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RESEARCH ARTICLE

An empirical approach using spatial and nonspatial data for surface water availability along a Canal

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Abstract Why it is necessary for canal administrators to understand what happens after canal water is discharged from a canal branch head? Canal water management involves complex issues of distance from water source, losses during conveyance, land-use pattern, crop mix and other socio-political considerations. It may be possible that there is scarcity or abundance of water along the canal length and the amount of canal water cannot meet the farmers' water demand. Canal water availability has to be therefore estimated at various points in the canal system. This document presents such an estimation using empirical analysis with spatial and nonspatial data. Sarda Sahayak Pariyojna (SSP) of Uttar Pradesh state, which is one of the largest operating irrigation systems in India, is taken as an example. This document focuses on the analysis using Geographic Information System (GIS) mapping-based decision support tools, water discharge from different canal branch heads, estimation of conveyance losses and surface water availability in each subdistrict. The sensitivity analysis has been also conducted to capture the variability and uncertainty of many parameters used in this study.

Keywords Canal water, Conveyance losses, GIS, Sensitivity analysis

Introduction

Sarda Sahayak Canal Irrigation System is one of the largest canal irrigation systems in India situated in the most populated state of Uttar Pradesh, irrigating over 16 districts covering an area of over 16 lakh ha. It is a barrage-based irrigation system, with Sarda and Ghaghra barrages as the two main water head systems. This study highlights the estimation of surface water availability in all the subdistricts from where the seven major branches (i.e., Dariyabad, Faizabad, Sultanpur, Barabanki, Haidergarh, Pratapgarh and Allahabad) pass in the Sarda Sahayak command area. The only available statistics with any state government is the discharge data from a particular branch head. This study highlights the estimation of water loss due to seepage and evaporation, and from remaining water, how much amount of water is used per the irrigation requirement in a particular subdistrict. The remaining unused water will be flowing to the next subdistrict. Considering the area of interest over the past century, Uttar Pradesh state, India, has developed one of the largest irrigation systems in the world. Sarda Sahayak Pariyojna is the largest canal irrigation system in Uttar Pradesh. In the early era, the irrigation system was designed to mitigate the effect of long-term droughts, while looking at the recent scenario, with the introduction of high-yielding varieties of rice and wheat, the irrigation requirement has increased significantly. As a result, the state has endeavoured to augment the canal flow through the systematic rehabilitation and remoulding of existing canal infrastructures on a regular basis. Sarda Sahayak Pariyojna is a government's intervention in 1968 by providing canal irrigation to the unserved areas falling under the command area of the Sarda Canal Project (SCP) commissioned in 1926. The 260-km-long feeder channel of SSP that emerged from the banks of Sarda river located in Sarda Nagar village of Lakhimpur Kheri district provides canal irrigation to 16 districts of central and eastern Uttar Pradesh. The SSP aims at irrigating culturable command area (CCA) of 1.677 million ha with 70% irrigation intensity. The project was completed in the year 2000 with an estimated cost of 13 billion (Planning Commission, 2010; Evaluation study report, 2007).

According to Rowshon *et al.* (2009), irrigation is the largest water use in the world, using up to 85% of the available water in the developing countries (Plusquellec *et al.*, 1994). Different irrigation methods affect the crop yield due to effectiveness in the water management practices (Gupta *et al.*, 2010). Improving water use efficiency in

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irrigated agriculture is therefore a thrust area of research. The growing demand for water has put additional stresses on available water, ushering in the need for efficient utilization of water in the irrigation sector with different methods of management (Santhia and Pundarikanthanb, 2000). Estimating water availability along the canal could provide useful insights to canal administrators for planning water discharge levels and schedules efficiently. This empirical study has been conducted based on time series data, as it is not practical to measure canal water available at each and every point on a canal system.

Estimation of Water Losses

The discharge of the feeder canal in Sarda Sahayak Canal Irrigation System is 23,500 cu ft/s, which is the highest in Uttar Pradesh. It irrigates rabi and kharif crops extensively, with sugarcane, wheat and rice being the main crops. It is mainly fed by glaciers. The region, covered by Sarda Sahayak Command Area Development Project, lies in the central and eastern part of Uttar Pradesh extending from 25.05° to 28° north latitude and 80.20° to 83.05° east longitude (Rajaram, 1993) covering 16 districts and 46 subdistricts.

The area is characterized by gradual slope from north-west to south-east and is formed by recent alluvial deposits of the Ganga plain. Lithologically, the region, like other parts of the plain, contains alluvial soils with massive beds of clay, either sandy or calcareous, corresponding to soil mud and sand. Since the region forms a part of the alluvial plain of the Ganga valley, it exhibits no significant contrasts in physiography. It slopes gradually from north-west to south-east, with the highest point of 182.87 m above the sea level at Nakha in Lakhimpur Kheri district. From here, the general gradient of the land towards the southeast is very gentle; the highest point above the sea level is 147.52 m near Biswan (Sitapur) and the lowest point above the sea level is 97.84 m near Faizabad (Rajaram, 1993) (see Figure 1).

Data Collection and Digitization

The water distribution along the canal for irrigation purposes would require estimation of available water volumes at various points. However, water volume discharge data is available only at canal bifurcation points at seven branch heads. We used GIS-based methodology first to digitize this data and then to estimate water losses and usage

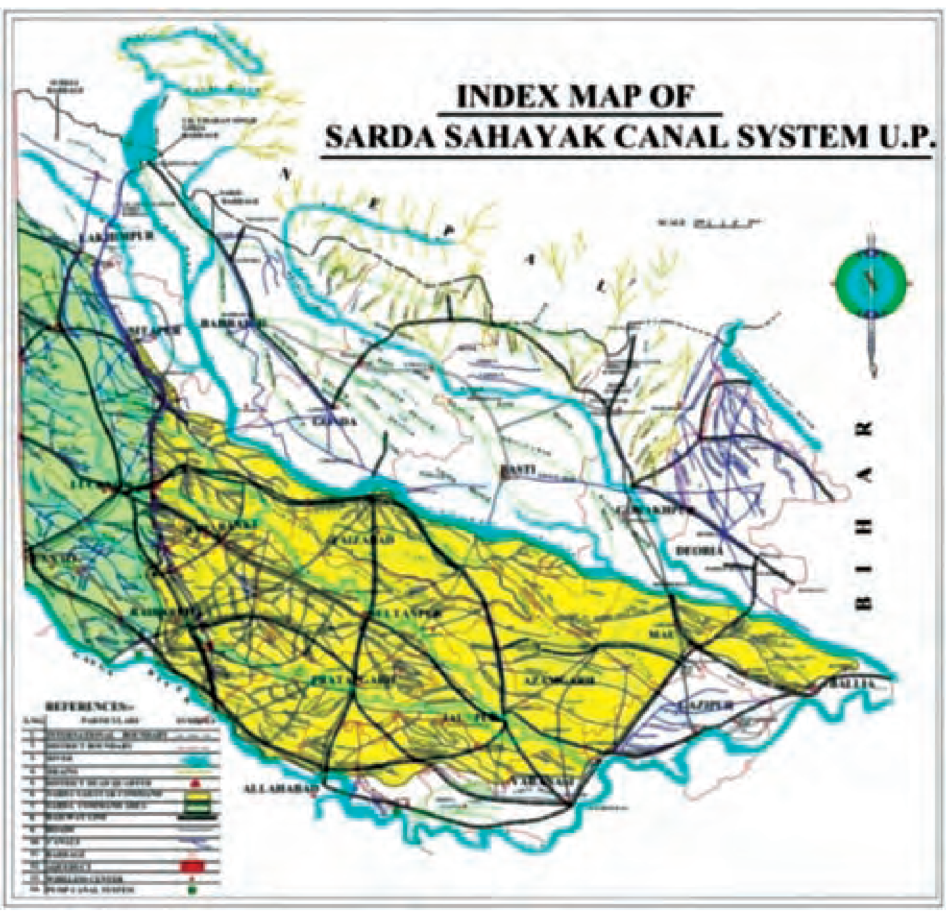


Figure 1 Index map of Sarda Shahayak canal irrigation system

along the canal to estimate water volume availability at any point along the canal.

Uttar Pradesh irrigation department at Lucknow has provided daily branch head discharge data from 1998 to 2008 for seven branches. These branches are Dariyabad branch, Faizabad branch, Sultanpur branch, Barabanki branch, Haidergarh branch, Pratapgarh branch and Allahabad branch. Five of them have their heads on the feeder channel. The discharge statistics of the branch head were in cubic feet per second (cusecs).

The map (refer back to Figure 1) was provided by Uttar Pradesh government as a raster format. This map was then georeferenced using data points based on Google Earth. The georeferenced map was digitized to generate spatial layers such as district boundary, subdistrict boundary, canal features, river bodies and road lines using ArcGIS 10.1 software. Refer to Figure 5 for the canal network in each subdistrict in the command area.

GIS tool “buffer” has been used to calculate the area covered by canal featured in a subdistrict, and “measure tool” has been used to calculate aerial distance from branch head to the subdistrict midpoint. Through buffering process, polygons are created to a specified distance around the input features. Figure 2 shows an example of buffer area of minors and distributaries in some of the subdistricts in Uttar Pradesh.

Furthermore, by using dissolve operation, all the overlapping has been removed from the buffers around the canal features. Using the measure tool, distance from branch head to subdistrict was measured. Refer to Figure 3 for diagrammatic representation of subdistrict-wise surface water availability. Thus, GIS software has played a major role in deciding the area fed by water for irrigation.

Materials and Methods

When water is released from the branch head, it travels along the canal and is tapped at various points for irrigation purposes. Some water is lost during conveyance due to seepage and evaporation losses. During transit through the canal, water seeps into the soil through the canal walls and canal bed and we term this loss as “water loss due to seepage”. Seepage loss depends on the canal geometry, canal lining, soil type and also water velocity. Some amount of water is also lost due to evaporation from the exposed water surface and we term this as “water loss due to evaporation”. Evaporation loss depends on temperature difference between the water surface and ambient air, relative humidity in the

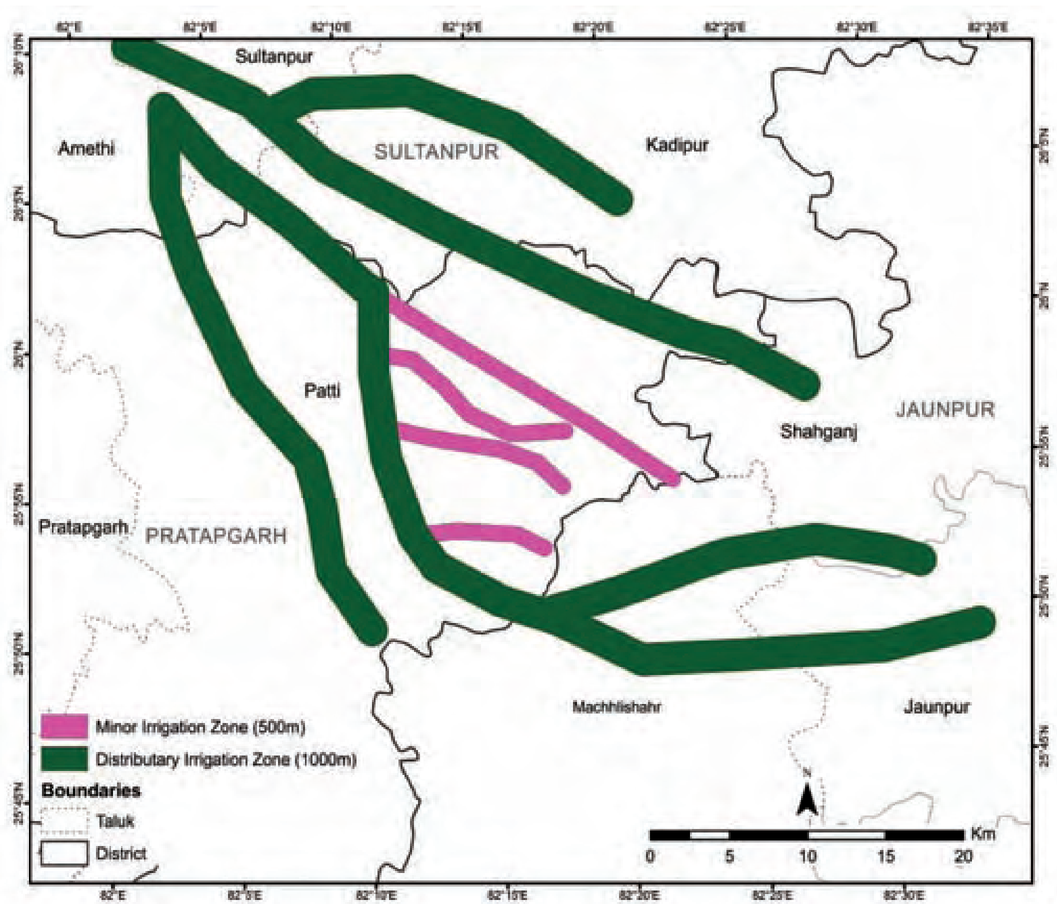


Figure 2 GIS-based buffer analysis of canal features

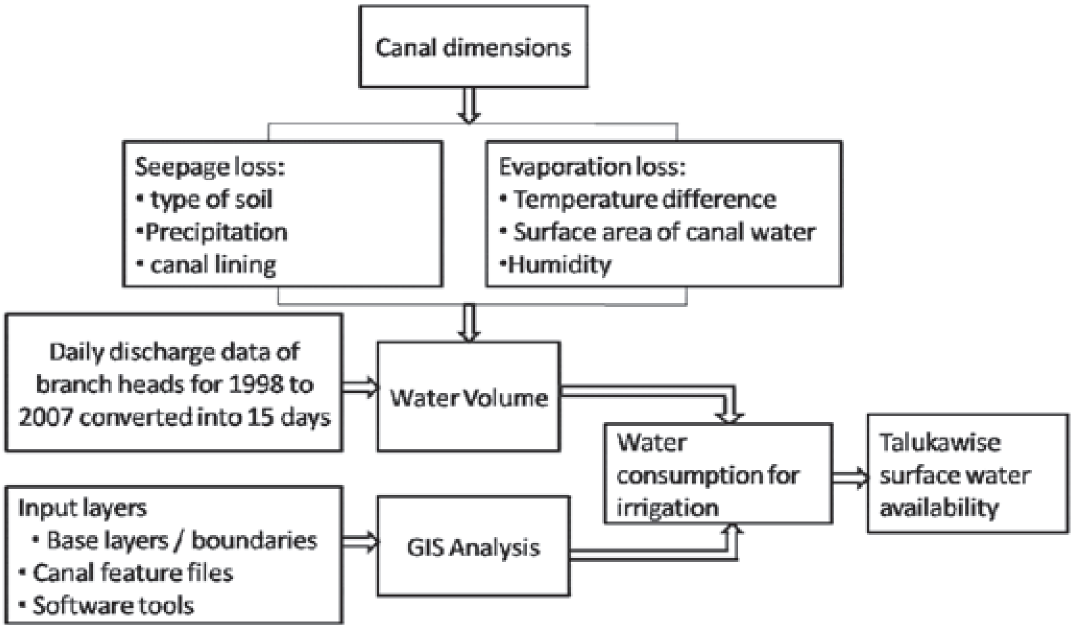


Figure 3 Flowchart showing application of spatial and nonspatial data to estimate surface water availability

ambient air, vapour pressure on the canal surface, wind speeds and surface area of the canal. Both of the losses vary from season to season. Conveyance loss estimation is required to check overall water balance in the water input to a canal and water consumed through irrigation, seepage and evaporation. Figure 3 provides a methodological framework. We have assumed similar soil type, moisture, humidity and temperature difference to exist at any given point in time across all parts of the canal. The losses are reported as a percentage of volume of total water discharged.

Loss Estimation

Conveyance losses (water loss due to evaporation and seepage) have been estimated for Dariyabad branch based on daily water discharge data availability as a time series for 1999–2007 at its head and tail ends. No other branch has daily discharge data for both its head and tail ends. Hence, Dariyabad branch was used to estimate losses. Branch head daily discharge data was converted into 15 days water volumes to balance out any day-to-day variations in water discharges. Since we are estimating percentage water losses in volumetric terms, this 15-day volumetric aggregation of daily water flows will not have any adverse impact on loss estimation using real-time water flows. Figure 4 explains the various geometric parameters.

where B is the bed width = 19.50 m; H_w the water height = 3.50 m; H:W the side slope = 1.5:1

Using these parameters:

$S = H_w / W$

$1.5 = 3.5 / W$

Therefore, $H_s = (3.5^2 + 2.33^2)^{0.5}$

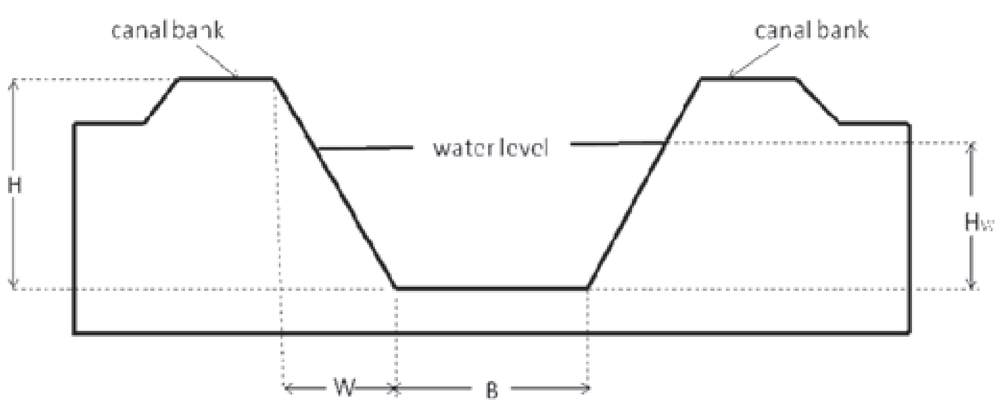


Figure 4 Canal cross-section

$H_s = 4.206\ m$

where S is the slope, H_w the water height, W the horizontal distance and H_s the slant height.

$SA_s = L \times H_s * 2 + W_B$

$= (68000 \times 4.206 \times 2 + 68000 \times 19.5)\ m^2$

$= 1898081\ m^2$

where SA_s is the surface area for water loss due to seepage, L the length of canal and W_B the bed width

$SA_e = L \times W_t$

$= 68000 \times (19.5 + 2 \times 2.33)\ m^2$

$= 16428000\ m^2$

where SA_e is the surface area for water loss due to evaporation and W_t the width at the top of the canal.

Estimation of Water Loss due to Evaporation

As discussed previously, evaporation losses depend on temperature difference between the water surface and ambient air, relative humidity in the ambient air, vapour pressure on the canal surface, wind speeds and surface area of the canal. Some experiments recorded that about 0.5 m water is lost due to evaporation in 15 days (Physics Forum, 2011). We have, however, taken a range of 0.25–0.9 m in 15 days to account for various driving forces, with the mean as 0.5 m.

Water loss due to evaporation = $0.5 \times 10^3 \times 1.64 = 0.00082\ km^3$

For 16–31 July, 1998, the amount of water discharged from Dariyabad branch head was 0.22 km^3.

Hence the percentage of loss of water due to

Evaporation by volume = Evaporated water/sent water

= 0.00082/0.22 = 0.37%

The above calculation for water loss due to evaporation is in line with other similar estimations. For instance, according to Akkuzu *et al.* (2007), approximately 0.3% of the total stream is lost due to evaporation (Badenhorst *et al.*, 2002). The 0.25–0.9 m loss in 15 days provides a loss percentage of 0.2–0.7 %.

Estimation of Water Loss due to Seepage

In most irrigation projects, water distribution, particularly during the dry period, fails to achieve one objective while trying to improve another, especially in unlined canal projects with a high seepage rate (Kalu *et al.*, 1995). Therefore, it is necessary to consider seepage losses in irrigation estimation for a canal system. We have used the following equation for estimation:

Seepage water = (water input at head – water output at tail) – water for irrigation – water loss due to evaporation.

The total water consumed (the difference in the amount of water at head and tail) of the Dariyabad branch is 0.06323 km^3. Water for irrigation during this period is 0.0481 km^3. Thus, the amount of seepage water is 0.013350 km^3. Hence, the percentage of seepage loss per volume is seeped water/water input × 100%. For the 15-day time period, the discharge water volume is 0.2246 km^3, and it gives 5.94% as seepage loss by volume.

Some other authors have also estimated seepage losses. Alam and Bhutta (2004) Weller and McAteer (1993) and Shahid *et al.* (1996) reviewed all seepage measurement techniques and discussed the statistical treatment of random errors in the inflow–outflow method. With fairly precise current metering, the errors indicated in the inflow and outflow measurements are reported to be as high as ±110%. The recommended test by the authors reaches long enough to have seepage losses at least 5% of inflows, and according to Akkuzu *et al.* (2007), approximately 0.3% of the total stream is lost due to evaporation alone (Badenhorst *et al.*, 2002).

Thus, the total conveyance loss (evaporation + seepage) per our estimation work out to be 6.31% by volume.

Results and Discussion

The surface water availability at any point along the canal has been estimated based on water discharged from the individual branches, upstream seepage, evaporation losses and water used for irrigation upstream. The surface water was estimated at the canal entry point of the sub-district (see Figure 5).

The districtwise data for the total length and capacity of canal network at the branch, distributory and minor levels was obtained from the Detailed Project Report (2008–2009) of the Sarda Sahayak Command Area Development and Water Management Project. This data was then narrowed down to the subdistrict level using a detailed irrigation map of the Sarda Sahayak Command Area.

The irrigation water requirement in the subdistricts has been estimated using the evapotranspiration (ET0) data estimated by Singh *et al.* (2010) (see Table 1). The subdistrict level cropwise irrigated area over the years has been obtained

Table 1 Irrigation water requirement for crops (mm)

Crops	1995	2000	2005	2010
Bajra	314	299	278	259
Cotton	719	685	636	593
Gram	536	266	306	363
Groundnuts	493	469	436	407
Jowar	394	375	349	325
Maize	512.5	443	432	428
Oilseeds	349	223	233	253
Potato	484	241	276	328
Rice	833	729	708	695
Sugarcane	667	636	591	551
Wheat	167	83	95	113

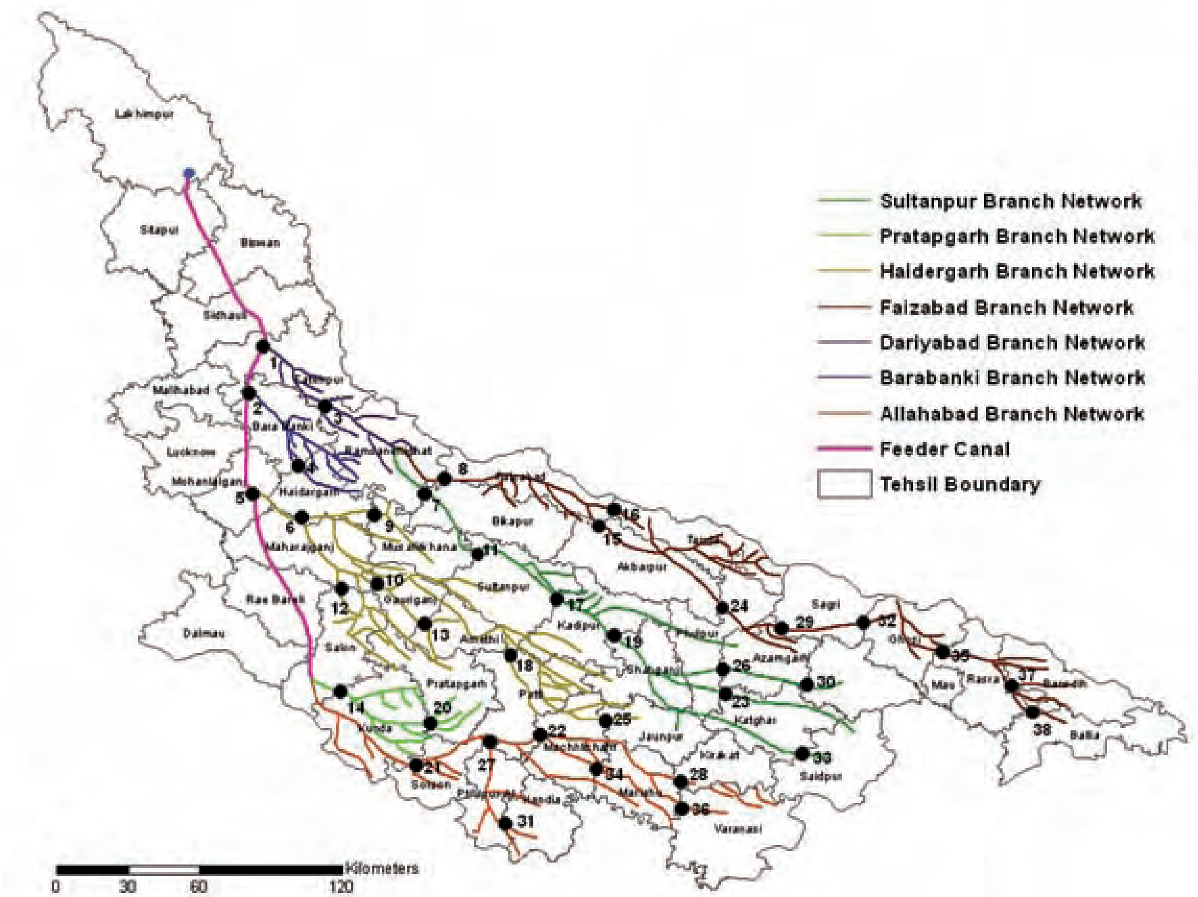


Figure 5 Branch network of the Sarda Sahayak Command Area

from the District Sankhyakiya Patrika (2010) of Uttar Pradesh. The irrigation water requirements (ET0) are verified and estimated using the Hargreaves Method. The estimated ET0) for the subdistrict is listed in Table 1.

A 'volume' of water is available in the branch with a constant flow rate. Using this, water availability is estimated at the subdistrict boundary, that is, at the point where the branch enters the subdistrict (see Figure 6).

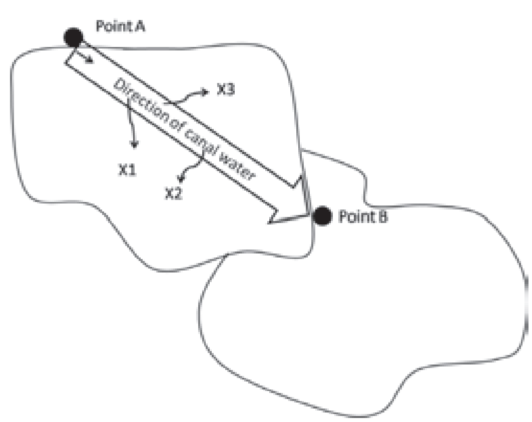


Figure 6 A generalized picture of canal water flow

where, Point A is the starting point of canal in the subdistrict 1; Point B the starting point of sub-district – 2; X_1 the water loss due to evaporation; X_2 the water loss due to seepage; X_3 the water used for irrigation (irrigation water requirement).

Thus, if the water starts running from Point A, it will experience three types of water losses:

1) Water loss due to seepage
2) Water loss due to evaporation
3) Water requirement for irrigation

By considering these three major reasons, a formula has been prepared (Formula 1).

Formula 1: Water availability at a subdistrict by a branch = Water discharge by branch – (water discharge by branch × percentage of canal length in the previous subdistrict × conveyance loss) – (irrigation water requirement by canal in previous sub-district)

If more than one branch is entering the subdistrict (see Figure 7A), then the total water availability is the sum of all the branches, and if a branch splits in two or more districts (see Figure 7B), the discharge at the end point of the subdistrict is distributed accordingly with the number and width of the branches in the subsequent subdistrict. For

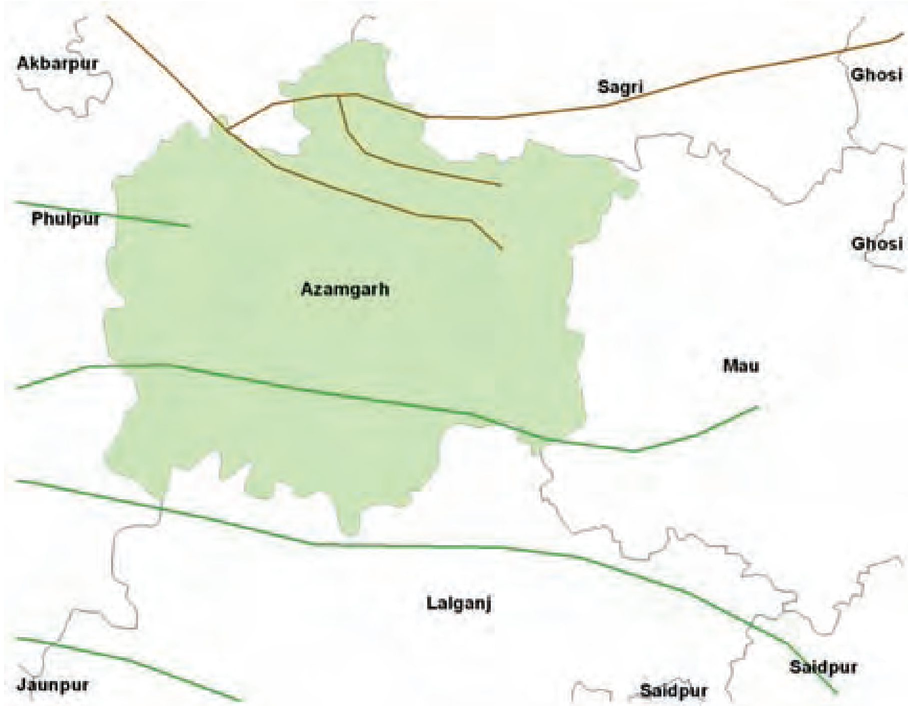


Figure 7A More than one branch is entering a subdistrict

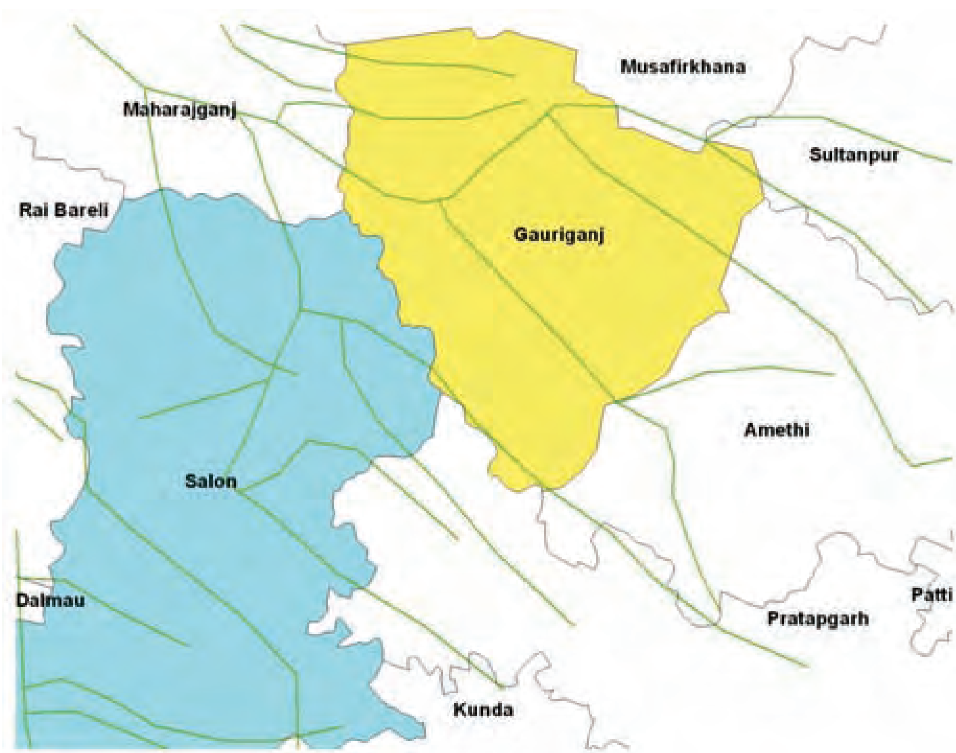


Figure 7B A branch is splitting into more than one subdistrict example, if a branch divides in two, the water availability by the branch in subdistrict 1 is (1/2) of the parent subdistrict.

Surface water availability is mainly estimated based on irrigation water requirement and geographical layout of a subdistrict. Among the series of subdistricts, the one located at east gets water, which is not consumed by the subdistrict in the west in terms of irrigation water requirement and loss. Here in special cases, the length of canal features, the width of canal features and the number of canal features are also considered. From one subdistrict, if a branch is being split into more than one subdistrict or if a canal network is more complicated, the estimation is based on the following method:

If we consider Maharajganj subdistrict (point #6), the water available in the canal at the entry point of the subdistrict is estimated (A). Based on the ratio of the width of the distributaries to the width of branch, water flown into each branch and distributaries was estimated. Per the calculation of total (seepage + evaporation) loss, loss was applied to each of the branch and distributaries (B). Again taking into consideration the width ratio of minor to the distributaries, water available to the minor was estimated and applied loss to the water amount in the distributaries (C). Water consumption by crops was estimated (D), and loss in the branch for the water was not distributed to the distributaries and minor (E). Therefore, the water available at the exit point of the subdistrict in the canal would be

F= A–(B+C+E)–D.

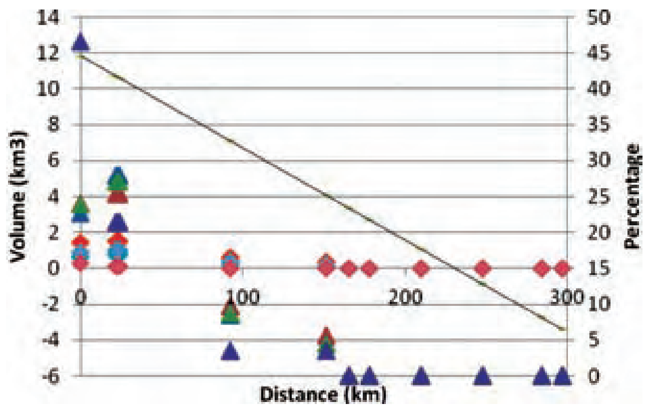
This branch distributes water to three subdistricts - (1) Musafirkhana – one branch (2) Gauriganj – two branches (3) Salon – three branches.

The water going to Musafirkhana is estimated as follows:

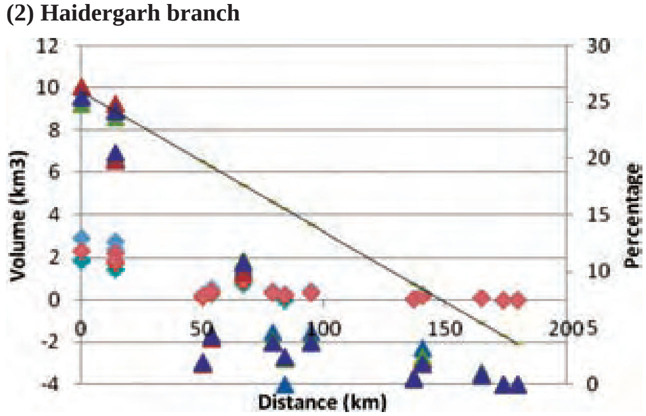
G= F (number of branches in Musafirkhana/total split branches) × (width of the branch to Musafirkhana/width of the branch entering Maharajganj).

Similar estimation is made for Gauriganj and Salon. Based on the above-mentioned method, surface water availability is estimated in volume in each subdistrict by its respective branch head. It is obvious that if the subdistrict is closer to the particular branch head, it will have more water than the far one. But in many cases, it is found that this is not true when the number of canal features and the ratio of their size are taken into calculation. Although a subdistrict is close to the branch head but if the total length and size of its canal network are less than the far one, it will possess less amount of water than the far one. Here, the number of canal features is taken from the command area map and a CADA report, whereas the ratio of the width of canal features is estimated from Google Earth. Thus, the distance is not the only factor while deciding the availability of the surface water to the subdistrict but other canal parameters are also important. Although this is true in quite a few cases and it is found that overall as distance increases, surface water availability decreases. In the entire branch network studied, this fact has been found to be true. Figure 8 shows some charts of some of the major branches, which reveal both facts that are mentioned previously. Figure 8 shows the trend of the volume of water available and the percentage of water in each subdistrict with respect to distance.

(1) Faizabad branch



(2) Haidergarh branch



(3) Allahabad branch

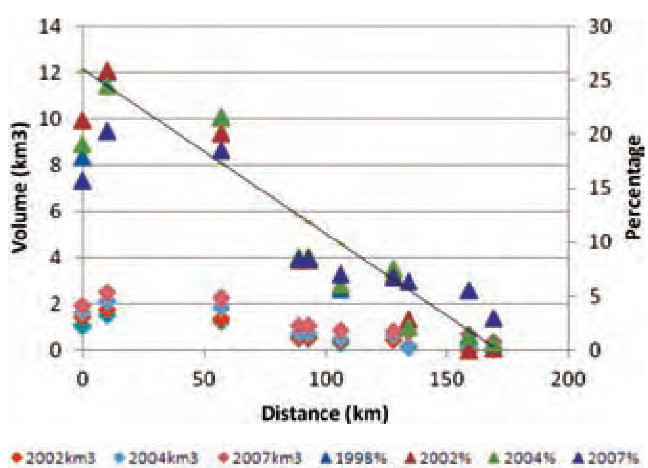


Figure 8 Decreasing trend of surface water availability with increasing distance

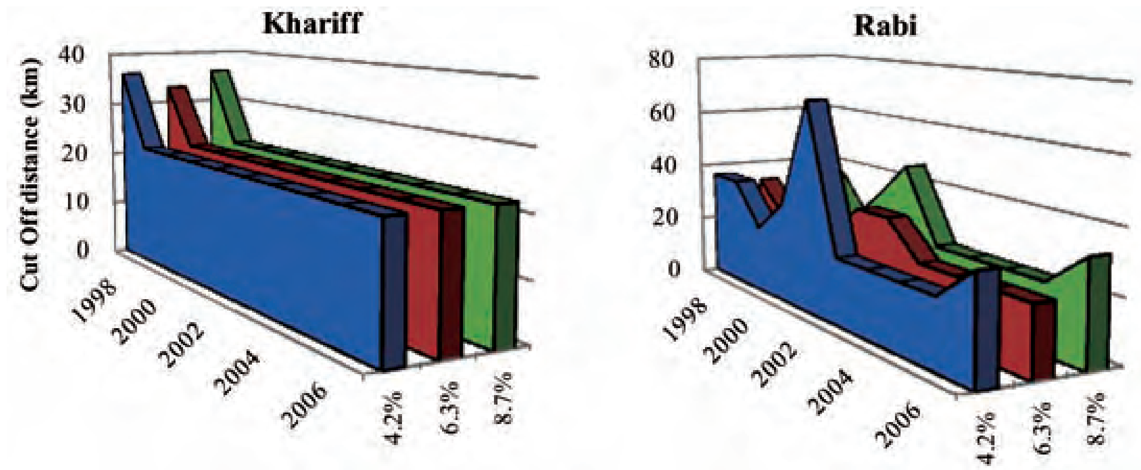


Figure 9 Sensitivity curves

Impact of Water Losses on Surface Water

Sensitivity Analysis

Following Clara and Milorad (2010) and Kijne's (1996) work on sensitivity analysis, an analysis was carried out on 10 years cut-off distances (maximum water reaches to the distance from the barrage) for three respective seasons, rabi, kharif and zayed, to assess how sensitive the conclusions are to the assumed water loss (6.3%). In an Indian scenario, for unlimited trapezoidal canal, seepage loss varies from 4% to 8% (Swamee *et al.*, 2000), and as we considered 0.2–0.7% as evaporation loss, sensitivity analysis has been carried out for 4.2, 6.3 and 8.7% where some important variables such as canal width, water height, number of irrigations, buffer irrigated area and the water consumed at each branch attributed to surface water availability calculation remain constant.

Figure 9 represents two sensitivity curves for two primary seasons, kharif and rabi. Zayad season has not been considered for this analysis as in most of the months the canal remains closed during this period. Therefore, lack of proper data has not encouraged a very clear picture for the zayad season. It is an attempt to test the sensitivity of water reach points to the assumed water loss (4.2, 6.3 and 8.7%) keeping other variables unchanged. In Figure 9, the red area shows the trend of water reach over the years when water loss is 6.3%. The blue one represents trend line for water loss 4.2% and green one for 8.7%. The sensitivity analysis identifies that the water reach to subdistricts is almost the same for all three ranges of water loss. It has not deviated much or produced any biased result for assumed water loss (6.3%). On the other hand, it is quite clear from the graphs that the trend of water reaching to subdistricts is the same for three different water losses in the kharif season. These three curves show the same reach of canal water over the 10 years with the same peak in 1998. In rabi season, the same trend has also been found with no major variations.

Furthermore, another striking point is peak water reach at 6.3% lies in between 4.2% and 8.7% based on the availability of surface water. Comparing the two seasons kharif and rabi, it has been found that the farthest reach of canal water is experienced during rabi season for any of the loss situation compared with kharif season. It may be supported by the fact that water loss will be less in kharif season, which is characterized by higher rainfall, higher water content on soil and huge humidity along with moderate temperature, which triggers lower seepage loss, resulting in less requirement of canal water. On the other hand, rabi season experiences a dry weather, is less moist compared with kharif season and has moderate humidity, which is attributed to moderate water loss and requirement of more canal water for irrigation. Therefore, canal water reach in rabi season is more compared to kharif season. The results of the sensitivity analysis indicate that the trigger for different values for water loss does not play any significant role in water availability and its reach in subdistricts. Irrespective of the water loss being 4.2% or 6.3% or 8.7%, its impact on surface water reach is minimal. Therefore, 6.3% water loss (used for this study) is good enough to consider for calculating surface water availability for three respective seasons, kharif, rabi and zayad.

Conclusions

It is obvious that only water discharge data at canal head is not the only indicator in deciding whether farmers are getting enough water for agriculture or not. An integrated strategy for surface water requires its conservation, sustainable use and equitable sharing with attention to quality and use efficiency; and there is always a threat of evaporation and pollution. Other two resources of water are more complex to handle such as rainwater, which needs mandatory harvesting and dealing with climate change challenges, and groundwater, which needs sustainable management of aquifer and its treatment as private or public goods with a challenge of managing excessive water mining and pollution. Thus, by estimating the surface water available for irrigation purposes in each subdistrict, canal administrators may be facilitated about policy implications on water allotment, which can lead to higher irrigation efficiency. The estimation of water loss has been considered as 6.31% by water volume. However, sensitivity analysis shows that by applying a range of water losses (i.e., 4.2–8.7%), not much variation is observed in the amount of surface water available for irrigation. Therefore, water losses due to seepage and evaporation may not be the deciding factor for how far water reaches along a canal. Rather, other factors such as maintenance level and siltation in the canal may be more prominent factors on how much water flows through the canal and reaches far-end farmers. Spatial analysis plays such a major role in deciding directions as well as distance, which brings into light many factors that would remain unknown with nonspatial analyses. Thus, one can implement the same model to estimate conveyance loss as well as surface water availability at the subdistrict level. By looking at the real picture with the surface water available at a subdistrict level, water demand along the canal can be projected more realistically, and thus administration can make new policies to overcome canal water scarcity or abundance, and thereby overcoming surface water mismanagement. It will overall help farmers in getting canal water on time and thus can lead to better agricultural outputs.

Acknowledgement

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