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Water Resources Management in the Ganges Basin: A Comparison of Three Strategies for Conjunctive Use of Groundwater and Surface Water

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Abstract The most difficult water resources management challenge in the Ganges Basin is the imbalance between water demand and seasonal availability. More than 80 % of the annual flow in the Ganges River occurs during the 4-month monsoon, resulting in widespread flooding. During the rest of the year, irrigation, navigation, and ecosystems suffer because of water scarcity. Storage of monsoonal flow for utilization during the dry season is one approach to mitigating these problems. Three conjunctive use management strategies involving subsurface water storage are evaluated in this study: Ganges Water Machine (GWM), Pumping Along Canals (PAC), and Distributed Pumping and Recharge (DPR). Numerical models are used to determine the efficacy of these strategies. Results for the Indian State of Uttar Pradesh (UP) indicate that these strategies create seasonal subsurface storage from 6 to 37 % of the yearly average monsoonal flow in the Ganges exiting UP over the considered range of conditions. This has clear implications for flood reduction, and each strategy has the potential to provide irrigation water and to reduce soil waterlogging. However, GWM and PAC require significant public investment in infrastructure and management, as well as major shifts in existing water use practices; these also involve spatially-concentrated pumping, which

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may induce land subsidence. DPR also requires investment and management, but the distributed pumping is less costly and can be more easily implemented via adaptation of existing water use practices in the basin.

Keywords Ganges Basin · Seasonality · Artificial recharge · Flood reduction · Conjunctive use

1 Introduction

Synchronization of seasonal water availability with demands is a water resources management challenge in many agricultural river basins (e.g. Camnasio and Becciu 2011; Pavelic et al. 2012). Excess wet season river flow causes flooding, while low flows are often inadequate for dry season water supply. This results in conflicts between upstream and downstream users in transboundary rivers (e.g. Uitto and Duda 2002; UNDP 2006). Under a changing climate, seasonal extremes (Kundzewicz et al. 2010) and supply–demand imbalance (Immerzeel et al. 2010) are likely to increase. One approach to managing water resources in such basins is upstream storage of excess wet-season river flow for use during dry season. This requires conjunctive-use management strategies (Coe 1990). Effective conjunctive use of surface water and groundwater results in a total annual system yield that exceeds the sum of the yields of the separate components (Bredehoeft and Young 1983).

Traditionally, dams and reservoirs are used for surface water storage, but these are costly, are prone to evaporative loss, and have adverse environmental effects (e.g. Baxter 1977; Gupta 1992). In contrast, aquifers can act as efficient water reservoirs with minimum evaporative loss and no surface area for inundation (Bouwer 2000). Artificial recharge technologies are often effective means of using subsurface reservoirs for water storage (see Bouwer 2002 for a review).

This study reexamines the idea of pumping-induced subsurface storage of monsoonal river flow along the Ganges River and its tributaries, originally proposed by Revelle and Lakshminarayana (1975) as the 'Ganges Water Machine' (GWM). Two additional conjunctive use strategies are also explored. The potential effectiveness of each strategy and the primary factors affecting their functioning are assessed with numerical modeling. The implications for irrigation water supply, flood management, reduction of waterlogging, and maintenance of downstream dry season flow are considered with a focus on the State of Uttar Pradesh (UP), India (Fig. 1), the largest water user in the upper basin. This work provides insights into the feasibility of these strategies and indicates directions for future investigations.

In the original GWM study, Revelle and Lakshminarayana (1975) estimated that at least 60 billion m^3 of monsoonal river flow can be stored in the subsurface during dry season along 3,000 km of river reaches in the upper Ganges Basin. However, this estimate assumes homogeneous isotropic aquifers with purely horizontal flow. In this study, models are two-dimensional cross sectional with vertical anisotropy (ratio of horizontal to vertical hydraulic conductivity, K_h/K_v) that reflects the hydrogeologic stratification of aquifer fabrics allow consideration of vertical flow and head differences, important factors that control the storage dynamics.

1.1 Water Resources Management Issues in the Ganges Basin

The Ganges River basin (Fig. 1) has highly seasonal river flow. Due to the influence of the Asian southwest monsoon, over 80 % of total annual rainfall, varying from <1 m in the west to

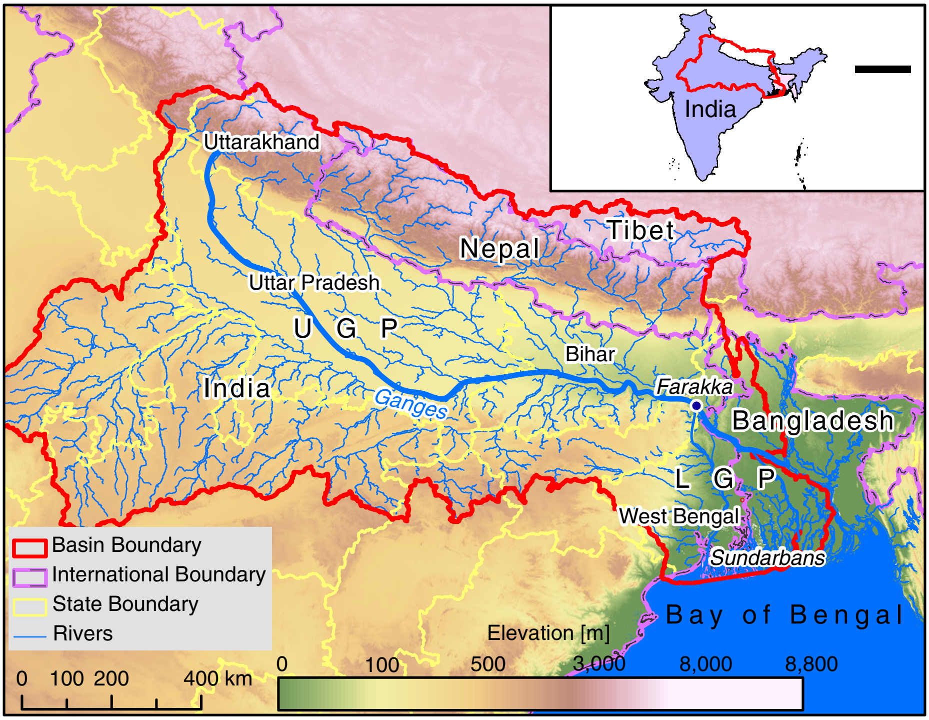

Fig. 1 Map showing extent of the Ganges basin in India, Nepal, Tibet and Bangladesh. *UGP* upper ganges plain and *LGP* lower ganges plain. Elevation data source: Jarvis et al. (2008)

>2 m in the east, occurs between June and September (O'Hare 1997). Thus, extensive monsoonal flooding in the Ganges plain occurs annually (Mishra 1997). However, the entire basin suffers from water scarcity during the rest of the year, leading to conflicts between upstream and downstream users (Bandyopadhyay 1995).

Natural seasonality is intensified by anthropogenic influences. Upstream diversion of Ganges flow for irrigation occurs in UP and Bihar (Figs. 1 and 2a). Additional diversions occur at Farakka Dam (Fig. 1) to maintain navigability of Kolkata Port in India. These diversions make it difficult to meet downstream dry-season Ganges flow requirements, particularly important for maintaining the delicate salinity balance in the coastal zone (Mirza 1998) crucial for sustaining the unique ecosystems of the world's largest mangrove forest, the Sundarbans (Fig. 1) (Gopal and Chauhan 2006).

Conjunctive use of groundwater and surface water already occurs in many UP canal irrigation areas, but not to full potential, largely due to lack of management (Garduño and Foster 2010). In these areas, unmanaged water use and the greater cost of groundwater compared to surface water creates interlinked management issues. Surface water is used preferentially in canal head areas where it is readily available, forcing farmers in canal tail areas to pump groundwater when surface water becomes scarce (World Bank 2010). The result is a reduction in crop yield due to rising water tables and soil waterlogging in canal head areas (Singh et al. 2012), whereas in canal tail areas, groundwater use is unsustainable and water tables decline over time (Gandhi and Bhamoriya 2011) resulting in increasing pumping costs.

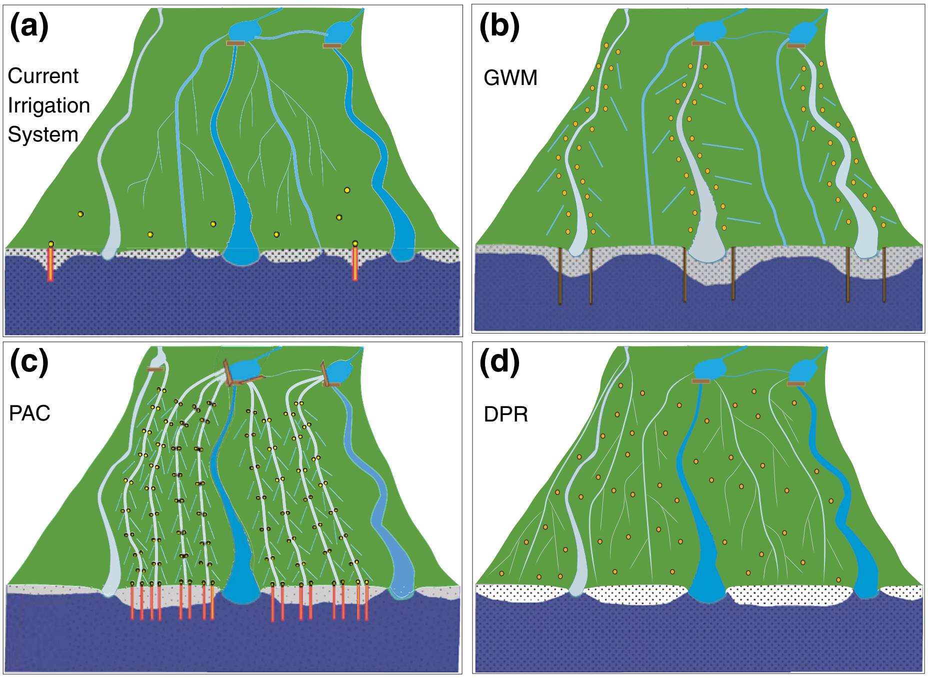

Fig. 2 Schematics of **a** current irrigation system in UP **b** GWM **c** PAC and **d** DPR. The section views show the dry season water table with some wells, and the map views show the rivers (*wide lines*), canals (*narrow lines*) and wells (*yellow dots*). Rivers and canals in blue carry water throughout the year; others are dry during dry season and carry water during the monsoon only

2 Methods

Employing numerical models to simulate strategies for seasonal subsurface water storage, a generic sensitivity analysis determined the factors that most affect the storage and water table dynamics. Plausible values and variations of underlying parameters were determined primarily from published literature (Section A-2, online resources). Then, with guidance of the sensitivity analyses, strategies were constructed and groundwater pumping, storage, and water-table dynamics were simulated to evaluate their efficacy.

2.1 Management Strategies

All three strategies considered involve dry season groundwater pumping to induce recharge from rivers and/or canals. However, the strategies differ in pumping configuration, as discussed below.

2.1.1 Ganges Water Machine (GWM)

In this strategy, intensive dry season pumping in narrow bands along rivers lowers the water table (Fig. 2b). Infiltrating river water raises the water table during the following monsoon season. This induced storage is pumped out during the following dry season, creating a cycle of storage and release that eventually reaches dynamic equilibrium. Distributary canals (lined to avoid water loss during transport) carry pumped water to irrigation fields. For this scheme to operate effectively, rivers must be ephemeral - dry during the dry season (Chaturvedi and Srivastava 1979).

2.1.2 Pumping Along Canals (PAC)

This strategy resembles GWM except that intensive dry season pumping is located along major ephemeral diversion canals, rather than along rivers (Fig. 2c). Here, diversion canals carrying river flow during the monsoon season are unlined to allow infiltration. Like GWM, all other distribution canals are lined to avoid water loss.

2.1.3 Distributed Pumping and Recharge (DPR)

This strategy involves dry season groundwater pumping at point of use via small-capacity irrigation pumps and canal irrigation in monsoon season (Fig. 2d). Dry season groundwater pumping lowers the water table rather uniformly throughout the basin, whereas during monsoon, river flow routed through canals provides groundwater recharge, which is then pumped out in the next dry season.

2.2 Model Setup

Groundwater flow was simulated using the USGS-MODFLOW code (Harbaugh et al. 2000). Aquifer cross-sections extending from the center of infiltrating rivers or canals to half the distances between two adjacent rivers or canals were modeled in 2-D (Fig. 3). Vertical boundaries were no-flow symmetry boundaries. The bottom boundary was also no-flow, either at the aquifer base (for sensitivity analysis, GWM and PAC) or water table (DPR). Although

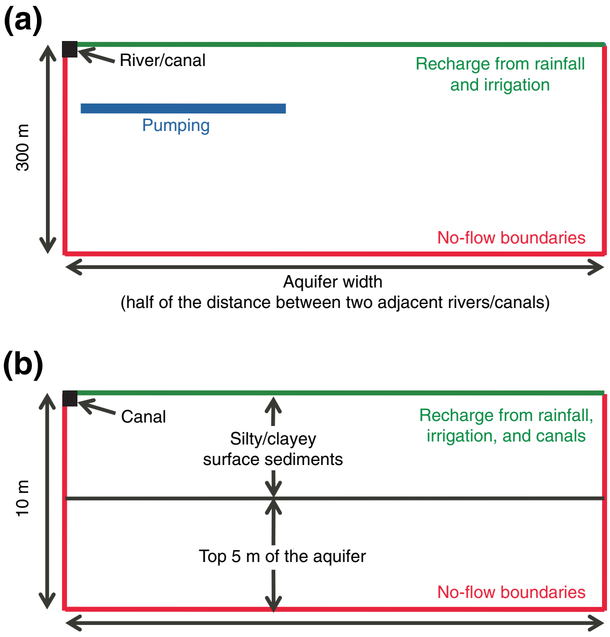

Fig. 3 Cross-sectional model setup for **a** sensitivity analysis, GWM, and PAC strategies, and **b** DPR strategy

the water table is not a true no-flow boundary, for DPR it is assumed that groundwater recharge reaches the water table and raises it uniformly. With the assumption of no lateral gradient and negligible compressive storage, the water table can be represented as a no-flow boundary. Areal recharge from rainfall and irrigation return flow was assigned to the model top using MODFLOW's recharge package. Potential recharge from rainfall and irrigation was estimated using the criteria in Government of India (1997) (Section A2, online resources). The MODFLOW drain condition was used to limit water-table rise above land surface, thus limiting actual recharge where the water table is high. Rivers and canals were modeled with MODFLOW rivers, a head-dependent flux boundary condition. Parameter values used in each strategy are listed in Table 1.

2.2.1 Sensitivity Analysis

The one-dimensional GWM model set-up of Revelle and Lakshminarayana (1975) was simulated in the 2D framework of this study, allowing vertical flow to occur. This was regarded as the base reference case for sensitivity analysis. Hydraulic conductivity, vertical anisotropy, riverbed conductance, specific yield, groundwater recharge from rainfall and irrigation, aquifer width, river width, and river type (perennial vs. ephemeral) were varied and the annual groundwater storage volume and simulated pre-monsoon head compared.

2.2.2 Ganges Water Machine GWM

Seasonal groundwater storage for GWM was simulated for eight different type areas identified in UP (Section A-3, online resources), categorized based on the spatial distribution of the parameters identified as important by sensitivity analysis. Riverbed conductance was calculated considering the $K_{v\text{-river}}$ and thickness of riverbed sediments as 2.5 m/d and 15 m,

Table 1 Model parameters used for the sensitivity analysis, GWM, PAC, and DPR strategies

Parameters	Sensitivity analysis (Base case)	GWM	PAC	DPR		
Horizontal hydraulic conductivity [m/d]	15.2	15.2	15.2	0.015–15.2		
Vertical hydraulic conductivity [m/d]	15.2	0.15	0.15	0.015–1.52		
Specific yield	0.25	0.16	0.16	0.16		
River/canal leakage rate [m/d/m^2 river bed]	0.61	Simulated	Simulated	Simulated		
Leakage period [days]	120	120	120	120		
Groundwater pumping rate [m^3/d][a]	45	72–200	22–30	NA		
Pumping period [days]	240	240	240	NA		
Pumping depth interval [m]	50–150	100–200	50–100	NA		
Wellfield width [km]	4	4	1	NA		
River or canal width/depth [m]	300/5	300/5–900/5	100/1	Field 0.5/0.3	Secondary 2/0.5	Primary 10/2
Aquifer width [km]	8	15–30	2.5 and 5	0.1	1	5

[a] Pumping rate is per unit length of river or canal on each side

respectively (Chaturvedi and Srivastava 1979). The river was modeled as ephemeral with 5 m constant water depth during monsoon season. The aquifer was considered vertically anisotropic due to layering of low and high permeability sediments common in fluvial deposits of the region (Michael and Voss 2009a). The coefficient of anisotropy (K_h/K_v) was estimated by simulating flow through a hypothetical heterogeneous aquifer system constructed based on published lithological data (Section A-2, online resources).

One set of simulations was performed for each type-area parameter combination (Table ESM-1, online resources). The range of potential annual storage volume for each type area was evaluated by considering three design pre-monsoon heads (30 m, 50 m, or 80 m, at dynamic steady state at the lateral and vertical well-field center). The 30 m pre-monsoon head was chosen following Revelle and Lakshminarayana (1975); the other two were chosen to assess potential for greater storage. For each type area, pumping rates necessary to obtain the design heads were determined by trial and error. Basin-wide pumping and storage volumes were calculated by multiplying simulation results per unit river length by actual river length and by a factor of two to account for both sides of each river.

2.2.3 Pumping Along Canals (PAC)

The model setup of PAC resembles GWM (Fig. 3a), but with 100 m wide and 1 m deep infiltration canal. Canal-bed conductance was calculated considering $K_{v\text{-canal}}$ and thickness of canal-bed sediments as 0.86 m/d and 5 m, respectively, because the 5 m thick silty surficial layer present in much of the basin (e.g. Ala Eldin et al. 2000; Umar et al. 2001) is not likely to be incised by the shallow canal channels. The range of potential annual storage volume was determined for two different canal spacings, 10 km and 5 km. Pumping rate was determined by trial and error to achieve the maximum possible pumping rate that reaches a dynamic steady state. The width and spacing of recharging canals are the design parameters for PAC; these were kept constant throughout UP. Therefore, unlike GWM, separate models are not necessary for different type areas.

2.2.4 Distributed Pumping and Recharge (DPR)

For DPR, infiltration from three types of surface canals were simulated. Canal spacing, width and depth of each canal type were estimated based on GIS data on Jaunpur Branch canals in UP (Raut 2009) overlain on Google Earth (Table 1). It was assumed that the total monsoonal groundwater recharge would be pumped out during the subsequent dry season, resulting in the same pre-monsoon water table elevation each year. Thus, only infiltration was simulated, not groundwater pumping (Fig. 3b).

DPR models consisted of two geologic layers: surface sediments and aquifer. Two cases for the top, 5 m thick layer were considered: silty (K=0.15 m/d) and clayey (K=0.015 m/d). The aquifer layer had K_h of 15.2 m/d and K_v of 1.52 m/d (anisotropy 10:1). A lower anisotropy ratio than in GWM and PAC was used because the top low-K layer was explicitly represented and the vertical aquifer extent was much less. Canals were specified as constant head boundaries.

Storage was estimated sequentially in three different models with different-size channels explicitly represented. First, simulated storage from field channels was determined by multiplying simulated storage volume per unit length of field channels by their total length in that area. This value was used as groundwater recharge for simulation of secondary distribution canals. Finally, the sum of the storage per unit area of field channels and secondary distributary canals was used as groundwater recharge for primary canal simulations.

2.3 Groundwater Pumping Cost Estimation

Pumping cost was estimated by converting lift energy into diesel fuel volume. Lift energy, calculated after Abadia et al. (2008) is:

$$Gross\ power(kW) = Q\rho gH/3600000\varepsilon,$$

where Q is pumping rate (m^3/h), ρ is density of water (kg/m^3), g is gravitational constant (m/s^2), ε is pump system efficiency (%), and H is pumping lift (m) (here defined as vertical distance from the water table to ground surface). Power is then converted to diesel fuel energy requirement considering 0.25 l of fuel equivalent to 1 kW-hour (Robinson 2002) and assuming a 55 % pumping system efficiency (Abadia et al. 2008).

2.4 Study Limitations

To tractably calculate efficacy of management strategies, assumptions are required to simplify complexities in the systems. A key assumption is that basin-wide average values of aquifer parameters are applicable for analysis. However, the Ganges aquifer fabric consists of highly heterogeneous fluvial sediments with substantial local variation in hydrogeologic parameter values that will impact local efficacy. The most critical parameters to characterize are aquifer K_h and K_v and riverbed and surficial sediment conductances. These parameters control time-development and extent of drawdown during pumping and aquifer storage volume. Further, stratification of low and high permeability layers is represented in the model using vertical anisotropy. Although this accounts for small-scale layering, the actual distribution of low-K sediments below rivers will affect vertical connectivity and thereby infiltration and storage. Another important limitation is lack of access to groundwater level monitoring data for model calibration. Such data would be essential for calibration of site-specific models. Another factor not directly considered here is development of an unsaturated zone below recharging rivers and canals. Unsaturated conditions reduce K between the river bottom and water table, resulting in reduced groundwater infiltration compared to fully saturated conditions. The time response of water table to infiltration can also be affected by heterogeneity in the unsaturated zone (Flint and Ellett 2004). The greatest effect might be for GWM, for which the thickest unsaturated zone would occur.

3 Results

3.1 Results of Sensitivity Analysis

Results of all sensitivity simulations are summarized in Table ESM-2 in online resources. In the base-case simulation, hydraulic heads reach dynamic steady state after a few decades of pumping, with seasonal head fluctuations decreasing with distance from the river (Figure ESM-3, online resources). In the base case, maximum simulated pre-monsoon water table depth is about 34 m at 3 km away from the river (Figure ESM-4, online resources) and 22 million m^3/year infiltrates per km river. For the 3,000 km river reaches considered by Revelle and Lakshminarayana (1975), annual storage is 66 billion m^3, similar to their estimate of 60 billion m^3.

River type (perennial vs. ephemeral) is found to be the most important factor controlling total monsoonal flow storage volume. Although for the same pumping rate and aquifer conditions, total annual storage for perennial and ephemeral rivers is the same, 70 % of the storage is from dry season flow for perennial rivers. This ‘short-circuiting’ of river water to pumping wells increases cost per unit monsoonal flow storage, in agreement with Chaturvedi and Srivastava (1979). Since pumping along perennial rivers would be inefficient, sensitivity to all other parameters was tested only for ephemeral rivers and canals. For both river types, storage volume is highly sensitive to riverbed conductance (C) as long as it is lower than the K_v. For $C > K_v$, K_v primarily controls the leakage through riverbed.

Hydraulic conductivity in an isotropic aquifer controls dynamic steady-state hydraulic head and time required to reach it. A low-K system takes longer to reach dynamic steady state with deeper hydraulic head than a high-K system. High anisotropy (i.e. lower K_v) also significantly increases time to reach a dynamic steady state and results in a deeper pre-monsoon head for the same pumping rate (Figure ESM-5 in online resources).

Specific yield (S_y) has little effect on induced river recharge and time development of the steady-state condition, but there is an impact on hydraulic head. A 50 % reduction in S_y from base case values results in a 38 % decrease in pre-monsoon head at dynamic steady state compared to that of the base case.

Areal groundwater recharge also affects time development and depth of the water table and pumping-induced storage volume. For a given pumping rate, higher recharge results in earlier development of dynamic steady state with a shallower pre-monsoon head than the base case. However, because additional recharge partially supplies withdrawal, there is a concomitant reduction in storage from the river infiltration. The same is true for aquifer width because this changes areal recharge. Increased river width also reduces time to reach dynamic steady state and water table depth due to an increase in infiltration rate.

3.2 Results for Three Strategies Applied to UP

The total annual storage achieved with each strategy is reported here as a sum over the State of UP at dynamic steady state. The estimates are based on three design water table depths for GWM, two canal spacings for PAC, and two surface sediment types for DPR. The estimated total annual subsurface storage of river flow for GWM is 17 billion m^3, 28 billion m^3, and 46 billion m^3 for 30 m, 50 m, and 80 m pre-monsoon design hydraulic head, and for the total annual groundwater pumping of 58 billion m^3, 80 billion m^3, and 110 billion m^3, respectively (storage for individual type areas are given in Table ESM-3, online resources). For PAC, estimated groundwater storage rate per km canal length is approximately 1.7 million m^3 per year. Assuming that PAC canals would exist only along reaches of the rivers considered for GWM pumping development, the total annual groundwater storage in UP is 20 billion m^3 and 40 billion m^3, and the required annual groundwater pumping is 64 billion m^3 and 85 billion m^3 for 10 km and 5 km canal spacing, respectively. Total annual storage for DPR would be 14 billion m^3 and 90 billion m^3 with required annual groundwater pumping of 56 billion m^3 and 132 billion m^3 for clayey and silty top soil, respectively, assuming that DPR would be implemented in the 12 Mha irrigated area in UP. Over 85 % of total groundwater storage in DPR occurs through field channels rather than primary and secondary distributary canals because of their extremely dense networks.

The difference between pumping and the storage volumes is the actual recharge from rainfall, irrigation return flow, and existing canal seepage. This increases with time as the drawdown cone grows, eventually reaching a steady percentage of potential recharge specified on the model top. Depending on design head, actual recharge varies between 60 and 100 % of potential recharge (Figure ESM-6, online resources).

The cost of pumping depends on both depth to water (H in Section 2.3) and annual pumping volume. Both pumping cost and storage are maximized when the system reaches dynamic steady state; the reported figures below are minimum and maximum estimates at dynamic steady state. The estimated annual energy requirements would be 7 and 36 GW for GWM, 3.7 GW and 4.9 GW for PAC, and 3.7 GW and 4.9 GW for DPR. Considering the current diesel price in India as 0.86 USD per liter (Sahu and Sharma 2012), annual pumping costs would be 1.5 and 7.7 billion USD for GWM, 0.8 and 1.0 billion USD for PAC, and 0.4 and 0.9 billion USD for DPR.

4 Discussion

4.1 Implications for Reducing Seasonality in River Flow

The two primary goals of water resources management in river basins with extreme seasonality are reduction of wet season flooding and enhancement of dry season water supply. The conjunctive use schemes simulated in this work would achieve these goals, though outcomes would depend on complex factors.

Estimated storage in the scenarios considered for UP represents a percentage of average monsoonal river flow (Table 2), which does not necessarily translate directly into flood reduction. Flooding in the Ganges Basin occurs intermittently during the 120-day monsoon season, typically after heavy rains limited to 10–20 % of the period (Soman and Kumar 1990). In contrast, storage through infiltration occurs continuously throughout the monsoon season, decreasing over the season, particularly for GWM (Figure ESM-7, online resources). More-thorough analysis of flood-reduction benefits, outside the scope of the current study, would include estimation of peak flow reduction during a particular flood event rather than percentage of average monsoonal flow reduction, as considered here. Nevertheless, qualitative

Table 2 Strategy comparison. Ranges are for low to high storage scenarios. For GWM, the range encompasses three design drawdown scenarios, for PAC the range is for two different canal spacing, and for DPR the range is for silty to clayey near-surface sediment permeability values

Relative benefits/Drawbacks	Ganges Water Machine (GWM)	Pumping Along Canals (PAC)	Distributed Pumping and Recharge (DPR)
Storage (% of average monsoonal flow in Ganges exiting UP)[a]	~ 7–19 %	~ 8–16 %	~ 6–37 %
Ratio of storage volume to annual volume pumped	0.29–0.42	0.31–0.47	0.25–0.68
Annual cost per m^3 water storage [USD]	0.09–0.17	0.04–0.03	0.03–0.01
Proportion of the pumped water available for irrigation	0.57–0.77	0.78–0.84	0.91–0.96
Annual irrigation water cost per ha land irrigation [USD]	230–450	80–70	40–35
Increase of dry season flow (% of current dry season flow in Ganges exiting UP)	>25 %	>25 %	>25 %
Risk of land subsidence near well-fields	High	Low	None
Disruption of domestic water supply	Yes	Possible	No
Requires ephemeral rivers	Yes	No	No
Complexity/intensity of planning, management and maintenance	High	High	Low

[a] (Based on the estimated 240 BCM monsoon season flow at UP-Bihar boundary; source: World Bank, Ganges Strategic Basin Assessment: A Regional Perspective on Risks and Opportunities, unpublished)

insights on reduction of flood intensity and duration can be developed. Infiltration during the early part of monsoon season would result in a lower river stage before peak flood flow, so channels would accommodate more peak flow. Additionally, flow reduction would occur because of river flow diversion for canal-based monsoon irrigation. Further, an increase in irrigation activity is likely to increase groundwater recharge as evidenced from Bangladesh (Fig. 1) (Michael and Voss 2009b; Shamsudduha et al. 2011), thereby decreasing immediate runoff generation from overland flow. Lastly, in GWM, since the water table along river channels where flooding occurs would be deep, floodwater could infiltrate the subsurface quickly, reducing flood duration. Storage volumes reported here are for implementation of schemes in UP only. Additional storage and flood reduction might be achieved should these strategies also be applied in parts of the upstream and downstream states, Uttarakhand and Bihar (Fig. 1).

Ganges dry season flow can be increased by directly rerouting a portion of pumped water to the river downstream of well-fields (for GWM) or by stopping the current practice of using dry season flow for irrigation, which would occur under all strategies. Currently, surface water-based irrigation projects in UP annually withdraw about 28 billion m^3 of river-flow (Planning Commission 2007), at least half during dry season. If this 14 billion m^3 were not diverted, dry season flow in the Ganges at the UP-Bihar boundary would increase by approximately 25 %.

4.2 Implications for Irrigation and Waterlogging Management in the Upper Basin

All three strategies have potential to provide irrigation water, though the efficacy varies among strategies. GWM may provide 33–85 billion m^3 of dry season irrigation water per year whereas PAC and DPR may provide 50–71 billion m^3/y and 51–127 billion m^3/y, respectively. These volumes were estimated by deducting non-irrigation dry season water demands in UP from total seasonal pumping under each strategy (Section A-6, online resources). Assuming a 50 cm dry season irrigation water demand per unit irrigated area in UP (Planning Commission 2007), the available water, if used entirely for irrigation, would satisfy the needs of 6.6–17 Mha for GWM, 10–14 Mha for PAC, and 10–25 Mha for DPR. Under the best-case scenario, there would be sufficient water to expand the current 12 Mha irrigation are in UP (Planning Commission 2007) by an additional 20–100 %.

Irrigation water cost also varies among strategies. Based on model results, the cost of dry season irrigation water/ha irrigated land is USD 230–450 for GWM, USD 70–80 for PAC, and USD 35–40 for DPR. These estimates represent total annual irrigation water cost/ha under the proposed strategies, because rainfall and diverted river flow satisfy needs of the monsoon season crop. Compared to the current cost of groundwater irrigation in UP (USD 100–150/ha/year, Garduño and Foster 2010), PAC and DPR might significantly reduce overall agricultural production costs. Reduction of groundwater pumping costs due to reversal of declining water table trends resulting from enhanced groundwater recharge from monsoon season canal irrigation (similar to DPR) is already evidenced in some local areas in UP (Sakthivadivel and Chawla 2002).

All three management strategies have potential to reduce soil waterlogging, a common issue in UP canal-irrigation areas by maintaining deep water tables. GWM pumping would lower the water table, reducing waterlogging within 15–25 km of the rivers (Fig. 4a). PAC and DPR pumping would lower the water table, reducing waterlogging throughout UP (Fig. 4b, c). However, in high recharge areas, DPR may not effectively eliminate waterlogging because the post-monsoon water table may rise close to the surface as shown in Fig. 4c for silty surface sediments.

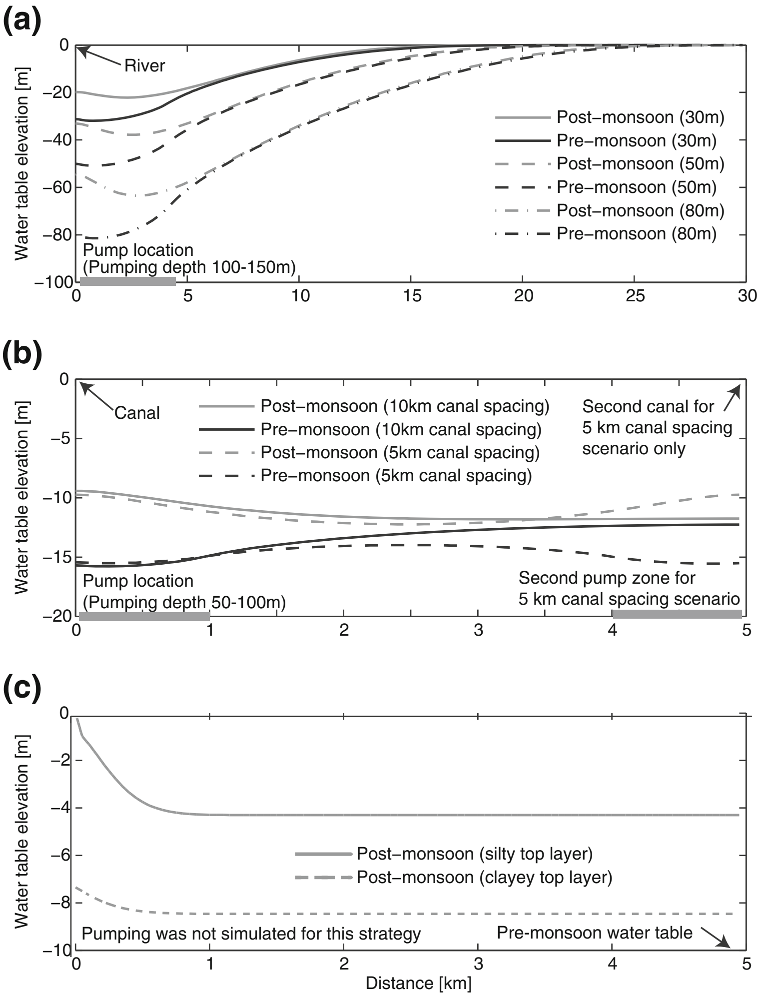

Fig. 4 Example model results, simulated water table elevations at dynamic steady state. **a** GWM for 30 m, 50 m, and 80 m design pre-monsoon head scenarios. **b** PAC for 10 km and 5 m canal spacing scenarios. **c** DPR for silty and clayey surficial layer scenarios

4.3 Strategy Comparison: Storage and Irrigation Costs

The storage cost differs among the strategies (Table 2). Cost depends on pumping required per unit storage and average lift. For GWM, increase in lift is greater than increase in storage with increased pumping. Thus, despite an increase in ratio of storage to pumped volume (Table 2), storage cost increases. For PAC, average lift is almost the same for all scenarios, resulting in nearly constant cost per unit storage (Table 2). For DPR, average lift is lower for the high storage scenario than for the low storage scenario because greater infiltration results in a shallower water table at the end of the infiltration period. However, cost may vary spatially depending on local hydrogeological conditions. Two factors may reduce storage costs for GWM. Areas with high K_v would have a shallower water table, and naturally-ephemeral rivers would reduce the need for flow maintenance in dry season. In contrast, PAC and DPR cost would increase in areas with thick, clayey surficial sediments due to reduced canal-bed leakage

Differences in groundwater irrigation cost among strategies are due to pumping cost and proportion of water available for irrigation. The proportion of pumped water available for irrigation is least for GWM followed by PAC (Table 2). This is because a significant proportion of pumped water needs to be returned to the river to maintain downstream dry season flow for these strategies. Moreover, this study assumes that distributary canals for these two strategies are lined. Should canals not be lined, there would be a further reduction of available water for irrigation resulting in a net increase in irrigation water cost. DPR is free of these considerations.

4.4 Strategy Comparison: Implementation Needs and Potential Adverse Impacts

All three strategies would require appropriate planning and regular monitoring. These would be particularly complex for GWM and PAC. GWM would require careful regulation of existing dams and in some cases dam renovation or new dam construction to divert dry season river flow upstream of well-fields and re-introduction of water downstream of well-fields along perennial rivers to maintain dry river conditions. Similarly, PAC would require careful regulation of canals to carry water during wet season and remain dry during dry season. Regular monitoring of the water table and permeability of infiltrating river or canal beds would be essential to ensure efficient operation, as clogging is a common problem in artificial recharge (Bouwer 2002). Planning, maintenance, and monitoring of these strategies require a high level of government coordination. This may be difficult because separate departments currently manage the groundwater, surface-water-based irrigation, and groundwater-based irrigation in UP.

Adverse environmental impacts are associated with GWM more than with the other strategies. The dry river condition required along river reaches with well fields would impact river ecosystems, likely with major environmental consequences. Diversion would also disrupt river-based sewage management facilities currently in operation in many cities along these river reaches in UP (e.g. Varanasi city; Hamner et al. 2006). In addition, the dry river conditions required by GWM would have social impacts related to religious and other cultural activities centering on the Ganges and tributaries.

A potential hazard of groundwater pumping is subsidence. The deeper water table of GWM may induce compression of Ganges alluvium clays and silts, a common result of regional-scale groundwater withdrawal in alluvial aquifers (e.g., Galloway and Burbey 2011). A lowering of land elevation near rivers may exacerbate flooding in these areas. PAC could also result in land subsidence but it would likely be of lower magnitude due to less induced drawdown than in GWM. Since DPR drawdown is very low, the risk of land subsidence is negligible.

A substantial water table lowering near rivers and canals has additional implications. First, pumping-induced infiltration of river water could alter aquifer geochemical conditions (Bourg and Bertin 1993; Doussan et al. 1997), with potential subsurface clogging or contaminant mobilization. Second, the lower water table resulting from GWM may cause existing domestic shallow tube wells and irrigation pumps to become non-functional and the current domestic water-supply system, dependent on privately-owned shallow hand-pumped tubewells, would require modification.

4.5 Socio-Political Implementation Challenges

The most significant socio-political challenge in implementing these strategies is the need to change current water use practices. All strategies considered require groundwater-based dry season irrigation, whether pumped at point of use by farmers (DPR) or from designed well fields by the government (GWM and PAC). However, current groundwater pumping is costly, ~USD 100–150/ha per year, whereas canal water costs only USD 5/ha/year. The proposed strategies would minimize this disproportional distribution of costs among users, as a canal head user would use as much groundwater as a canal tail user. Although this would reduce overall groundwater pumping cost for UP (at least for PAC and DPR), in canal head areas it would locally increase fiscal burdens on either the water resource/irrigation departments or on the water users. This factor may be an important socio-political impediment for which local incentives may need to be developed as part of a successful implementation plan.

5 Conclusions

The analysis presented in this paper, based on simplified scenarios, demonstrates that all three strategies have potential for effectively managing the dual water excess - water scarcity problem in the Ganges Basin. These strategies would increase dry season flow and decrease monsoonal flow in rivers, while augmenting water supply for irrigation and reducing the extent of soil waterlogging. Modeling suggests that annual monsoonal storage would be between 17 and 46 billion m^3 for GWM, 20 and 40 billion m^3 for PAC, and 14 and 90 billion m^3 for DPR. These volumes correspond to 6–37 % of the average monsoonal flow in the Ganges exiting UP. However, the cost, management, and infrastructure requirements for implementation can be very high. The strategies require re-engineering of the river and canal systems, and significant changes in irrigation practices throughout the basin. GWM is the most costly to operate, and has greatest potential for adverse environmental impacts due to the required pumping intensity, followed by PAC. DPR has the lowest operating cost, but still requires significant management and infrastructure investment.

Although this analysis encompasses a wide range of scenarios, the actual efficacy of the conjunctive-use management schemes considered would vary in the basin depending on local aquifer geology, the local nature of riverbed and surficial sediments, river stage, river geometry, topography, and other hydrologic, geologic, and anthropogenic factors. Implementation would require testing in pilot projects within limited areas. Observations made in such projects can provide direct information for improving design, perhaps by narrowing the possible range of hydrogeologic parameters and conditions for each local area and by improving the modeling analysis to provide more locally descriptive predictions of system response.

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