Groundwater Flow in the Ganges Delta

Basu *et al.* (*1*) reported that 2×10^{11} m³/year of groundwater flows directly into the Bay of Bengal, an outflow equivalent to 19% of the discharge from the Ganges-Brahmaputra river system. They showed that this estimate of flow could have important consequences for the interpretation of marine strontium isotope records, because strontium concentrations are higher in Ganges delta groundwater than in Ganges-Brahmaputra river water. The flow could also have implications for the origin and fate of other groundwater constituents in the Ganges delta that could be flushed by such rapid regional flow, such as the dangerously high concentrations of arsenic contaminating millions of drinking water wells (*2*). Here, I show that the large estimate of regional groundwater flow by Basu *et al.* is implausible given the extremely flat topography of the Ganges delta, and that the young helium-tritium ratios that they find in groundwater may reflect irrigation pumping rather than basin-scale flow.

The physical plausibility of the Basu *et al.* flow estimate may be considered by applying Darcy's law, without application of hydrologic models that require specification of boundary fluxes. One hundred kilometers inland from the coast of the Ganges delta, elevations reach only 5 to 10 m above sea level, and the water table reaches only 2 to 4 m above sea level (*3*). Assuming upper bounds for aquifer thickness and hydraulic conductivity [pp. 2.1–2.22 in (*4*)], Darcy's law indicates that maintaining the discharge estimated by Basu *et al.* requires a hydraulic gradient of ~0.06 perpendicular to the coast (*5*). Such a gradient implies dramatic artesian conditions, with a potentiometric surface ~300 m above sea level 5 kilometers inland; such conditions do not exist in this area. Even if the assumed aquifer thickness is further increased to 2 km—an implausible depth for rapid, topographically driven flow in low-relief terrain—the implied artesian conditions remain incorrect. Furthermore, many aquifers in coastal areas suffer from high salinity [pp. 2.1–2.22 in (*4*)] that would be flushed out if groundwater flowed so quickly to the coast.

Basu *et al.* estimated groundwater flow to the ocean by first calculating an average groundwater recharge rate of 0.6 m/year from helium-tritium dating of wellwater extracted below 30 m, and then assuming that this recharge flows directly to the Bay of Bengal. As an alternative hypothesis, irrigation pumping and local flow cells, rather than regional flow to the ocean, may draw young groundwater to depth. Although the highest groundwater extraction rates are in the northwest of Bangladesh, groundwater extraction is also widespread on the delta. The gross groundwater extraction rate for the delta region can be estimated at approximately 25 cm/year (*6*), which implies an annual downward groundwater velocity of approximately 1.25 m/year assuming an aquifer porosity of 0.2. This downward velocity is somewhat less than the 2 to 3 additional meters that Kinniburgh and Smedley have estimated for drawdown by irrigation pumping (*7*) for a hypothetical cross section. Some references describe irrigation pumping at the specific locations sampled by Basu *et al.* (*8*). Many wells are screened below 30 m, and pumping drives complex flow patterns that extend below the screened depth. In some areas, local topography may also drive groundwater flow below 30 m, but in these areas most of the discharge is also local (*9*). Basu *et al.* considered groundwater discharge directly to the Bay of Bengal. However, such local flow cells could conceivably provide some additional flux of strontium into rivers downstream of the locations where strontium concentrations and river flows were measured.

During the onset and recession of monsoon floodwaters, hydraulic head values change dramatically. However, flooding drives very little groundwater flow because inundation erases lateral gradients and downward flow by compression of water is negligible. Hydraulic gradients that emerge after the floodwaters recede are bounded by the mild topographic gradient.

Basu *et al.* supported their estimate of groundwater flow to the ocean by citing the large coastal groundwater discharge estimated by Moore *et al.* (*10*) from offshore measurements of barium and radium. In that study, however, it was recognized that the estimated fluxes may represent saltwater circulation as well as freshwater discharge. The large observed barium and radium fluxes during the dry season, when water table elevations and fresh groundwater discharge along the coast are low, may be explained by desorption of barium and radium by saline water that moves up rivers and circulates through sandy sediments with the tidal cycle. Here, it is clear that Basu *et al.* have considered only fresh groundwater discharge, because their strontium measurements and age dates were determined from inland freshwater wells.

In summary, the groundwater fluxes used by Basu *et al.* to calculate subsurface strontium fluxes to the Bay of Bengal are not physically realistic. However, their helium-tritium isotopic dates provide valuable information for characterizing groundwater flow in the Ganges Delta. The young ages of deep groundwater may indicate active circulation by pumping and irrigation, rather than subsurface flowpaths that continue for up to 100 kilometers to the coast. Circulation by pumping and irrigation, rather than large-scale flow to the ocean, implies less flushing of groundwater solutes and, hence, smaller fluxes of strontium to the ocean.

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References and Notes

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3. "National water plan project final report: Volume 2, Resources; chapter 10, water resources" (Ministry of Irrigation, Government of Bangladesh, Dhaka, 1986), pp. 2 and 82.
4. British Geologic Survey, Department of Public Health Engineering, Government of Bangladesh, Mott MacDonald Ltd., *Groundwater Studies for Arsenic Contamination in Bangladesh. Phase I: Rapid Investigation Phase*, main report and five supplementary volumes (1999; www.bgs.ac.uk/arsenic/bphase1/b_intro.htm).
5. Darcy's law for fresh groundwater outflow, Q, at the coast is $Q = WBKi$, where W is the coast length (500 km), B is an upper limit on the aquifer thickness (200 m), K is an upper limit for hydraulic conductivity (10^{-3} m/s), and i is the gradient.
6. Bangladesh Ministry of Agriculture (*11*) reported 335,581 and 16,592 wells south of the Ganges pumping at rates of 15 and 56 liter/s, respectively. Three months of pumping at 6 hours a day over 44,600 km² implies an average rate of about 25 cm/year. This is less pumping than the 800 hours a year assumed in (*4*).
7. D. G. Kinniburgh, P. L. Smedley, "Arsenic contamination of groundwater in Bangladesh" (British Geologic Survey Report WC/00/19, 2001; www.bgs.ac.uk/arsenic/Bangladesh).
8. According to Bangladesh Ministry of Agriculture (*11*), the densities of irrigation wells in Nawabganj, Shibganj, and Meherpur are sufficient for extraction rates ranging from 43 to 65 cm/year, assuming 6 hours of pumping for 3 months, which gives downward groundwater velocities ranging from 2 to 3 m/year using a porosity of 0.2. Likewise, British Geological Survey *et al.* [vol. S3, p. 18 in (*4*)] estimated an extraction rate of 45 cm/year for the 21 km² study area in Faridput. Yokota *et al.* (*12*) mapped seven deep irrigation wells in Samta Village.
9. J. Toth, *J. Geophys. Res.* **68**, 16 (1963).
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Response: The comment by Harvey is not the first statement noting large discrepancies between estimates of submarine groundwater discharge (SGD) from geochemical tracer flux indicators and those from hydraulic modeling. Before responding to the specifics of Harvey's comment, we point out that these

discrepancies, although important and in need of resolution, are not central to the main conclusions of our study (1) on the marine Sr budget. A principal conclusion of our paper was that the groundwater in the Bengal Basin has approximately 10 times more dissolved Sr than in the adjacent water of the Ganges-Brahmaputra river system. Even allowing a conservative SGD, equivalent to 10% of surface riverine flow, if this were also true for the global Sr cycle, it would have a tremendous impact on the seawater Sr isotope balance, effectively doubling the Sr flux to the oceans.

Harvey questions the plausibility of our estimates (1) of large submarine groundwater discharge (SGD) to the Bay of Bengal, and suggests that our calculated tritium-helium isotopic ages of groundwater may reflect recent irrigation pumping effects on groundwater flow. Younger (2) used a similar analysis of physical hydrologic conditions to question the presence of substantial submarine groundwater discharge into the South Atlantic Bight, estimated by Moore (3) on the basis of spatial distribution of ^{226}Ra in the nearshore waters. However, the claims of Younger were refuted by Moore and Church (4), who showed that the physical constraints derived from simple mathematical formulations of Darcy flow may not fully describe the SGD process. Additional research is necessary to develop appropriate models of SGD to explain excess ^{226}Ra and Ba observed in the Atlantic Ocean as well as in the Bay of Bengal (5). In particular, uncertainty in average hydraulic conductivity (K_h) related to "dual permeability" of floodplain sediments—the proportions of high-K_h channels and low-K_h overbank sediments—should be

considered, as well as density-driven SGD and tidal pumping effects (6).

Stable isotope data for oxygen and hydrogen and other chemical data (7, 8) of the groundwater allow an evaluation of Harvey's interpretation that our ^{3}H–^{3}He-based flow rate primarily reflects increased irrigational pumping in recent years (Fig. 1). The groundwater of our study (1) had oxygen and hydrogen isotope ratios ranging from −2.4 to −7.1 per mil and −12 to −50 per mil (7), respectively (Fig. 1). All samples plot on or slightly below the meteoric water line, which suggests an origin from local rain and rivers from the Bengal Basin as well as from the Himalaya. The isotopic compositions of groundwater collected in 1979 (dark diamonds in Fig. 1) were nearly the same as those collected in 1999 (light triangles in Fig. 1). If pumping in the past two decades had resulted in a large recycling of groundwater through irrigated fields, with high evaporation during the dry season, one would certainly expect a substantial isotopic shift toward heavier values in the 1999 data relative to the 1979 data, which is not seen. This comparison argues strongly against Harvey's contention of groundwater drawdown by irrigation pumping, which has reached its highest extraction rates in the past 20 years. The British Geological Survey report cited by Harvey (9) also concluded after considering groundwater extraction rates in Bangladesh in 1995 that "large-scale groundwater abstraction for irrigation has limited impact on regional groundwater flow velocity" [vol. S3, p. 35 in (9)].

The similarity of the 1979 and 1999 isotope data could also be due to a steady state between the groundwater and irrigational

pump water attained before 1979. However, there was effectively little irrigational pumping before 1979 in the Bengal Basin. Moreover, our isotopic data clearly demonstrate that the system of irrigational pump water and the groundwater in the Bengal Basin had not reached a steady state by 1979, because if it had done so one would expect the stable isotope data to fall off the local meteoric water line. Similarly, agricultural tracers such as PO_4^{-3} and NO_3^{-} are uniformly low (8) at depth in groundwater of the Bengal Basin, indicating limited infiltration of pumped irrigational water to depth. Thus, Harvey's interpretation of our young groundwater ages as reflecting irrigational pumping is not acceptable.

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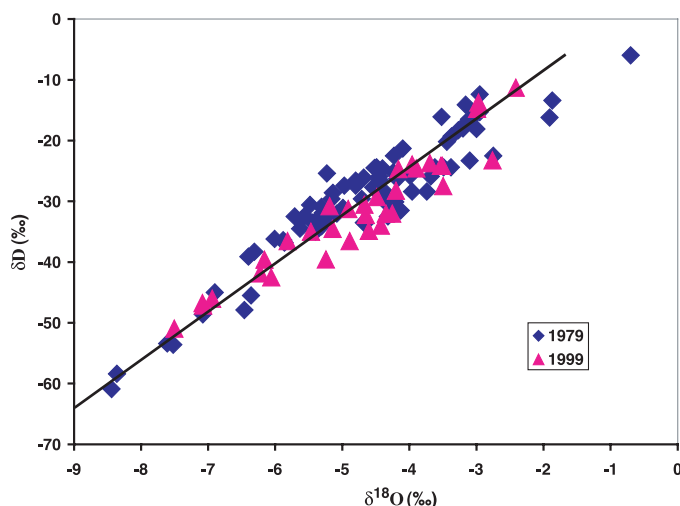
Fig. 1. Stable oxygen and hydrogen isotope compositions of Bengal Basin groundwater collected in 1979 and 1999, after (7). The 1979 data of approximately 100 samples are almost the same as the 1999 data, all falling on the local meteoric water line.