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The Water and Salt Balance of Polders / Islands in the Ganges Delta

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We present a conceptual understanding of the polder salt and water balance processes with a simple model that encapsulates the understanding. The model simulates reasonably well the dynamics of water and salt measured in field experiments at three sites. A feature of both the field measurements and the model is the increase of salinity in the soil and surface water bodies during dry season, despite rainfall exceeding potential evapotranspiration by 0.5 to 1.3 m annually amongst the experimental sites, which should flush salt out of the canals and ponds fairly and quickly. The observed salt in the canals and ponds presumably results from continual re-supply of salt. Capillary rise from a salty groundwater table could supply some salt that would cycle through the soil and into the surface drainage system to the canals and ponds; this behaviour is shown in the model. To remove salt from the polder, canal drainage must be managed effectively. Drainage is also likely to be important at the crop or field level. Irrigation will involve the addition of salt as well as water to the soil surface; the amount will depend on the salt concentration in the water supply. Without adequate field drainage, some of the added salt is likely to be leached downward to the water table in the wet season, only to be brought back again to the surface by capillary rise in the next dry season; over several years, this would lead to high salt concentrations that could limit crop growth. Field drainage should therefore be used in polder cropping systems.

(***Key words:*** *Drainage, Model, Polder salt and water balance, Salinity)*

Large areas of the Ganges Delta comprise islands or polders of low-lying alluvial sediments, which have been protected by embankments and are used for cropping (Mainuddin *et al*., 2014, 2019). Cropping is difficult in polders[1], particularly in the dry season. During the early part of the dry season, waterlogging of the heavy soils causes problems with crop establishment. Later in the dry season, as the soils dry out, the salt concentration rises and can damage plant growth. Furthermore, there is limited opportunity to store fresh water for irrigation. The limited crop productivity contributes to the high incidence of poverty and limited livelihood prospects in the region.

Increasing crop production is desirable, and will depend upon management of the water and salt in a polder. The longer soil can be kept free from waterlogging on the one hand, and excessive dryness and high salinity on the other, the more the cropping options available and the greater the productivity of a given crop. Furthermore, management of the ponds and canals to keep them free of salt will result in some modest quantities of water being available for irrigation. In some polders, where water in the surrounding rivers is sufficiently fresh, there may be opportunities for irrigation using river water.

In this paper we discuss the processes underlying the water and salt balances in a typical polder, and outline a simple model that encapsulates our understanding. We describe some results of simulating the field experiments discussed in other papers in this special issue (Kabir

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[1] A polder is a piece of low-lying land reclaimed from the sea or a river and protected by dykes or embankments. In Bangladesh, the term polders is generally used for such pieces of land, whereas in West Bengal, the term islands is generally used. Here we will use the term polders.

et al., 2019; Saha *et al*., 2019; Sarker *et al*., 2019; Sarkar *et al*., 2019) that help illuminate our understanding. Finally, we discuss some management implications that follow from the understanding.

Water and salt balances in polders: processes and a simple model

Huge quantities of sediment are deposited every year in the Ganges delta (Akter *et al*., 2016), resulting in the formation of new lands, typically as islands surrounded by the distributary river channels and the sea. The sediment deposition is in a brackish to saline environment, so newly formed lands have saline soils and groundwater. Such lands may receive more salt from flooding by seawater during storm surges. Other processes remove salt from the newly formed land: annual rainfall exceeds evapotranspiration, so there is an excess of water which, as it drains out of the land, may carry salt with it; flooding by freshwater from the rivers during the wet season also leads to an excess of water which may carry salt as it drains away, deeper in the aquifers of the Ganges aquifer system there is a general flow of fresher groundwater from the extensive Ganges aquifer to the Bay of Bengal which, over a long period, will flush out salt at least from some deeper parts of the aquifer system (Michael and Voss, 2009).

Alongside these natural processes which may increase or decrease the amount of salt on newly formed land could be attributed to anthropogenic origins. Building embankments around newly formed land creates polders, and prevents most flooding by either the rivers or the sea. It also reduces fresh sediment deposition on the land in the polders, leading to more sedimentation in, and raising of, the river channels. Major floods may still overtop the embankments. The excess water from rain and the occasional floods must be allowed to drain out from the polder, so drainage channels (natural or man-made) are used for this purpose, managed with sluice gates in the embankments where a channel leaves a polder. The sluice gates and channels may also be operated to allow water, and hence salt, into the polder for irrigation or other uses such as maintaining the water level in shrimp ponds.

MATERIALS AND METHODS

Water and salt balance model

The key processes governing the water and salt balance in a polder are shown in Fig. 1. We have developed a monthly time-step model of polder water and salt balances that replicates as a series of equations and the conceptual understanding is depicted in Fig. 1. The soil is modelled as a simple bucket, defined by saturated water content, a field capacity and a wilting point. A water content above saturation leads to runoff, between field capacity and saturation becomes downward drainage to the water table, unless the water table rises to very shallow and cannot accept any more drainage. The soil also receives water (and salt) by capillary rise from the underlying shallow water table using a standard unsaturated soil flow equation given by Salvucci (1993) and using values for soil properties and soil suction as a function of water content from the pedo-transfer functions of Rawls and Brakensiek (1989).

Water (but not salt) is lost by soil evaporation and vegetation transpiration, using a crop coefficient type

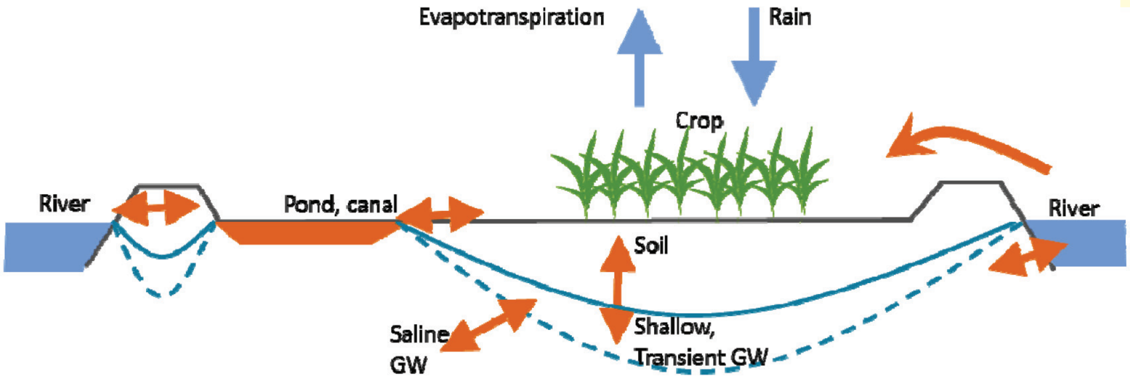

Fig. 1. Schematic diagram of key processes governing water and salt balances in a polder. The blue arrows depict the movement of water without salt – rainfall and evapotranspiration. The brown arrows depict the movement of water and salt between four main water and salt stores; the rivers, groundwater, surface canals and ponds, and the soil. GW denotes groundwater.

model. The basis of the crop coefficient approach is described in Allen *et al*. (1998) and Doorenbos and Kassam (1979). The crops may be affected by salinity using the salt stress coefficient approach described in Allen *et al*. (1998). In this approach, crop ET is unaffected provided the salt concentration is below a threshold value (which varies from crop to crop). Above the threshold value, ET reduces with increasing salt concentration; the rate of reduction with soil salinity being crop dependent.

The ponds and canals are treated as single unit with defined area and depth. They receive rainwater and lose water by evaporation (according to a pan coefficient model), neither of which transfers any salt (so rainwater dilutes the salt, while evaporation concentrates it). They also receive surface drainage from the surrounding land (at a salt concentration which depends on the degree of mixing with the soil water). If the surface drainage is in excess of the unused volume of the ponds and canals, it is assumed to drain instantly (*i.e*. within the monthly timestep) out of the polder into the river. The ponds and canals may receive water (and salt) from the rivers, either to top up the water in the ponds and canals, or to supply the irrigation demand of the crops, or both. They may also receive water and salt from infrequent flood inundation events. The only similar model known to us is the daily time step model of Payo *et al*. (2017).

Water balance, salt balance, and mass balance errors: calculation principles

Water balances are calculated for the soil water, shallow groundwater and ponds and canals by mass balance equations of the form:

Water store (t + dt) = Water store (t) + Water gains (dt) – Water losses (dt) + Error (dt) ...(1)

Where, t is the time and dt is the timestep (one month). The individual gains and losses are calculated by the simple models described above.

Salt masses are calculated for the soil water, shallow groundwater and ponds and canals by mass balance equations of the form:

Salt store (t + dt) = Salt store (t) + Salt gains (dt) - Salt losses (dt) + Error (dt) ...(2)

Where, individual gains and losses are calculated from water flows and salt concentrations in the water. The mass balance error in each equation is explicitly calculated and is always small (of order 10^{-8} or less for water or 10^{-6} or less for salt of the size of the other terms in the mass balance equations in all timesteps).

RESULTS AND DISCUSSION

Model simulations of field experiments

Field experiments, described elsewhere in this special issue, were conducted at Amtali and Dacope in Bangladesh, and Gosaba in West Bengal, India which have annual average rainfall and potential evapotranspiration, respectively of about: 2.5 and 1.2 m; 1.8 and 1.3 m; and, 1.9 and 1.4 m. At each of three field sites, there are many experimental plots involving different crops and management, described elsewhere in this Special Issue. Some of the water and salinity data collected at or near these plots can be compared to the results of the polder salt and water balance model. However, the plots cover just a small fraction of the overall polder area, and conditions differ somewhat from plot to plot. The polder model, on the other hand, considers the polder as one large entity, with just one value for each quantity such as soil salinity, or groundwater depth. Some field results of groundwater levels are available from earlier years, not associated with the project experiments, but which extend the range of results useful for comparison and so are used below alongside the results from the project field experiments. Furthermore, climate data are not available for the period of the field experiments, so climate data up to 2010 have been used. Therefore, the comparison of model results to the field readings can be no more than a general comparison.

With these limitations in mind, Fig. 2 shows the comparison of several quantities collected in the field with results from the polder water and salt balance model. The longest period of field readings is from some water table level readings taken by Institute of Water Modeling (IWM) in the years from 2014-16 at Amtali, and from 2010-12 at Dacope. These readings are shown compared to the model results for 2008-10. The other field readings are from the project experiments from late 2016 to early 2018, and are superimposed staring in the second year of the model results. At Gosaba, field readings are also from the project experiments conducted from late 2016 to early 2018, and are superimposed starting in the second year of the model results. Note that the soil salinity readings were of

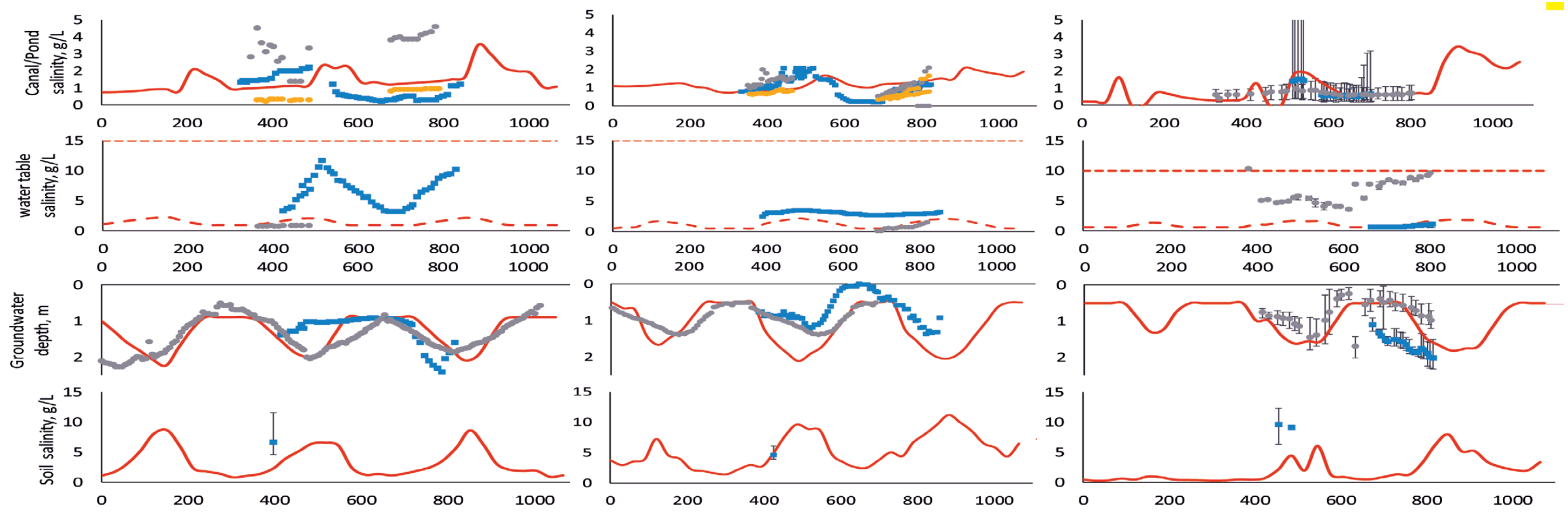

Fig. 2. *Comparison of field readings (points, with bars showing the range where there was more than one reading) with polder salt and water balance model results (lines) for Amtali (left), Dacope (middle) and Gosaba (right). The top row of plots shows the salt concentration in ponds and canals. The second row shows the salt concentration measured in wells, together with that modelled for a deeper salty aquifer layer (line with short dashes) and a shallow, fresher aquifer layer (line with long dashes). The third row of plots shows the groundwater level, with the earlier IWM readings in the grey points. The bottom row of plots shows the salt concentration in the soil. The X axis in each case shows time, in days. The wet season is indicated by periods of shallow groundwater (third row), which coincides with periods of low salinity in the ponds and canals, the groundwater and the soil*

electrical conductivity EC1:5. We have converted them to salt concentrations (Cs) using the formula suggested by Ed Barrett-Lennard, Murdoch University, Western Australia (personal communication): Cs (g L^{-1}) = 0.64 x $EC_{1:5}$ (dS m^{-1}) x 5 x 100 / W (%), where W is the gravimetric moisture content.

The modelled results generally show similar behaviour to the measured results. The modelled canal and pond salt concentrations and the groundwater depths fall within the range of the measured results. The dry season increase in pond / canal salinity and increase in groundwater depth are seen both in the model results and measured data. The modelled soil water salt concentration is generally of right order, but there are too few measured results to properly test the model.

The groundwater in the polder model is assumed to behave as a shallow freshwater lens sitting above a deeper salty water table. The lens is assumed to form and grow with the excess of rain in the wet season, which will drain through the soil, leaching and diluting salt as it passes. In the dry season, the lens will be depleted by capillary uprise, drawn up by the potential gradient established as the soil surface dries out. The salt concentration will increase if the freshwater lens is depleted, since any further capillary rise will then draw up the salty deeper groundwater. The second row of plots in Fig. 2 shows as the dashed line with long dashes the modest rise and fall of the salt concentration in the shallow lens. The deeper groundwater is assumed to be at a constant salinity, shown by the dashed line with the short dashes.

The field measurements show one series at each site with salt concentrations similar to the modelled fresh lense. At Amtali and Gosaba, another series shows salt concentration varying roughly between that of the modelled freshwater lens and that of the assumed deeper groundwater layer. It is possible that the piezometer is open to allow water and salt to flow (in and out) over a range of depths. Water at different depths would then mix and the salt concentration in the piezometer would be intermediate between that of the different layers. As the dry season progresses and a shallow fresh layer is depleted, the water in the piezometer would be increasingly dominated by the saltier deeper water. This mixing would result in the behaviour shown in Fig. 2. Thus, Fig. 2 is consistent with the assumed groundwater behaviour.

Perhaps the most striking aspect of the comparison in Fig. 1 is that the three sites show broadly similar behaviour in terms of both modelled and measured quantities. The salt concentrations in ponds/canals and groundwater and the way they change through the dry and wet seasons are similar at all three locations, as is the fall and rise of groundwater with the dry and wet seasons.

All three sites have an annual rainfall total which exceeds the annual potential evapotranspiration by several hundred mm and so all three are likely to have salinity and groundwater depth behaviour strongly influenced by the availability of excess fresh water to flush salt out and replenish the groundwater in the wet season. It is possible that this masks other differences which could arise from different soil characteristics, or different management.

The main consideration resulting from the understanding of the polder salt and water balance processes and the model is the importance of drainage to remove salt. The field experiments and the model both show that the behaviour of water and salt in the polders is highly dynamic, varying throughout the year. The salt concentration in the dry season reaches values of around 10 g L^{-1} (varying somewhat from site to site and from year to year) in the soil water, and around 2 - 4 g L^{-1} in the canal and pond water. With an excess of rainfall over potential evapotranspiration that varies from 0.5 to 1.3 m annually amongst the sites, there would seem to be enough water to leach salt out of the soil, and particularly to flush it out of the canals and ponds fairly and quickly. The salt in the canals and ponds must result from a continual re-supply of salt, either from the groundwater or from the rivers. Re-supply from the rivers cannot be discounted under some drainage channel management regimes. However, it seems likely that capillary rise from a salty groundwater table would supply salt that would cycle through the soil and into the surface drainage system to the canals and ponds; this behaviour is shown in the model. To remove salt from the polder, canal drainage must be managed effectively.

Drainage is similarly likely to be important at the crop or field level. Irrigation has proven to be useful in the field experiments (see elsewhere in this special issue). But irrigation will involve the addition of salt as well as water to the soil surface; the amount will depend on the salt concentration in the ponds and canals. Without adequate drainage, some of the added salt is likely to be leached downward in the wet season to the water table, only to be brought to the surface again by capillary rise in the next dry season. This recycling of salt would, over several years, lead to high salt concentrations that could limit crop growth.

Finally, we note the model will be useful for investigating new water and salt management procedures, and for investigating factors such as climate change. Model assessments of these factors will be reported elsewhere.

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