Evaluation of the sustainability of deep groundwater as an arsenic-safe resource in the Bengal Basin

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Tens of millions of people in the Bengal Basin region of Bangladesh and India drink groundwater containing unsafe concentrations of arsenic. This high-arsenic groundwater is produced from shallow (<100 m) depths by domestic and irrigation wells in the Bengal Basin aquifer system. The government of Bangladesh has begun to install wells to depths of >150 m where groundwater arsenic concentrations are nearly uniformly low, and many more wells are needed, however, the sustainability of deep, arsenic-safe groundwater has not been previously assessed. Deeper pumping could induce downward migration of dissolved arsenic, permanently destroying the deep resource. Here, it is shown, through quantitative, large-scale hydrogeologic analysis and simulation of the entire basin, that the deeper part of the aquifer system may provide a sustainable source of arsenic-safe water if its utilization is limited to domestic supply. Simulations provide two explanations for this result: deep domestic pumping only slightly perturbs the deep groundwater flow system, and substantial shallow pumping for irrigation forms a hydraulic barrier that protects deeper resources from shallow arsenic sources. Additional analysis indicates that this simple management approach could provide arsenic-safe drinking water to >90% of the arsenic-impacted region over a 1,000-year timescale. This insight may assist water-resources managers in alleviating one of the world's largest groundwater contamination problems.

modeling | hydrology | water resources management | sustainable development | transboundary aquifer

The densely populated Bengal Basin region of Bangladesh and India, although traversed by two of the world's largest river systems and recipient of several meters of rainfall yearly, faces unparalleled water-supply problems. High concentrations of dissolved arsenic, released from sediments into groundwater, present risk of severe health effects for the estimated 85 million people drinking shallow groundwater in affected areas. The 2004 Implementation Plan for Arsenic Mitigation of the Government of Bangladesh (www.sdnpbd.org/sdi/policy/doc/arsenic_policy.pdf) recommends location-specific solutions, with a return to the use of low-arsenic surface water where possible, a source largely abandoned in the 1970s in response to severe health effects caused by microbial pathogens. Thirty years later, surface water quality has deteriorated further and use for domestic supply requires extensive treatment; such infrastructure does not exist and construction is not economically feasible, particularly, in rural villages where much of the population resides.

Options for arsenic avoidance or removal exist, but practical and social impediments limit their use. Household-based filters and low-arsenic dug wells require significant maintenance (1, 2), pond water is too polluted for purification by sand filters, and rainwater harvesting is seen as a solution only during monsoon (2). Treatment plants for shallow groundwater have been constructed in some areas, but a survey of 577 high-cost facilities in West Bengal, India, indicates that 82% are ineffective (3). Piped water systems that tap low-arsenic groundwater supplies are a preferred alternative, although the higher cost and maintenance effort may reduce their appeal (2). Hand-pump wells are inexpensive, require minimal maintenance, and are the most popular water supply technology, used by >95% of the population.

Arsenic concentrations in groundwater are highly variable laterally on large (4) (supporting information (SI) Fig. S1) and small (5) spatial scales but display a consistent vertical pattern: high arsenic (>50 μg/liter) rarely occurs at depths >150 m below land surface (4–7). Installing deeper domestic wells (currently, most are shallower than 100 m), a process already begun in some areas (8), is a simple solution that does not require extensive infrastructure. Deep wells would initially produce low-arsenic groundwater and exhibit the lowest disease risk of household alternatives (9). A program employing the deeper resource, combined with monitoring and switching to safe wells when high arsenic concentrations are detected, has been recommended (8, 10) and, if successful, would dramatically reduce arsenic exposure and adverse health effects (11). Although this management alternative would provide low-arsenic water for the short term, once released from sediments into solution, arsenic is transported by groundwater and has demonstrated limited retardation in shallow parts of Bengal Basin aquifers (12). Thus, arsenic may migrate downward, eventually contaminating the deeper water.

A sustainable management alternative will supply water of sufficient quantity and quality for both domestic and irrigation purposes indefinitely. The sustainability of a low-arsenic deep-groundwater supply hinges on the origin of water pumped from deep wells: if groundwater flow paths to a well avoid high-arsenic regions, the well could permanently produce low-arsenic water. In practice, sustainability need not require permanent avoidance of high arsenic concentrations in wells; a management alternative that provides a supply of low-arsenic water over a long time period may be considered sufficiently sustainable for present management purposes. Management alternatives that employ deep groundwater must aim to protect it from contamination by shallower arsenic and thus must be rooted in a clear understanding of groundwater flow at depth.

Sustainability depends primarily on groundwater flow paths, which are controlled by hydrogeologic characteristics and the pattern of pumping. Quantitative hydrogeologic analysis based on numerical simulation of the physics of groundwater flow in the Bengal Basin is required to evaluate the complex three-dimensional flow field for various management alternatives. The goal of this analysis is to elucidate the potential for large-scale flow at depth that could deliver low-arsenic water to wells for long periods by evaluation of flow patterns to pumping wells in current and alternative future pumping configurations. For initial consideration, this analysis disregards chemical processes;

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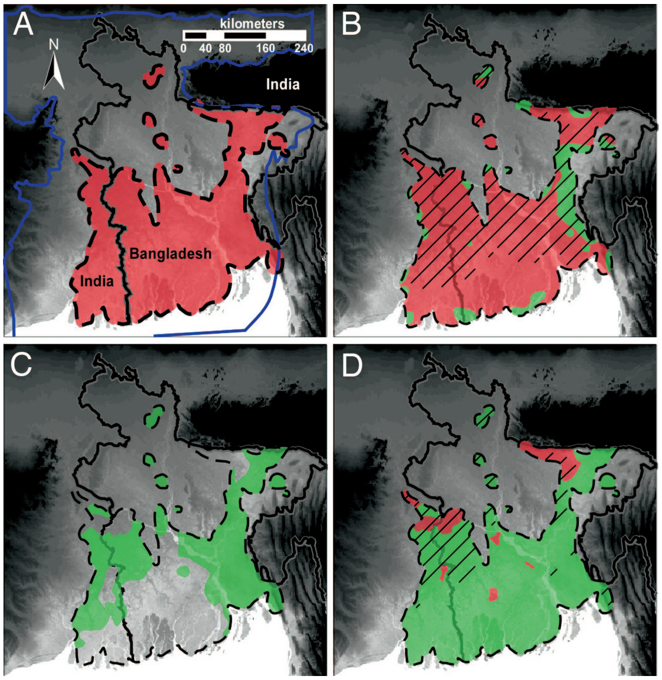

Fig. 1. Maps of Bengal Basin region and evaluation criteria for base-case simulations. (*A*) Land-surface elevation is shown in gray scale (16). Dashed black contour encloses high-arsenic region shown in red. Blue contour indicates model boundary. Black contour is Bangladesh border. (*B*) Deep pumping alternative: map of primary and secondary criteria. Areas that are sustainable or have long travel times (>1,000 years) are green. Areas that are not sustainable and have short travel times (<1,000 years) are red. Hatching indicates areas where domestic well lift is >12 m. (*C*) Split pumping alternative: green indicates sustainable areas only. (*D*) Split pumping alternative: colors as in *B*.

it is assumed that arsenic in solution remains in solution and that arsenic does not enter solution on a flow path previously low in arsenic.

Model

A contour encompassing the approximate region where dissolved arsenic concentrations greater than the Bangladesh drinking-water standard of 50 μg/liter were measured in Bangladesh (4) and West Bengal, India (School of Environmental Studies, Jadavpur University, 2006, http://www.soesju.org/arsenic/wb.htm) is shown on Fig. 1*A* and Fig. S1. This analysis tests two primary management alternatives for pumping in this high-arsenic region and compares these with the current pumping configuration where most wells are shallow. For the "deep" alternative, intended to provide low-arsenic water for both domestic and irrigation purposes, all wells within the high-arsenic region are installed in deeper low-arsenic zones. For the "split" alternative, intended to provide low-arsenic water for domestic supply (but not for irrigation purposes), only domestic wells within the high-arsenic region are installed in the deeper zone and irrigation wells remain shallow. Irrigation pumping is initially included in all scenarios because its elimination is an unrealistic alternative for the near future.

Each management alternative is assessed, via modeling analysis, by using two *primary* criteria for domestic pumping: *sustainability* and *travel time*. If pumped water is derived from recharge occurring outside the high-arsenic region, the deep well is considered a *sustainable* source of low-arsenic water. Where the recharge location is within the high-arsenic region, the deep well may be considered sustainable in practice, if advective *travel times* of 1,000 years elapse between recharge and discharge. If a well meets these two criteria, it is considered to provide an arsenic-safe water supply. A *secondary* criterion is that the *lift* (difference between ground-surface elevation and hydraulic head in the domestic pumping interval) is <12 m; many currently used intermediate-lift pumps lift water no more than 12–15 m (13; E. Stewart, http://www.cee.mtu.edu/peacecorps/documents_july03/Human_Powered_Pumps_FINAL.pdf), although higher-lift hand-pump technology is available.

To carry out the analysis, a numerical model [using MODFLOW (14)] that simulates saturated groundwater flow in three dimensions was developed. Model construction and study of major controls on regional flow in the Bengal Basin aquifer system are described in Michael and Voss (15). The model encompasses all unconsolidated basin sediments: the boundaries (Fig. 1*A*) extend laterally to hard-rock formations or the Bay of Bengal, and vertically from land surface to the depth of shale or basement. Large-scale analysis is required for evaluation of sustainability, and model borders are natural hydraulic boundaries of the system so that flow paths are not artificially limited by the extent of the model.

Land-surface elevation (16) is a steady-state hydraulic head boundary condition at the top of the model. The assumption is conservative with respect to sustainability because hydraulic head cannot be reduced at the model surface due to pumping, providing an unlimited source of water. This increases the occurrence of local, unsustainable flow paths (originating from high-arsenic surface areas near wells). Neither model input nor results vary in time because the strongly seasonal hydrology and irrigation pumping have a short-term cycle, whereas travel times along most flow paths from recharge locations to wells span many seasonal cycles; seasonality has little effect on long-term flow paths (15).

The dense lateral distributions of domestic and irrigation wells are represented in the model as continuous horizons at typical pumping depths wherein the quantity of water pumped varies areally (15). Inexpensive shallow domestic wells with hand pumps are often privately owned; 7–11 million are in use in Bangladesh alone (4). Irrigation wells are fewer, operating only during the dry season at greater capacity and at somewhat greater depth. Basinwide estimates (based on irrigated area and population) indicate that irrigation pumping, 0.21 m/yr, is an order of magnitude greater than domestic pumping, 0.019 m/yr, an estimate supported by previous studies (6, 17).

Heterogeneous stratigraphy is represented in the model by upscaled hydrogeologic properties. Inverse modeling using hydraulic head and groundwater age data, analysis of lithologic logs, and geostatistical simulation allowed estimation and corroboration of parameter values (15).

The "base-case" model reflects the most likely basinwide aquifer properties and pumping rates and depths, as follows. Horizontal hydraulic conductivity (Kh) is 5×10^{-4} m/s, vertical anisotropy (ratio of Kh to vertical hydraulic conductivity, Kv) is 10^4, and effective porosity is 0.2. Pumping depths are 10–50 m for the shallow domestic wells, 50–100 m for shallow irrigation wells, and 150–200 m for deep wells, with pumping rates as estimated above. The high upscaled anisotropy value used was consistent among all estimation methods and with the conceptual model established from geologic understanding (15).

The robustness of the base-case model in predicting the performance of management strategies was determined in this study by use of alternative models and comparison of results. Aspects of the model expected to have the greatest impact on results were evaluated. Horizontal and vertical hydraulic conductivity values were varied over the range of possible combinations determined from regional analysis (15) extended to include vertical anisotropy values of 10^3 and 10^5. The depth of the deep domestic pumping interval was decreased to 110-150 m

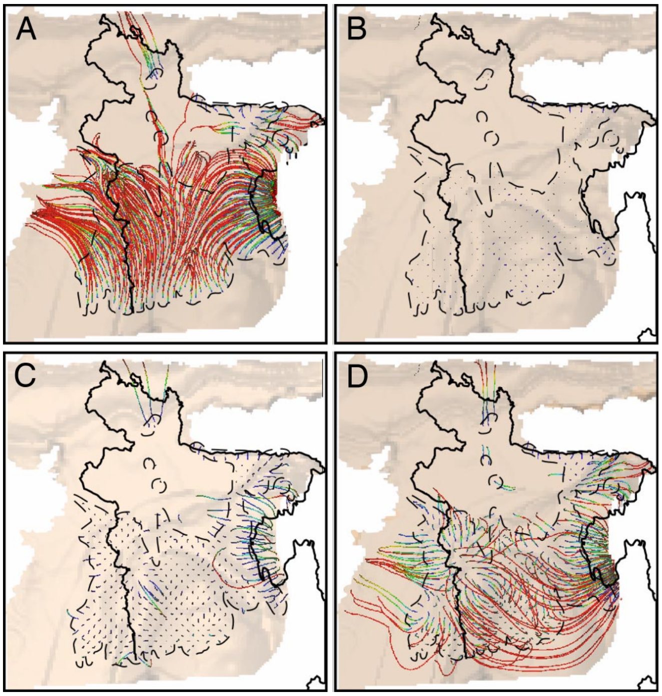

Fig. 2. Groundwater flow paths for base-case simulations to locations at depths of 175 m for predevelopment scenario (*A*), 30 m for current shallow pumping situation (*B*), 175 m for deep pumping alternative (*C*), and 175 m for split pumping alternative (*D*). Black line is Bangladesh border. Colors represent travel times: red indicates longest times (6,000+ years). Flow lines with short lateral travel distances appear as specks.

and increased to 200-250 m, and both domestic and irrigation pumping rates were individually halved and doubled. The model's top boundary condition was varied by increasing the elevation of the northern, eastern, and western edges from 100 to 200 m. A model with individual wells in a local area was created to test sensitivity of results to discrete, rather than areally distributed, well locations.

Simulated flow paths were used to track the advective motion of water. The paths selected for study of recharge locations end at points on a 14-km grid within the high-arsenic region at the depth of domestic well pumping (which depends on the management alternative). Paths were determined in a postprocessing step [using MODPATH (18)] after each (MODFLOW) groundwater model simulation by backward tracking from the grid of endpoints to the points of recharge at the surface.

Results

Base-Case Simulations. Modeled predevelopment flow paths from recharge locations to a depth of 175 m below the high-arsenic region are long (average lateral travel distance, 99 km). This indicates the potential for a sustainable arsenic-safe water supply (should pumping not disrupt natural flow paths) (Fig. 2*A*, Table 1) because 60% of flow paths to the potential deep-pumping horizon are recharged outside the high-arsenic region (Table 1) and travel times are long. The median predevelopment travel time from recharge to this horizon is 10,000 years, consistent with groundwater age estimates of 3,000 years to 15,000 years at depths >100 m in Bangladesh (19).

In contrast, a model of the current "shallow" pumping situation indicates significant disruption of the natural flow system (15), wherein 99.5% of wells in the high-arsenic region (Table 1) draw water locally from the ground surface within the high-arsenic region (Fig. 2*B*). This confirms the current state of the system with high dissolved arsenic in shallow well water. Modeled lateral travel distances average <1 km, with median travel time of 37 years (Table 1), consistent with groundwater-age estimates of <55 years for depths shallower than 30 m at sites in Bangladesh (6, 20, 21).

In the deep pumping alternative, modeled flow paths (Figs. 2*C* and 3*A*) mimic the shallow pumping situation; locally recharged water is pumped nearly everywhere. Deeper pumping at the current rate is largely unsustainable with regard to production of arsenic-safe groundwater (87% of wells in the high-arsenic region recharge locally; average lateral travel distance, 8 km; Table 1). The median travel time (315 years) is greater than for shallow pumping, but the simulation shows that arsenic could eventually migrate to deep wells, potentially contaminating the entire interval above the deep wells.

Model results for the split pumping alternative indicate that recharge locations for the domestic well horizon are largely at the surface in low-arsenic areas (Figs. 2*D* and 3*B*). In this alternative, flow paths are considerably longer than in the other pumping configurations (average lateral travel distance, 46 km; median travel time, 1,900 years; Table 1). The success of the split alternative is partly a result of a hydraulic barrier induced by the strong shallow irrigation pumping. The high rate of irrigation pumping combined with aquifer anisotropy creates a continuous horizon of low hydraulic head. Where this horizon has a lower head than does the deeper domestic pumping horizon, flow from the deeper horizon is upward, not downward. Thus, the recharge area for domestic wells in such a region cannot be at the surface above the wells, but must be at a great lateral distance (Fig. 3*C*).

The split pumping alternative, in the base-case model, outperforms the current shallow situation and deep alternative for the primary evaluation criteria and outperforms the deep alternative for the secondary criterion (Table 1 and Fig. 1 *B–D*). Forty-two percent of the high-arsenic region is sustainable (Fig. 1*C*) and travel times to domestic wells are extremely long. Fully 90% of the flow paths to domestic wells in the high-arsenic region satisfy at least one of the two primary criteria (Fig. 1*D*). A portion of the northern part of the high-arsenic region, where the aquifer thins, does not satisfy the secondary criterion for pump lift (Fig. 1*D*). In contrast, for the deep alternative, the total area satisfying the primary criteria is only 14% of the high-arsenic region, and much of the area would require high-lift hand-pump technology (Fig. 1*B*).

Sensitivity Analysis. Model features, parameter values, and pumping depth and rate are approximate; true values may vary widely by location in the basin. An analysis of the sensitivity of base-case model results to these factors indicates that the above evaluation of pumping strategies is robust. The split alternative is superior to the deep alternative over a wide range of model variations, in the sense that all three evaluation criterion values are greater (Table 1) for the split alternative.

The criteria for sustainability are most sensitive to model values of hydraulic conductivity. The lowest percentage of flow paths originating outside the high-arsenic region (21%) and the lowest percentage of the area with drawdown <12 m (0%) were simulated with a vertical anisotropy of 10^5, a value much larger than expected for the true anisotropy. The lowest median travel time of 873 years occurs when vertical anisotropy is lowest. However, for each variation, even the lowest simulated values of the primary criteria for the split pumping alternative are substantially greater than those of the base-case current shallow situation or deep alternative.

All three evaluation criteria improve with well depth, although deeper wells are more expensive to install; in practice, an optimal depth may be found. Domestic pumping rate affects performance predictably: higher domestic pumping rates diminish performance for fixed irrigation pumping rates. Increasing the irrigation pumping rate might be expected to improve split

Table 1. Summary of simulation results and sensitivity analysis

					Primary criteria		Secondary criterion
Pumping scenario	Domestic well depth, m	Pumping rate	Kh, m/s	Kh/Kv	As safe, %*	Long travel time, %[†]	Low lift, %[‡]
Pumping strategy variation							
Predevelopment	175[§]	—	5×10^{-4}	10^{4}	60	94	100
Predevelopment	225[§]	—	5×10^{-4}	10^{4}	64	94	100
Shallow	10–50	Base case	5×10^{-4}	10^{4}	0.5	0	78
Deep	150–200	Base case	5×10^{-4}	10^{4}	13	7	30
Split	150–200	Base case	5×10^{-4}	10^{4}	42	84	71
Deep	200–250	Base case	5×10^{-4}	10^{4}	17	13	18
Split	200–250	Base case	5×10^{-4}	10^{4}	45	90	73
Split	110–150	Base case	5×10^{-4}	10^{4}	34	54	71
Parameter variation							
Split	150–200	Base case	5×10^{-4}	10^{3}	24	47	100
Split	150–200	Base case	5×10^{-4}	10^{5}	21	90	0
Split	150–200	Base case	5×10^{-3}	10^{4}	65	49	100
Split	150–200	Base case	8×10^{-4}	1.6×10^{3}	50	81	96
Split	150–200	Base case	2×10^{-4}	2×10^{4}	22	87	0
Split	150–200	Base case	8×10^{-4}	8×10^{4}	28	90	0
Split	150–200	Base case	2×10^{-4}	2.2×10^{3}	29	76	98
Split	150–200	Base case	8×10^{-4}	10^{3}	49	77	99
Split	200–250	Base case	5×10^{-4}	10^{3}	24	58	100
Split	200–250	Base case	5×10^{-4}	10^{5}	25	94	0
Pumping rate variation							
Split	150–200	Half-domestic	5×10^{-4}	10^{4}	42	89	76
Split	150–200	Double-domestic	5×10^{-4}	10^{4}	37	59	60
Split	150–200	Half-irrigation	5×10^{-4}	10^{4}	49	88	99
Split	150–200	Double-irrigation	5×10^{-4}	10^{4}	31	63	35
Deep	150–200	No irrigation	5×10^{-4}	10^{4}	50	90	100

Percentage of area within the high-arsenic region for which:

*Sustainability criterion: recharge locations for wells are outside of the region.

[†] Travel time criterion: water takes >1,000 years after recharging to reach wells.

[‡] Lift criterion: there is an acceptable lift (<12 m) in the domestic well zone.

[§] Maximum depth at end of flow path.

alternative performance because of lower hydraulic head in the irrigation pumping horizon. However, doubling irrigation pumping negatively impacts all three criteria and halving pumping improves performance. This is because higher irrigation pumping creates a larger vertical zone of low hydraulic head that overwhelms the domestic well zone and eliminates the hydraulic barrier in some areas.

The sensitivity of model results to the top-boundary condition is minimal, and results are not listed in Table 1. Sensitivity to representing individual wells in the simulation is also low, and results are shown in Fig. S2.

Discussion

This analysis indicates that the split management alternative could deliver arsenic-safe drinking water over a 1,000-year timescale in nearly the entire high-arsenic region of the Bengal Basin. The superior functioning of the split alternative is a natural consequence of groundwater physics in this regional aquifer and not a result of the peculiarities of spatial parameter distributions. Its effectiveness is due to minimal pumping at depth and the hydraulic barrier created by strong, shallow irrigation pumping that prevents shallow, high-arsenic water from reaching deep domestic wells. Further, the split alternative generates a hydraulic gradient that induces upward flow in sustainable areas, so that neither fast-transport pathways (resulting from heterogeneity in hydraulic conductivity) nor poor well construction (allowing water to move vertically through the well annulus) would result in downward migration of arsenic to domestic wells.

Additional factors considered below may either limit or improve the likelihood that the split alternative could provide a sustainable arsenic-safe groundwater supply.

Local-Scale Considerations and Implementation. Site-specific hydrogeologic characteristics (e.g., low local prevalence of clay layers or deep, high-capacity municipal pumping) could result in local downward vertical flow, and fast-transport pathways may cause arsenic arrival at wells earlier than indicated by large-scale analysis. Further, water-quality constraints (including high concentrations of dissolved chloride, manganese, iron, and arsenic) and thinning of the aquifer may prevent the use of deep groundwater in some areas. Such local features must be considered when implementing any management alternative.

Highly detailed local hydrogeologic characterizations cannot be widely accomplished, but simple observations could indicate the potential for successful implementation of the split alternative in each local area. Taste and color of water can indicate high concentrations of many common ions, and simple field tests for arsenic are available. Relative water levels among nearby wells of various depths will indicate the direction of the vertical hydraulic gradient, which in a successful pumping strategy should cause upward flow. These measurements may begin with the installation of the first deep well. Once in use, it would be important that wells are monitored regularly for arsenic concentration and hydraulic head levels; changes in the latter may

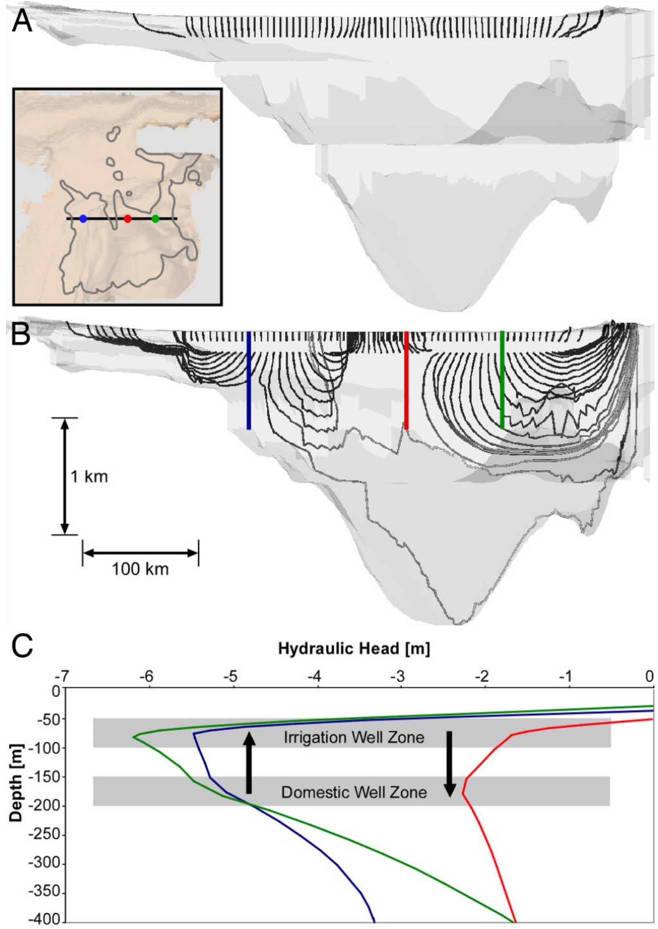

Fig. 3. Cross-section of flow paths to well depths and hydraulic head profiles for base-case simulations. View is from south, model surface is gray. (*A*) Deep pumping alternative flow paths. (*Inset*) Map view showing high-arsenic region (gray contour), location line for flow path ending points, and head profile locations (colored circles) of *B* and *C*. (*B*) Split pumping alternative flow paths. Colored lines are locations of head profiles in *C*. (*C*) Hydraulic head vs. depth at three locations. Head gradients of blue and green profiles indicate upward flow between pumping horizons; at these locations domestic wells capture water from distant recharge locations. Red profile shows hydraulic gradient resulting in downward flow to domestic wells. Flow paths of *A* and *B* connect surface recharge points to domestic and irrigation wells.

provide warning of changes in the former. The necessity of monitoring, which is not widely done for any well type, is illustrated by a long-term monitoring study (22) in which 51 community drinking-water wells were installed to depths from 35 to 150 m and monitored for several years. The four wells of the 51 that failed to produce low-arsenic water consistently during the monitoring period included three screened shallower than 60 m (perhaps too close to the level of irrigation pumping) and one screened at 125 m, but found to leak between 45 and 60 m deep.

Arsenic Chemistry. The widespread existence of oxidized sediments at depth would enhance the success of all deep-pumping strategies because of the capacity to remove dissolved arsenic. Geochemical modeling of groundwater (23) adapted for porosity of 0.2 and a downward flow velocity of 0.1 m/yr (average domestic pumping rate per area divided by porosity) indicates that even for the extremely high arsenic concentration of 900 μg/liter, 10 m of oxidized sediment could delay the arrival of arsenic concentrations greater than the World Health Organization drinking-water standard of 10 μg/liter for 4,200 years. Oxidized sediment is brown or orange, contrasting with younger gray sediment, so local drillers could identify the arsenic-immobilizing sediments by color (24), and set screens tens of meters below the gray-orange interface to take advantage of this natural filter when installing deep wells.

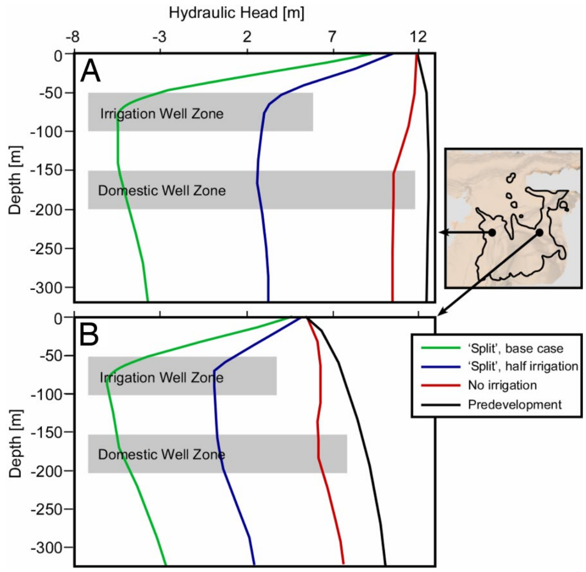

Fig. 4. Hydraulic head profiles for simulations with base-case and reduced irrigation pumping rates. Four simulated profiles are shown for each location illustrated in *Inset*: split alternative with base-case pumping, split alternative with half the irrigation pumping rate, deep domestic pumping with no irrigation pumping, and predevelopment. All parameters are base-case values. Gray bands show depths of pumping for simulations in which pumping is included. (*A*) Flow paths to deep domestic wells are sustainable (paths originate outside the high-arsenic region) for split base-case and half-irrigation pumping simulations. Flow paths are not sustainable for the ''no irrigation'' and predevelopment scenarios. (*B*) Flow paths to deep domestic wells are sustainable for all four pumping scenarios.

Arsenic in Irrigation Water. Despite advantages of the "split pumping" alternative for domestic supply, continued application of high-arsenic water to fields by irrigation using shallow groundwater may have adverse effects. Studies indicate that, although rice grown in severely arsenic-affected areas contains elevated arsenic concentrations on average (25), grains may be partially "shielded" from arsenic in the growing environment (26). However, soil arsenic concentrations may be increasing over time (27), and effects on food arsenic concentrations, human health, and crop productivity could be substantial (28).

Should the effects of arsenic accumulation in soil become severe, changes in irrigation practices may occur in the future. Values of the primary and secondary management criteria derived from the base-case model without irrigation pumping are similar to those of the split pumping, half-irrigation, and predevelopment scenarios (Table 1). Although the hydraulic barrier is eliminated, the domestic pumping rate is small enough that head profiles are similar to those of the predevelopment case and sustainability is intermediate between the split pumping alternative and predevelopment conditions (Fig. 4). Thus, it is possible that deep domestic wells would be largely sustainable irrespective of the shallow irrigation pumping rate.

Conclusions

More than 20 years after the discovery of dissolved arsenic in groundwater of Bangladesh and India, a socially and physically sustainable means of supplying safe drinking water has not been widely implemented. Millions of people continue to be exposed to toxic arsenic concentrations. Arsenic mitigation alternatives exist but most are difficult to implement and maintain, and some, including the use of surface water, may lead to other health issues. Installation of deep wells for both irrigation and domestic supply to tap low-arsenic water may seem a prudent alternative, but simulations show that large-scale installation of deep wells could eventually result in contamination of the deeper low-arsenic groundwater resource by inducing relatively rapid downward flow from high-arsenic regions.

Nevertheless, simulations also demonstrate a viable deep-pumping alternative. For $>90\%$ of the entire arsenic-impacted area, deep domestic pumping beneath a hydraulic barrier generated by shallow irrigation pumping or deep domestic pumping alone (should irrigation pumping be terminated in the future) could provide arsenic-safe water over a 1,000-year timescale. Simulations show that this split pumping management alternative is effective over a wide range of the hydrogeologic conditions possible in the Bengal Basin. In principle, this lack of sensitivity indicates robustness of the split alternative; neither greater knowledge of hydrogeologic conditions nor knowledge of the future evolution of groundwater usage are required for its viability. Moreover, its effectiveness may be enhanced by oxidized aquifer chemistry.

One-time installation of deep domestic wells is a simple, socially acceptable, and passive management alternative that, according to the results of this quantitative hydrogeologic analysis, could provide a sustainable source of arsenic-safe water for current and future generations. Restriction of irrigation pumping to shallow depths and widespread installation of deep domestic wells could bring an end to the ongoing poisoning in a large part of the Bengal Basin.

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