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Estimation of fluxes across boundaries for groundwater flow model using GIS

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The present study aims at using GIS hydrology tool for calculating inflow/outflow fluxes across the boundary of a study area in a situation where physical boundaries in the vicinity of the study area cannot be identified. This approach has an edge over the simplest approach of no flow or constant head boundaries alone, which may be far from reality. The reported methodology will improve groundwater modelling in the areas where the hydrological cycle is predicted because of climate change.

Keywords: Climate change, groundwater flow models, hydrological boundaries, lateral fluxes.

RECENT analyses using the terrestrial water storage-change observations from the NASA Gravity Recovery and Climate Experiment satellites have reported that groundwater is being dramatically depleted in the Indian states of Rajasthan, Punjab and Haryana (including Delhi). During the 2002–2008 study period, 109 km^3 of groundwater has been lost. The decreasing water levels in these regions are largely attributed to unsustainable consumption of groundwater for irrigation and other uses along with increased run-off and/or evapotranspiration, which may further be exacerbated by climate change[1]. In such regions, groundwater management is important to combat the emerging problem of its overexploitation and contamination[2]. Groundwater modelling in such regions can aid in its management. Numerical codes such as MODFLOW, FEFLOW, etc. are most commonly used for simulation of groundwater flow processes. However, there are many methodological challenges like data scarcity, especially unknown fluxes (boundary fluxes, recharge, leakage, evapotranspiration), heterogeneity and resulting parameter uncertainty and non-uniqueness of model calibration, which the researchers need to overcome in order to use a robust and dependable groundwater model. Considerable research has been undertaken for estimating the parameters of transmissivity and storage coefficient and recharge in deterministic groundwater models[3–10]. However, less research has been directed on estimation of boundary fluxes as these require both an accurate physical representation of the system and its differentiation from the adjacent groundwater system and appropriate specified boundary conditions. Attempts are generally made to use no flow or constant head boundaries alone, but this may not be always true and is also far from reality[11]. The absence of well-defined physical boundaries in the near vicinity of zone of interest and necessitate a methodology to compute influx and outflux at the boundaries. GIS is an important tool which offers facilities for creating profile graphs, extract values to a point, creating buffer, interpolation tools, etc. that could be used along with Darcy's law to estimate the average flow across a given boundary. In a groundwater flow and transport modelling of Pali district, Rajasthan, India, a GIS-based methodology was demonstrated to calculate the average flux across the boundary[11]. The study area boundary was grouped into eight segments on the basis of average values of gradients for individual line segments and the mean gradient values for these line segments

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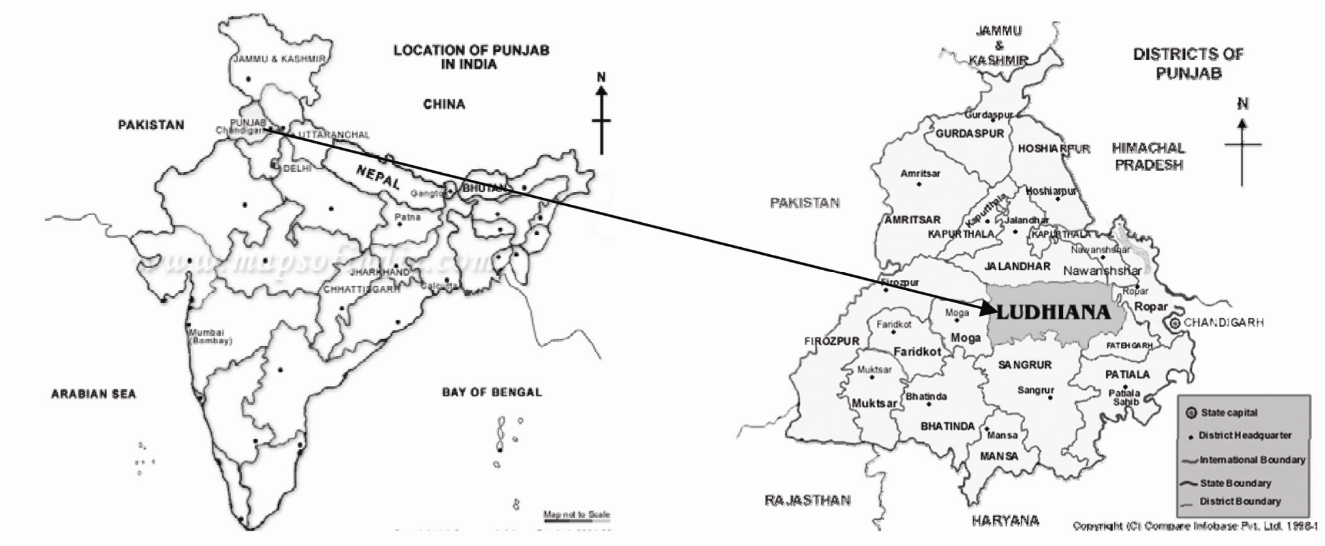

Figure 1. Location map of the study area.

were calculated. However, this study assumed partially penetrating ephemeral rivers as constant flow boundaries, wherein more appropriate boundaries were not available. Moreover, the length of the line segments had no relation with the groundwater model dimensions. Keeping this in view, the present study was undertaken to develop a GIS-based approach for estimating groundwater flux across boundaries of a study area taking into consideration the cell-based approach, wherein the boundaries cannot be assumed to be no-flow boundaries.

The study was carried out in Ludhiana district (75°52′E long. and 30°56′N lat.), Punjab, India (Figure 1). River Satluj forms the border of the district in the north with Jalandhar and Hoshiarpur districts. Ropar and Fatehgarh-sahib districts mark the eastern and southeastern boundaries respectively. The western border is adjoining Moga and Ferozpur districts. The geographical area of the district is 3767 sq. km and altitude varies from 221 to 273 m amsl. The district area is occupied by Indo-Gangatic alluvium of Quaternary age. The lithology of the area is heterogeneous, with the presence of several sand beds forming the principal aquifers separated by clay beds at various depths. The climate of the area is semiarid. The normal annual rainfall of the district is 730 mm, which is unevenly distributed. The southwest monsoon sets in from the last week of June and withdraws at the end of September, it contributes to about 78% of the annual rainfall.

Extensive datasets on the aquifer lithology (structural contours, borelogs, aquifer properties), piezometric levels, aquifer abstractions, climatic data, canal network and their L-sections were collected to simulate groundwater.

The study area was discretized into 740 cells, each of 2500 × 2500 m. The groundwater flow from a particular cell to one of the adjoining eight cells depending on the maximum/highest difference in hydraulic head values was simulated using MODFLOW-96 in PMWIN environment in a single-layer model (0–100 m), having 20 rows and 37 columns. In this study area, inflow/outflow is constrained by the boundaries – River Satluj in the north and no physical boundaries in the vicinity of the area on the other three sides. In the absence of well-defined physical boundaries in the near vicinity, these boundaries were considered as specified flux boundaries, and Darcy's law was used to calculate inflow/outflow per cell of the boundary at each point. Hydrology toolkit of GIS was used with the assumption that the groundwater level gradients do not change significantly for different seasons and hydrological properties of the boundary cells are reasonably known.

Initially, a flat buffer of 2500 m outside of the district boundary shapefile was created (Figure 2). Water-level surfaces from 44 observation wells, located in and around the study area and having consistent records, were prepared from pre-monsoon data (June) for the period from 2000 to 2010 using krigging interpolation tool in ArcGIS. The hydraulic head surfaces for different years were obtained by subtracting the water-table surfaces from the digital elevation model (DEM; obtained with the help of SRTM data and downloaded in Geotiff format from www.cgiar-csi.org/.../elevation/.../45-srtm-90m-digital-elevation-data) for the buffered area using extract by mask tool, specifying the cell size of 2500 × 2500 m and masking by buffered boundary shapefile.

Information regarding hydraulic parameters such as hydraulic conductivity and specific yield was estimated along with bottom elevation indirectly with the help of 44 well logs scattered all across the district (Figure 3). The bottom elevation surfaces were used to derive saturated thickness of the aquifer. The saturated thickness varies with change in the water table and was computed by subtracting water table surface raster from bottom elevation surface raster for different years. The surface rasters for these parameters were prepared using inverse distance weighing (IDW) interpolation tool in ArcGIS and were extracted for buffered area in a similar way using extract by mask tool as in the case of hydraulic head rasters. The selection of a different interpolation technique was based on lowest value of prediction error.

To the buffered hydraulic heads rasters, flow direction tool (option available in hydrology toolkit of ArcGIS) was applied for the estimation of boundary fluxes for groundwater model to identify the boundary cells from which groundwater flows out from the study area and the cells outside the boundary area contributing to groundwater inflow to the study area. The output raster of flow direction is one of the values, viz. 1, 2, 4, 8, 16, 32, 64, 128 for each cell, which defines the direction of groundwater movement from the particular cell. Figure 4 describes how a particular value indicates the direction of flow from the central cell. For example, if the value in the cell of interest is 1, it indicates that groundwater will flow from that cell to the adjacent cell on the right hand side.

A boundary area shape file was created by applying erase operation to the outside buffered and inside buffered files (Figure 5 *a*). Each of the buffered rasters of flow direction, hydraulic head, bottom elevation for different years and hydraulic conductivity rasters (all with cell size of 2500 m) was extracted by boundary shape file using extract by mask tool to obtain the parameter values in the boundary and adjoining cells.

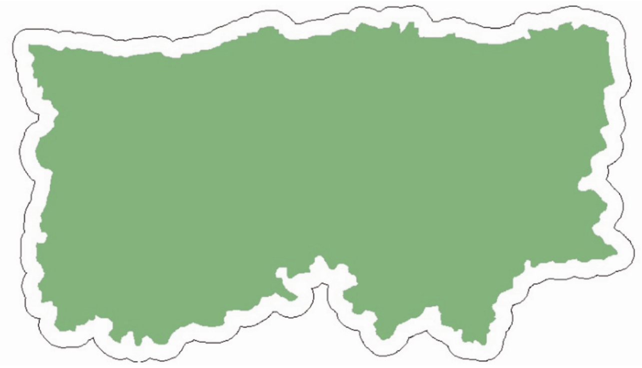

Figure 2. Outside buffer (2500 m) around Ludhiana district, Punjab.

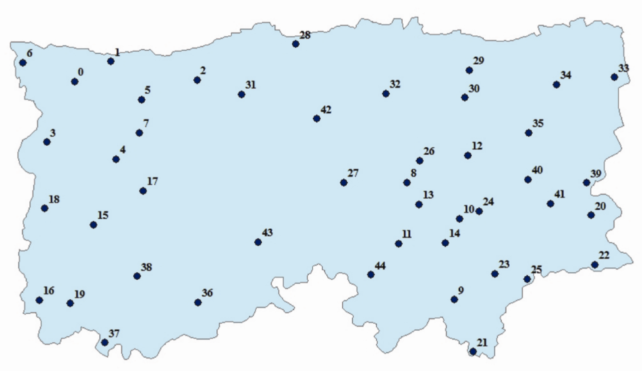

Figure 3. Location of boreholes for lithology information.

All the rasters created were then converted to ASCII format using raster to ASCII conversion tools. The ASCII files were imported in Microsoft Excel and the cells on the boundary were identified. Based on the flow direction of the boundary cells and outside cells, only those cells contributing to inflow/outflow of groundwater were identified and the flux was estimated using Darcy's law writing a code in Microsoft Excel

$$Q = Ki\,A,$$

where Q is the flow (m^3/day), K the average hydraulic conductivity of boundary and adjacent cells (m/day), $i = (H_2 - H_1)/L$ the hydraulic gradient (dimensionless), $H_2 - H_1$ the difference in hydraulic heads between two cells (m), L the distance between two cell nodes (here 2500 m, if the adjoining cells are horizontal/vertical and 3535.5, if the cells are at an angle), $A = B{*}W$ the area of cross-section perpendicular to the flow, B the saturated thickness which varies with the change in water table depth and W is the width of the cell (2500 m).

Applying the above-mentioned methodology, net flux for individual years was obtained (Table 1).

The average net flux from the three administrative boundaries computed was 3.5 Mm^3 yr^{-1} with 23.0 Mm^3 yr^{-1} influx and 19.5 Mm^3 yr^{-1} as outflux. It was also computed that the net flux could change only up to maximum of 1 mm in groundwater level. This implies that the assumption of inflow equals outflow made by other researchers is valid. It was also observed that Ludhiana district receives groundwater as influx from the east side and releases groundwater as outflow on the west side. Towards the south both influx and outflux were observed. Also, data collected over 10 years showed that the cells contributing to influx and outflux remained almost the same; however, there was variation in the magnitude of flux, due to change in hydraulic head as well as saturated thickness.

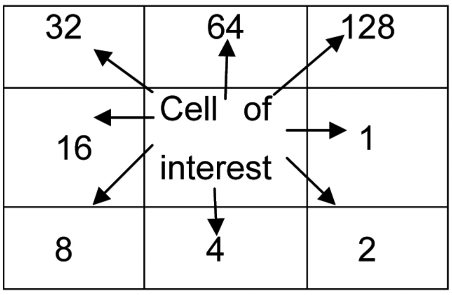

Figure 4. Direction of groundwater flow from the cell of interest.

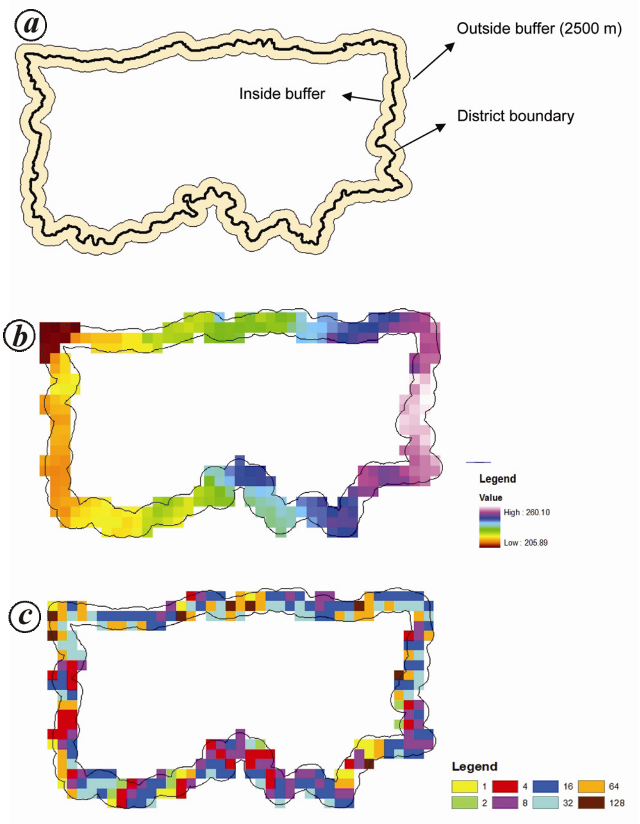

Figure 5. ***a***, Boundary shape file; ***b***, extracted hydraulic head; ***c***, flow direction raster (2001).

Table 1. Groundwater fluxes and change in groundwater levels in Ludhiana district, Punjab

Year	Influx ($m^3 yr^{-1}$)	Outflux ($m^3 yr^{-1}$)	Net flux ($m^3 yr^{-1}$)	Change in groundwater level (m yr^{-1})
2001	24.1	18.2	5.9	0.002
2002	19.3	17.8	1.4	0.000
2003	22.1	17.4	4.7	0.001
2004	24.3	21.2	3.1	0.001
2005	23.6	20.9	2.7	0.001
2006	24.3	21.3	3.0	0.001
2007	25.4	21.5	3.9	0.001
2008	22.5	17.6	4.9	0.001
2009	21.7	19.8	1.8	0.000
Average	23.0	19.5	3.5	0.001

The presented methodology, based on utilizing a sequence of GIS-based tools to calculate gradient across the boundary and then fluxes across such boundaries using Darcy's law from readily available data of water level and transmissivity, helps identify specific cells contributing to fluxes in the boundary region, which can be incorporated in MODFLOW by recharge/well package in these cells. However, estimates could be made more reliable if the water-level data are available at a shorter interval and the aquifer hydraulic parameters are obtained from pumping test data.

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Seismogenic active fault zone between 2005 Kashmir and 1905 Kangra earthquake meizoseismal regions and earthquake hazard in eastern Kashmir seismic gap

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The 2005 Kashmir earthquake of magnitude *Mw* 7.6 produced 75 km surface rupture showing 3–7 m vertical offset. The surface rupture nearly coinciding with the bedrock geology-defined Balakot-Bagh Fault (BBF) indicates reactivation of the fault. The BBF extends SE with right-step to the Reasi Thrust in Jammu

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