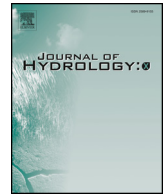




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Influence of landscape features on the large variation of shallow groundwater salinity in southwestern Bangladesh

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ABSTRACT

In southwestern Bangladesh, the large variation in groundwater salinity has only been elucidated in small-scale study areas and along large regional-scale gradients. We aimed to assess the regional shallow (< 60 m) groundwater salinity variation with a higher resolution as a function of landscape features and associated hydrological processes. Spatial variation in groundwater salinity was assessed using 442 EC measurements from previous studies and 1998 new EC measurements. Groundwater EC values were correlated with well location data (latitude, longitude and depth of the filter) and landscape feature data (elevation, soil type, land use and surface clay thickness). Additionally, we performed a geomorphological analysis of landscape features to infer associated hydrological processes. We interpret *wide fluvial zones* to be remnants of sandy deposits in large paleo channels which allow freshwater recharge, resulting in groundwater that is mostly (75%) fresh. *Narrow fluvial zones*, *tidal fluvial zones*, and *fluvial zones next to tidal rivers* are more susceptible to lateral saline water flow or saline water recharge by occasional tidal flooding, and only contain some shallow fresh groundwater in high-lying zones. *Tidal flat* or *tidal fringe* zones hardly contain any fresh groundwater. This study is the first to demonstrate the relation between landscape features, hydrological processes and regional groundwater salinity throughout southwestern Bangladesh. The main lines of our approach may be applicable in other coastal areas with available spatial landscape feature data, enabling a first prediction of groundwater salinity variation.

1. Introduction

Coastal regions and deltas are among the most heavily populated areas in the world and their water resources are experiencing increasing stress (Creel, 2003; Ranjan et al., 2006; Nicholls and Cazenave, 2010). One of the largest and most densely populated deltas is the Ganges–Brahmaputra–Meghna (GBM) delta. Here, manifestations of this stress are arsenic contamination of shallow groundwater resources (Nickson et al., 1998; Harvey et al., 2002), severe pollution of surface water resources (Alam et al., 2006; Bhuiyan et al., 2011), and limited availability of the meteorological water resources, due to pronounced seasonality (Chowdhury, 2010; Sharma et al., 2010). In the coastal southwestern region of Bangladesh, available drinking water is further limited by the salinity of the surface- and groundwater. The groundwater salinity variation in the coastal area is large and, therefore, hard to predict (George, 2013; Worland et al., 2015; Ayers et al., 2016; Rahman et al., 2018; Naus et al., 2019). The stress of saline water intrusion on the groundwater is increasing due to natural changes in the

form of natural land subsidence and sea level rise (Bhuiyan and Dutta, 2012; Fakhruddin and Rahman, 2014), and due to anthropogenic changes in the form of man-induced land subsidence, decreased Ganges outflow (Rahman et al., 2000) and increased groundwater extraction (Chowdhury, 2010). To determine occurrence of current drinking water problems and to mitigate future risk for the drinking water supply in southwestern Bangladesh, a proper understanding of the current groundwater salinity distribution and underlying controlling processes is required. Such general understanding can also aid in understanding groundwater salinity variation in other coastal regions around the world.

Most previous studies in southwestern Bangladesh focussed on understanding the groundwater salinity variation by identifying the controlling hydrological processes in small, local study areas (George, 2013; Worland et al., 2015; Ayers et al., 2016; Sarker et al., 2018; Naus et al., 2019). These studies have found much of the groundwater to be connate groundwater due to the subsurface lithology being characterized by thick covering clay layers and the landscape being flat leading

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to a stagnant hydrological system. The occurrence and thickness of surface clay layers with low infiltration capacity is described to explain how isolated the groundwater is and, therefore, whether the groundwater consists of solely connate water formed under paleo conditions or whether the groundwater salinity has also been influenced by active processes (George, 2013; Worland et al., 2015; Ayers et al., 2016; Sarker et al., 2018; Naus et al., 2019). Previous studies proposed several active processes that vary depending on the present-day landscape features. Freshwater recharge from rain or rain-fed pond water has been described in areas of higher elevation in southwestern Bangladesh (Naus et al., 2019), as well as in other coastal regions (Stuyfzand, 1993; Walraevens et al., 2007; Goes et al., 2009; de Louw et al., 2011; Santos et al., 2012). Salinization in low-lying areas has been attributed to three processes in southwestern Bangladesh: tidally influenced flooding (Naus et al., 2019), recharge by rainwater that has dissolved evaporite salts in the soil (Sarker et al., 2018), and recharge from aquaculture ponds (Paul and Vogl, 2011; Rahman et al., 2018; Naus et al., 2019). At a regional scale, the relevance of these hydrological processes is unexplored and, accordingly, the regional groundwater salinity variation remains poorly understood: Only some rough regional salinity gradients have been delineated, indicating a trend for salinity to increase from north to south (Bangladesh Water Development Board, 2013; Zahid et al., 2018). For assessing and overcoming water supply problems in the region a spatially more detailed understanding of the current groundwater salinity distribution and underlying controlling processes is required. We, therefore, set out to elucidate the regional shallow (< 60 m deep) groundwater salinity variation with a higher resolution and to determine the relevant controlling hydrological processes in a regional-scale study. We aimed to use our findings to construct guidelines for predicting the groundwater salinity throughout the region.

2. Study area

The study region (latitude 22° 12' to 23° 0', longitude 88° 53' to 89° 58') comprises the three southwesternmost districts of Bangladesh: Satkhira, Khulna and Bagerhat. The southern parts of these districts contain the largest tidal mangrove forest in the world, the Sundarbans, which was excluded from the study area. The remaining area is predominantly rural, with the main sources of income being agriculture and aquaculture. The topography, soil type and land use vary throughout the study area (Figs. A.1, A.2, A.3). Most of the area is low-lying with an elevation a few meters above mean sea level (Auerbach et al., 2015), increasing regionally towards the north and east (Fig. A1). At a smaller scale the topography is more varied (Fig. A1), with some high-lying areas up to 2 m higher than the low-lying areas (Naus et al., 2019). The dominant land use types are treed villages, one-season rice, aquaculture and irrigated rice, with treed villages and irrigated rice being located more often towards the north and at higher elevations than aquaculture or one-season rice (Naus et al., 2019; Fig. A2). A soil map is available for the Satkhira and Khulna districts from the Food and Agriculture Organization of the United Nations (FAO) (Food and Agriculture Organization of the United Nations, 1959, Fig. A3), indicating a variety of fluvial, tidal fluvial, tidal flat and tidal fringe soils, with fluvial soils occurring more in the north and in the west, tidal fringe soils occurring more in the east, and tidal flat soils occurring more in the south. The fluvial soils often occur on higher land; the other soil types also sometimes occur on relatively high-lying areas.

The region experiences an annual rainfall of around 2500 mm, with most of this precipitation falling in the monsoon from June to October. The monsoon season is followed by a cool dry winter in October to March, and a hot summer from March to June. The tidal rivers and creeks become saline at the end of the summer, in April and May (Bhuiyan and Dutta, 2012). In general, three aquifer types are recognized in Bangladesh (Mukherjee et al., 2009). In the south of Bangladesh, the Upper Holocene aquifers are found to depths of approximately 60 m. Below are the main, Middle Holocene aquifers, which are

found to approximately 150 m deep; the Late Pleistocene–Early Holocene aquifers extend deeper than 150 m. This study focusses on the groundwater salinity in the Upper Holocene aquifers, i.e. the first 60 m.

3. Methods

3.1. General approach

We used a three-way approach. First, we assessed how groundwater salinity throughout the region correlates with landscape features. Second, we performed a geomorphological analysis of landscape features to infer associated hydrological processes and their effect on groundwater salinity. Third, using landscape features we constructed practical guidelines to predict groundwater salinity throughout the region.

For our approach we required data already available or that could be rapidly collected at the scale of southwestern Bangladesh. We used three types of data: (1) Electrical Conductivity (EC) data from previous studies and collected during this study, to determine groundwater salinity; (2) Location data (x,y,z) of the EC measurements, to analyse how EC varies with depth and throughout the region; and (3) Geomorphological landscape features from various existing large-scale spatial data sources.

3.2. Data collection, data mining and data processing

The EC data was collected by the authors and MSc students from Dhaka University during multiple fieldwork campaigns from January 2014 to September 2018, using a low-cost method that consisted of measuring the EC of shallow groundwater (< 60 m deep) by pumping household tube wells along regional transects and detailed study areas throughout the region. The protocol for measuring EC from the tube wells included the purging of the stagnant water from the tube well by pumping each tube well for at least a minute. We expect the measurements collected over the span of several years to be comparable, as seasonal and inter-annual salinity variation is expected to be low because of the stagnancy of the connate-groundwater-dominated hydrological system (George, 2013; Worland et al., 2015; Ayers et al., 2016; Sarker et al., 2018; Naus et al., 2019). This low-cost method made it possible to collect 1998 new EC groundwater measurements at tube wells. Three handheld field measurement devices were used for the EC measurements: the HANNA HI 9829 (Hanna 127 Instruments, USA), the Hanna HI 98,311 (Hanna 127 Instruments, USA), and the 18.50.SA multimeter (Eijkelkamp, The Netherlands). Additional chemical analysis of the water samples was performed for a subset of sampling locations. For this, 221 groundwater samples were taken along 10 local-scale transects in January 2017 and January 2018. The samples were filtered through a 0.45 µm membrane and stored in 15 ml polyethylene tubes for analysis in the lab for Cl, SO₄ and NO₃ using ion chromatography. Alkalinity was measured within 36 h of sampling by titration (Hach Company, USA).

This data was augmented with data on shallow groundwater (< 60 m) from previously published articles and projects and from a datafile obtained from Vanderbilt University, see Table 1 for details. In total, our database consisted of 2440 EC measurements from the Upper Holocene aquifers (Table 1). The regional database on groundwater analyses was augmented with data from Naus et al. (2019) and Ayers et al. (2016), which provided an additional 136 samples, leading to a total of 357 hydrochemical samples (Table 1). These samples were used to infer the salinity from EC measurements, as explained in Section 3.3. The database of groundwater EC, chloride and alkalinity is available as Supplementary data.

Location data was collected for each EC measurement point during the field campaigns, and consisted of latitude, longitude and depth of the filter. The latitude and longitude of the measured tube wells were obtained by means of GPS, and the depth was estimated from details

Table 1
Groundwater and lithological data sources used in the study.

Data source	EC measurements of the shallow aquifer (< 60 m deep)	Samples with chloride and HCO ₃ data	Lithological data
This study	1998	221	14
Naus et al. (2019)	101	101	20
Ayers et al. (2016)	35	35	13
Data obtained from Vanderbilt University	211	–	–
Bangladesh Water Development Board (BWDB, 2013)	3	–	110
British Geological Survey (BGS) and Department of Public Health Engineering (DPHE) (2001)	–	–	547
Unicef MAR project	92	–	280
<i>Total</i>	<i>2440</i>	<i>357</i>	<i>984</i>

supplied by local residents on the filter depth and the number of pipes and filters used when installing the tube well. When the users sporadically did not remember or were in doubt about the depth of their tubewell, we did not include their tubewell.

For the landscape features, we used the data sources available at the scale of southwestern Bangladesh. These yielded data on elevation, land use, soil type and surface clay thickness. Elevation was estimated using Shuttle Radar Topography Mission data (SRTM) (Farr et al., 2007), taking into account that the exact values are not accurate as they have been affected by vegetation (Auerbach et al., 2015). Land use was based on supervised classification of cloudless Imagery from Landsat 8 (17th and 24th of March 2015, paths 137 and 138, row 44), calibrated with observations from aerial images and field observations. Soil type was derived from the FAO soil map (Food and Agriculture Organization of the United Nations, 1959). Since the soil map is approximately 70 years old, we could expect the dynamic nature of the delta to have led to differences compared to present-day circumstances, certainly on a small scale. However, visual similarities of the soil map (Fig. A3) with the SRTM (Fig. A1) and the land use map (Fig. A2) give confidence in its present-day validity. The thickness of the surface clay layer was based on borehole logs from various previous studies and from 14 newly constructed tube wells, see Table 1 for details. As the variation in surface clay thickness in southwest Bangladesh is large (Ayers et al., 2016; Naus et al., 2019) the interpolated clay thickness is only used for EC measurements less than 100 m from a borehole log. There were 313 such EC measurements.

3.3. Definition of salinity

Most salinity classifications for drinking water are based on chloride concentration in the water (Custodio and Bruggeman, 1987; Stuyfzand, 1993). However, salinity and EC are not only controlled by Cl but also by other anions, particularly SO₄ and NO₃, and by alkalinity. Therefore, we first assessed to what extent chloride controls EC as well as salinity in the study region by comparing the available hydrochemical analyses against the EC values. This revealed a large spread in combinations of chloride concentrations and EC, which particularly affects the interpretation of the salinity in the lower ranges (Fig. 1). At EC values lower than 5 mS/cm, alkalinity is prominent and can lead to an overestimated chloride concentration based on EC. Between 5 and 10 mS/cm, alkalinity is less prominent but may still be relevant when inferring salinity from the EC instead of from the chloride content. This confirms that EC is not always a good estimator for the chloride concentration. The large spread makes it impossible to perform chemical calculations based on the EC, such as calculations of the fractions of seawater. Nevertheless, the R² of 0.84 between EC and chloride gives us confidence to use EC to judge the groundwater salinity.

To differentiate between fresh and brackish groundwater, we used the drinking water guidelines of the Bangladesh government (Ayers et al., 2016), according to which groundwater with an EC of 2 mS/cm or less is potable. This definition is broader than the classification of

Stuyfzand (1993), as it results in some of the measurements interpreted as fresh having a chloride concentration above 300 mg/l. The other salinity classes were constructed based on the Stuyfzand classification (1993) and the approximate correlation between EC and chloride (Fig. 1). Groundwater was classified as brackish if it had an EC of 2–3.5 mS/cm, largely corresponding with a chloride concentration of 300–1000 mg/l. It was classified as brackish–saline if the EC was 3.5–5 mS/cm, corresponding with a chloride concentration 1000–2500 mg/l. It was classified as saline if the EC was > 5 mS/cm, corresponding with a chloride concentration > 2500 mg/l.

3.4. Statistical analysis

Various statistical and geostatistical tests were used to assess regional trends and EC variation with landscape features. Variation of EC with the ordinal location and landscape feature data (latitude, longitude, elevation, depth and surface clay thickness) was statistically analysed using Pearson's statistical test, with a significance threshold set at 0.05. Variation of EC with the nominal data consisting of land use and soil type was assessed using boxplots of the different classes. The distributions of the classes with 30 or more samples were tested for significant differences using Kruskal–Wallis (Kruskal and Wallis, 1952) and Dunn's tests (Dunn, 1964), with the significance threshold value adjusted according to Bonferroni correction (Dunn, 1961) by dividing the original value of 0.05 by the number of simultaneously tested classes. Regional trends in EC were also visually assessed after ordinary Kriging interpolation of the EC data, which has been applied before for soil salinity (Bilgili, 2013; Lobell et al., 2010). After trial and error, we decided to use a spherical variogram model, using the 8 nearest measurements to estimate the EC to prevent inclusion of data from too far away and to prevent oversensitivity to individual measurements.

To ascertain which variable controls the EC independently from possible cross-correlation, the EC data was split into classes according to latitude, longitude, elevation, clay thickness, depth, land use and soil type. The ordinal data was not assigned to these classes on the basis of cut-off points. Instead, expert judgement was used to obtain decently sized classes given the variable spread and number of measurements. The EC data was split into four subregions (northwest, northeast, southwest and southeast), three SRTM elevation classes (low, SRTM < 5 m; moderately high, 5 m ≤ SRTM < 8 m; and high, SRTM ≥ 8 m), two depth classes (shallow, depth < 30 m; deep, depth ≥ 30 m), and two clay thickness classes (thin, < 10 m; thick ≥ 10 m). For the nominal data, the EC data was split into the different land use and soil classes. For each of these classes, the variation between the EC and the ordinal data was statistically analysed using Pearson's statistical test, with a significance threshold set at 0.05. For the soil classes, the patterns of EC with SRTM elevation and filter depth were additionally analysed following local regression (LOESS) which constructs a moving-window correlation using localized subsets of the data (Cleveland, 1979).

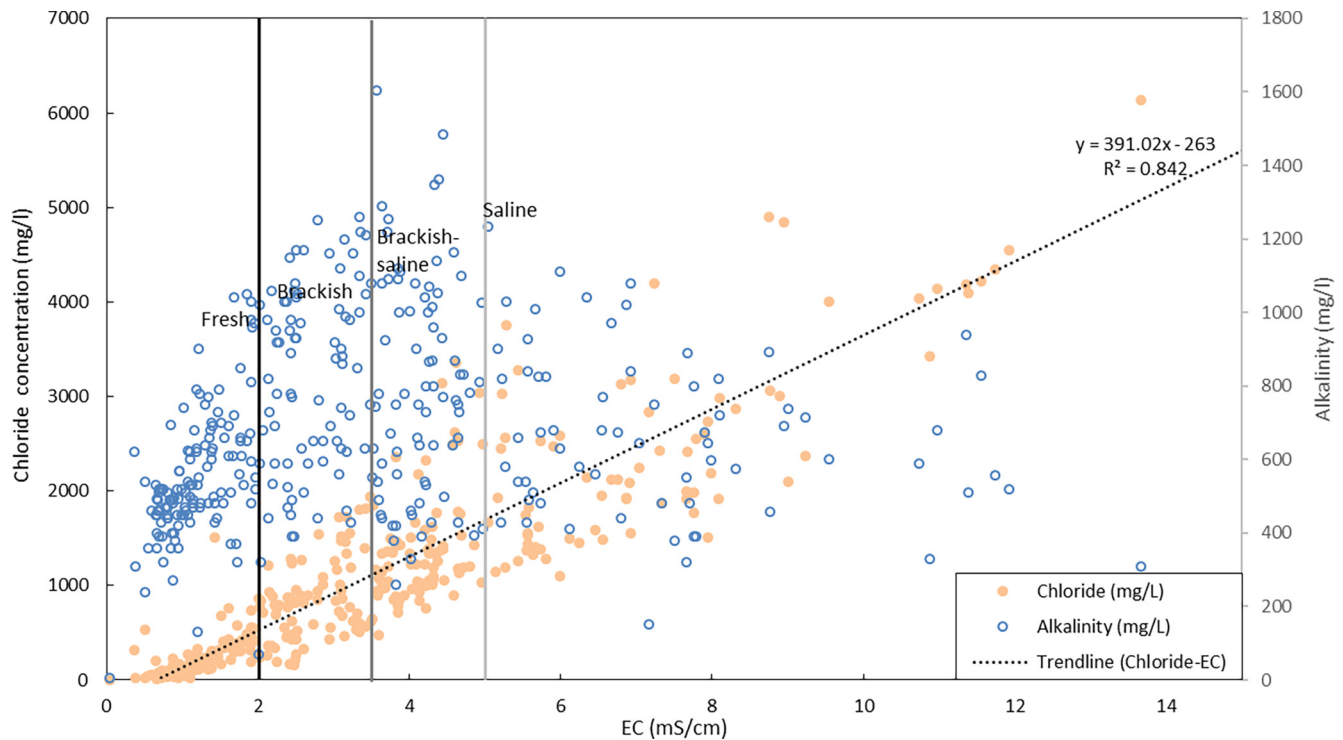


Fig. 1. EC plotted against chloride concentration and alkalinity for the dataset of hydrochemical samples. The vertical lines indicate the boundaries between the four recognized salinity classes.

4. Results

4.1. Regional variation

The Kriging interpolation reveals large-scale regional trends in groundwater EC (Fig. 2). In general, EC values increase from north to south towards the sea, with most groundwater in the north being fresh and most groundwater in the south, close to the Sundarbans, being saline. Between the predominately fresh north and the saline south, the groundwater salinity variation is large. In Satkhira district (west), this variation is visible as alternating areas of saline and fresh groundwater; in the Khulna district (centre), small areas with fresher groundwater were detected between more saline areas, and in the Bagerhat district (east), the groundwater salinity varies the most in the eastern part.

In Khulna district, where the Sundarbans extend furthest north, the area with predominately saline water extends further north than in the Satkhira and Bagerhat districts. The more saline nature of groundwater in Khulna compared to that in Satkhira and Bagerhat is also indicated by the absence of an area with predominately fresh groundwater: saline groundwater was detected up to the northern edge of Khulna district (Fig. 2).

4.2. Landscape feature data and EC

Table 2 shows the significant correlations between EC, latitude, longitude, SRTM elevation, clay thickness and filter depth. The Pearson's correlation coefficients ($|r|$) are not high: they vary between 0.05 and 0.44. EC correlates significantly with latitude, longitude and SRTM elevation, but has no significant correlation with filter depth or clay thickness. The correlations with latitude and longitude affirm the trends visible in the Kriging interpolation: EC increases southwards and eastwards. The negative correlation with SRTM elevation indicates that groundwater is fresher under higher areas than under lower areas.

The EC boxplots of the land use classes (Fig. 3) and the soil classes (Fig. 4) reveal that there are significant differences in the salinity of the groundwater below the different land use and soil classes. For the land

use classes, it should be noted that the sampling method has a bias in the number of measurements per land use class: most samples were taken in the treed villages, but the smallest group still contains 57 samples. Even so, significant differences are visible. Groundwater under irrigated rice is significantly fresher than groundwater under the other land use classes. Additionally, the one-season rice class contains significantly more saline groundwater than the treed villages class. The EC values for the irrigated rice class show rather limited salinity variation, while the salinity variation in the other land use classes is large (Fig. 3).

The EC variance in each soil class is high: for each soil class, the interquartile range is in two or more salinity classes. Six soil classes were excluded from the significance testing because they had < 30 observations. The Kobadak and Kodla fluvial soil classes (a, b) contain significantly fresher groundwater than the other soil classes (Fig. 4), while the tidal fringe flow soil class contains significantly more saline groundwater than the following four soil classes: fluvial Bhairab (c), tidal flat flow (d), tidal flat Amd (e) and tidal fluvial (f). Lastly, groundwater under fluvial Bhairab soils is significantly fresher than under tidal fringe soils.

4.3. Other correlations

Significant correlations are visible between the location and landscape feature data of the measurements (Table 2). Some of these correlations are similar to the trends described above in Section 2. SRTM elevation is relatively high in the north, in the east, and for fluvial soils, treed villages and irrigated rice.

The correlations with depth and clay thickness were not described in Section 2. The clay thickness, SRTM elevation and filter depth are all intercorrelated. Measurements in wells with a deeper filter tend to be from locations with a thicker clay cap ($r = 0.44$) and a lower SRTM elevation ($r = -0.21$), and consequently clay caps are thicker in areas with a lower SRTM elevation (-0.3). There is also a trend for filters to be deeper towards the north ($r = 0.23$); the filter depths for the soil classes fluvial Bhairab, tidal flat flow and tidal flat Amd are significantly deeper than those for the other soil classes, while the filter

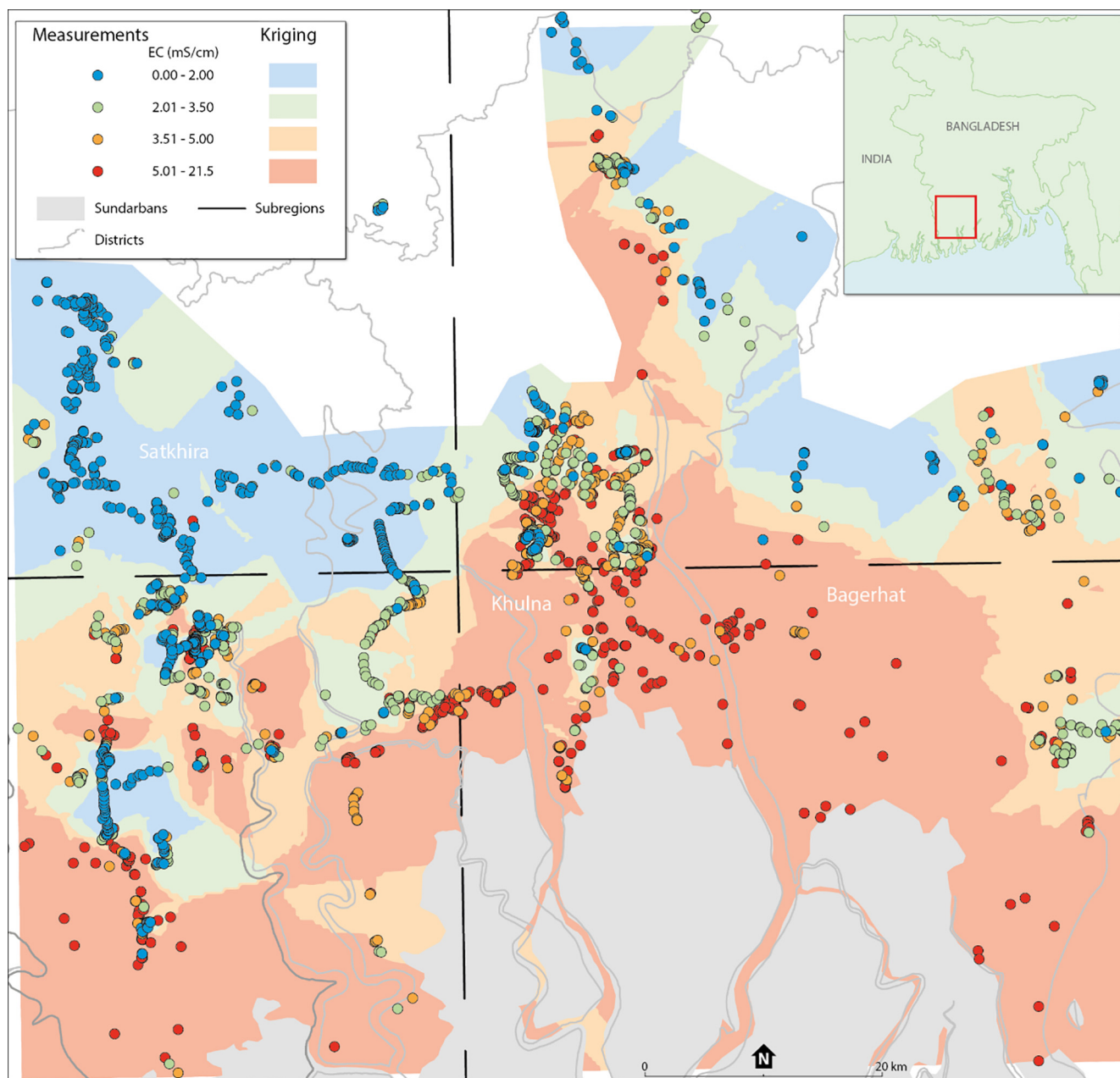


Fig. 2. EC measurements from groundwater wells in the Upper Holocene aquifers (< 60 m depth), indicated with circles, and the associated Kriging interpolation in the background. The lines indicating the subregions separate the region into the classes ‘Northwest’, ‘Northeast’, ‘Southwest’ and ‘Southeast’, as used in Table 3. Note that the Kriging interpolation should be seen as a rough visual assistance for the regional variation in groundwater salinity. For site-specific groundwater salinity assessments, we refer to the guidelines in the discussion.

Table 2

Correlation matrix of the nominal data, $p = 0.05$. Empty cells indicate correlations that are not significant. As a visual aid, we highlighted values between 0.3 and 0.4 purple, values between 0.4 and 0.5 light blue, and values above 0.5 green.

Latitude	-0.28				
Longitude	0.27	0.17			
Depth (m)	-	0.23	-0.05		
SRTM (m)	-0.25	0.17	0.15	-0.21	
Clay thickness (m)	-	-	-	0.44	-0.3
	EC (mS/cm)	Latitude	Longitude	Depth (m)	SRTM (m)

depths are shallowest for irrigated rice and the deepest for aquaculture.

4.4. EC correlations of the split data

The correlations between EC and the ordinal data for each subclass of location or landscape feature data are presented in Table 3. In general, the correlation coefficients are higher within the subclasses of the independent variables than for the entire dataset. The EC correlations in the different subregions differ only slightly. There are differences in correlations with latitude and longitude among the subregions, but they reflect the trends visible in the Kriging map (Fig. 2). There are no large differences in the EC correlations with SRTM elevation. Even in the northwest, where the groundwater under high and low areas is fresh, EC still varies with SRTM. This emphasizes the importance of this parameter on the groundwater EC. EC does, however, correlate

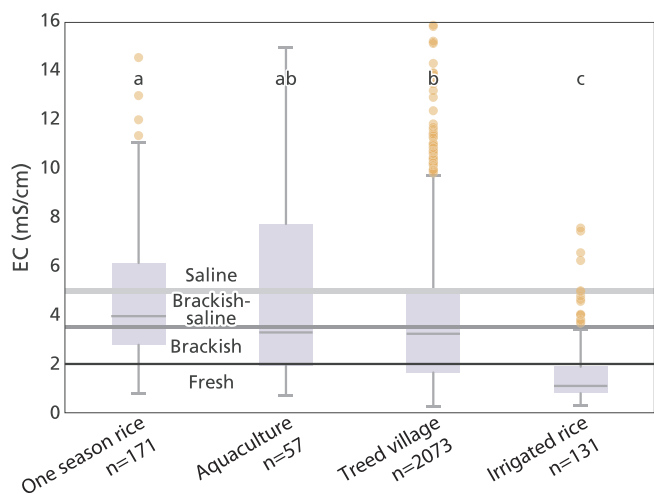


Fig. 3. Boxplots of groundwater EC values for the different land use classes. The horizontal lines indicate the salinity classes and the letters above the boxes indicate whether the medians of the classes are significantly different based on Dunn’s test ($p = 0.008$, following Bonferroni p-correction). Classes with similar letters have non-significant differences.

differently with filter depth between the regions, with the southwest showing a slightly positive correlation ($r = 0.11$) and the northeast showing a slightly negative correlation ($r = -0.11$), while the north-west and southeast show no correlation.

Between the high, moderately high and low-lying areas, there are differences in the correlation of EC with latitude, longitude, SRTM elevation and filter depth (Table 3). In low-lying areas (SRTM elevation < 5 m), EC increases more strongly southwards and with filter depth, indicating that groundwater in low-lying areas in the south is more saline, and that shallow groundwater is more saline than deeper groundwater. Moderately high (SRTM elevation 5–8 m) and high areas (SRTM elevation ≥ 8 m) show a stronger increase in groundwater

salinity towards the east, indicating that at higher elevations groundwater is more saline in the east than in the west. Only moderately high areas have a correlation with SRTM elevation, indicating that the change from fresher to more saline groundwater occurs gradually for the areas at intermediate elevations.

When split according to filter depth and clay thickness, clear differences in correlation are visible. The EC of the shallow groundwater and groundwater under a thin clay layer is controlled more strongly by elevation (Table 2), suggesting that the salinity of shallow or less isolated groundwater salinity is mostly controlled by elevation and not by regional-scale trends. In turn, deeper groundwater or groundwater under a thick clay layer correlates more strongly with latitude and longitude (Table 2), which indicates that the salinity of the more isolated groundwater is more related to regional salinity gradients.

There are differences in EC correlations between the different land use classes, when interpreting these differences, the uneven distribution of measurements across the land use classes must be taken into account. As most measurements are available for the treed village, the EC correlations are similar to those for the full dataset (Table 2). The correlations with EC for the land use classes aquaculture and one-season rice are similar to those for the low-lying areas: EC decreases with filter depth and also southwards, suggesting that saline water recharge from the surface occurs more often in the south and that it mostly affects the shallow groundwater.

Among the soil classes, there are different correlations with EC for latitude, elevation, depth and clay thickness (Table 2). The EC correlates more strongly with latitude in the tidal flat and tidal fringe soils than in the fluvial soils. The weaker correlation with latitude for the fluvial soils indicates that the fluvial Kodla and Kobadak soil classes contain fresh groundwater relatively independently from how far south the soils are located. The explanation for the absence of a regional EC gradient for the fluvial Bhairab soil class is that this soil type is present in only one location in the region, the north of Khulna district (Fig. A.3). Longitude correlates more strongly with EC for the tidal fringe and tidal flat flow soils than for the other soil types.

SRTM elevation is relevant for the groundwater salinity in the three

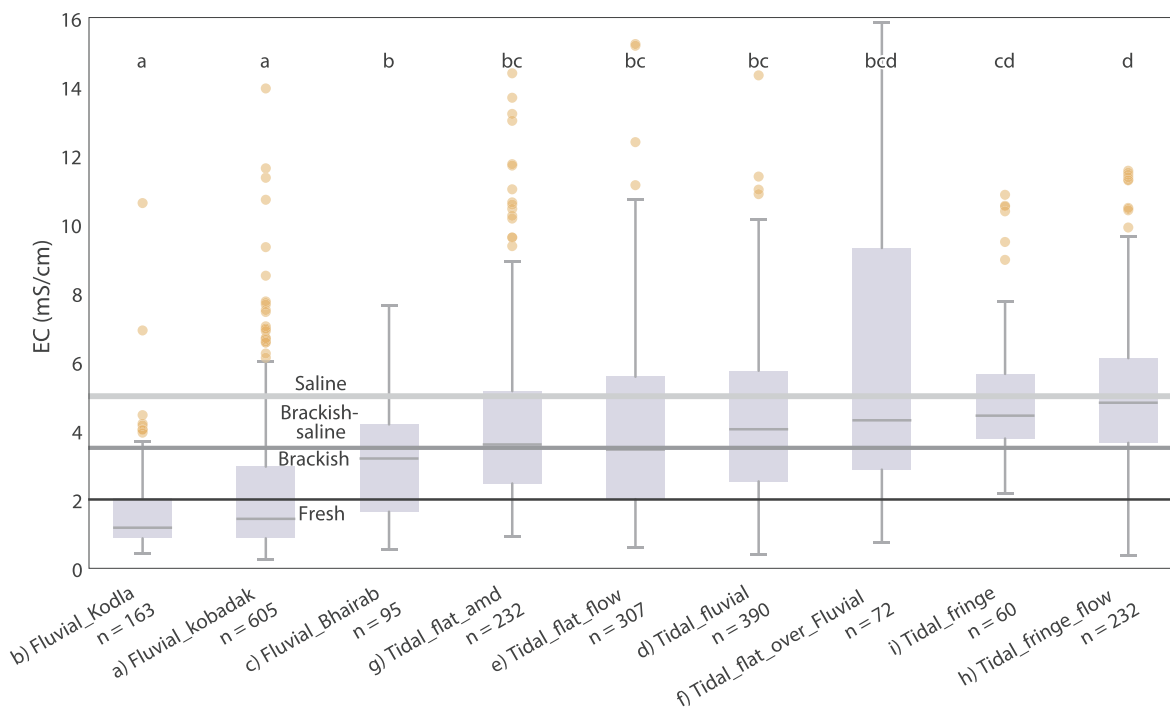


Fig. 4. Boxplots of groundwater EC values for the different soil classes from the FAO soil map (1959), Fig. A.3. The horizontal lines indicate the salinity classes and the letters above the boxes indicate whether the medians of the classes are significantly different based on Dunn’s test ($p = 0.0014$, following Bonferroni p-correction). Classes with similar letters have non-significant differences.

Table 3

Pearson's correlation coefficients (r) for EC vs latitude, EC vs longitude, EC vs SRTM elevation, EC vs filter depth and EC vs clay thickness after the EC database was split in classes according to different parameters. Empty cells indicate correlations that are not significant. As a visual aid, we highlighted values between 0.3 and 0.4 purple, values between 0.4 and 0.5 light blue, and values above 0.5 green. Grey cells have fewer than 30 measurements. The order of the soil classes is given according to the average EC, with the letters in front of the soil classes being determined according to the original legend of the soil map (Fig. A.3 and Fig. 6).

	Median		EC vs		EC vs	EC vs	EC vs clay thickness
	EC	n	lat.	EC vs long.	SRTM	Depth (m)	
All	3.19	2438	-0.28	0.27	-0.25		
Northwest:	1.05	379			-0.28	-0.11	
Northeast:	3.75	856	-0.22	-0.14	-0.24		
Southwest:	2.94	907	-0.32	0.15	-0.31	0.11	
Southeast:	5.56	296		-0.2	-0.25		
Low (<5m)	3.62	532	-0.37	0.19		-0.29	-0.37
Mid (>=5, <8m)	3.58	1233	-0.27	0.35	-0.16		
High (>=8m)	1.9	673	-0.17	0.38			
Shallow (<30m)	3.02	1190	-0.25	0.22	-0.33		
Deep (>=30m)	3.35	1248	-0.34	0.37	-0.18		
Thin (<10m)	2.83	196	-0.32	0.24	-0.4	0.2	
Thick (>=10m)	4.43	117	-0.41	0.3			-0.23
b.) Fluvial Kodla:	1.18	163	-0.26		-0.31	-0.31	-0.54
a.) Fluvial Kobadak:	1.44	605	-0.19	0.17	-0.28	0.13	
c.) Fluvial Bhairab:	3.19	95		-0.21	-0.31	-0.34	
g.) Tidal flat Amd:	3.6	232	-0.49	-0.15		-0.29	
e.) Tidal flat flow:	3.45	307	-0.49	0.46		-0.37	
d.) Tidal fluvial:	4.04	390	-0.3	0.12	-0.16	0.18	
f.) Tidal flat on fluvial:	4.3	72	-0.54		-0.3		
i.) Tidal fringe:	4.44	60	-0.54	0.44			
h.) Tidal fringe flow:	4.81	232	-0.38	0.19	-0.22		
Treed village:	3.24	2073	-0.26	0.25	-0.26		-0.6
Aquaculture:	3.29	57	-0.5	0.36	0.28	-0.54	
One-season rice:	3.96	171	-0.4			-0.23	
Irrigated rice:	1.1	131					

fluvial soil classes and in the tidal flat on fluvial soil class, and to a lesser extent in the tidal fluvial and the tidal fringe flow soil classes (Table 3, Fig. 5a). In the fluvial Kobadak and Kodla soils, the groundwater EC is mostly fresh in areas with a SRTM elevation above 6 m (Fig. 5a), while in the tidal fluvial and fluvial Bhairab classes, measurements start to be mostly fresh at SRTM elevations above 10 m. In the tidal flat on fluvial soil class, a correlation with high salinities is found for the low SRTM elevations (SRTM elevation < 5 m, Fig. 5a). EC does not correlate much with SRTM elevation for the tidal fringe, the tidal flat flow or the tidal flat Amd soil classes, which do not have many measurements at SRTM elevations above 10 m.

For most soil classes, the salinity decreases with depth (Fig. 5b). It decreases until approximately 30 m depth in the soil classes tidal fringe, tidal fringe flow, tidal flat on fluvial and tidal flat Amd, and it continues to drop until a depth of 60 m in the soil classes tidal flat flow, fluvial Kodla and fluvial Bhairab (Table 3, Fig. 5b). Conversely, the salinity of the shallow groundwater is fresher than the salinity of the deeper groundwater in the fluvial Kobadak and tidal fluvial soil classes (Table 3, Fig. 5b).

5. Discussion

The results indicate that the groundwater EC varies regionally with SRTM elevation, and between soil classes and land use classes. However, the correlations are not definite, and do not explain all the variation. Nevertheless, general trends are revealed, which we discuss

below. Subsequently, we present a geomorphological analysis of landscape features and we use the general trends as a basis to infer the associated hydrological processes to shed more light on what controls the groundwater salinity. The landscape features and their affiliated hydrological processes are then used to construct practical guidelines for predicting groundwater salinity throughout the region.

5.1. General trends

The correlation analysis and boxplots show some general trends between the landscape feature data and groundwater salinity. The groundwater under low-lying areas, one-season rice and tidal fringe soils is generally saline. The negative correlation of EC with filter depth in low-lying areas (SRTM elevation < 5 m), in areas with aquaculture, and in areas with one-season rice suggests the higher salinity there is caused by saline water recharge from the surface, as described in previous studies (Sarker et al., 2018; Paul and Vogl, 2011; Rahman et al., 2018; Naus et al., 2019). Additionally, the negative correlation of EC with clay thickness for the low-lying areas also suggests saline water recharge from the surface.

Under high-lying areas (SRTM elevation \geq 8 m), under irrigated rice and under fluvial Kodla and Kobadak soils, groundwater is generally fresh. The high SRTM elevation contributes to recharge by precipitation that results in fresh groundwater, as described in previous studies in Bangladesh and elsewhere (Naus et al., 2019; Stuyfzand, 1993; Walraevens et al., 2007; Goes et al., 2009; de Louw et al., 2011;

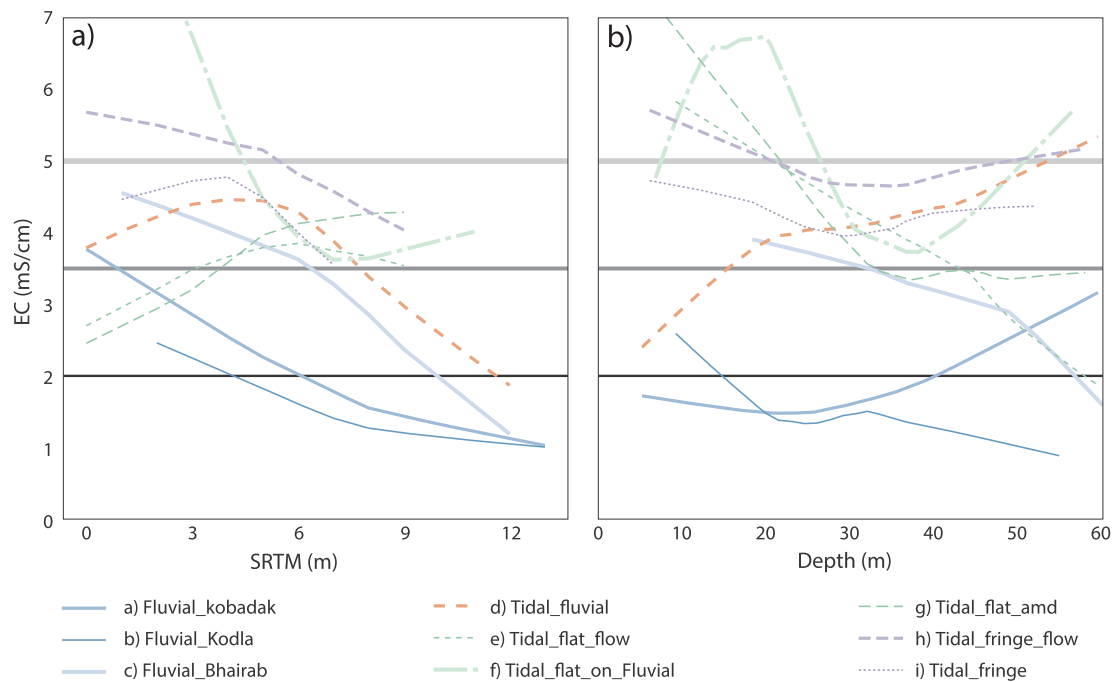


Fig. 5. Local regressions (LOESS) of (a) EC vs SRTM and (b) EC vs depth (m) for the different soil classes. SRTM is specified only for round numbers, so a relatively high smoothing/fraction value of 0.9 was used to create the LOESS, indicating that 90% of the data was used to create each point. For the depth, a smoothing/fraction value of 0.6 was used.

Santos et al., 2012). The Kobadak and Kodla soil classes reveal the occurrence of fresh groundwater most clearly, with the groundwater being significantly fresher than in the other soil classes (Fig. 4). A high SRTM elevation, however, provides less guarantee for fresh groundwater, as there are also many measurements that indicate brackish, brackish–saline or saline groundwater at high SRTM elevations (Fig. 5a). In the next section, we will discuss the relation between groundwater EC and landscape features in more detail.

5.2. Geomorphological analysis of landscape features

We used soil class as a primary indicator for landscape features and the geomorphological analysis as it is a reflection of sedimentology, elevation and operational hydrological processes. We clustered the soil classes in three landscape feature groups: (1) fluvial soils present in prominent large-scale meandering patterns, (2) tidal fluvial soils which surround the fluvial soils or are present in prominent smaller-scale meandering patterns, and (3) tidal flat and tidal fringe soils located in the low-lying flats or as moderately high to high narrow ridges (SRTM elevation 5–10 m) next to channels, creeks or roads.

5.2.1. Fluvial soils

The spatial occurrences of the fluvial Kodla, fluvial Kobadak and fluvial Bhairab soils resemble large-scale fossil meanders oriented from northwest to southeast throughout the region (Fig. A.3, Fig. 6a, b). A detailed hydrogeological study of one of the fluvial Kobadak soils indicated that they consist of the sandy remnants of paleo channel deposits (Naus et al., 2019), with the elevation difference being caused by differences in autocompaction between the sandy sediments of the paleo channel and the clayey sediments of the surrounding paleo flats (Vlam, 1942; van der Sluijs et al., 1965; Naus et al., 2019). The high-lying areas with fluvial soils are expected to have formed similarly throughout the region. Here, the direction of the fluvial fossil meanders corresponds with the direction of meandering rivers during the progradation (Shamsudduha and Uddin, 2007). The large amounts of fresh groundwater found down to approximately 30 m under many of these fluvial soils could result from recharge of groundwater during the long

period that the fossil meanders have been present, enhanced by the presence of very permeable sandy deposits (Vacher, 1988) and the absence of flooding with saline water from tides or tidal surges (Naus et al., 2019). Similar occurrence of fresh water recharge in higher elevated areas have been described in other brackish or saline coastal areas (Stuyfzand, 1993; Walraevens et al., 2007; Goes et al., 2009; de Louw et al., 2011; Santos et al., 2012). It should be noted that the areas with fresh water recharge are also more sensitive to waste water influences, such as from pit latrines in the treed villages, which could pollute and contribute some salinity to the groundwater (McArthur et al., 2012).

Brackish or saline groundwater was also detected under the fluvial soils. Looking at the soil map, it seems that the areas of fluvial soils with brackish to saline groundwater are narrower than the areas of fluvial soils with fresh groundwater (Fig. 6c, d). The narrowness could hamper the formation of fresh groundwater lenses, possibly because they are more susceptible to lateral saline groundwater flow or to saline water recharge from occasional flooding. Additionally, some of the fluvial soils with brackish or saline groundwater are adjacent to tidal channels (Fig. 6c, d), so they might be influenced by flooding or infiltration of saline water from the tidal channel. This could also explain the more saline groundwater in the Bhairab fluvial soil, which occurs next to the tidal Rupsa river (Fig. A.3). Nevertheless, a limited amount of shallow, fresh groundwater was also detected under the narrow strips of fluvial soils.

5.2.2. Tidal fluvial soils

The tidal fluvial soils are in low-lying areas surrounding the fluvial soils, or occur as high-lying narrow fossil meanders (Fig. A.3, Fig. 6e, f). This group sometimes contains shallow fresh groundwater, but only when the soils are at SRTM elevations above approximately 8 m (Fig. 5a). There are several possible explanations for the tidal fluvial soils having a higher salinity than the fluvial soils. Firstly, as the name suggests, these tidal fluvial soils are formed by tidally influenced rivers, which were probably subjected to some marine influence during sediment deposition, similar to the salinity in the present-day tidal rivers (Bhuiyan and Dutta, 2012). Secondly, they are found in similarly

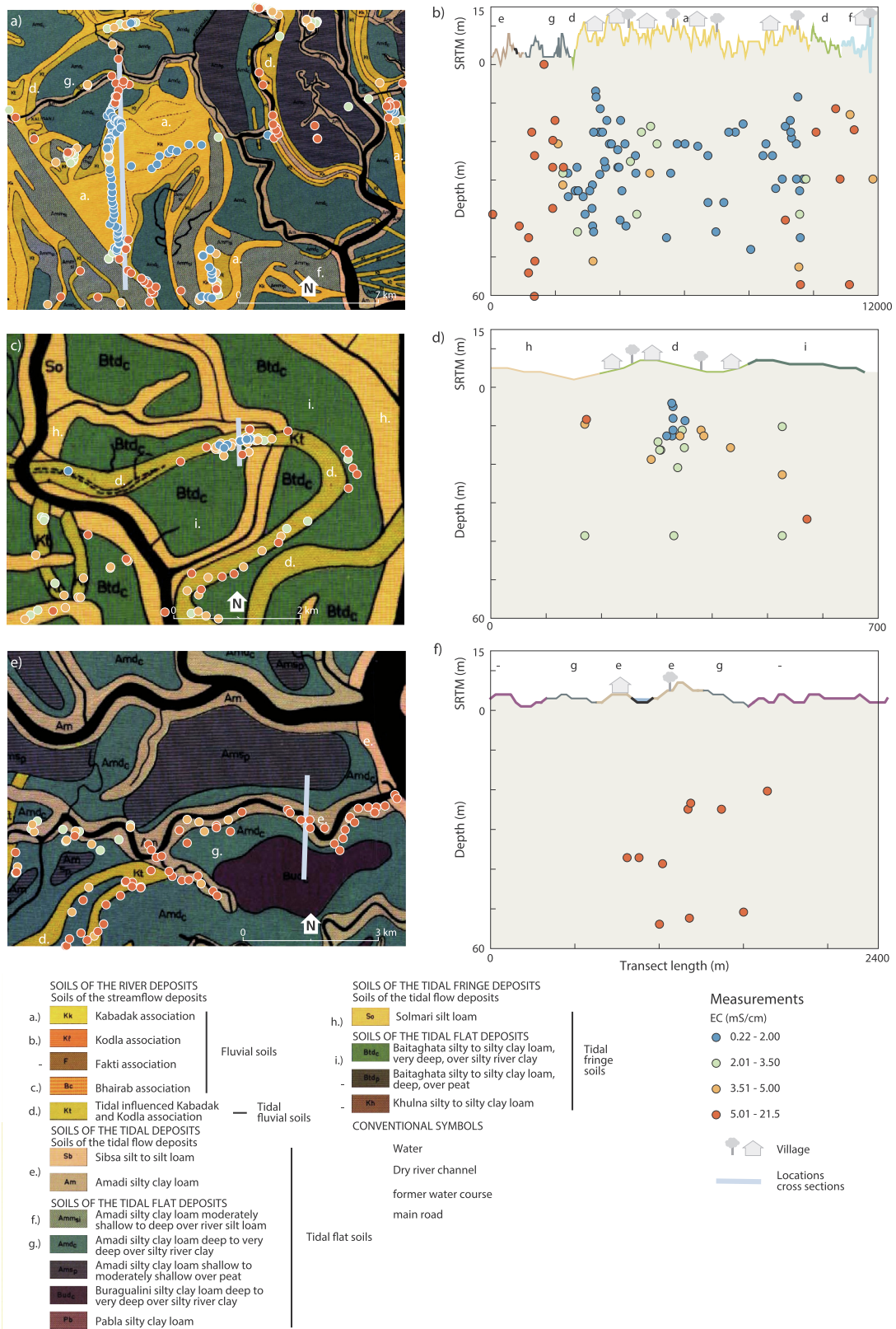


Fig. 6. Examples of soil landscape features (left) with associated cross section (right). The wide fluvial soils are shown in panels (a) and (b), the tidal fluvial soils are shown panels (c) and (d), and the tidal flat and fringe soils are shown in panels (e) and (f). The underlying map at the left is the soil map from the Food and Agriculture Organization of the United Nations (1959), of which the legend is presented below the figure.

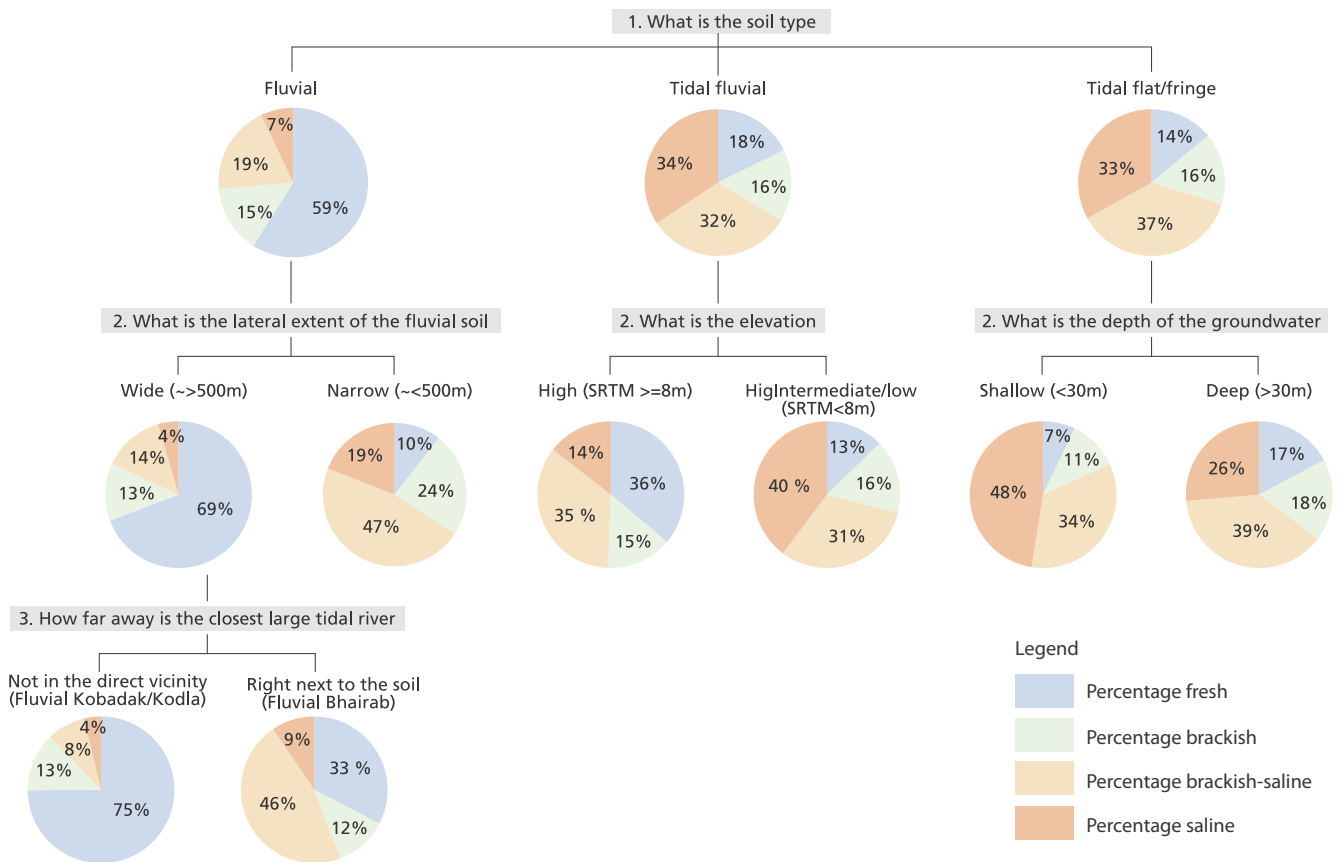


Fig. 7. Flowchart to identify landscape features to predict the groundwater salinity. Starting from the top it shows leading questions and subsequent answers. The pie charts show the percentages of fresh, brackish, brackish-saline, and saline groundwater measurements for each sub step.

narrow strips as the narrow fluvial soils, suggesting more sensitivity to lateral salinization following saline water recharge in the surrounding low-lying areas (Naus et al., 2019; Paul and Vogl, 2011; Rahman et al., 2018; Sarker et al., 2018). Lastly, it is possible that the relatively small tidal fluvial features were deposited more recently than the large-scale paleo channels, so have had less time to be recharged by fresh groundwater. Nevertheless, some fresh groundwater is present in the shallow part of the aquifer under these tidal fluvial soils on high-lying areas. This is likely the result of recharge with fresh water.

5.2.3. Tidal flat and tidal fringe soils

The various tidal flat or fringe soils are usually present as low-lying flats or as very narrow ridges next to contemporary tidal creeks, tidal rivers or roads (Fig. A.3, Fig. 6e, f). For the soil classes tidal fringe and tidal flat (flow and Amd), there is a lack of correlation between EC and SRTM elevation (Table 2). This suggests that the high areas have a similar salinity to the low-lying areas and that freshwater recharge is completely absent in the higher-lying areas of these soils. Both the tidal flat on fluvial soil and tidal fringe flow soil have a negative correlation between EC and SRTM elevation, but the groundwater remains saline in the high areas. The correlation with SRTM elevation, therefore, does not necessarily indicate freshwater recharge in high areas, but instead indicates possible saline water recharge in the low-lying areas (Naus et al., 2019; Paul and Vogl, 2011; Rahman et al., 2018; Sarker et al., 2018). The narrow ridges are expected to be natural tidal creek levees or manmade embankments and roads, both of which would result in the occurrence of mostly clayey material towards the top of the soil profile (Weinman et al., 2008). The local lithology could hamper freshwater recharge in the higher parts of the various tidal flat or fringe soils. Additionally, both the natural levees of the tidal creeks and the embankments have formed relatively recently, which also limits how

much influence freshwater recharge might have had. In the tidal flat or fringe soils, what gives guidance for predicting groundwater salinity is not the SRTM elevation but regional trends (Table 2). The regional gradient of groundwater increasing in salinity eastwards is similar to the direction the coastline has accreted during the Holocene (Shamsudduha and Uddin, 2007) and could also explain why the tidal fringe soils are more saline than the tidal flat soils. The salinity in the tidal flat soils also correlates with the thickness of the clay layer and with depth, which suggests that possible saline water recharge from the surface mostly affects the part of the groundwater that is less isolated, as we will discuss in Section 5.3.

5.3. Deeper connate groundwater not affected by landscape features

The inconclusive correlations and large variation in salinity with landscape feature data is expected to be related to the prominent occurrence of connate groundwater (Worland et al., 2015; Ayers et al., 2016; Naus et al., 2019). There are several indications that relatively deep groundwater is less controlled by landscape features than relatively shallow groundwater. Firstly, the EC of deeper groundwater correlates less with SRTM elevation than the EC of shallow groundwater (Table 3). Secondly, the shallow groundwater is fresher than the deep groundwater under the fluvial Kobadak and tidal fluvial soils, whereas the shallow groundwater is more saline than the deep groundwater under the tidal flat Amd and tidal flat flow soils, under one-season rice and under aquaculture (Table 3). These differences suggest that the deep groundwater could mostly consist of connate water, and that its salinity varies independently from landscape features and is controlled by the hydrological conditions prevailing when the aquifer became sealed off. In Bangladesh, the salinity of the deeper, paleo-controlled groundwater correlates generally more strongly with the regional

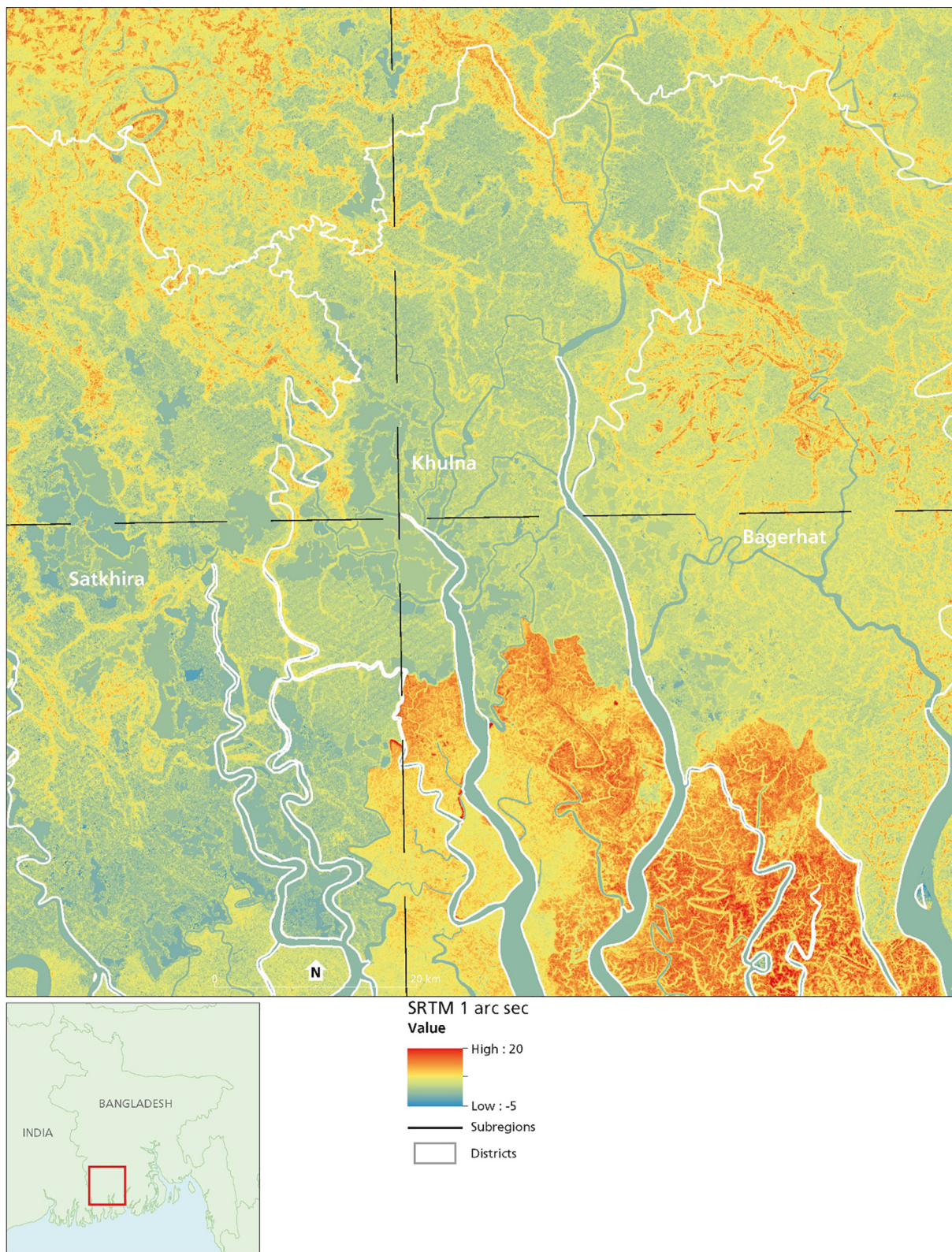


Fig. A.1. Shuttle Radar Topography Mission data (SRTM) in the region (Farr et al., 2007).

north-south and west-east gradients than does the salinity of the shallow groundwater. As stated before, these gradients are linked to the distance to the coastline and with the northwest to southeast direction in which the coastline accreted during the Holocene (Shamsudduha and Uddin, 2007). As a consequence, the deep groundwater in tidal flat flow soils in the northwest is fresh. Additionally, in the southern part of the

Khulna district, there are some fresh groundwater pockets deeper than 30 m which probably formed under slightly fresher conditions than the surrounding more saline groundwater. To understand and predict the occurrence and the salinity of connate groundwater, it is necessary to have detailed lithological data and detailed understanding of the paleo conditions (Naus et al., 2019). The importance of paleo conditions to

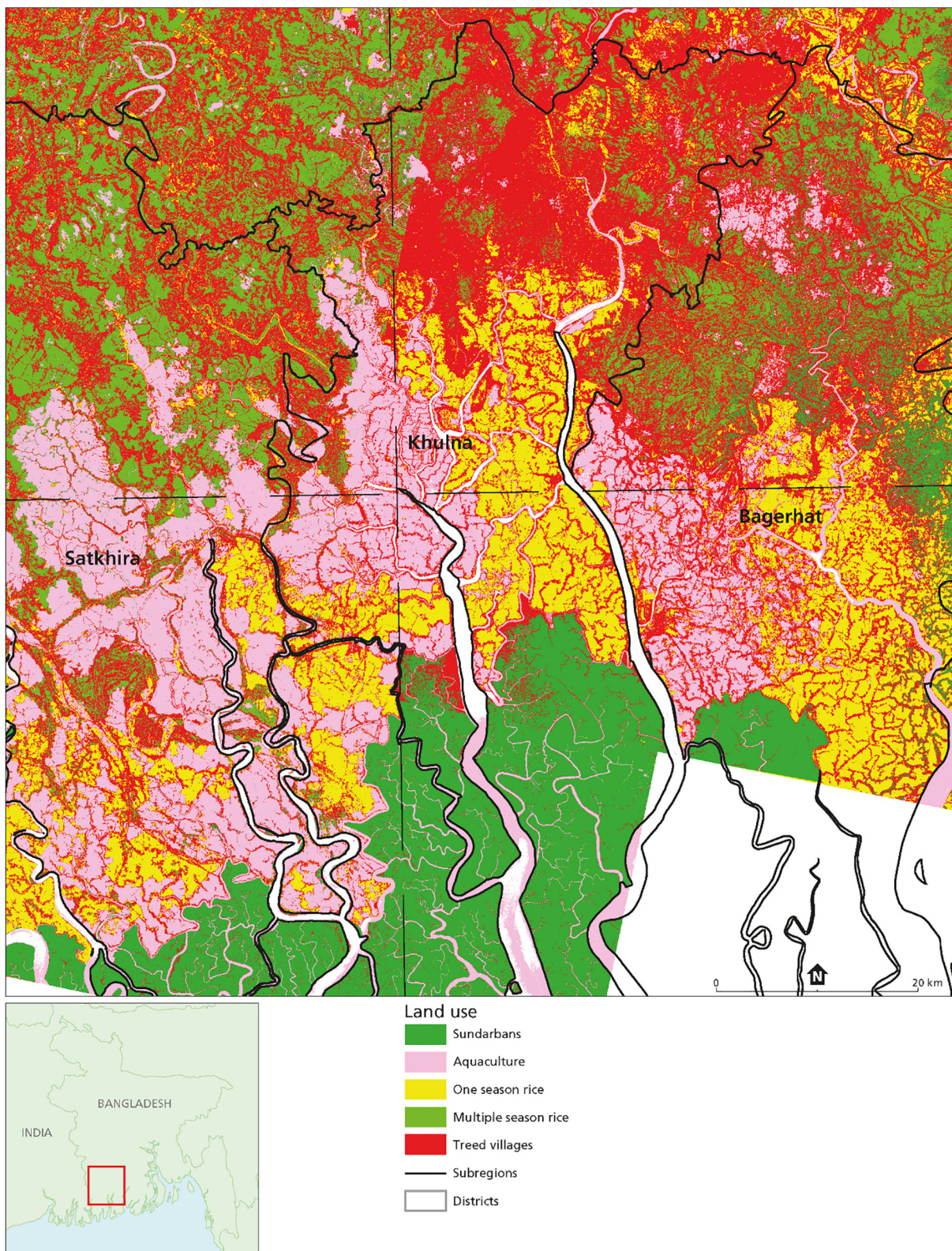


Fig. A.2. Land use in the region based on supervised classification of cloudless Imagery from Landsat 8 (17th and 24th of March 2015, path 137 and 138, row 44), calibrated with observations from aerial pictures and field observations.

understand contemporary groundwater salinity in deeper groundwater has also been reported elsewhere, for example in the Mekong delta (Tran et al., 2012), in Suriname (Groen et al., 2000), and in the Netherlands (Delsman et al., 2014).

5.4. Practical guidelines for predicting groundwater salinity in southwestern Bangladesh

The geomorphological analysis above must be seen as a first step towards presenting possible explanations for the regional groundwater

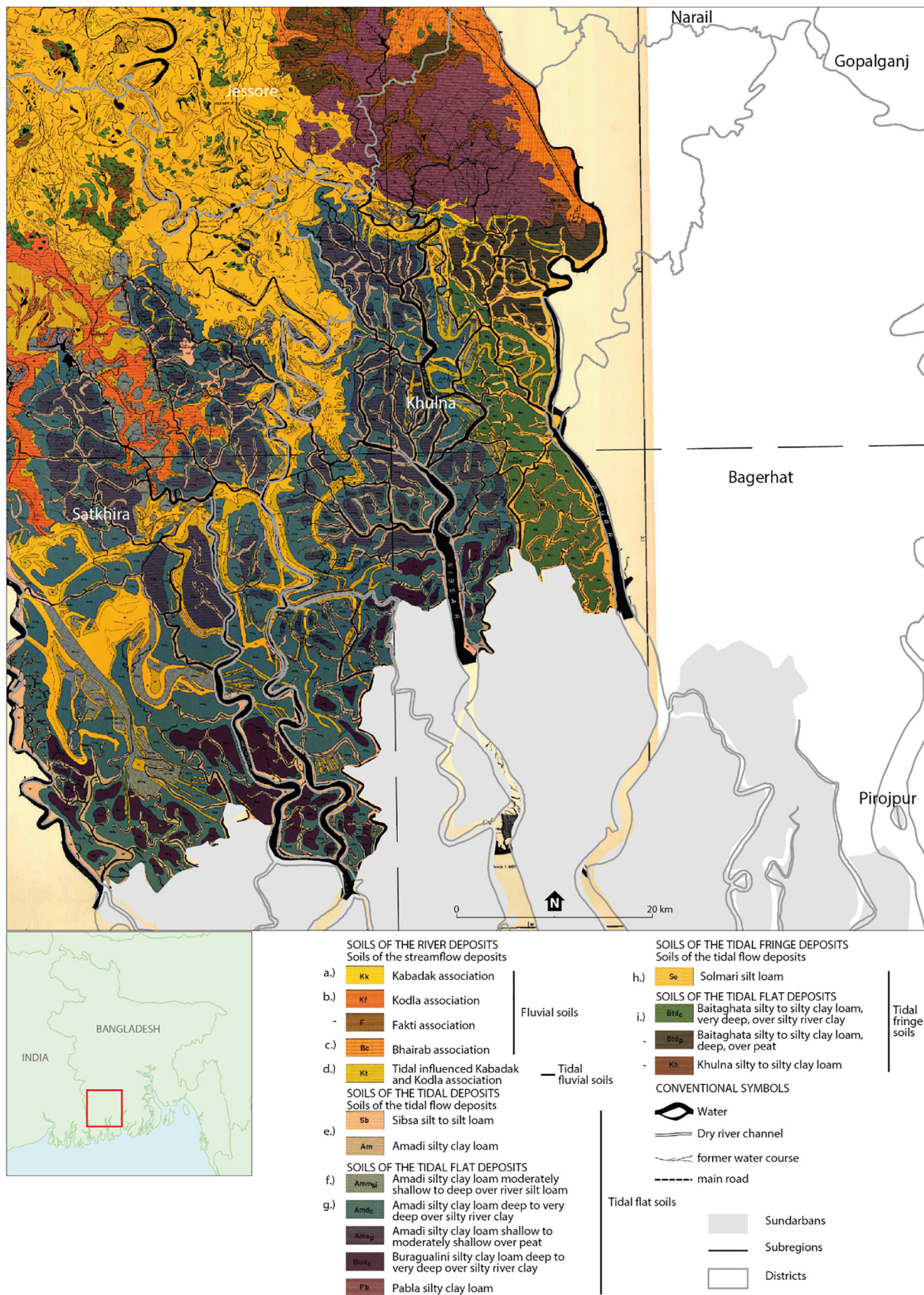


Fig. A.3. Soil map of part of the study area (Food and Agriculture Organization of the United Nations, 1959).

salinity variation in southwestern Bangladesh. Even though there remain, uncertainties related to the paleo and present-day hydrological processes, caused by insufficient knowledge of the lithology, recharge rates and groundwater flow, and the occurrence and scale of tidal and marine intrusions, we feel our analysis of relations between groundwater EC and landscape features and the associated controlling hydrological processes provides valuable information for practical applications related to groundwater exploration and for future geohydrological studies in the study area. Based on the above interpretation of the dominant hydrological processes for various landscape features, we therefore constructed guidelines for the prediction of groundwater salinity throughout the region, in the form of a flow chart (Fig. 7). Soil type, lateral extent of the soil type, elevation, depth below surface and distance to tidal rivers were used as distinguishing factors. The criterion for the width of the areas with fluvial soils was set at approximately 500 m, with the final division being done by expert judgement following visual inspection of the landscape features. The values for SRTM and depth used in the flowchart were estimated based on the patterns revealed by the LOESS results (Fig. 5).

For each distinguished landscape features group, percentages were calculated for the occurrence of the 4 EC salinity classes distinguished. These percentages can be interpreted as the chance of finding each of the salinity classes in a landscape features group. Fig. 7 illustrates that the best chance of finding fresh groundwater is under fluvial soils (59%), especially under wide areas containing fluvial soils (69%) and far away from tidal rivers (75%). In the rest of the landscape features groups, the chances of finding fresh groundwater are lower and depend on local conditions. In tidal fluvial soils, some fresh groundwater occurs in the high-lying parts, and in tidal flat areas, there is a slight chance of finding connate fresh groundwater whose location cannot be determined based on landscape features. The chance of finding saline water is highest under tidal flat or tidal fringe soils in wells < 30 m deep (48%).

The occurrence of the wide fluvial soils could explain some of the regional groundwater salinity patterns. In the Khulna region, hardly any fluvial soils are present, except for the fluvial soils with some limited fresh groundwater that occur next to the Rupsa river. This lack of fluvial soils reflects the anomaly of more saline groundwater towards the north in Khulna district, and suggests that the reason for this increase in salinity is that for most of the Holocene, Khulna district has consistently been a low-lying area. The lack of paleo channels has also been suggested by Hoque et al. (2014), who described the Khulna region as having been part of the paleo interfluvium during the Pleistocene, in contrast to Satkhira and Bagerhat, which were interpreted to be part of the paleo channel areas.

The flow chart uses the fluvial soils with a large lateral extent as a landscape feature factor that indicates high chances for fresh groundwater. The FAO soil map used in this study, however, only covers the western and central parts of the study area (Fig. A.3). The SRTM-elevation map shows areas with a high elevation in the northeastern part of the study area (Fig. A.1), which resemble those of the fluvial fossil meanders with a large lateral extent in the northwest. This suggests similar paleo channel structures in the northeast with high chances for fresh groundwater. Unfortunately, we have too few EC measurements in the northeast to be able to verify this, but our approach illustrates how landscape features in areas without EC measurements can be used to estimate groundwater salinity. The main lines of the approach used here for southwestern Bangladesh may be applied similarly in other coastal areas with available spatial data on elevation, soil types and other landscape feature data, to infer first-order prediction of possible groundwater salinity variation.

6. Conclusions

This study is the first to illustrate the relation between landscape features, hydrological processes and the shallow (< 60 m) groundwater

salinity throughout southwestern Bangladesh. This knowledge is directly relevant for assessing and overcoming water supply problems in the region. Additionally, the main lines of our approach may be applicable to predict groundwater salinity variation in other coastal areas with available spatial landscape feature data.

We conclude that geomorphologically analysed landscape features can be used to determine which controlling hydrological processes can be expected and to make a first prediction of the groundwater salinity. The chance of fresh water recharge and subsequent occurrence of shallow fresh groundwater is highest (75%) in wide occurrences of fluvial soils type Kodabak and Kodla that are not in the vicinity of tidal rivers. These wide occurrences of fluvial soils are interpreted to be remnants of sandy deposits in large paleo channels. High-lying areas with other soil types are interpreted to be more susceptible to lateral saline water flow or saline water recharge by occasional tidal flooding, and consequently have a lower chance of finding fresh groundwater. The chance of saline water recharge and subsequent occurrence of saline water is highest (48%) in wells < 30 m deep under tidal flat or tidal fringe soils.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.hydroa.2019.100043>.

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