Sustainability of a shallow aquifer in Yamuna-Krishni interstream region, Western Uttar Pradesh, India: a quantitative assessment

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Abstract The Yamuna-Krishni interstream is part of the Central Ganga Plain, which is very fertile and is famous for sugarcane cultivation. Due to increasing demand to meet agriculture requirements the abstraction of groundwater has increased manifold in the last few decades. Although the area hosts potential aquifers, due to uncontrolled pumping the shallow aquifer is adversely affected. For proper management of any basin it is essential that careful water balance studies should be carried out. Keeping this in view, an attempt has been made to evaluate groundwater balance of the area. The Groundwater Resource Estimation Committee 1997 (GEC, 1997) methodology, with a few additions, is applied to compute the groundwater resources. Since subsurface horizontal flows significantly affect the input and output components in an alluvial aquifer, emphases have been given to precisely estimate various inflows and outflows. The river-aquifer interaction and other boundary flows were estimated using Visual MODFLOW Pro 4.1. The results of water balance show that the net recharge into the interstream region is 413.08 million m³ and discharge is 477.33 million m³, leaving a deficit balance of 64.25 million m³. Therefore, the status of groundwater development is 116%, which puts it in the over-exploited category. This is also reflected by the continuously falling water level situation in the basin. Thus, the hydrogeological and water balance studies shows that the groundwater development has attained a critical state in the region.

Key words hydrogeology; groundwater budget; river-aquifer interaction; Yamuna-Krishni; interstream; India

INTRODUCTION
Quantification of the groundwater resource is a basic prerequisite for efficient groundwater resource development (Sophocleous, 1991) and this is particularly vital for India, with a widely prevalent semi-arid climate. Due to increasing demand to meet agriculture requirements the abstraction of groundwater has increased manifold in the last few decades. The heavy demand for groundwater sometimes leads to excessive withdrawal, which is often reflected in serious imbalance of hydrogeological situations at a later date. The indiscriminate utilization of groundwater in the last few decades has reached a state termed over-exploitation.

The situation in the study area is no exception. Groundwater is the main source for agricultural, domestic and industrial uses, and its utilization has increased manifold in previous years. The increasing agricultural activities and other anthropogenic influences have detrimentally affected the groundwater regime, which is envisaged by depletion of dynamic groundwater resource in the area. Previous hydrogeological investigations in the area were mainly carried out by the Central Ground Water Board (CGWB) and Groundwater Department of Uttar Pradesh (UP) government. Khan (1992) and Kumar (1994) carried out systematic hydrogeological investigations in Muzaffarnagar district and studied the first group of aquifers. They identified numbers of blocks under the over-exploited category. The blocks are small administrative units of a district, in order to carry out the developmental plan at the micro level. A water balance study using water table fluctuation and tritium method was carried out in parts of the Yamuna-Krishni interstream area by Ahmed & Umar (2008). The result of water balance studies show a negative balance and place the area under over-exploited category basin of groundwater balance.

The effective groundwater budgets of an alluvial area require proper understanding of the hydrodynamics of the basin. It is therefore imperative to identify various recharge and discharge components of the groundwater regime and their effect on its variation with time.

This paper attempts to precisely present the groundwater budget estimates of an alluvial aquifer, including all variable components of groundwater recharge and discharge. The study area was divided into two zones for assessment purpose, i.e. canal command area and non-command...
area. A canal command area is one which comes under major or medium surface water irrigation and a non-command area that lacks any major or minor surface water irrigation scheme.

STUDY AREA
Location and physiography
The study area, in Muzaffarnagar district of Uttar Pradesh in India, lies between latitudes 29°15′ and 29°41′45″N and longitudes 77°05′ and 77°27′E and covers an area of about 1060 km², lying to the west of Muzaffarnagar township (Fig. 1). The rivers Yamuna and Krishni form the western and eastern boundary of the study area.

The area exhibits a gentle slope due south and southwest where the elevation ranges between 245 m near Shamli in the north to 230 m in the south in the village Mawi.

Rainfall and climate
The area on an average receives 727 mm of annual rainfall. The rainfall in the study area for 2005 and 2006 was 606 mm and 435 mm, respectively. Statistical results of historical rainfall data show that the rainfall is scanty and erratic in nature and mainly confined to 25–30 days a year. The area enjoys a subtropical climate, with very hot summers and moderately cold winters. The maximum and minimum temperatures being 45°C in June and 4°C in January.

Land use/land cover
The area under cultivation has marginally decreased from 90.5 to 88.8% during 1972–2005. The same period has witnessed a doubling of population from 1.8 to 3.54 million. The area

Fig. 1 Location map of the study area.
occupied by settlements has increased from 2 to 10%. Groundwater use has proportionally increased.

HYDROGEOLOGICAL FRAMEWORK

Geologically, the area is characterized by >1000 m of Quaternary sediments, which rest over a basement rock quartzites of Delhi Super group. Delhi quartizes are underlain by Bundelkhand Granitoid Complex (Kumar, 2005). The subsurface data available from shallow boreholes down to a depth of 122 m indicate that the top clay layer is persistent throughout the area, varying in thickness from 3 to 20 m. This is underlain by a more porous granular zone, intervened by several sub-regional clay beds. Local aquifers tend to behave as a single aquifer. The granular zone, composed of medium to coarse sand and gravel, forms >80% of the total thickness of formations encountered, particularly in southeastern and southern parts of the basin (Umar et al., 2008).

The pre-monsoon (June 2006) and post monsoon (November 2006), depth to water table ranges from 5.76 to 21.96 and 5.18 to 21.02 m bgl (metres below ground level). The deep water table conditions occur in the central part of the study area. The average fluctuation ($\Delta h$) for command and non-command area is 0.708 and 0.388 m, respectively. Figure 2 is a water table contour map of June 2006.

![Fig. 2 Water table contour map (June 2006).](image)

A perusal of Fig. 2 shows that the general groundwater movement is from NNE to SSW. However, local groundwater flows are also common, which are very conspicuous and scattered away from the right bank of Eastern Yamuna Canal (EYC). These distorted patterns of flow direction in all likelihood are the outcome of overdrafting in these areas. The elevation of water table ranges from 246 m asl in the extreme NE boundary of the district, to 219 m asl in the southern part of the study area. The groundwater flow direction at the left bank of EYC is towards the Krishni River, with an average hydraulic gradient of 1.25 m/km. While from its right bank the groundwater flows in a NE–SW direction. Two prominent groundwater troughs are seen in the left half of the area, at locations Kairana and Bipur. The possible reason for these troughs is indiscriminate pumping of groundwater for agricultural uses.

The long term water level behaviour was analysed for four permanent hydrograph stations, Fig. 3(a) and 3(b). Of these four stations, Jalalabad and Thanabhawan hydrographs represent the command area and Kandela and Bhoora represent the non-command area.
The hydrographs indicate that there is a progressive decline in the water level trend within the study area, especially for the last 3–4 years, the decline trend seems pronounced and persistent. A trend line was fitted on the graphs using t-statistic for testing significance of observed regression coefficient, the values of r-square and r for the given data set shows 95% level of confidence. The average annual decline in the command and non-command areas ranges between 0.3 to 1.53 and 0.40 to 1.08 m, respectively.

Aquifer parameters

One long duration and eight short duration pump tests were conducted in the area by the Central Groundwater Board (CGWB) and State Groundwater Department (SGWD). The transmissivity and hydraulic conductivity values range between 1265–4003 m²/day and 9.8–26.6 m/day, respectively (Bhatnagar et al., 1982). In addition hydraulic conductivity of sand samples collected from depth range of 25–45 m was determined using a constant head permeameter. The K values obtained by permeameter ranges from 1.0 to 7.7 m/day, which corresponds to a typical conductivity value for fine to medium grained sand (Todd, 1980).

GROUNDWATER BUDGET ESTIMATION

Methodology

The Groundwater resource Estimation Committee 1997 (GEC, 1997) method has been adopted to compute the groundwater budget. The GEC’97 recommendations have incorporated a number of changes in its previous methodology, bringing out more clarity in the application.
and as such the groundwater resources so computed would be nearer to the real field situation. The salient features of GEC’97 methodology are listed below:

- It is proposed that the total geographical area of the unit for resource evaluation is divided into sub areas such as canal command area and non-command areas, hilly regions, and saline groundwater areas, and resource assessment is then made for these sub areas. Variations in geomorphological and hydrogeological characteristics may be considered within the unit.

- For alluvial areas specific yield values may be estimated from analysis of pumping tests. However, norms for specific yield values in different hydrogeological regions may still be necessary for use in situations where the above methods are not feasible due to inadequacy of data.

- Norms for return flow from groundwater and surface water irrigation are revised, taking into account the source of water, crop type (paddy or non-paddy) and depth of groundwater level.

Taking these recommendations into consideration, the study area was divided into canal command area and non-command area for the assessment purpose (Fig. 4). The value of specific yield is taken from pumping test data, irrigation return flow, canal seepage and surface water irrigation is estimated with the help of statistical data, field data and recommended values for seepage, etc. by GEC’97. The river–aquifer interaction, horizontal in and outflow components were calculated using groundwater flow modelling.

The groundwater fluctuation method is used for recharge assessment in the monsoon season. The monsoon season is taken from June to October. The Kharif crops (paddy, maize, maiz, maiz...
fodder) are cultivated during this period. The rainfall recharge in the non-monsoon season is a small component and hence estimated empirically. The non-monsoon season is taken from November to May. The Rabi and Zaid (wheat, oilseeds, pulses, watermelons, etc.) crops are cultivated during this season. Thus, the study proceeds with two type of subdivision, i.e. season-wise and area-wise. The season-wise subdivision corresponds to monsoon and non-monsoon season and area-wise subdivision accounted for command and non-command areas.

**Estimation of groundwater recharge for the monsoon season in non-command area**

The water level fluctuation method is applied for the monsoon season to estimate the recharge. The groundwater balance equation for the monsoon season in non-command area is given by:

\[ R_G - D_G - B + I_S + I = S \]  

\( R_G \) = gross recharge due to rainfall and other sources including recycled water; \( D_G \) = gross groundwater draft; \( B \) = base flow into streams from the area; \( I_S \) = recharge from streams into groundwater body; \( I \) = net groundwater inflow into the area across the boundary (inflow-outflow); \( S \) = groundwater storage increase.

All quantities in equation (1) refer to the monsoon season only.

To signify the total recharge equation (1) can be rewritten as:

\[ R = S + D_G + B - I_S - I \]

\( R \) = possible recharge, which is gross recharge minus the natural discharge in the area in the monsoon season.

Substituting the expression for storage increase, \( S \), in terms of water level fluctuation and specific yield, equation (2) becomes:

\[ R = h \times S_y \times A + D_G + B - I_S - I \]

\( h \) is rise in water level in the monsoon season; \( A \) is the area for computation of recharge; and \( S_y \) is specific yield.

The recharge calculated from equation (3) gives the available recharge from rainfall and other sources for the particular monsoon season. For non-command areas, the recharge from other sources may be recharge from recycled water from groundwater irrigation, recharge from tanks and ponds and recharge from water conservation structures, if any. The rainfall recharge is given by:

\[ R_{rf} = R - R_{gw} - R_{wc} - R_t \]

\( R_{rf} \) = recharge from rainfall; \( R_{gw} \) = recharge from groundwater irrigation in the area; \( R_{wc} \) = recharge from water conservation structures; \( R_t \) = recharge from tank and ponds.

**Estimation of groundwater recharge for the monsoon season in the command area**

For command areas, recharge from other sources includes recharge due to seepage from canals, recharge due to return flow from surface water irrigation and groundwater irrigation, recharge from storage tanks and ponds, and recharge from water conservation structures. The recharge from rainfall is given by:

\[ R_{rf} = h \times S_y \times A + D_G - R_c - R_{gw} - R_{sw} - R_t - R_{wc} \]

\( R_c \) = recharge due to seepage from canals; \( R_{sw} \) = recharge from surface water irrigation; \( R_{wc} \) and \( R_t \) are not applicable in the present study area.

**Estimation of recharge through rainfall during the non-monsoon season**

The recharge from rainfall during the non-monsoon season may be estimated based on the rainfall infiltration factor, provided that the normal rainfall in the non-monsoon season is greater than 10% of the normal annual rainfall. If the rainfall is less than this threshold value, the recharge due to rainfall in the non-monsoon may be taken as zero (GEC’97). The infiltration factor is taken as 22% of total rainfall. The non-monsoon rainfall recharge in command and non-command areas are estimated as 11.06 and 15.89 MCM, respectively.

**Recharge through irrigation returns**

Since groundwater is the major source of irrigation in the study area, a large part of it can return to the aquifer by direct infiltration. The infiltration
factor is dependent upon several factors, including soil types and texture, depth to water table, types of crop and method of application of water. It varies widely ($S_f = 0.15–0.45$) for the prevailing three crops pattern i.e. Rabi, Kharif and Zaid (GEC’1997). The seepage for a particular crop type is the product of irrigation water applied and seepage factor ($S_f$). The recharge through irrigation returns for command and non-command areas are calculated as 98.15 and 92.26 MCM, respectively.

Recharge through canal seepages Recharge through percolation from canals depends on the infiltration capacity of the canal sub-surface lithology, extent of wetted perimeter, length of canal (Karanth, 1987). The wetted perimeter and total length of different canals was determined. Data of total numbers of running days were collected from the District Irrigation Department. Canal seepage was calculated by using the following formula:

$$
\text{Canal seepage} = \text{length} \times \text{wetted perimeter} \times \text{total running days} \times \text{specific loss}
$$

Total seepage through canal in monsoon season is 28.4 MCM. Out of this, 20.0 MCM is taken for the command area. In the non-monsoon season total seepage is 38.13 MCM.

Recharge through surface water application Recharge also takes place through surface water irrigation. The surface irrigation water applied is taken out by multiplying irrigated area with applied water depth. Seepage factor ($0.3 < S_f < 0.4$) is used which is same as recommended by GEC’97 for alluvial areas. Recharge through surface water irrigation in command area is 12.82 while in non command area is only 4.13 MCM.

River–aquifer interaction The Yamuna and Krishni rivers form western and eastern boundaries of the area, and actively participate in groundwater dynamics. The river aquifer interaction is achieved by using a finite difference model, Visual MODFLOW 4.1 (Fig. 4). For, this purpose the river was divided into six segments such that each segment represents a uniform river stage. The rivers are assumed to be between 3 and 25 m wide with a depth of water between 0.4 and 1.0 m. Two-dimensional x–z (profile) steady-state numerical model solutions are used to explore the interaction between the river and aquifer; a variety of boundary conditions are considered, including recharge at the water table. The altitudes of river stage and river bed bottom are measured accurately. The river boundary package is employed at rivers Yamuna and Krishni.

Estimation of horizontal inflows Subsurface inflows are the function of hydraulic gradient, width of the boundary and transmissivity. Horizontal inflows are to be included in the groundwater budget in order to obtain accurate results. Inflow components are calculated at the north and southern boundary of the study area. The groundwater flow model is used to estimate subsurface inflow and outflow.

Total annual recharge

The total annual recharge is obtained as the sum of recharge in the monsoon season and recharge in the non-monsoon season, where in each season, the recharge comprises of recharge from rainfall and recharge from other sources. Table 1 shows the estimates of total annual recharge.

Estimation of groundwater discharges

The groundwater discharges from the study area includes draft through pumpage, evaporation from water table and subsurface horizontal outflows.

<table>
<thead>
<tr>
<th>Area</th>
<th>Rainfall recharge</th>
<th>Irrigation returns</th>
<th>Canal seepage</th>
<th>Recharge through surface water irrigation</th>
<th>Stream inflow</th>
<th>HIF**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Command</td>
<td>42.18</td>
<td>98.15</td>
<td>50.00</td>
<td>12.81</td>
<td>6.4</td>
<td>3.3</td>
</tr>
<tr>
<td>Non-command</td>
<td>76.44</td>
<td>92.26</td>
<td>16.53</td>
<td>4.13</td>
<td>5.1</td>
<td>5.78</td>
</tr>
</tbody>
</table>

MCM*: million cubic metre; HIF**: horizontal inflow.
Estimation of groundwater draft through pumpage

The database on the number of groundwater structures existing in the area was collected from an inventory of wells during several field visits. The data of the borewell census from the District Statistical Department was also used for this purpose. Three types of borewells were categorized on the basis of their yield. Discharges of these wells were 1500 L/min, 250 L/min and 60 L/min, respectively. The unit yearly draft for these wells has been assigned by GEC’1997, which varies from 0.2, 0.037 and 0.0075 MCM, respectively. The annual unit draft is used to calculate groundwater draft for different seasons. The total draft calculated in the monsoon season in command and non-command areas are 88.51 and 105.71 MCM, whereas in non-monsoon season in command and non-command areas it varies between 128.63 and 150.32 MCM, respectively.

Evaporation from water table (EVAP)

This component is evaluated using the relation developed by Coudrain et al. (1998). Evaporation flux is expressed as an inverse power function of the piezometric depth below the soil surface, independently of the soil characteristics. The EVAP component is calculated for the area having a shallow water table:

$$EVAP = 71.9(Z)^{-1.49}$$

where, $Z =$ Water depth from soil (m).

The EVAP component is calculated as 1.77 mm. The groundwater discharge through EVAP for command and non-command areas is 0.16 and 0.20 MCM, respectively.

Estimation of horizontal outflows

The subsurface flows leaving the study area are termed as horizontal outflows. The subsurface out flow in command area during monsoon and non-monsoon season is 0.78 and 0.76, MCM respectively. In the non-command area it is 1.12 and 1.09 MCM, respectively.

Total discharges

The total discharge is the sum of groundwater draft through pumpage, evaporation from water table and groundwater outflows. The estimates of groundwater discharge are given in Table 2.

Stage of groundwater development in the study area

The stage of groundwater development (%):

$$\text{Stage of groundwater development} = \left(\frac{\text{Existing Gross Groundwater Draft}}{\text{Net Annual Groundwater Availability}}\right) \times 100$$

The stage of groundwater development for the command and non-command area is worked out separately and is given in Table 3.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Total discharge in the study area (MCM).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Command</td>
<td>Draft through pumpage</td>
</tr>
<tr>
<td>Command</td>
<td>217.15</td>
</tr>
<tr>
<td>Non-command</td>
<td>256.08</td>
</tr>
</tbody>
</table>

Baseflow to Yamuna* and Krishni River**.

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Stages of groundwater development.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Command area</td>
<td>Gross groundwater draft (MCM)</td>
</tr>
<tr>
<td>Command area</td>
<td>218.84</td>
</tr>
<tr>
<td>Non-command area</td>
<td>258.49</td>
</tr>
<tr>
<td>Total</td>
<td>477.33</td>
</tr>
</tbody>
</table>
CONCLUSIONS

The results of the groundwater budget show a negative balance of 6.00 MCM and 58.25 MCM in command and non-command areas, respectively. The deficit balance implies that groundwater in both types of area is excessively pumped. The stage of groundwater development in command and non-command areas is 103% and 129%, respectively. Thus, the stage of groundwater development has reached its maximum and the sub-basin is categorized under the dark category. This fact is also substantiated by a long-term water level declining trend in both type areas. The high abstraction rate poses a threat to the sustainability of groundwater in an area which is heavily relied upon. A few negative effects of over abstraction in the study area are listed below.

- Increased drawdown leads to an increased cost of development, due to more energy consumption, the early replacement and deepening of wells and pumps, and the need to enhance energy facilities.
- The high groundwater withdrawal, which is responsible for water table decline, will affect the low cost farming due to the high cost of installation of deep tubewells.
- The groundwater flow pattern is changed. This may favour the infiltration of contaminated surface water.
- The over abstraction in the flood plains of the River Yamuna effect the nature of the stream, and hence the base flow characteristics. This may also lead to some ecological disturbances in time.

The estimation of groundwater always carries some errors. The uncertainties lie with the estimations of groundwater draft and gross groundwater recharge, owing to the limitations in the assessment methodology, as well as uncertainties in the data. Thus efforts should be made to minimize the computational errors. Apart from uncertainty regarding aquifer media, like specific yield and rainfall recharge, other factors like the tubewell census, and water requirements for particular crop types also contributes to the errors in groundwater budget estimates.

RECOMMENDATIONS

It is very clear from the estimates that the development of groundwater in the region is intense and hence a slight change in one of the components, e.g. an increase in draft or a decrease in recharge, will further seriously deplete the groundwater storage. It is therefore clear that strict controls on groundwater abstraction need to be introduced in order to manage the groundwater resources of the Yamuna-Krishni sub-basin. The following recommendations are suggested based on the findings. In order to reduce total abstraction, even the present rate of pumping has to be carefully controlled. For example, groundwater withdrawal could be reduced in non-command areas.

- The groundwater abstraction can be focused on deeper aquifers. The study carried out by CGWB in alluvial parts of Central Ganga Plain have revealed the existence of a huge reserve of groundwater in the deeper aquifer, which has not been fully utilized. The thickness of the alluvium in the area exceeds 500 m and only a small fraction of this is under active circulation due to prevailing shallow groundwater development. Therefore, it is suggested that a deeper aquifer should be tapped.
- Suitable measures for augmentation of groundwater resources may be adopted, e.g. artificial recharge may ease the situation in the southern part before the situation becomes unmanageable.
- In the past, every village in western Uttar Pradesh boasted of having ponds, which have been a very good source of groundwater recharge, at least locally. Now, it was observed during the field surveys that the ponds have disappeared due to encroachment by local people. This has retarded the groundwater recharge of the shallow aquifer. Thus revival of such a structure is recommended.
- The present canal irrigation system in the study area is restricted to the vicinity of the main canal. The irrigation channels in the downreaches do not receive water from the feeder canals...
and thus require a proper management policy to ensure the availability of water at the tail ends of canal, vis-à-vis irrigation channels.

- Conjunctive use of surface water and groundwater resources is the optimal method of obtaining maximum possible water development.
- There is an urgent need to enforce some regulation on groundwater pumpage to avoid misuse of this precious resource.
- The awareness of farmers towards the groundwater recharge would be a milestone in managing the groundwater resources.

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