19 Salinity Dynamics and Water Availability in Water Bodies over a Dry Season in the Ganges Delta

Implications for Cropping Systems Intensification

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19.1 INTRODUCTION

The Ganges Delta is the world's largest delta containing the outlets of three major rivers, the Ganges, Brahmaputra and Meghna (Chowdhury 2010); it covers ~200,000 km² in Bangladesh and the Indian state of West Bengal (Alam et al. 2003; Mukherjee et al. 2007). A major tributary of the Ganges River is the Gorai-Madhumati River, which is the main source of fresh water in south-western Bangladesh (Mondal 2016). Since 1975, freshwater flow during the winter season (November to March) has decreased in the Gorai-Madhumati River due to the construction of the Farakka Barrage in India on the Ganges river (Mirza 1998), which is one of the reasons for elevated river salinity and increased salinity in the surrounding land. In addition, tidal salt water intrusion into rivers and aquifers is increasing salinity thereby making freshwater unavailable in the hydrologically connected canals and ponds (Mahmuduzzaman et al. 2014). In the south-central part of the Ganges Delta, the Meghna River remains fresh throughout the year. This study focuses on the water resources on agricultural land near Dacope, Khulna in south-western Bangladesh.

The south-western region, which comprises ~15% of the total area of Bangladesh, has a limited area of *Rabi* season cropping due to the perception that severe soil and water salinity would otherwise result in poor yields (BBS 2018). However, salinity (expressed as the electrical conductivity of the water – EC_w) changes seasonally, being highest in the late *Rabi* season (*Rabi* season covers the period from November to March; Payo et al. 2017) when the weather is dry and hot (mean maximum and minimum temperatures increase by 7.1°C and 5.8°C from December to March, Figure 19.1B), and early in the *Kharif*-1 season (March–June, Payo et al. 2017) during the hot and humid summer. In the main season for wetland rice, the *Kharif*-2 or monsoon season (June–November, Payo et al. 2017), the EC_w of all water sources, including surface water and groundwater, decreases because of seasonal rainfall. About 78% of the total yearly rainfall (~1,730 mm per annum) falls during the *Kharif*-2 season. Smaller but significant amounts of rainfall can fall between December and March (Yu et al. 2019). Water from canals, ponds or groundwater is used for irrigation of dry season (*Rabi* season) crops (e.g. *Boro* rice, sunflower, wheat, maize, mustard, potato, watermelon and spinach) and *Kharif*-1 crops (e.g. mung bean, sesame and *Aus* rice). A review of the limitations and prospects associated with the cropping system intensification in this region (Bell et al. 2019) suggested that changing the cropping season by early establishment of *Rabi* crops would reduce crop dependence on water for irrigation especially late in the *Rabi* season

FIGURE 19.1 Weather variables as a function of time during the study period: (A) cumulative rainfall and evaporation, (B) maximum and minimum temperature and (C) vapour pressure deficit (VPD). Values are from the Khulna meteorological station 17.3 km north of Dacope.

when water is in short supply and its salinity is highest. Early crop establishment after the monsoon season needs to remove standing water but retain soil water storage after early harvested *Kharif-2* rice so that crops can utilise fresh soil water for critical growth stages and minimise exposure to soil and water salinity until later growth stages (Bell et al. 2019; Kabir et al. 2019). Therefore, water availability and its quality are important factors enabling crops to reach their potential yield during the dry season in these saline areas.

Previous reports (Akanda et al. 2017; Hossain et al. 2019; Kabir et al. 2019; Mondal et al. 2006; Murad et al. 2018) on water resources in south-western Bangladesh have generally focused on the EC_w rather than the availability of water as constraints to cropping. For example, the mean monthly EC_w (1997–2004) of the Kazibachha River ranged from ~ 1.5 dS m^{-1} in January to ~ 20 dS m^{-1} in April or May at Kismat Fultola village, Khulna District (Mondal et al. 2006). The EC_w of canal water increased from 4.3 dS m^{-1} on 5 December 2016 to 9.8 dS m^{-1} on 18 April 2017 during the maize growing period at Benarpota Upazila, Satkhira, Khulna (Murad et al. 2018). And, of particular relevance to Dacope, the case study area of the present investigation, the EC_w of river water increased from 12 dS m^{-1} on 10 January 2017 to 13.9 dS m^{-1} on 30 April 2017, but the EC_w of the canal and pond water varied between 0.7–0.9 and 0.3–0.6 dS m^{-1} , respectively, between 30 December 2016 and 30 April 2017 (Akanda et al. 2017). In a sowing date study on wheat at Dacope, bundled canal and pond water were used for irrigation and the salinity remained below 3 and 2 dS m^{-1} , respectively (Kabir et al. 2019). Groundwater, the remaining water source, was reported to vary in EC_w between 1.5 and 2.3 dS m^{-1} from 5 December 2016 to 18 April 2017 at Benarpota Upazila, Satkhira District, Khulna, and between 1.1 and 1.3 dS m^{-1} from 30 December 2016 to 30 April 2017 at Dacope, Khulna (Akanda et al. 2017; Murad et al. 2018).

We hypothesise that EC_w is regulated by the volume of water stored in controlled canals or ponds, due to the influence of three factors: weather variables (cumulative evaporation, maximum temperature and vapour pressure deficit), hydrological connectivity to a river and elevation above mean sea level. We further hypothesise that lower elevation ponds or canals have a higher risk of shallow saline groundwater intrusion since the pond water level is more likely to be lower than the phreatic groundwater level. In addition, these ponds are more prone to receiving overland flow due to rainfall, which washes salt from the surrounding land surfaces. Another hypothesis is that the closer the pond is to a tidal river, the more susceptible its water will be to seepage of saline water from the river due to hydrological connectivity.

In this study, we explore the hypothesis that water availability rather than its EC_w is the main constraint to cropping systems intensification in this environment because changes in the planting date of *Rabi* season crops and crop choice, together with best-practice agronomy and irrigation, can be designed to manage, minimise or avoid the damaging effect of elevated EC_w on crop yields (Bell et al. 2019). Also, the relationships between EC_w and water availability with elevation above mean sea level and weather variables are explored. We examine the possibility of the conjunctive use of non-saline and slightly to moderately saline irrigation water from bundled canals and ponds for intensifying dry season cropping. Finally, we synthesise knowledge about the trends of EC_w and water availability in the *Rabi* and *Kharif-1* season

to propose novel cropping patterns to expand the area of *Rabi* season crop production. Our study focused on the salinity dynamics and water availability in water bodies in the *Rabi* and *Kharif*-1 season at a case study area at Dacope, Khulna in southwest Bangladesh.

19.2 MATERIALS AND METHODS

19.2.1 STUDY LOCATION AND WEATHER CONDITION

Our study was conducted on water bodies (canal, pond, river and groundwater) in Dacope, Khulna (Figure 19.2) to characterise salinity dynamics and water availability during the *Rabi* and *Kharif*-1 seasons from December 2017 to May 2018. Three canals (locations 1, 2 and 3) were selected (Figure 19.2B), and each canal was divided into 3–5 sections. Each location also included three ponds and tube wells, with positions illustrated in Figure 19.2B. In the case of the Sundarban River, three measuring points were selected shown in Figure 19.2B. The sampling was conducted on one (March–May), two (January–February) or three (December) days per week.

FIGURE 19.2 Location map of the study area and survey points at Dacope, Khulna, Bangladesh. (A). Location map of Bangladesh showing the large rivers (labelled BD water areas) and the position of Dacope, Khulna at the south-west of Bangladesh, (B). Survey points at Dacope on the river (circles), and three different locations for canal (diamonds), pond (heptagon) and groundwater (triangle) samples.

19.2.2 WATER SALINITY

The EC_w of all water bodies was recorded at high and low tides using a portable EC meter (Model: HI 8733).

19.2.3 INFLUENCE OF ELEVATION AND WEATHER VARIABLES ON WATER SALINITY AND WATER AVAILABILITY

Data on the weather factors tested for their influence on EC_w (cumulative evaporation, maximum temperature and vapour pressure deficit) were collected from Khulna weather station while elevation above mean sea level was determined by mobile phone-operated elevation software (altimeter) at each survey point. Rainfall and evaporation were measured by 8-inch diameter ordinary rain gauge and USA class A Pan according to the World Meteorological Organization.

19.2.4 CALCULATION OF VOLUME OF CANAL AND POND WATER

The length and width of each canal were calculated in Google Earth. The length and width of ponds were determined with a measuring tape. Canals and ponds were considered to be rectangular in shape and in cross-section with depth. Water depth was measured one (March–May), two (January–February) or three (December) days per week, depending on the rate of change in EC_w . The volume of water at different times was calculated by multiplying the area of the water body by the water depth.

19.2.5 CULTIVATION PRACTICE

Farmers of this region cultivate a range of dry season crops with both high- and low-water requirements including *Boro* rice (~1–2% of current cultivated land), sunflower, wheat, maize, potato, watermelon and bottle gourd. More than 90% of total cultivable land is kept fallow (personal communication). Among the crops, *Boro* rice needs ~870 mm of applied water (data from Jessore, Khulna) of good quality from crop establishment until maturity (Hossain et al. 2018), bottle gourd and watermelon need weekly irrigation, whereas sunflower, wheat, maize and potato need only two–four irrigations in total to reach their yield potential. The usual planting time (farmer's practice) for *Rabi* crops is from the last week of January to the first week of February.

19.3 RESULTS

19.3.1 WEATHER CONDITIONS

Figure 19.1 shows weather variables at Khulna weather station during the study period (<http://www.bmd.gov.bd>). During the study period, the total rainfall was 29 mm, of which 20 mm fell from April to the first week of May (Figure 19.1A). The mean daily evaporation was 2.8 mm (calculated from Figure 19.1A). Temperature (maximum and minimum) and vapour pressure deficit increased between January and March (Figures 19.1B,C).

19.3.2 VARIATION OF RIVER, CANAL, POND, AND GROUNDWATER SALINITY OVER TIME

The EC_w of river, canal, pond and groundwater significantly increased during the progression of the *Rabi* season until the middle of the *Kharif*-1 season (Figure 19.3). The EC_w of the river and of canals 2 and 3 increased significantly ($P < 0.001$;

FIGURE 19.3 Scatter diagrams showing the relationship between EC_w of water bodies and time: (A) mean river and canal water, (B) pond water and (C) groundwater from tubewells (TW). For linear lines of best fit (not shown), the P - and R^2 values are indicated. In case of water quality, canal 1: slightly (green) to moderately saline (orange), canal 2 and 3 and river: slightly to severely saline (green, orange, red and pink), pond 6: non-saline to slightly saline (blue), pond 3 and 8: slightly saline (green), pond 1, 2, 4, 5, 7 and 9: slightly to moderately saline (orange), TW 2, 3, 4, 6, 7 and 8: moderately saline (orange) and TW 1 and 5: highly saline (red).

$r^2 = 0.88$ to 0.90) with time with the highest value recorded in mid-April (Figure 19.3A). Among the three canals, the canal at location 1 was not directly linked with the river due to the construction of a major bund; consequently, the EC_w was $\sim 90\%$ lower than that of the river during the peak time but still increased significantly ($P < 0.001$; $r^2 = 0.95$) with time (Figure 19.3A). The EC_w of this canal increased from 2 dS m^{-1} in February to a maximum of 2.9 dS m^{-1} in mid-April. The EC_w values of canals 2 and 3 were positively ($P < 0.001$) correlated with mean river EC_w with r^2 values of 0.98 and 0.99 . The river EC_w increased from 2 dS m^{-1} on 26 December to a maximum of 24.6 dS m^{-1} in mid-April.

The mean pond EC_w at the three locations increased significantly ($P < 0.01$ – < 0.001) with time, with r^2 values for linear correlations of 0.45 – 0.96 (Figure 19.3B). The EC_w of three ponds (3, 6 and 8) remained below 2 dS m^{-1} over the dry season, while for four ponds (1, 4, 7 and 9) the EC_w increased from 2 dS m^{-1} in February to a maximum of 2.6 dS m^{-1} between mid-April and late May and for two ponds (2 and 5) the EC_w reached a maximum of 4.2 dS m^{-1} in mid-April. In terms of water quality criteria¹, pond 6 was non-saline to slightly saline, and ponds 8 and 3 were slightly saline, and these would have been suitable for supplying water for human consumption as well as for irrigation². Ponds 1, 4, 7 and 9 were slightly to moderately saline with maximum EC_w values below 3 dS m^{-1} and these could have been suitable as water sources for late irrigation. Ponds 2 and 5 had higher EC_w values but were still slightly to moderately saline and water could have been used for late irrigation in grain filling stages (i.e., wheat, sorghum, cowpea and maize)³.

The EC_w of the groundwater at three locations increased significantly ($P < 0.05$ to < 0.001) with time, with r^2 values for linear correlations of 0.21 to 0.90 (Figure 19.3C). Among the tube wells (TW), three (TW 4, 6 and 8) had EC_w values that increased from 2.3 dS m^{-1} on 9 December to a maximum of 4.1 dS m^{-1} on mid-April, and five (TW 1, 2, 3, 5 and 7) had EC_w values that increased from 3.1 dS m^{-1} on 9 December to a maximum of 5.5 – 5.7 dS m^{-1} between mid-April and the end of May. In the case of water quality, TW 2, 3, 4, 6, 7 and 8 were moderately saline; this water could be used for later-stage irrigation (grain filling), whereas TW 1 and 5 were highly saline and this water was not suitable for irrigation.

19.3.3 RELATIONSHIP BETWEEN ELEVATION AND WEATHER PARAMETERS WITH WATER BODY SALINITY

Elevation and weather criteria were tested for their relationships with the EC_w of pond water (Figures 19.4 and 19.5). The EC_w of pond water was negatively correlated ($P < 0.05$ to < 0.01) with elevation above mean sea level (MSL) (Figures 19.4A and 19.4B). However, for each elevation, the EC_w increased with time until April (Figure 19.4A and 19.4B) and decreased after April (not shown) due to rainfall (Figure 19.1A).

A strong correlation was found between cumulative evaporation and EC_w in the river, canals, ponds and groundwater; exponential lines of best fit were significant ($P < 0.001$ with r^2 values of 0.89 – 0.98 ; Figures 19.5A and 19.5D). Maximum temperature and vapour pressure deficit were of lower importance; exponential lines of best fit were significant ($P < 0.001$) but r^2 values were 0.48 – 0.65 (Figures 19.5B and 19.5E) and 0.57 – 0.76 (Figures 19.5C and 19.5F), respectively.

FIGURE 19.4 Relationships between EC_w of pond water and elevation above mean sea level for sampling times between December and April: (A) scatter points showing mean monthly EC_w values and elevation above mean sea level for months from December to April (B) and exponential lines of best fit to these points showing the P - and R^2 value ranges.

FIGURE 19.5 Relationships between mean river, canal, pond and groundwater EC_w and weather variables during the *Rabi* and early *Kharif-1* season: (A, D) effect of cumulative evaporation, (B, E) effect of maximum temperature and (C, F) effect of vapour pressure deficit (VPD). Parts A, B and C show river and canal EC_w values. Parts D, E and F show pond and groundwater EC_w values. The points have been fitted to exponential lines of best fit with the P - and R^2 values indicated.

FIGURE 19.6 Relationships between relative water volume (V_r) in canals and ponds over time: (A) canal at location 1 and location 2 and (B) the mean for all ponds. The points were fitted to exponential lines with the P - and R^2 values indicated.

19.3.4 VARIATION OF WATER AVAILABILITY IN CANALS AND PONDS OVER TIME

Ponds and canals differed by orders of magnitude in the maximum volumes of water that these contained. The canals at locations 1 and 2 contained 3,089 m³ and 16,961 m³ respectively, whereas the measured ponds contained a maximum of 244 to 1,078 m³ of water. Because of this variation, we transformed the volume of water in canals and ponds to values relative to ‘maximum water content’ – defined as the water content of canals on 1 December and ponds on 9 December, respectively. Figure 19.6 shows change in relative water volume (V_r) in canals (A) and ponds (B) over the dry season period. For all water bodies, the relative volume of water decreased exponentially ($P < 0.001$; r^2 values 0.52 to 0.93) with time between early December and mid-April (Figure 19.6). After mid-April, the water volume stored in canals and ponds increased due to rainfall (Figure 19.1A).

19.3.4.1 Relationship between Relative Salinity and Relative Water Volume

One way to test whether there was connectivity between ponds and the surrounding sources of water and salt (rivers and shallow groundwater) was to test whether the EC_w of the water increased as expected with a decline in the water body volume by evaporation and irrigation water extraction. That is, a doubling of EC_w for a halving of water volume would indicate that only evaporation determined EC_w while deviation from this relationship would indicate the accumulation of salt in water bodies from external sources, irrigation water extraction, or leakage of water from the water body. To determine this, we built scattergrams of the volume of water in canals and ponds relative to ‘maximum water content’ against the EC_w of water in canals and ponds relative to EC_w when canals and ponds were at maximum water content (Figure 19.7). These scattergrams included the theoretical line showing the expected increase in relative EC_w associated with a decline in volume relative to maximum. Values above this line (i.e. relative EC_w values greater than expected assuming that

FIGURE 19.7 Relationships between water body (canal and pond) relative water volume (V_r) and relative EC_w during December to May: (A) change in V_r of canals over time, (B) change in V_r of ponds over time, (C) scattergram for canals showing the effect of V_r (as a % of volume on 1 December) on relative EC_w (% EC_w on 1 December) and (D) scattergram for ponds showing the effect of V_r (% volume on 9 December) on relative EC_w (as a % of EC_w on 9 December). In case of water quality, canal 1: slightly (green) to moderately saline (orange), canal 2 and 3: slightly to severely saline (green, orange, red, and pink), pond 6: non-saline to slightly saline (blue), pond 3 and 8: slightly saline (green) and pond 1, 2, 4, 5, 7 and 9: slightly to moderately saline (orange).

increases in EC_w were due to evaporation and irrigation water extraction) might suggest that salt was entering water bodies from the surrounding land, groundwater or rivers. It was found that the decline in a relative water volume (V_r) of canals and ponds was significantly correlated ($P < 0.05$ to < 0.001) with the increase in their relative salinity over time (Figures 19.7C and 19.7D). Changes in EC_w with V_r for the canal at location 1 (Figure 19.7C) was below the theoretical line suggesting that there was a little intrusion of salt through the bund protecting the canal from the river while irrigation water extraction decreased V_r . However, points for the canal at locations 2 and 3 (Figure 19.7C), were substantially above the hypothetical line indicating that factors in addition to evaporation, direct connectivity to tidal river and irrigation water extraction controlled EC_w . For the canal at location 3, there was a little change at all in relative volume but the EC_w values increased about 30-fold.

Among the ponds, ponds 4, 5 and 6 were above and ponds 1, 2 and 8 were partially above the hypothetical line, while ponds 3, 7 and 9 were below the hypothetical line (Figure 19.7D). The ponds that had substantial seepage of salt into the water were ponds 4, 5 and 6. The other ponds had little leakage salt or entry salt from outside the pond. A major change in salinity at 100% volume for pond 4, 80% volume for pond 8 and 113% volume for pond 6 might be explained by the runoff of rainfall as over-land flow into the pond, or by seepage into the pond from hydrological connectivity to river or from shallow groundwater. However, the relative increase in salt into the leaky ponds was far less (2.5-fold) than into the uncontrolled canals connected to the river (about 30-fold) (Figures 19.7C and 19.7D).

19.3.5 RELATIONSHIP BETWEEN WEATHER PARAMETERS AND WATER AVAILABILITY

Figure 19.8 shows correlation between the relative water volumes of canals and ponds with the weather variables during the *Rabi* and up to the middle of the *Kharif-I* season. Cumulative evaporation, maximum temperature and vapour pressure deficit were negatively correlated ($P < 0.001$) with the relative water volume (V_r) of the canal with r^2 values of 0.75, 0.63 and 0.23, respectively (Figures 19.8A–19.8C). A similar relationship ($P < 0.001$) was found between the V_r of pond and weather variables with r^2 values of 0.71, 0.50 and 0.58 (Figures 19.8D–19.8F).

19.4 DISCUSSION

Previous work on water resources in saline coastal areas of the Ganges Delta has generally focused on EC_w in surface water and groundwater as the major constraint to the irrigation of dry season crops (Akanda et al. 2017; Hossain et al. 2019; Kabir et al. 2019; Mondal et al. 2006; Murad et al. 2018). However, this study has also examined the quantity of water in bunded canals and ponds because EC_w can be regulated by changes in water volume, hydrological connectivity to landscape and weather variables. This discussion is focused around three themes. We discuss the changes in EC_w and water availability in the bunded canal and ponds, the causes of change in EC_w and the availability of water in canals and ponds, and the use of these water resources for dry season cropping.

FIGURE 19.8 Relationships between relative water volume of canals and ponds (V_r) with the weather variables during the *Rabi* and up to the middle of the *Kharif-1* season: (A, D) effect of cumulative evaporation, (B, E) effect of maximum temperature and (C, F) effect of vapour pressure deficit (VPD). Parts A–C are canal V_r values and parts D–F are pond V_r values. The points have been fitted to linear lines of best fit with the P - and R^2 values indicated.

**19.4.1 SALINITY AND WATER AVAILABILITY DYNAMICS
IN THE BUNDED CANAL AND PONDS**

In the present study, the EC_w of a controlled or banded canal during the late *Rabi* and early *Kharif-1* (mid-April) seasons was ~90% lower than that of the uncontrolled canal directly linked with the tidal saline river (Figure 19.3A). Similar EC_w values in controlled canals (1.3 to 3.0 dS m⁻¹ in the same study area and 1.1 to 2.3 dS m⁻¹ in Amtali, Barisal) have been previously recorded during the dry season (Hossain et al. 2019; Kabir et al. 2019). The best time for placing the bund in canals was when the river EC_w was below 4 dS m⁻¹ on 10–15 December (Hossain et al. 2019). For a protected canal, the EC_w increased 2.3 fold from the first week of December 2016 until mid of April 2017 in Benarpota, Satkhira, Khulna (Murad et al. 2018). By contrast, river EC_w increased 13 fold from January to April or May at Kismat Fultala village, Khulna (Mondal et al. 2006).

In the present study, the EC_w of ponds fell in the range 0.5–4.2 dS m⁻¹ and ponds could be considered a promising source of irrigation for dry season cropping (Figure 19.3B). In the same study area, in the dry season of 2016–2017, pond water remained non-saline (Akanda et al. 2017; Kabir et al. 2019). However, the current storage capacity of ponds was not sufficient to meet the irrigation requirements. To solve this issue, the involvement of government agencies for promoting pond development is important (Bell et al. 2019).

Relative water volume of the controlled canal and of ponds decreased over time during the study period (Figure 19.6). This water volume change might be due to cumulative evaporation (increasing EC_w), extraction for irrigation or loss by drainage (not changing EC_w), groundwater infiltration (increasing EC_w) into ponds and later rainfall (decreasing EC_w). However, groundwater level in one location remained lower than the pond water depth from November until May 2017–2018. Therefore, there was no chance of inflow towards the pond from groundwater for that location but there was a chance of outflow from the canal towards the groundwater (not measured during the study). In this study, volume change for canal and ponds over time was attributed mostly to water extraction for irrigation and evaporation. Further water balance research is needed involving measuring groundwater and water body water elevations together with cumulative evaporation, extraction/drainage, groundwater infiltration and rainfall over time.

In the current study, the increase in relative EC_w of a bunded canal and several ponds (3, 7 and 9) with the decrease in relative water volume due to evaporation and irrigation water extraction was below the hypothetical line (doubling the EC_w for a halving of water volume due to evaporation and irrigation water extraction) (Figures 19.7C and 19.7D). This water would have been suitable as a source of irrigation for dry season cropping. By contrast, the relationship between relative EC_w and relative water volume of uncontrolled canals and other ponds (4, 5 and 6) was substantially above the theoretical line. This suggesting that these ponds might have high connectivity to the adjacent tidal river, or that there had been overland flow from rainfall, which allowed additional salt to enter the water body (Figures 19.7C and 19.7D). Groundwater EC_w remained in the range of 2.3–5.7 dS m^{-1} over the dry period (Figure 19.3C). Groundwater can, therefore, be considered a supplementary water resource if controlled canal and pond water volumes are insufficient.

19.4.2 CAUSES OF CHANGE IN WATER SALINITY AND WATER AVAILABILITY

A further cause suggesting hydrological connectivity of stored water to the landscape was the highly significant negative relationship between elevation above mean sea level and pond EC_w (Figures 19.4A and 19.4B). At present, we do not know for sure the cause of this relationship. Perhaps, the intrusion of shallow saline groundwater into ponds is affected by the depth to water-table and the periodic lowering of pond level during extraction for irrigation, and this is related to the elevation above sea level since the water-table will be deeper in the elevated parts of the landscape and shallower in the less elevated parts of the landscape: there may also be differences in groundwater salinity with elevation. Given this, we would expect more seepage (and therefore saline intrusion) from shallow groundwater in ponds with low elevation. The app that we have used does not specify vertical resolution of the elevation measurement but we note there was a strong correlation between elevation and EC_w which suggests there was a physical relationship between elevation and EC_w . This could be tested by measurement of depth to water-table around ponds using high-resolution digital elevation surveying or differential global positioning system devices together with shallow groundwater EC_w at differing elevations in the landscape.

In the current study, among the weather variables, cumulative evaporation was the most important cause for increasing salinity (Figures 19.5A and 19.5D). We propose that the mechanism for this effect was by decreasing relative water volume along with irrigation water extraction (Figures 19.8A and 19.8D). Cumulative evaporation was also positively ($P < 0.001$) correlated with maximum temperature and vapour pressure deficit. Analysis of 40 years (1970–2017) of climate data in the coastal zone of Bangladesh showed that maximum temperature increased to 0.04°C per year (Yu et al. 2019). Further increases in temperature may exacerbate the increases in EC_w of stored water by decreasing water volume due to increased evaporation and extraction of irrigation water. Precipitation after April increased the water storage in canals and ponds (Figures 19.7A and 19.7B) and decreased their EC_w (Figures 19.3A and 19.3B). This water can be used for seedbed preparation of *Kharif-1* rice. For example, in Amtali, Barishal, in 2018–2019, *Kharif-1* rice cropping area was reduced drastically due to lack of fresh surface water (no rainfall) during seedbed preparation (Bell et al. 2019).

19.4.3 UTILISATION OF IRRIGATION WATER FOR DRY SEASON CROPPING

In this study, water quality measurements suggested three types of pond water (non-saline to slightly saline, slightly saline and slightly to moderately saline) during the *Rabi* season and into the middle of the *Kharif-1* season (Figure 19.3B). The EC_w of the bunded canal was also non-saline to slightly saline throughout the season (Figure 19.3A). Therefore, considering the water availability, importance should be given on alternative crops rather than *Boro* rice because of its requirement for substantial volumes of water of low salinity (Bell et al. 2019) and on more water-efficient irrigation methods such as drip irrigation (Mahanta et al. 2019) and also to employing mulches and tillage to decrease soil salinity and conserve soil water (Paul et al. 2020a,b; Sarangi et al. 2018a, b). We suggest that the cropping area could be increased by early sowing of *Rabi* season crops including waterlogging-tolerant, salt-sensitive crops (grass pea and mustard) along with existing salt-tolerant non-rice crops (sunflower, maize, wheat, barley and watermelon) as well as through the conjunctive use of non-saline and slightly to moderately saline water during the dry season (Kabir et al. 2019). Fitting a non-rice crop (mustard, garden pea, spinach and potato) into the *Rabi* season after *Kharif-2* rice increased the overall benefit-cost ratio relative to that from a single *Kharif-2* season rice in the same study area (Saha et al. 2019). Also, the focus should be given on the development of alternative crops which are of short duration, and tolerant to early waterlogging, and to salinity and drought at the end of the growing season (Bell et al. 2019). Drainage strategies to facilitate earlier sowing and harvest of *Rabi* season crops might enable these crops to escape waterlogging at the start of the growing season and ripen before the adverse effects of salinity and drought at the end of the season curtail yield (Bell et al. 2019; Kabir et al. 2019). Another opportunity is to increase the storage capacity of existing water bodies (canal and pond) (Bell et al. 2019) so that water can be stored during the monsoon season from rainfall as well as from river sources when water salinity is below 2 dS m^{-1} . Rainfall from February to April may be beneficial for increasing storage of freshwater in ponds

and bunded canals. Indeed, the possibility of 20 mm and 50 mm rainfall events has increased by 25–65% and 5–30% in the last 30 years during February to April (Yu et al. 2019). At the same time, a more effective weather forecasting system could enable surface water storage decisions during infrequent heavy rainfall during the dry season which may also alleviate damage from flooding of crop fields. Finally, cutting down on direct evaporation from the surface of the ponds and bunded canals might be possible by cultivating lightweight vine-type vegetables on top of the water bodies supported by bamboo and rope trellises. However, ponds and canals in lower-lying land need to be protected from runoff of saline surface water from higher land.

19.5 CONCLUSION

In the coastal zone of the Ganges Delta, an increase in soil and water salinity and drying of soil profiles during the dry season impedes the production of *Rabi* crops by farmers. Current practices involving a delay in crop establishment increases the exposure of non-rice crop to increasing soil and water salinity, decreasing surface water availability and increasing dependency on groundwater. The salinity of canals and ponds started to increase after February and reached a maximum during mid-April. Pond and groundwater salinity was comparatively lower than the river and canal (without bund) water salinity. The water salinity of the canals isolated from the river remained comparatively low (1.1–2.9 dS m⁻¹). Cumulative evaporation, water extraction and saline water intrusion were the most important factors for increasing water salinity and decreasing the volume of stored water. Therefore, if crop irrigation can be mostly completed by February, stored water would remain sufficiently low in EC_w to be used for irrigation (0.5–3.9 dS m⁻¹).

The present study relates to a particular part of the Ganges, Brahmaputra and Meghna Delta where river salinity is high in the dry season. Further study is required at other locations in the delta with either continuous fresh or saline river water flow, and with differences in elevation above mean sea level and distance from the river to determine how the present case study results can be extrapolated more widely.

Therefore, it is recommended that the early establishment of non-rice crops, increasing the existing storage capacity of reservoirs (canal and pond), construction of temporary bunds in canals and ponds before the *Rabi* season, cultivation of lightweight leafy vegetables to shade the canals and pond and strengthening the weather forecasting system can increase agricultural productivity and food security for low-lying deltas.

ACKNOWLEDGEMENT

The authors are grateful to the Australian Centre for International Agricultural Research (Project LWR/2014/073) for financial support and for a John Allwright Fellowship to the senior author. The senior author is also thankful for travel grants from Murdoch University and the Saline Futures Conference that allowed the oral presentation of the research from which this paper is derived. We are grateful to the people of Dacope for cooperation during the survey.

ENDNOTES

1. Irrigation water was classified for salinity (EC_w ; $dS\ m^{-1}$) as follows (modified after Rhoades et al. (1992) : 0–0.7 (non-saline), 0.7–2 (slightly saline), 2–5 (moderately saline), 5–10 (highly saline), 10–25 (severely saline), 25–45 (extremely saline) and $>45\ dS\ m^{-1}$ (brine).
2. According to Rhoades et al. (1992), non-saline ($<0.7\ dS\ m^{-1}$) water can be used for drinking and irrigation; slightly saline (0.7 – $2\ dS\ m^{-1}$) water can be used for irrigation.
3. Studies of crops (wheat, sorghum, cowpea and maize) suggest that plants are more sensitive to saline water irrigation at their initial growth stages and are less sensitive at the later stages of growth (Maas et al. 1983; Maas and Poss 1989a,b; Maas et al. 1986).

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