Crab burrows as conduits for groundwater-surface water exchange in Bangladesh

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Crab burrows as conduits for groundwater-surface water exchange in Bangladesh

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Key Points:
- Crab burrows can substantially increase groundwater recharge in Bangladesh
- Isotope and water balances constrain pond, groundwater, and rice field fluxes
- Findings reconcile disparate observations on aquifer recharge from ponds

Supporting Information:
- Readme
- Movie S1
- Text S1, Figures S1–S5, and Tables S1–S2

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Abstract Groundwater recharge affects water budgets and groundwater quality on the deltas and floodplains of South and Southeast Asia. Rain and flooding rivers recharge groundwater during the monsoon; irrigated rice fields and surface water bodies recharge aquifers during the dry season. Groundwater throughout the region is severely contaminated by arsenic, and recent research suggests that quantifying and characterizing recharge is important to understand whether recharge flushes or mobilizes arsenic from aquifers. At a field site in Bangladesh, we found that burrows of terrestrial crabs short-circuit low-permeability surface sediments, providing the primary conduit for recharge. We combine field observations along with a model that couples isotope and water balances to quantify the effect of crab burrows on aquifer recharge. Given the wide distribution of burrowing crabs and the surficial geology, we suggest that crab burrows provide widespread conduits for groundwater recharge.

1. Introduction

Semi-terrestrial freshwater crabs are ubiquitous pests in rice fields across South and Southeast Asia and are also found in ponds, canals, and rivers [*Rahman et al.,* 2008; *Wagle,* 1924; *Yeo et al.,* 2007]. Ninety years ago *Wagle* [1924] mapped (Figure 1e) networks of crab burrows in rice field soils that extended 8 m laterally and reached depths of at least 3 m. All crabs have gills that must remain wet, and many semi-terrestrial crabs achieve this by storing a small volume of water that must be replenished regularly in the brachial chambers that house the gills [*Burggren and McMahon*, 1988]. Thus, semi-terrestrial crabs gain an advantage by digging burrows deep enough to access groundwater [*Warner*, 1977]. To ensure an uninterrupted source of water, burrows must reach at least the maximum depth to which the water table drops at the end of the dry season. *Wagle* [1924] found that the angle of burrows is closer to vertical in regions where the water table drops quickly but more horizontal where it drops slowly. He proposed that crabs dig at a constant rate while adjusting the angle of burrows to track the decline of the water table. Animal burrows are known to be conduits for recharge in many environments [*Susilo and Ridd,* 2005; *Xin et al.,* 2009; *Carol et al.,* 2011; *Beven and Germann*, 1982]. For example crayfish burrows are conduits for rapid drainage of constructed wetlands in the US [*Biebighauser*, 2011]. The length and ubiquity of crab burrows found at our site and throughout South Asia [*Fernando*, 1960; *Ng and Kosuge*, 1997; *Yeo et al.,* 2007; *Ng and Ng*, 1987] suggest that they may serve as important conduits for groundwater recharge.

Mechanisms of aquifer recharge have been a focus of hydrologic studies in the Ganges Basin because of their importance to groundwater sustainability [*Revelle and Lakshminarayana,* 1975] and more recently because recharge can affect groundwater arsenic concentrations [*Harvey et al.,* 2006]. Man-made ponds used for aquaculture, water supply, and waste disposal are widespread throughout Bangladesh [*Harvey et al.,* 2006; *Neumann et al.,* 2009a]. At our study site in the district of Munshiganj ponds cover approximately 11% of the land area and contribute up to 40% of aquifer recharge [*Harvey et al.,* 2006]. This recharge has been linked to groundwater contaminated by arsenic [*Neumann et al.,* 2009a]. *Neumann et al.* [2009a] argue that pond recharge carries dissolved organic carbon that stimulates arsenic release from sediments and that it may also mobilize sedimentary organic carbon that can further drive arsenic release [*Neumann et al.,* 2014]. To study this recharge, we constructed a new pond on land previously used for rice cultivation and installed observation wells in the sediment and aquifer beneath the pond.

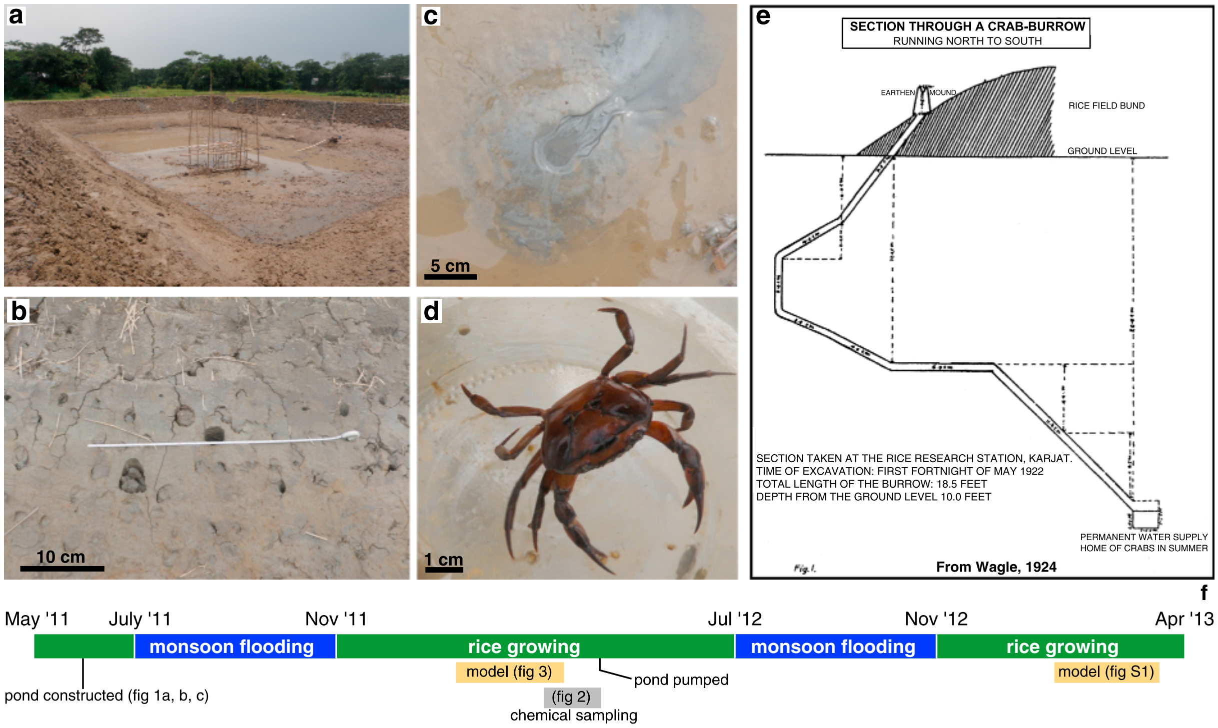

Figure 1. Study pond during construction. (b), Exposed crab burrows on the sides of the pond. (c), Crab burrow on pond bottom, with sandy water flowing out. (d), Crab (Sartoriana spinigera) found living in the pond. (e), Crab burrow diagram from *Wagle* [1924]. (f), Timeline of events.

2. Methods

Pressure transducers were deployed in the pond and in a well installed in the center of the pond screened ~3.7–4.7 m below the pond bottom. The elevations of both transducers were surveyed relative to a local datum by digital theodolite, and the recorded pressures were converted to hydraulic heads after adjusting for changes in atmospheric pressure recorded from a barometric pressure sensor.

Rainfall and pan evaporation data were collected from a meteorological station located 4 km from our field site and operated by the Bangladesh Water Development Board [see *Neumann et al.,* 2009b for data collection methods of meteorology station]. Measurements of air temperature and dew point for the time frame of this study were obtained for Dhaka through the Global Historical Climatology Network maintained by NOAA. Pond surface water temperature was measured using a thermistor attached to a float in the center of the pond.

Samples for pond stable water isotopes were collected ~30 cm beneath the pond water surface at several different times during the study period. Data from a thermistor chain deployed in our pond show that the water column was well mixed when we collected samples (Figure S4). The samples were analyzed for δ^2H by isotope ratio infrared spectroscopy on a wavelength-scanned cavity ring-down spectrometer with a precision of 1.6‰. Reported δ^2H values are the average of two replicate injections of a sample.

Na, K, Mg, Ca, and Si were analyzed by ICP-OES. NH_3-N was analyzed spectrophotometrically using the Nessler Method, and alkalinity was analyzed by gran titration.

The water chemistry data (Na, K, Mg, Ca, Si, NH_3-N, and alkalinity) reported for the pond, burrow, and shallow aquifer samples were all collected in March 2012. The chemistry values reported for the burrow water are the average of four samples collected flowing up from crab burrows. The value reported for the shallow aquifer water is from a sample collected on a well installed within the center of our study pond and screened in the shallow aquifer sediments at a depth of 4 m beneath the pond.

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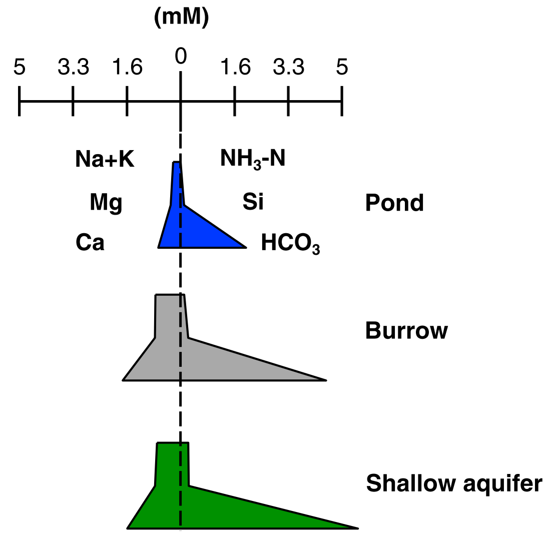

Figure 2. Stiff diagrams of pond, burrow, and shallow groundwater chemistry. After pumping the pond dry, flow was temporarily reversed to discharge from the burrows. The chemical composition of discharge has chemistry similar to shallow groundwater but distinct from pond water, indicating that burrows are tapping the shallow aquifer.

3. Pond Construction and Observation of Crab Burrows

At our field site, the shallow aquifer is composed of alternating beds of silts and sands and is overlain by a 3 m thick clay layer that extends to the land surface. The pond (Figure 1a) was constructed following local practice, with a team of ~40 men manually excavating a 25 m × 30 m pit from the upper 2 m of the three meter thick surficial clay and building a 1.5 m high berm around the pond. This raised barrier is annually overtopped by monsoon floodwaters, and the water level in the pond remains higher than the elevation of the water table after the floods recede, producing a downward gradient that drives aquifer recharge.

During the excavation we observed that burrows were conduits for flow between the surface and the aquifer. Crab burrows approximately 3 cm in diameter (Figure 1c) were dotted across the clay floor and sides of the pit at a density of about one opening per square meter. The spatial density of crab burrows we observe is similar to data from *Wagle* [1924], who found an average of 2.3 burrows per square meter in a study of 45 rice fields in India. We identified the species (Figure 1d) as *Sartoriana spinigera* (Family Gecarcinucidae) a freshwater crab that according to *Rahman et al.* [2008] is "abundant in shallow water bodies such as paddy fields" and ponds and is "widely distributed all over Bangladesh" [*Rahman et al.*, 2008; *Yeo and Ng*, 2012]. Physical and chemical evidence confirm that the burrows penetrated the 2 m of silty clay that was excavated and then continued through the remaining meter of silty clay to the underlying sandy aquifer. During construction we pumped the pond nearly dry, temporarily reversing the normal flow direction so groundwater would flow upward into the pond. We observed groundwater discharging through the burrows into the excavated pond, transporting aquifer sand, and depositing mounds of sand around the burrow openings (Figure 1, Movie supporting information). Furthermore, chemical analysis of the water flowing out of the burrows at that time closely matched that of the shallow groundwater (Figure 2) rather than the overlying pond water. Comparison of the burrow water and shallow aquifer water stiff diagrams (Figure 2) shows that these two waters have very similar concentrations and relative proportions of major chemical constituents (Na, K, Mg, Ca, NH_3-N, Si, and HCO_3). However, the pond water chemistry is distinct from that of the burrow and shallow aquifer water, with much lower concentrations of elements derived from mineral weathering (i.e., Na, K, Mg, Ca, and Si). Arsenic levels in the pond water, crab burrow water, and shallow aquifer water were all low and close to our detection limit, with concentrations of 5, 5, and 7 ppb, respectively. One year following pond construction, we again pumped the pond to temporarily lower the pond water level below the water table and again observed sandy water flowing from crab burrows. Thus, crab burrows provide a pathway between surface water and the sandy aquifer that bypasses the low permeability surficial clay layer.

Because the experimental pond was excavated on a rice field, our findings show that crab burrows provide preferential flow paths beneath rice fields and the underlying sandy aquifer. These burrows penetrated from a rice field through the clay to the aquifer before the pond was excavated. The excavation revealed deep burrows that are consistent with the unexplained preferential flow paths observed in previous dye tracer tests [*Neumann et al.*, 2009b]. These flow paths are particularly important in focusing recharge from rice fields through the bunds [*Neumann et al.*, 2009b], the raised property boundaries that are not plowed, and hence contain burrows that remain intact after plowing destroys burrows across the rest of the field.

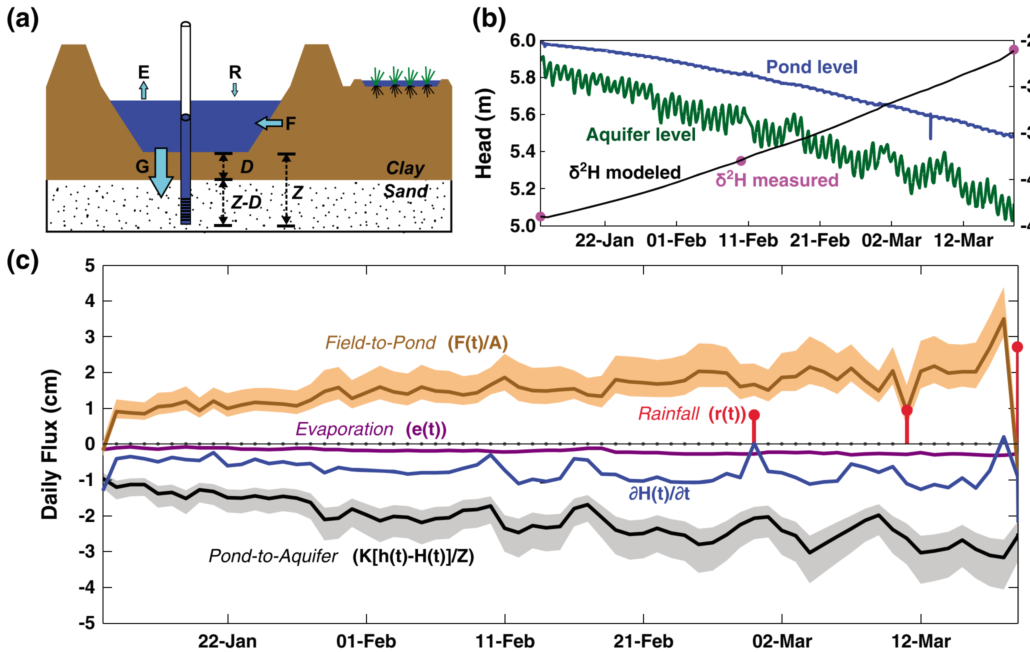

Figure 3. (a), Illustration of pond water budget. Thicknesses of sediment layers beneath pond (dashed, double-sided arrows); Z, distance from pond bottom to well screen; D, thickness of clay beneath the pond. Fluxes into and out of the pond (blue arrows); F, flux from rice field sediments; G, flux to aquifer; R, rainfall; E, evaporation. (b), Modeled evolution of pond water δ^2H (black line), δ^2H measured on pond water samples (purple circles), measured pond water levels (blue line), measured aquifer water levels (green line) for year 2012. (c), Modeled daily fluxes into and out of the pond for year 2012 (see equation (1)). Shaded area around modeled flux curves encompasses model calculations made with the δ^2H of rice field inflow water increased and decreased by one standard deviation of the sampled values (see supporting information for discussion of uncertainty).

4. Isotope and Water Balance Modeling

We combined hydrologic data and stable water isotope data recorded over 2 years to quantify water fluxes in and out of the constructed pond and determine the effect of crab burrows on net groundwater recharge. The gradient between hydraulic head in the pond and aquifer (Figures 3b and S1.b) indicates that the pond consistently discharges during the dry season, and the measured decline in pond water level shows a daily net loss of water from the pond in excess of calculated evaporation. Two observations indicate that the pond also receives lateral inflow from irrigated fields while it is discharging to the aquifer. First, water levels in the rice fields adjacent to our pond exceeded the pond water level so that there is a hydraulic gradient from rice fields to the pond and from the pond to the aquifer. Second, shifts in the pond stable water isotopes are far greater than can be explained by evaporation alone, but are consistent with inflow of the isotopically heavy rice field water (Figure S5).

To estimate the individual fluxes to and from the pond we coupled Darcy's law with mass balance equations for both water and the stable water isotope concentration in the pond:

$$\frac{\partial H(t)}{\partial t} = K\frac{[h(t) - H(t)]}{Z} + r(t) - e(t) + F(t)/A \quad (1)$$

$$\frac{\partial [H(t)\,C_p(t)]}{\partial t} = K\frac{[h(t) - H(t)]}{Z}C_p(t) + r(t)C_r(t) - e(t)C_e(t) + F(t)C_F(t)/A \quad (2)$$

The flux through the pond bottom is specified by Darcy's law where K is the effective hydraulic conductivity between the pond and the aquifer at depth Z where the hydraulic head in the aquifer *h* is measured and *H* is the water level of the pond; *r* is the rainfall rate, *e* is the evaporation rate, *F* is the volumetric flux from rice fields to the pond, and A is the area of the pond. The concentrations of deuterated water in the pond and the fluxes are given by C_p, C_F, C_r, and C_e. The concentration of deuterated water ($C = [^2H]/([^1H] + [^2H])$) is given as the mole fraction of deuterium to total hydrogen in a sample of water. The flux from fields *F(t)* and the effective hydraulic conductivity K are determined by simultaneous solution of equations (1) and (2).

All other quantities in equations (1) and (2) are either measured or calculated from meteorological data (see methods and supporting information).

The effective hydraulic conductivity of the sediments between the pond and the aquifer is the harmonic average of the hydraulic conductivity of the sediment layers in this interval.

$$K = \frac{Z}{\frac{D}{K_P} + \frac{Z-D}{K_S}} \quad (3)$$

where K_p and K_S are the hydraulic conductivities of the pond bottom and sandy sediments, respectively, and Z and D are the depth of the well below the pond bottom and the thickness of the clay, respectively (Figure 3a). Substituting in D, Z, K, and K_S, which was measured by aquifer pump tests [*Ashfaque*, 2007], allows us to calculate a value for K_p.

$$K_P = \frac{-D}{\frac{-Z}{K} + \frac{Z-D}{K_S}} \quad (4)$$

5. Results and Discussion

The results show that crab burrows greatly increase groundwater recharge through the surface clay beneath the pond. We calculate that K_p, the effective conductivity of the clay underlying the pond, is ~4×10^{-2} m day^{-1}, several orders of magnitude greater than laboratory measurements of undisturbed silty-clay from this site [*Neumann et al.,* 2009b]. Because the clay layer is made conductive by crab burrows, the water loss from the pond is dominated by the flux to the aquifer. This flux increases from ~1 to ~3 cm day^{-1} as the aquifer head drops faster than the pond level over the irrigation season (Figure 3). The inflow from the rice fields into the pond, calculated as the volume of flow divided by pond area, also increases over the irrigation season from ~1 to ~2 cm day^{-1}.

The effect of crab burrows on aquifer recharge can be estimated by calculating the Darcy flux between the pond and aquifer under conditions of no crab burrows. Setting the vertical conductivity of the pond bottom to that of undisturbed silty-clay (4×10^{-4} m/day) eliminates the effect of flow through crab burrows and reduces the calculated flux by a factor of 100. Thus pond recharge to the aquifer is dramatically enhanced by crab burrows that provide conduits through the clay.

Previous work by *Harvey et al.* [2006] to estimate pond recharge did not include a stable water isotope balance and neglected lateral inflow to ponds from rice fields. Here we calculate the error in estimated pond recharge caused by neglecting lateral inflow to the pond from rice fields by solving the water balance (equation (1)) without the term for lateral inflow from fields. The estimated flow from the pond to the aquifer falls to only 57% of the flow calculated from solving the complete coupled water and stable isotope balances and fails to match the observed shifts in the pond stable water isotopes (Figure S5).

Data from nearby ponds in Munshiganj indicate that recharge from ponds diminishes in older ponds. After construction of a pond, the underlying sediments remain continuously saturated, so crabs may reduce or curtail burrowing through the pond bottom and preexisting burrows may clog with fine grain sediments and microorganisms [*Baveye et al.,* 1998]. Applying the water and isotope balance method to a pond immediately adjacent to our study pond that is at least a decade older indicates that the effective vertical hydraulic conductivity of the clay underlying the old pond is one third that of our newly constructed pond (see supporting information). Previously measured water levels from five ponds within 2 km of our study pond indicate that water levels decline over rates ranging from nearly the same as our constructed pond to much lower rates that are consistent with estimated evaporation alone [*Harvey et al.,* 2006]. This variability in discharge rates appears consistent with the variability of pond ages. Indeed, the magnitude of recharge from ponds, and its importance to groundwater arsenic concentrations appears to vary widely across different locations in South and Southeast Asia. Investigators have linked arsenic contamination to surface water recharge from wetlands in Cambodia [*Polizzotto et al.,* 2008] and constructed ponds at our site in Munshiganj, Bangladesh [*Neumann et al.,* 2009a], and also West Bengal [*Lawson et al.*, 2013]. At these sites, recharge from surface water appears to carry chemical constituents that mobilize arsenic. Rapid recharge through burrows may also explain the presence of *Escherichia coli* and the marked seasonal variability in *E. coli* levels seen in Bangladeshi groundwater [*van Geen et al.,* 2011; *Leber et al.,* 2011]. Since *E. coli* rapidly die off within the subsurface, recharge from a contaminated surface source would have had to occur within months [*Rozen and Belkin,* 2001]. Other investigators have studied ponds that appear to contribute little recharge. On three intensively studied ponds in West Bengal, India *Sengupta et al.* [2008] found that little pond water recharged the aquifer. Given that all three of their studied ponds have histories extending back beyond the memory of locals, with two of them pre-dating 1965, their results are consistent with our hypothesis that the effective conductivity of pond sediments decreases over time as burrows are clogged, or their findings could simply reflect thick uncompromised clay sediments beneath the ponds.

The results described here imply that recharge through burrows in rice fields may increase in regions where the annual minimum elevation of the water table is dropping. Intensive groundwater pumping is driving a decline in the annual minimum water table over approximately 70% of Bangladesh with an average decrease of 1.6 m from 1980 and 2007 [*Shamsudduha et al.,* 2011]. Consequentially, the water table now falls below surficial clays in locations where, prior to intensive pumping, the water table remained continuously above the interface of surficial clays with underlying aquifers [*Shamsudduha et al.,* 2011]. It is possible that crabs will extend their burrows through surficial clays to reach an uninterrupted water supply, bypassing surficial clays that once blocked recharge.

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