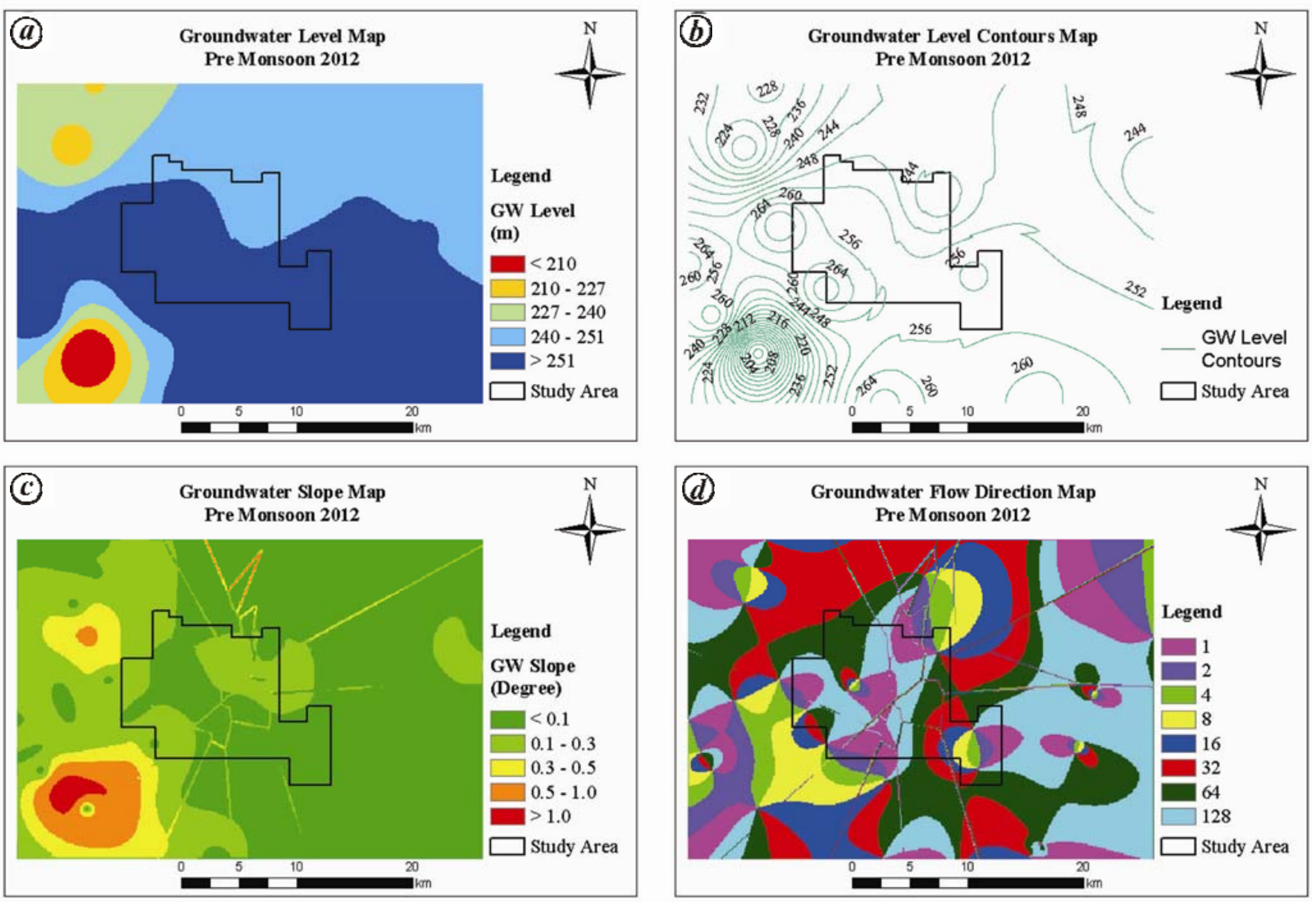

Figure 6. Maps showing Groundwater features for pre-monsoon year 2012.

Table 4. Total groundwater flux (m^3/day) across the boundary

	At pre-monsoon time				At post-monsoon time			
Year	Minimum	Maximum	Mean	Sum	Minimum	Maximum	Mean	Sum
2003	–355.16	466.27	14.28	10107.86	–353.79	467.17	15.84	11213.80
2004	–349.17	462.43	14.16	10028.66	–345.64	455.81	13.65	9664.23
2005	–337.96	451.49	13.26	9390.17	–328.59	439.15	12.12	8584.13
2006	–394.33	515.24	14.10	9982.43	–364.71	478.78	13.11	9285.26
2007	–358.90	478.08	12.20	8640.48	–360.22	479.73	12.11	8572.32
2008	–353.28	472.53	11.78	8342.55	–351.97	468.33	10.53	7452.73
2009	–248.56	333.37	3.01	2128.28	–245.48	330.12	0.62	437.29
2010	–220.09	294.67	2.73	1932.34	–234.17	314.79	3.01	2128.33
2011	–289.92	272.51	2.91	2058.29	–294.83	267.40	3.59	2540.66
2012	–242.61	222.76	1.25	884.20	–237.67	212.57	0.94	665.59
2013	–197.77	163.49	–10.51	–7439.22	–214.65	180.76	–5.42	–3834.59

Table 5. Quantity of groundwater flux (m^3) during monsoon period

	Flow rate (m^3/day)			
Year	Pre-monsoon	Post-monsoon	Mean flow rate (m^3/day)	Volume of water flow (m^3) in monsoon period
2003	10,107.86	11,213.80	10,660.83	1,140,708.81
2004	10,028.66	9,664.23	9,846.45	1,053,570.15
2005	9,390.17	8,584.13	8,987.15	961,625.05
2006	9,982.43	9,285.26	9,633.85	1,030,821.95
2007	8,640.48	8,572.32	8,606.40	920,884.80
2008	8,342.55	7,452.73	7,897.64	845,047.48
2009	2,128.28	437.29	1,282.79	137,258.53
2010	1,932.34	2,128.33	2,030.34	217,246.38
2011	2,058.29	2,540.66	2,299.48	246,044.36
2012	884.20	665.59	774.90	82,914.30
2013	–7,439.22	–3,834.59	–5,636.91	–603,149.37

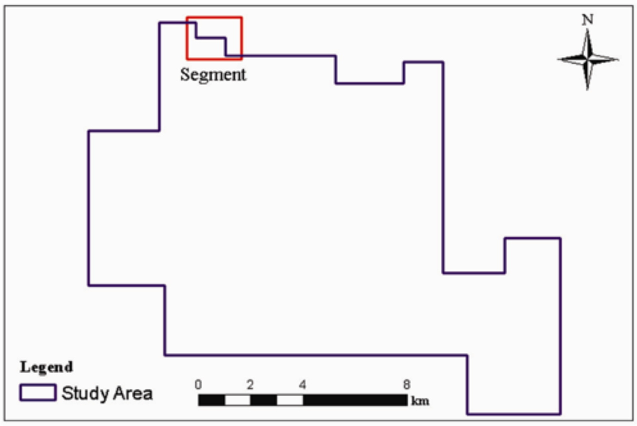

Figure 7. Simplified boundary with segment.

Map for the velocity component perpendicular to the boundary is prepared using eq. (3)

$$v_p = v_d \times M_f, \quad (3)$$

where v_p is the velocity component perpendicular to the boundary and M_f is the multiplying factor. The multiplying factor values are obtained from flow direction map using eight direction flow model as shown in Table 3.

Map for groundwater flux through a cell (f_x) into the region and total flux (F_T) through the entire boundary is prepared using eqs (4) and (5), respectively

$$f_x = v_p \times \mathrm{ST} \times \mathrm{CW}, \quad (4)$$

$$F_T = \sum_{\mathrm{bnd}} f_x, \quad (5)$$

where f_x is the groundwater flux per unit cell; ST is saturated thickness, that is, the difference of the groundwater surface elevation and bed rock elevation; CW is cell width and F_T is the summation of groundwater flux from each cell across simplified boundary of the study area.

Results and discussion

The groundwater level elevation map is prepared for both pre and post-monsoon groundwater levels for all years from 2003 to 2013. The minimum and maximum levels of water table during pre- and post-monsoon periods depend on the rainfall during the preceding period. In general, the maximum level of water table is found during post-monsoon period and minimum level of water table is found during pre-monsoon period.

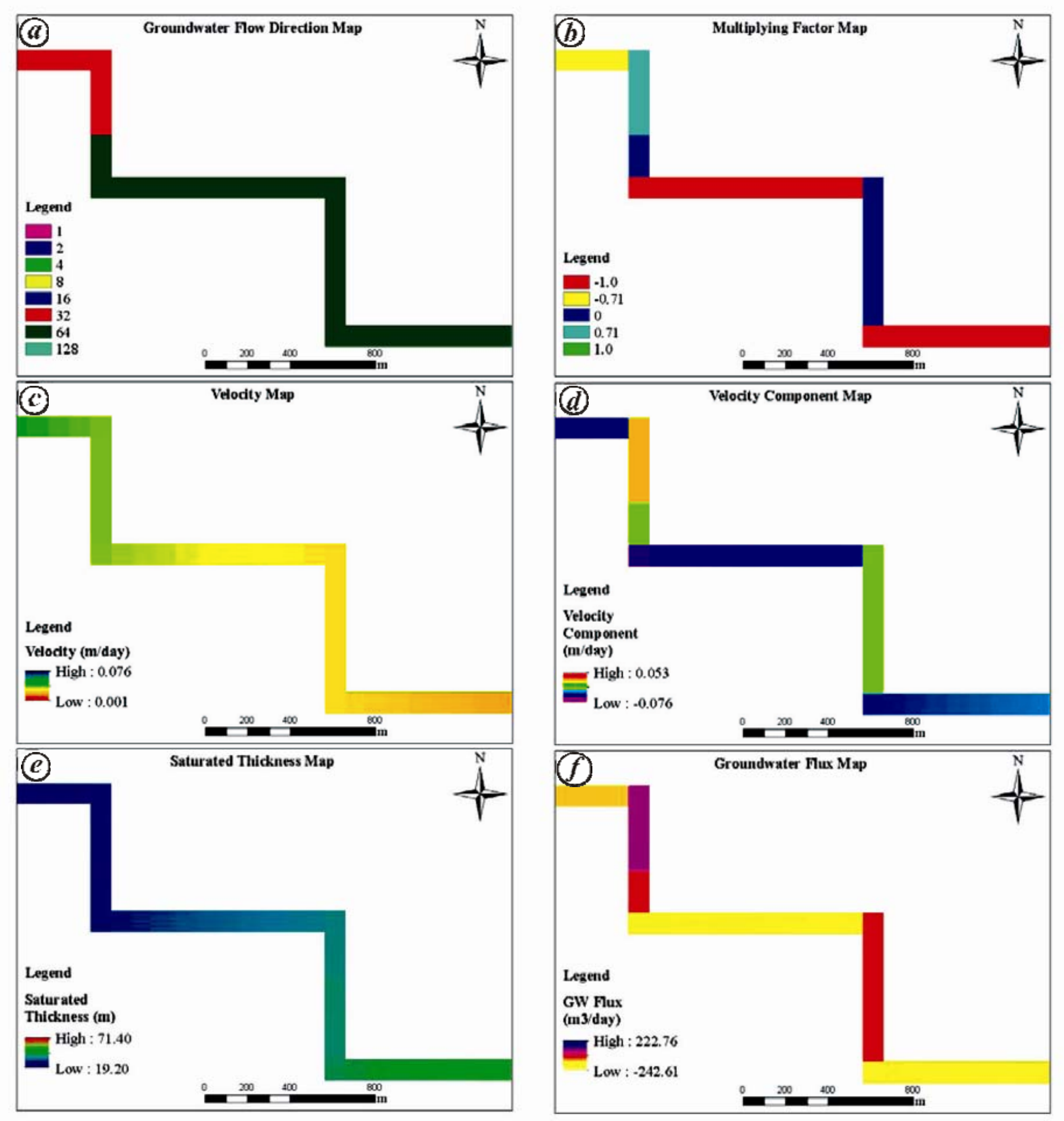

Figure 8. Different maps constructed at simplified boundary for pre-monsoon year 2012.

Table 6. Quantity of groundwater flux (m^3) during non-monsoon period

Year	Flow rate (m^3/day) Post-monsoon	Flow rate (m^3/day) Pre-monsoon (next year)	Mean flow rate (m^3/day)	Volume of water flow (m^3) in non-monsoon period
2003–04	11,213.8	10,028.66	10,621.23	2,740,277.34
2004–05	9,664.23	9,390.17	9,527.20	2,467,544.80
2005–06	8,584.13	9,982.43	9,283.28	2,395,086.24
2006–07	9,285.26	8,640.48	8,962.87	2,312,420.46
2007–08	8,572.32	8,342.55	8,457.44	2,182,019.52
2008–09	7,452.73	2,128.28	4,790.51	1,240,742.09
2009–10	437.29	1,932.34	1,184.82	305,683.56
2010–11	2,128.33	2,058.29	2,093.31	540,073.98
2011–12	2,540.66	884.20	1,712.43	441,806.94
2012–13	665.59	–7,439.22	–3,386.82	–877,186.38

Table 7. Total groundwater flux during annual period

Year	Total flux (m^3) Monsoon	Non-monsoon	Total
2003-04	1,140,708.81	2,740,277.34	3,880,986.15
2004-05	1,053,570.15	2,467,544.80	3,521,114.95
2005-06	961,625.05	2,395,086.24	3,356,711.29
2006-07	1,030,821.95	2,312,420.46	3,343,242.41
2007-08	920,884.80	2,182,019.52	3,102,904.32
2008-09	845,047.48	1,240,742.09	2,085,789.57
2009-10	137,258.53	305,683.56	442,942.09
2010-11	217,246.38	540,073.98	757,320.36
2011-12	246,044.36	441,806.94	687,851.30
2012-13	82,914.30	–877,186.38	–794,272.08

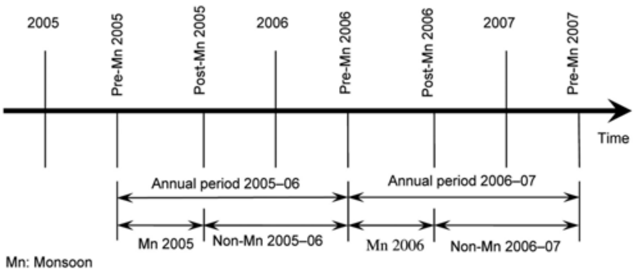

Figure 9. Seasonal distribution.

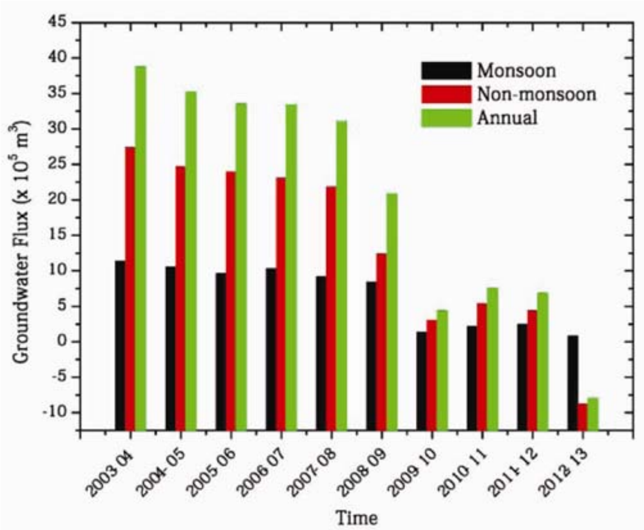

Figure 10. Bar diagram showing groundwater flux variation.

Different maps are constructed using groundwater level map (Figure 6 *a*) such as groundwater level contours map (Figure 6 *b*), groundwater slope map (Figure 6 *c*) and groundwater flow direction map (Figure 6 *d*). The groundwater level elevation map and contours map for pre-monsoon year 2012 is shown in Figure 6. Contours map shows the lines of equal elevation of water level with 4 m interval. For pre-monsoon year 2012, the groundwater level elevation ranges from maximum of 267.2 m to minimum of 182.80 m above mean sea level; while for post-monsoon year 2012, the corresponding figures are maximum 267.10 m and minimum 184.30 m. Figure 7 indicates that the results of boundary cells are shown only for a segment, which is red in colour, so that variations in boundary cell are clearly depicted at that scale. Figure 8 shows the different map which are constructed for the boundary segment of the study area.

Groundwater flux across the KBNIR boundary of the study area is extracted in the form of cell values from the Groundwater Flux map using 'zonal statistics as table' in Spatial Analyst Tools. The extracted data is in form of attribute table, which is further converted into the spreadsheets. The values include the maximum, minimum, range, mean, standard deviation and sum of the cell values (groundwater flux through each cell). Table 4 shows the minimum, maximum, mean and sum of groundwater flux for entire boundary of the study area for pre- and post-monsoon year. The quantity of groundwater flux is considered as inflow to the boundary, if (positive) and outflow from the boundary, if it is (negative).

From the analysis of Table 4, it is clear that the groundwater flux across the boundary is decreasing regularly. It can occur because of lowering of water table to deeper depth where hydraulic gradient (groundwater slope) conditions are not favourable for the groundwater flux as inflow. Maximum total groundwater flux is found during pre- and post-monsoon year, 2003 and minimum total rate of flow is found during pre and post-monsoon year 2012.

Quantity of groundwater flux across the simplified boundary can be estimated on basis of the seasonal distribution. Figure 9 represents the seasonal distribution for 2006 and 2007. It is assumed that monsoon period starts from 1 June and continues up to the 15 September; whereas non-monsoon period starts from 16 September and continues up to the 31 May of next year. The monsoon period includes 107 days and non-monsoon period includes 258 days (259 days for leap year).

First mean flow rate is calculated taking average of groundwater flux. For monsoon period, it is the average of groundwater flux during pre- and post-monsoon time for same year, whereas for non-monsoon period, it is the average of groundwater flux during post-monsoon and pre-monsoon of next year as shown in Tables 5 and 6. The quantity of groundwater flux is calculated by multiplying the mean flow rate by number of days corresponding to the monsoon or non-monsoon period. Annually, groundwater flux is calculated by summing the flux from monsoon and non-monsoon periods just following that (Table 7). For the study area, the calculated mean groundwater flux through the simplified boundary is about 6.63×10^5 m^3 for monsoon period, 13.75×10^5 m^3 for non-monsoon period and 20.38×10^5 m^3 annually.

Figure 10 represents the bar diagram between the groundwater flux across the boundary during monsoon period, non-monsoon period and annual period and shows gradual decrease in groundwater flux inward to the study area. Flux of monsoon period varies from maximum of 11.41×10^5 m^3 in 2003 to minimum of 0.83×10^5 m^3 in 2013. Similarly, for the non-monsoon period, it varies from maximum 27.4×10^5 m^3 in 2003–04 to minimum -8.77×10^5 m^3 in 2012–13; and for annual period, it varies from maximum 38.8×10^5 m^3 in 2003–04 to minimum -7.94×10^5 m^3 in 2012–13.

Conclusions

A GIS-based methodology has been developed that allows estimating groundwater flux across the boundary on cell basis using ground levels and borelog data. In absence of missing values in original data, geostatistical method is used to determine the required missing value using spatial interpolation. In this study, the boundary of the study area is digitized to a simplified boundary. Simplified boundary of the study area is enclosed only by horizontal (top and bottom) and vertical (left and right) boundaries and includes 708 cells. This methodology has been applied to estimate groundwater flux through a simplified boundary of the study area. Darcy's law and (D8) flow model algorithm are used to reveal the direction of groundwater flow across the boundary and then raster calculator was used to convert from flow direction to multiplying factor using map algebra expression. Groundwater flux has been estimated by implementing the above methodology. Groundwater flux is calculated as the multiplication of mean of groundwater flow rate during premonsoon month and corresponding post-monsoon month and the duration of flow across the simplified boundary of the study area. Results from this study revealed the significant role of GIS tools. The mean annual groundwater flux across the boundary is estimated as 20.38×10^5 m^3. The study can be further useful in estimation of net recharge to the groundwater in this area. The results indicate the GIS-based methodology based on groundwater level and borelog data of the aquifer systems and highest the efficiency of the method. The obtained maps can be used as a reference map for groundwater analysis.

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