Vulnerability assessment of the coastal aquifers in the Cox's Bazar area, Bangladesh using hydrochemical tools and the GALDIT model

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I hereby certify that the complete work described within this thesis is the original work of the author and this Ph.D thesis entitled

“Vulnerability assessment of the coastal aquifer in the Cox’s Bazar area, Bangladesh using hydrochemical tools and the GALDIT model”

Part of this dissertation has been published in the international journal and presented in several conference proceedings. Any published (or unpublished) data, ideas and /or methods from the work of others are fully acknowledged by the standard referencing practices.

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Suraiya Fatema

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Fatema, S., Marandi, A., Schüth, C. (2018) The sensitivity of stable isotopes to assess the seawater intrusion in the coastal area of Bangladesh-a case of Cox's Bazar alluvial aquifer. IAH Conference 9-14 Sep, Daejeon, South Korea.

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ABSTRACT

The Cox's Bazar region at the south-eastern coast of Bangladesh has gradually been changed from a rural settlement into a densely populated urban area, caused by the rapid growth of tourism. Nearly 2 million visitors visit every year for enjoying its unbroken 120 km long sandy beach during the dry season. Water demand is mainly covered by groundwater, and the hotels and resorts are typically operating their own groundwater wells without metering and regulations. Thus, overexploitation and possible seawater intrusion threatens the groundwater resources and its sustainability in the coastal aquifers. In this study, the temporal and spatial variations in groundwater quality concerning hydrochemistry and hydraulic heads in the Cox's Bazar area were evaluated over a period of four years, and an analysis of the effects of the groundwater extractions on the status of the groundwater resources has been conducted. At the same time, the hydrochemical data were also combined with the stable isotopes of $\delta^{18}O$, $\delta^{2}H$ and $\delta^{34}S$ for identification of sources of salinity in the coastal aquifers of Cox's Bazar area. Finally, to assess the vulnerability to seawater intrusion, a qualitative approach of GALDIT model was used to give a visual overview of saltwater intrusion vulnerabilities. Due to the pronounced seasonality of rainfall, the aquifer system was found to be highly dynamic even without human interference, and seawater intrusion into the aquifers from the Bay of Bengal as well as from the Bakkhali river in the north was detected. The groundwater abstraction caused groundwater levels in some touristic centers to be already permanently below sea level, and a trend to a further lowering of hydraulic heads was observed. Such situation coincides with an overall tendency of increasing electrical conductivities in the groundwater. The Cl^-/Br^- mass ratios also showed a clear inclination of seawater mixing in the groundwater as well as surface water. Seawater mixing with groundwater can be explained by the combined effects of overexploitation of groundwater and the tidal influence in the surface water. The isotopic composition of $\delta^{18}O$ and $\delta^{2}H$ in groundwater samples is scattered along the GMWL and LMWL. Although the apparent contribution (f_{sea}) of seawater in the groundwater samples varies from 1 to 25% and in the surface water 4 to 99% depending on distance and season, it is difficult to identify one reason for the scattered isotopic composition found in shallow wells (depth <50 m), intermediate wells (depth 50-150 m) and deep wells (depth >150 m). This scatter could be due to seawater mixing, evaporation or scatterings of rainwater isotopic composition. In such a case, $\delta^{34}S$ isotopes turned out to be a useful tool to identify seawater encroachment in the coastal aquifers of Cox's Bazar. $\delta^{34}S$ in sulphate in groundwater samples located close to the Bay have a similar $\delta^{34}S$ isotopic composition as modern sea water. The negative linear correlation of $\delta^{34}S$ with SO_4^{2-}/Cl^- mass ratios also confirmed the source of salinity from seawater.

Similarly, the results of the vulnerability index modeling depict that the area close to the Bay of Bengal and Bakkhali river is more vulnerable to seawater intrusion than the south-eastern part of the study area. The results of this research also revealed that 9% and 78% of shallow wells are highly and moderately vulnerable to seawater intrusion, respectively, and 13% are potentially at low risk under the present condition. At the same time, considering sea level rise of 0.5 m would result in a substantial increase of the highly and moderately vulnerable areas in this coastal aquifer. In this case, 22% of the shallow wells (<50 m) are highly susceptible to seawater encroachment upon sea level rise. The consistency of the hydrochemical and isotope data with the vulnerability zoning map indicates that for a sound and sustainable development of the Cox's Bazar region, water management strategies and a regulatory framework for water abstraction and its central distribution must be developed. These findings also suggest that a combined approach using hydrochemical, isotopic, and qualitative indicators like the GALDIT index could be an essential tool for sound decisions in water resources management in coastal aquifers.

ZUSAMMENFASSUNG

Die Cox-Bazar-Region an der Südostküste von Bangladesch hat sich allmählich von einer ländlichen Region in ein dicht besiedeltes Ballungsgebiet verwandelt, welches durch das rasante Wachstum des Tourismus verursacht wurde. Fast zwei Millionen Touristen besuchen jedes Jahr den 120 km langen Sandstrand, vorwiegend in der Trockenzeit. Der Wasserbedarf wird hauptsächlich durch das Grundwasser gedeckt, und die Hotels und Resorts betreiben in der Regel ihre eigenen Grundwasserbrunnen ohne das Entnahmemengen aufgezeichnet werden oder behördliche Vorschriften bestehen. Übernutzung gefährdet somit die Grundwasserressourcen in den Küstenaquiferen und es besteht die Gefahr des Eindringens von Meerwasser. In dieser Studie wurden die zeitlichen und räumlichen Schwankungen der Grundwasserqualität in Bezug auf die Hydrochemie sowie die hydraulischen Verhältnisse im Cox-Bazar-Gebiet über einen Zeitraum von vier Jahren untersucht. Dazu wurden die hydrochemischen Daten auch mit Messungen von stabilen Isotopen ($\delta^{18}O$, $\delta^{2}H$ und $\delta^{34}S$) kombiniert, um die Ursachen der Versalzung der Küstenaquifere im Cox-Bazar-Gebiet zu identifizieren. Um die Anfälligkeit der Küstenregion für das Eindringen von Meerwasser zu beurteilen, wurde schließlich ein qualitativer Ansatz mit Hilfe des GALDIT-Modells verwendet. Aufgrund der ausgeprägten Saisonalität der Niederschläge erwies sich das Aquifersystem auch ohne Eingriffe des Menschen als sehr dynamisch, und das Eindringen von Meerwasser in die Aquifere aus dem Golf von Bengalen sowie vom Bakkhali-Fluss im Norden wurde festgestellt. Die Grundwasserentnahme führte dazu, dass der Grundwasserpegel in einigen touristischen Zentren bereits dauerhaft unter dem Meeresspiegel lag, und es wurde ein Trend zu einer weiteren Absenkung der hydraulischen Höhen beobachtet. Diese Situation fällt mit der allgemeinen Tendenz zusammen, dass die elektrischen Leitfähigkeiten im Grundwasser über die Zeit ansteigen. Auch die Cl^-/Br^- Massenverhältnisse zeigten eine deutliche Meerwasserkomponente im Grundwasser sowie im Oberflächenwasser. Das Eindringen des Meerwassers in die Grundwasserleiter kann durch den kombinierten Effekt der Übernutzung des Grundwassers sowie durch den Gezeiteneinflusses im Oberflächenwasser erklärt werden. Die Isotopendaten ($\delta^{18}O$ und $\delta^{2}H$) der Grundwasserproben streuen entlang der GMWL und der LMWL. Obwohl der scheinbare Anteil (f_{sea}) des Meerwassers in den Grundwasserproben je nach Entfernung von der Küste und Jahreszeit zwischen 1 und 25%, und im Oberflächenwasser zwischen 4 und 99% variiert, kann dies nicht mit Hilfe der Isotopendaten in den Grundwasserproben aus unterschiedlichen Tiefen (Tiefen <50 m; Tiefen 50-150 m; Tiefen > 150 m), nachvollzogen werden. Das könnte auf Mischungseffekte, Evaporation, oder die allgemeine Streuung der Isotopenzusammensetzung des Regenwassers zurückzuführen sein. In diesem Fall erwiesen sich $\delta^{34}S$-Isotope als nützliches Instrument um das Eindringen von Meerwasser in die Küstenwasserleiter von Cox's Bazar zu belegen. $\delta^{34}S$-Werte in Sulfat in nahe der Bucht gelegenen Grundwasserproben weisen eine ähnliche $\delta^{34}S$-Isotopenzusammensetzung auf wie das Meerwasser.

Auch die negative lineare Korrelation von $\delta^{34}S$ mit SO_4^{2-}/Cl-Massenverhältnissen bestätigen den Meerwassereinfluss in den Proben. In ähnlicher Weise zeigen die Ergebnisse des GALDIT Modells, dass das Gebiet in der Nähe des Golfs von Bengalen und des Bakkhali-Flusses anfälliger für das Eindringen von Meerwasser sind als der südöstliche Teil des Untersuchungsgebiets. Die Ergebnisse zeigten auch, dass 9% bzw. 78% der flachen Brunnen stark oder mäßig anfällig für das Eindringen von Meerwasser sind und 13% unter den gegenwärtigen Bedingungen möglicherweise ein geringes Risiko aufweisen. Gleichzeitig würde ein Anstieg des Meeresspiegels um 0,5 m, dass dies zu einem erheblichen Anstieg der stark und mäßig gefährdeten Gebiete in diesem Küstengrundwasserleiter führt. In diesem Fall sind 22% der flachen Brunnen (<50 m) bei einem Anstieg des Meeresspiegels stark anfällig für das Eindringen von Meerwasser. Die Konsistenz der hydrochemischen Daten und der Isotopendaten mit der Vulnerabilitätskarte zeigt, dass für eine solide und nachhaltige Entwicklung der Cox‘s Bazar Region Wassermanagementstrategien und ein regulatorischer Rahmen für die Wasserentnahme und ihre zentrale Verteilung entwickelt werden müssen. Diese Ergebnisse deuten auch darauf hin, dass ein kombinierter Ansatz, der hydrochemische, isotopische und qualitative Indikatoren wie den GALDIT-Index verwendet, ein wesentliches Instrument für fundierte Entscheidungen im Wasserressourcen-Management in Küstenaquiferen sein kann.

TABLE OF CONTENTS

DECLARATION OF AUTHORSHIP i

ACKNOWLEDGEMENT ii

SHORT CURRICULUM VITAE iii

ABSTRACT iv

ZUSAMMENFASSUNG vi

TABLE OF CONTENTS viii

LIST OF FIGURES x

LIST OF TABLES xii

ABBREVIATION xiii

1. Introduction 1

1.1. Motivation 1

1.2. Study concept and thesis outline 2

2. General background of the study 3

2.1. Seawater-groundwater interaction – hydrodynamic aspects 4

2.2. Seawater-groundwater interaction – hydrochemical aspects 5

2.3. Seawater-groundwater interaction – methods for identification 7

2.3.1. Electrical conductivity 7

2.3.2. Sodium/Chloride ratios 7

2.3.3. Chloride/Bromide ratios 8

2.3.4. Stable water isotopes 9

2.3.5. Sulphate isotopes 11

2.4. Seawater-groundwater interaction – definition of risk areas 12

3. Description of the study area 13

3.1. Climate 14

3.2. Current land use pattern 15

3.3. Geology 16

3.4. Hydrogeological condition and overview of water resources 19

3.4.1. Groundwater 19

3.4.2. Status of groundwater exploitation and use 20

3.4.3. Surface water 21

3.4.4. Current state of water resources management and protection 22

4. Materials and methods 23

4.1. Groundwater level monitoring and equipment 23

4.2. Survey to identify the hotel location and water balance calculation 24

4.3. Water sampling and analysis 24

4.3.1. Sampling for the hydrochemical analysis 24

4.3.2. Sampling for the stable isotopes (δ^2H, $\delta^{18}O$ and $\delta^{34}S$) 26

4.3.2.1. Laboratory sample treatment and analysis (δ^2H, $\delta^{18}O$) 26

4.3.2.2. Analysis of sulphur isotope ($\delta^{34}S$ and $\delta\ ^{18}O$) 27
4.4. GALDIT approach for seawater vulnerability assessment of the coastal aquifer 27

5. Results and discussion 30
5.1. Groundwater dynamics over the study period 30
5.2. Estimation of water consumption and water balance 31
5.3. Hydrochemical characteristic of coastal water resources 33
5.4. Assessment of groundwater recharge and seawater intrusion using stable isotopes 38
5.4.1. Isotopic composition of $\delta^{18}O$, $\delta^{2}H$ of the surface water and groundwater and it's sensitivity for freshwater and seawater interaction 38
5.4.2. Sulphur isotopes to identify seawater intrusion 43
5.5. Assessment of seawater intrusion potential in coastal aquifers using GALDIT vulnerability index 45
5.5.1. GALDIT groundwater vulnerability mapping 45
5.5.2. Risk and scenario assessment of seawater intrusion in the Cox's Bazar coastal aquifer 49
5.5.2.1. Scenario 1: Seawater hazard based on the pumping wells distribution 49
5.5.2.2. Scenario 2: Computation of vulnerability index in the context of sea level rise 50

6. Conclusion and outlook 52
6.1. General conclusion 52
6.2. Outlook 54

References 56

Appendix 64

LIST OF FIGURES

Fig. 1: Schematic diagram of the study outline....................3

Fig. 2 : Conceptual figure of the freshwater-seawater interface in a coastal aquifer (not to scale) (Barlow 2003)....................4

Fig. 3: Conceptual figure of seawater intrusion into a coastal aquifer and upconing due to pumping (not to scale) (USGS 1999). 5

Fig. 4: Linear relation between EC and seawater fraction in a freshwater sample 7

Fig. 5: Na^+/Cl^- molar ratios in relationship to Cl^- concentrations, indicating different processes (modified after Jacks and Rajagopalan 1996) 8

Fig. 6: Change of Chlorine/Bromine mass ratios during mixing of seawater and freshwater....................9

Fig. 7: a) The generalized relationship between δ^2H and $\delta^{18}O$ values measured in precipitation worldwide and processes affecting its isotopic composition (Oerter et al. 2017); b) Evolution of the stable isotopic composition of water for different water salinization processes (Yurtsever 1996)....................10

Fig. 8: General map of the area of interest in Cox's Bazar, Bangladesh 13

Fig. 9: Projection of population growth in the next 40 years in Cox's Bazar city area, Bangladesh (based on BBS 2013 report). 14

Fig. 10: Monthly mean precipitation (bars), mean maximum temperature (dotted line) and mean maximum relative humidity (solid line) (1980 to 2011) in the Cox's Bazar area....................14

Fig. 11: Land use pattern in and around Cox's Bazar town, Bangladesh. 15

Fig. 12: Tectonic elements of Bangladesh (BGS and DPHE 2001)....................16

Fig. 13: Surface geology and their possible sequence in the Cox's Bazar city and surround....................17

Fig. 14: Geological units of the study area (based on GSB unpublished data)....................18

Fig. 15: Major lithological distribution of selected boreholes in the study area. Lithological information was collected from BWDB and DPHE (Fatema et al. 2018)....................19

Fig. 16: Current situation of water use and conceptual aquifer system of the Cox's Bazar area, Bangladesh (not to scale). 20

Fig. 17: Maximum and minimum tidal height in the Bakkhali river near Cox's Bazar from 2014 to 2016 (Data source: BIWTA). 21

Fig. 18: Location of the study area showing groundwater and surface water sampling locations. In the magnified area the main touristic centers are located (Fatema et al. 2018). 25

Fig. 19: Rainfall and groundwater level fluctuations in selected piezometers from 2012 to 2016. Data from the year 2012 and 2013 were collected by the Bangladesh Water Development Board (Fatema et al. 2018)....31

Fig. 20: Cl^-/Br^- against Cl^- concentration of the dry period of 2015 indicating mixing between seawater and groundwater as well as anthropogenic contamination (Fatema et al. 2018)....33

Fig. 21: Variation of electrical conductivity of surface water samples between the wet and dry period in the investigated area (Fatema et al. 2018)....34

Fig. 22: Piper diagram including all samples collected. a) shallow wells (<50m), intermediate wells (50-150m)and surface water samples, b) deep wells (>150m) samples, and. The symbol size in the diamond (note the different scale for 'a' and 'b') represents the TDS value excluding the extreme values of seawater and surface water (Fatema et al. 2018). 36

Fig. 23: Change in Na^+/Cl^- molar ratios and Cl^- concentration of water samples from the end of the wet period in 2014 to the end of the dry period in 2016. The tail of the data points represents wet period samples whereas the head depicts dry period samples (Fatema et al. 2018). 37

Fig. 24: Distribution of $\delta^{18}O$ and $\delta^{2}H$ isotopes in surface water between 2014 to 2016, GMWL (Craig 1961) and PWLSR from GNIP station of Cox's Bazar. Symbol size indicates precipitation values. 40

Fig. 25: Distribution of electrical conductivity between the wet and the dry period of 2014-2015. 41

Fig. 26: Cross plot of the $\delta^{2}H$ and $\delta^{18}O$ of all groundwater samples from 2014 to 2016, GMWL (Craig 1961) and PWLRS from GNIP station of Cox's Bazar. Symbol size indicates precipitation values. 42

Fig. 27: Isotopic composition of selected groundwater samples in compare with EC contribution. The symbol size indicates the EC of the samples....43

Fig. 28: Cross plot of $\delta^{34}S$ and $\delta^{18}O$ of selected water samples. On the right, the relationship between the $\delta^{34}S$ and the distance from the coast of Cox's Bazar. The symbol size represents the mass ratio of SO_4^{2-}/Cl^-....44

Fig. 29: Parameters of GALDIT method for the Cox's Bazar coastal aquifers. 46

Fig. 30: GALDIT vulnerability map of the Cox's Bazar coastal aquifer. Zone I, II and III represent the locality, hotel development and less exploitation of groundwater zones respectively**.** 48

Fig. 31: Distribution of the pumping wells in the study area....50

Fig. 32: Computed GALDIT vulnerability Index (GVI) of the Cox's Bazar coastal aquifer for the scenario of sea level rises 0.5 m....51

LIST OF TABLES

Tab. 1: Concentration of major chemical constituents in seawater (Hem 1985) 5

Tab. 2: Calibration data of standards for $\delta^{18}O$ and $\delta^{2}H$ isotopes 27

Tab. 3: Summary of the data and the methods used to compute the GALDIT vulnerability index and scenario assessment for the Cox's Bazar coastal aquifer 29

Tab. 4: GALDIT parameters used in the study and their ranks based on the range (Chachadi et al. 2001 with modification)...29

Tab. 5: Index of vulnerability to seawater intrusion 30

Tab. 6: Statistical distribution of fundamental physical and chemical parameters of collected groundwater samples over the time of 2014-2016 (Fatema et al. 2018) 38

Tab. 7: Seasonal range of $\delta^{18}O$ (‰) and $\delta^{2}H$ (‰) of the water samples...39

ABBREVIATION

a	Year
a.s.l	Above sea level
ASR	Aquifer storage and recovery
BEX	Base exchange index
BBS	Bangladesh bureau of statistics
BGS	British geological survey
BIWTA	Bangladesh inland water transport authority
DPHE	Department of public health engineering of Bangladesh
EC	Electrical conductivity
f_{sea}	Seawater fraction
GMWL	Global meteoric water level
GNIP	Global network for isotopes in precipitation
GSB	Geological survey of Bangladesh
GVI	Groundwater vulnerability index
ha	Hector
IAEA	International atomic energy agency
IBR	Indo-burman ranges
IPCC	Intergovernmental panel on climate change
LGEL	Local government engineering department
LMWL	Local meteoric water level
MAR	Managed aquifer recharge
MSL	Mean sea level
PWLSR	Precipitation weighted least squares regression
SLR	Sea level rise
TCFB	Tripura-chittagong folded belt
TDS	Total dissolved solids
VCDT	Vienna canyon diablo troilite
VSMOW	Vienna standard mean ocean water
WTF	Water table fluctuation

1. Introduction

The introduction of this research work includes the motivation of the study and later the specific tasks to achieve the overall aim which is to elaborate a database to better manage the limited coastal groundwater resources in Cox's Bazar, Bangladesh.

1.1. Motivation

Coastal zones, representing the land-sea interface, are highly dynamic and are extensively used for various activities. Typically, coastal zones are (i) densely populated with large urban centers, (ii) attract industrial enterprises as they offer access points to global marine trade, and (iii) are intensely used for agriculture, especially in the coastal plains. On the other hand, the low elevation of large parts of the coastal zones makes them vulnerable to, i.e. climate change that is predicted to result in a cumulation of extreme climatic events, and global sea level rise (Michael 2013; Werner et al. 2013). The results of sea level rise undoubtedly affect the position of the freshwater/saltwater interface in many coastal aquifers. Moreover, the water demand of the dense population and the agricultural activities frequently lead to overexploitation of the local groundwater resources with resulting seawater intrusion into coastal aquifers (Van Camp et al. 2014; Naderi et al. 2013; Kallioras et al. 2013; Ferguson and Gleeson 2012; Dogan and Fares 2008; Oude Essink 2001).

Coastal zones also represent an attractive environment for touristic activities, and tourism is a major economic factor in many coastal countries. This is especially important for developing countries, where tourism provides jobs and diversification of the economy (Gössling 2001). However, the water demand of touristic resorts and centers, and the dense infrastructure leading to decreased natural groundwater recharge put additional stress on the water resources. The environmental and ecological consequences of these factors are not always considered sufficiently (Oude Essink 2001; Mas-Pla et al. 2014).

Cox's Bazar at the south-eastern coast of Bangladesh is an example of such touristic development, mainly for its unbroken 120 km long sandy beach. In recent years, the rural setting of Cox's Bazar has gradually been changed into a densely populated urban region with unplanned developments caused by the rapid growth of tourism. Due to the subtropical monsoon climate in the Cox's Bazar area with the main precipitation falling from the month of May to month of October, the tourist season is mainly limited to the dry season from the month of November to the month of March. Furthermore, public holidays and the long weekends can also increase the additional demand for groundwater (Houben et al. 2014) apart from peak season of tourism. This scenario indicates the typical mismatch between the increased water demand in the touristic peak time and the availability of potentially large water volumes during the off-season.

Water demand in the region is therefore covered mainly by groundwater, and hotels and resorts are typically operating their own groundwater wells without metering and regulations. Moreover, unrestricted and unregulated groundwater extraction can lead to changes in the coastal aquifer systems and enhance the risk of seawater encroachment (Kallioras et al. 2013; Post 2005). The mismatch between water demand and availability, in combination with the extensive use of groundwater as well as the flat and low topography of the Cox's Bazar area, potentially leads to overexploitation of the coastal aquifers that might result in seawater intrusion (Yu et al. 2016; Rabbani et al. 2010; Yu et al. 2010).

Moreover, sea level rise is also reducing the gradient between the hydraulic head of the groundwater and the sea level. For Bangladesh as a whole, the vulnerability to sea level rise is highlighted in several studies (CCC 2016; Minar et al. 2013; Bhuiyan and Dutta 2011; Yu et al. 2010) and seawater intrusion has been recognized as of relevance for the coastal areas of Bangladesh (Mahuduzzaman et al. 2014; Rasel et al. 2013; Seddique et al. 2013; Yu et al. 2010).

Thus, to delineate the sources of saltwater and its possible consequences on the environment are significant for proper management of the groundwater reserve in the coastal area of Bangladesh. The mechanism of salinity evolution and spatial distribution of fresh and saline groundwater are crucial to investigate for such management of the available coastal groundwater.

There is only limited literature assessing the quantity and quality of freshwater used in the tourism industry and its environmental consequences especially related to the saltwater intrusion problem in the area. Therefore, it is the ultimate necessity to study and to understand the dynamic of the coastal system together with the influence of additional stress on it. Thus, this dissertation aims to investigate the groundwater resources and the pressure on it as a case study of the south-eastern Cox's Bazar district of Bangladesh.

1.2. Study concept and thesis outline

The specific research concept of this study included the following tasks:

(i) to evaluate the effects of the groundwater extractions on the status of the groundwater resources;

(ii) to understand the dynamics between surface water, groundwater, and seawater in the Cox's Bazar;

(iii) to identify the vulnerable zones for seawater intrusion that will help to the decision making to manage available coastal groundwater resources in a more sustainably.

These tasks are achieved by determining the quality of the groundwater by delineation of seawater intrusion regarding hydrochemistry, evaluating the hydrogeological conditions in the coastal areas and developing a zonation map of salinity of the region as a basis for management scenarios. With this, an extensive data set on groundwater hydrochemistry and groundwater dynamics of the coastal groundwater of Cox's Bazar has been generated, including major ions, isotope data and hydraulic heads. In addition, data on water demand and consumption have been generated based on literature data and own field investigations. Finally, a vulnerability zonation map of the Cox's Bazar coastal aquifer has been created for decision making.

To achieve the goals of the project, the following outline has considered for this study (Fig. 1):

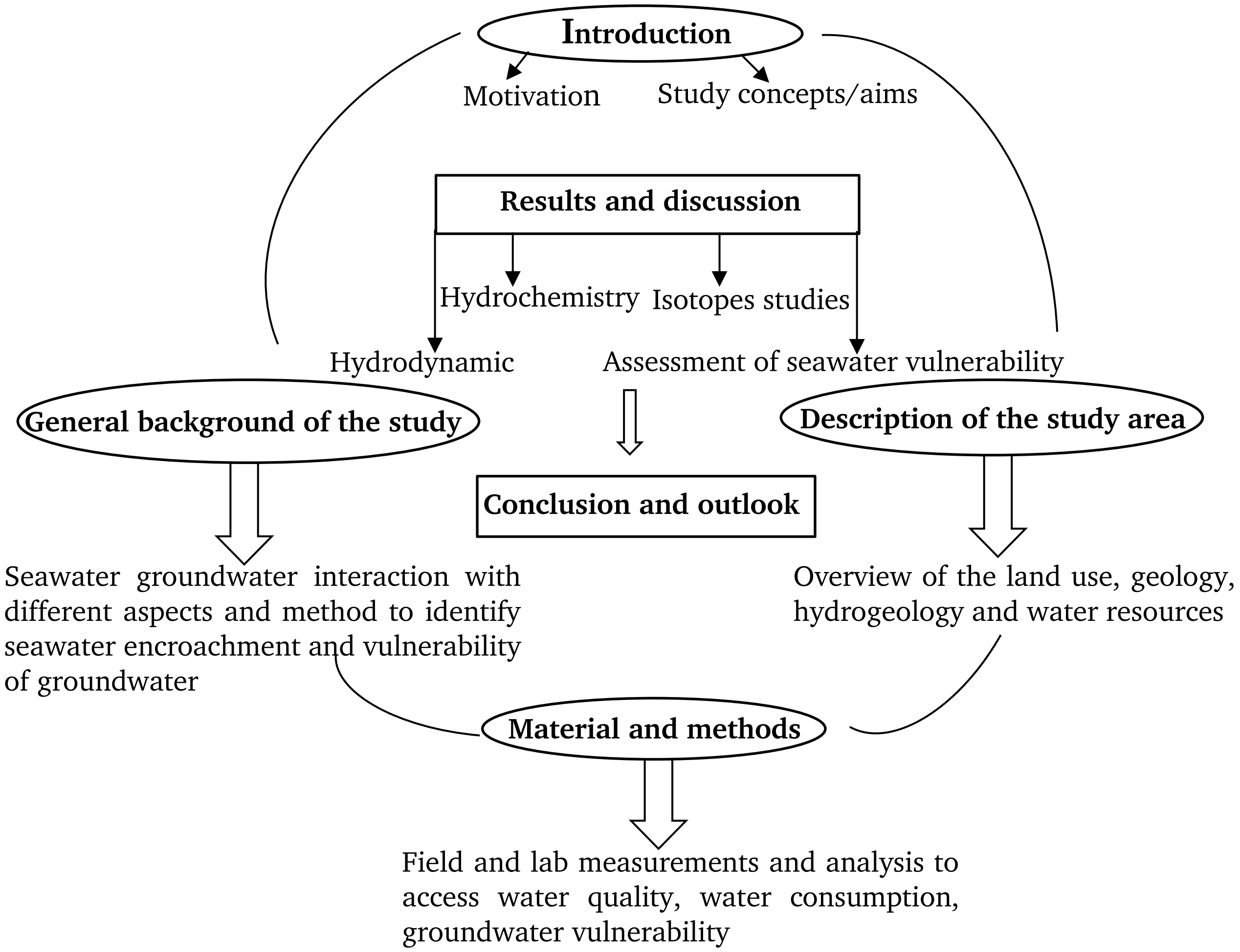

Fig. 1: Schematic diagram of the study outline.

2. General background of the study

The occurrence of saltwater in fresh groundwater is one of the most important threats in managing water resources. Salinization is a term that mainly indicates the increasing concentration of dissolved ions compared to the background concentrations by any source in the system (Richter and Kreitler 1993). Different classifications have been applied in the literature to characterize the water based on the salinity. Those classifications are based on different parameters like electrical conductivity (EC; μS/cm), total dissolved solids (TDS; mg/L) and chloride content (Cl; mg/L). Robinove et al. (1958) classified the groundwater in five categories based on the TDS as fresh (TDS $<$ 1000 mg/L), slightly saline (1000 $<$ TDS $\leq$ 3000 mg/L), moderately saline (3000 $<$ TDS $\leq$ 10000 mg/L), very saline (10000 $<$ TDS $\leq$ 35000 mg/L) and briny (TDS $>$ 35000 mg/L). On the other hand, Freeze and Cherry (1979) classified it with different values as fresh (TDS < 1000 mg/L), brackish (1000 < TDS ≤ 10000 mg/L), saline (10000 < TDS ≤ 100000 mg/L) and brine water (TDS > 100000 mg/L).

There are a variety of potential sources that can increase the natural TDS level, and some might be natural, and others could be of anthropogenic origin. However, for this study we focus on the basics of seawater intrusion in coastal areas that is driven by hydraulic head differences between seawater and groundwater, and on the associated hydrochemical effects altering the hydrochemistry of the native groundwater.

2.1. Seawater-groundwater interaction – hydrodynamic aspects

Under natural conditions the flow of groundwater in coastal aquifers is generally directed towards the sea, as a result of the topography in the respective area. This freshwater flow prevents seawater from intruding into the coastal aquifers (Richter and Kreitler 1993) and typically a dynamic equilibrium exists between the freshwater and the seawater. Due to the higher density of saltwater, a wedge-shaped boundary between the seawater and the freshwater is formed, extending below the landside. The depth of the interface below sea-level (z (m)) is determined by the elevation of the groundwater table above the seawater (h (m)) (Fig. 2).

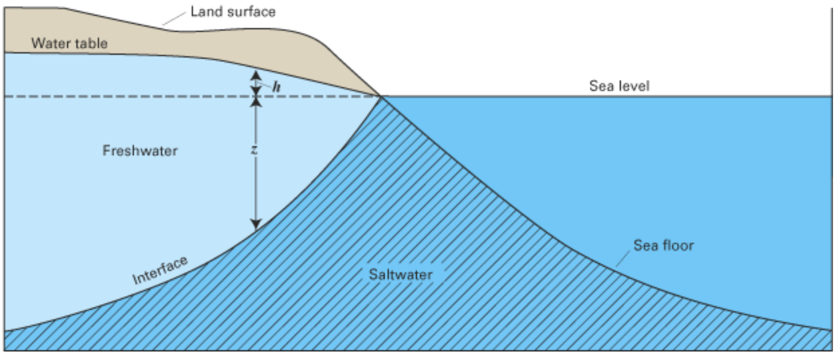

Fig. 2 : Schematic figure of the freshwater-seawater interface in a coastal aquifer for the steady state condition (not to scale) (Barlow 2003).

The relationship between the elevation of the groundwater above sea-level and the depth of the interface below sea-level were independently described by W.B. Ghyben in 1888/1889 and by W. Herzberg in 1901, resulting in the so called Ghyben-Herzberg equation:

$$z = \frac{pf}{ps - pf}\ h \dots\dots\dots\dots\dots\dots\dots\dots\dots \text{(1)}$$

Where p_f and p_s are the density (g/cm^3) of the freshwater and seawater, respectively. Assuming the average density of freshwater to be 1000 g/cm^3 and that of seawater to be 1025 g/cm^3, one meter of freshwater thickness above sea-level in the aquifer would result in 40 m of freshwater thickness below sea-level.

Especially extensive pumping in coastal aquifers can influence the natural equilibrium and reduce the hydraulic head of fresh water above sea-level, enabling an upconing of seawater (USGS 1999) (Fig. 3). As a consequence of the Ghyben-Herzberg equation one meter of headloss in the groundwater will result in a seawater upconing of 40 m.

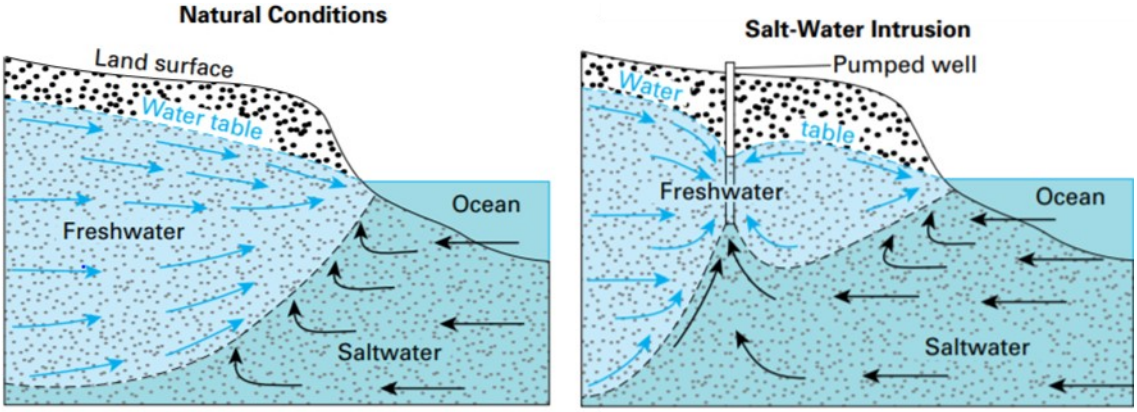

Fig. 3: Conceptual figure of seawater intrusion into a coastal aquifer and upconing due to pumping (not to scale) (USGS 1999).

In principal also sea-level rise, low groundwater recharge, or extreme tides can result in an enhanced dynamic of the freshwater-seawater interface and especially pronounced seasonality in rainfall can lead to significant hydraulic head changes (Hanor and Evans 1988; Richter and Kreitler 1993). However, hydraulic head changes due to excessive pumping are typically much more pronounced, but are variable in space and time, further complicating the dynamics within the coastal aquifers.

2.2. Seawater-groundwater interaction – hydrochemical aspects

The hydrochemical composition of seawater and groundwater are distinctively different. Seawater has an average TDS of 35000 mg/l that may be locally somewhat lower or higher. Tab. 1 shows an average composition of seawater with respect to the major anions and cations. Main components of seawater are sodium (Na^+) and chloride (Cl^-) accounting already for 84 % of the TDS.

Tab. 1: Concentration of major chemical constituents in seawater (Hem 1985)

Constituent	Concentration (mg/L)	Percent	Total Percent
Chloride, Cl^-	19,000	54	54
Sodium, Na^+	10,500	30	84
Sulfate, SO_4^{2-}	2,700	8	92
Magnesium, Mg^+	1,350	4	96
Calcium, Ca^{2+}	410	1	97
Potassium, K^+	390	1	98
Bicarbonate, HCO_3^-	142	0.4	98.4
Bromide, Br^-	67	0.2	98.6

On the contrary the hydrochemical composition of freshwater, i.e. groundwater, is quite variable and determined by the geological conditions in the aquifer. Compared to the seawater, TDS values are much lower and groundwater chemistry in coastal areas is typically dominated by calcium (Ca^{2+}) and bicarbonate (HCO_3^-) resulting from dissolution of carbonates. Sodium and especially chloride are of less importance.

This significant difference triggers specific processes when seawater intrudes into a freshwater aquifer, especially related to ion exchange on aquifer materials. Ion exchange on charged surfaces is triggered by three principles in descending order, (i) the higher the valency of an ion, the higher its affinity to the exchanger site, (ii) the smaller the hydrated radius of an ion, the higher its affinity, and (iii) the higher the concentration of an ion in the water phase, the higher its affinity. In case an ion has less affinity due to lower valency (e.g. (Na^+), high concentrations of that ion would outcompete ions with higher valency but low concentrations (e.g. Ca^{2+}).

Clay minerals, organic matter, some oxides and hydroxides as well as minerals like quartz carry a negative surface charge at or around neutral pH, making them potential cation exchangers (Appelo and Postma 2005). Due to this, cation exchange is much more important in aquifers compared to anion exchange.

Due to the dominance of calcium in fresh groundwater the cation-exchanger sites are typically occupied by calcium. However, if seawater with high Na^+ and Cl^- concentrations intrudes into such an aquifer, the concentration effect leads to an exchange of Na^+ with Ca^{2+}, resulting in changes in the hydrochemical composition of the water (Appelo and Postma 2005):

$$Na^+ + {}^1/_2\, Ca - X \rightarrow\ Na - X + {}^1/_2\, Ca^{2+} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2)}$$

where X is the exchanger. Na^+ is taken up by the exchanger while Ca^{2+} is released. Since the dominant anion Cl^- is not exchanged and its concentration stays constant, the water quality changes from a NaCl to a $CaCl_2$ type (Appelo 1994; Hounslow 1995; Appelo and Postma 2005).

The reverse process takes place during freshening, i.e. when fresh water with Ca^{2+} and HCO_3^- ions flushes a saltwater aquifer, the water type changes again from a $CaCl_2$ type to a Na HCO_3^- type (Hounslow 1995; Appelo and Postma 2005).

$${}^1/_2\, Ca^{2+} + \mathrm{Na} - \mathrm{X} \rightarrow\ {}^1/_2\, Ca - X + Na^+ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3)}$$

In coastal aquifers these changing hydrochemical conditions cannot always be clearly identified, as due to the various processes influencing hydraulic heads, the two processes might happen at the same time in different parts of the aquifer. They might also change frequently at one location.

2.3. Seawater-groundwater interaction – methods for identification

There are various methods for the determination of the interaction between seawater and groundwater. Besides the comparison of the hydraulic heads in the sea and in the groundwater for gradient evaluation, the majority of the methods are based on simple mixing models. It is assumed that certain hydrochemical parameters in the two end members, seawater and groundwater, are significantly different and can be determined separately (Gnanasundar and Elango 1999; Bergelson et al. 1999; Kim, et al. 2003; Appelo and Postma 1999; Richter and Kreitler 1993; Davis et al. 1998; Sathish et al. 2011).

2.3.1. Electrical conductivity

The most obvious parameter, and in addition simple to measure in the field, is the electrical conductivity (EC). While the typical electrical conductivity of seawater is about 50000 μS/cm, most fresh groundwater has EC values that are much lower (<1000 μS/cm). In principal, therefore, small quantities of seawater in fresh groundwater should be easy to detect as the relation between the fraction of seawater in the groundwater and the resulting EC values is linear (Fig. 4). As an example, considering 1% of seawater mixed into groundwater, having an EC of 1000 μS/cm would result in an EC value for the mixture of 1490 μS/cm.

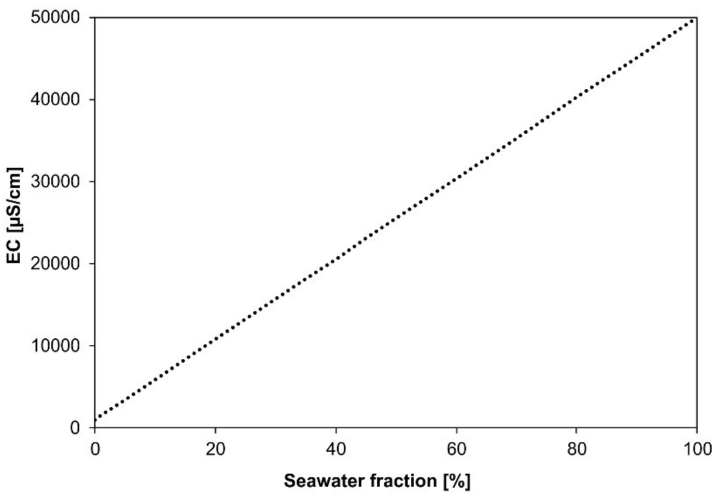

Fig. 4: Linear relation between EC and seawater fraction in a freshwater sample.

However, changes in EC values of groundwater not necessarily indicate an influence of seawater, as (i) the EC values of groundwater within an aquifer might change also due to changes in the geological units or the unconsolidated sediments, (ii) cross formational flow due to hydraulic windows between aquifers, (ii) due to evaporation of rainwater or sea spray before infiltration, or (iv) due to contamination by human activities, e.g. waste disposal, leaking sewer systems or agricultural practices. Therefore, other methods are used together with the EC to delineate real seawater intrusion from other factors influencing EC.

2.3.2. Sodium/Chloride ratios

Sodium (Na^+) and chloride (Cl^-) account already for 84 % of the TDS in seawater (Tab. 1), and on a molar basis this ratio is typically quite constant and around 0.86 (-). Rainwater or fresh groundwater as the other endmember, have typically molar ratios between sodium and chloride close to 1 (-) (Shanyengana et al. 2004; Jacks and Rajagopalan 1996; Mercado 1985).

Based on this, different processes occurring in a coastal aquifer can therefore be evaluated based on the Na^+/Cl^- molar ratios. A Na^+/Cl^- molar ratio close to 0.86, independent on Cl^- concentrations, would therefore indicate simple mixing between seawater, as one end member, and freshwater (Fig. 5) (McCaffrey et al. 1987; Mercado 1985). Samples located above the mixing line at low Cl^- concentrations would indicate dissolution effects in the aquifer, or, at higher Cl^- concentrations, could also indicate freshening effects with cation exchange (Eq. 3).

Samples below the mixing line could indicate cation exchange (Eq. 2) during seawater intrusion (Fig. 5). (Mercado 1985). However, similarly to the limits of the EC method, changes of the Na^+/Cl^- ratio in the freshwater could also result from anthropogenic impacts.

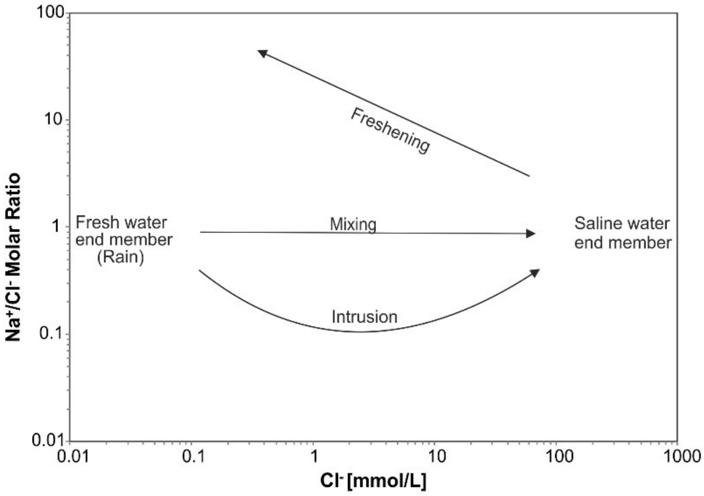

Fig. 5: Na^+/Cl^- molar ratios in relationship to Cl^- concentrations, indicating different processes (modified after Jacks and Rajagopalan 1996).

2.3.3. Chloride/Bromide ratios

As the positively charged sodium is not conservative in an aquifer, due to ion exchange reactions, mass ratios of the two anions chloride and bromide were used as an additional method that is not influenced by ion exchange in the aquifer (Richter et al. 1986; McCaffrey et al. 1987). Bromide concentrations in seawater are relatively small, compared to Chlorine, and the Cl^-/Br^- mass ratio of seawater reaches approximately 300, based on the location. In groundwater Cl^-/Br^- mass ratios are typically much less than 200 for young groundwater (Davis et al. 1998, 2004), and also concentrations are much lower. As in this case ratios are compared and the concentrations of the two ions in the two end-members are quite different, the relation between the ratio and the fraction of seawater in groundwater is not linear. The effect of mixing between seawater and freshwater on the Cl^-/Br^- mass ratios as shown in Fig. 6 assuming a Cl^-/Br^- mass ratios in seawater and freshwater to be ~285 and ~10, respectively.

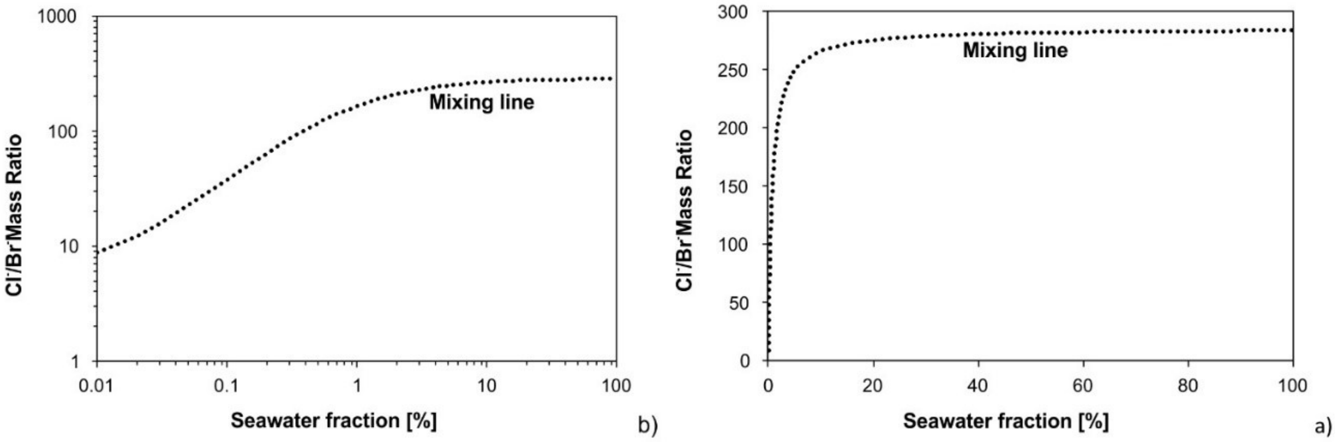

Fig. 6: Change of Chlorine/Bromine mass ratios during mixing of seawater and freshwater.

For interpretation of field data, typically the Cl^-/Br^- mass ratio is plotted against the Cl^- concentration in the sample. Deviations from the mixing line, however, would indicate different sources for chlorine or bromine, depending on higher or lower ratios.

2.3.4. Stable water isotopes

Another method to assess different sources of salinity in groundwater are based on the ratios of the stable isotopes of the water molecule ($^{18}O/^{16}O$, $^{2}H/^{1}H$), and for interpretation these are often combined with other hydrochemical data (Yurtsever 1994; Gaye 2001; Faye et al. 2005; Bouchaow et al. 2008; Gattacceca et al. 2009; Carreira et al. 2014).

Thus, people around the world are widely using hydrochemical data together with the stable water isotopes to understand the hydrological cycle and water geochemistry (Fritz and Fontes 1980; Rosanski et al. 1993; Clark and Fritz 1997; Kendall and McDonnell 1998; Criss 1999; Mook 2001; Allen 2004; IAEA 2005; Carrasco-Cantos 2015; Kattan 2018). The concept of the isotope approach is based on the fact that the isotopic composition of different water sources might be very different, due to well-known fractionation processes during e.g. evaporation or condensation in different climatic conditions (Gonfantini 1986; Clark and Fritz 1997; IAEA 2005). Consequently, any changes of the groundwater composition due to natural (i.e. rainfall, seawater intrusion) or anthropogenic inputs (i.e. wastewater, irrigation water) into an aquifer might alter the isotopic composition of the mixed water, compared to the pure groundwater (Payne et al. 1979).

The fractionation processes are triggered by the mass differences between the light and heavy isotopes of an elements, and the resulting different isotopic compositions of the water molecule can be sensitively determined with standard analytical methods. Therefore, stable isotopes are effectively used worldwide to identify and characterize the mixing between different waters, groundwater movement and salinity sources and origins of salinity in coastal environments (Vengosh et al. 1997, 2005; Carreira et al. 2014).

To compare stable isotopes in different applications, typically a common standard is required. For water, the usual standard is the Vienna Standard Mean Ocean Water (VSMOW), distributed by the International Atomic Energy Agency (IAEA) located in Vienna. The delta (δ) notation is used to quantify stable isotopes as relative ratios, e.g. for the oxygen atom, expressed in permill (‰):

$$\delta\ sample\ (permil) = \left(\frac{\text{R sample}}{\text{R reference -1}}\right).1000 \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (4)$$

By definition, the isotopic composition of the VSMOW standard for $\delta^{18}O$ and $\delta^{2}H$ is 0 (‰) respectively, and the isotopic composition of modern seawater is close to this, depending on the location where the sample was taken. It might also vary over time. When seawater intrudes into groundwater, the isotopic composition of groundwater will be changed, and tends to move towards the seawater value, depending on the fraction of seawater in the sample.

It was also found, that the average isotopic composition of oxygen and hydrogen in rainwater worldwide follows a linear trend. Plotting $\delta^{18}O$ and $\delta^{2}H$ data of long-term global precipitation, Craig (1961) introduced the Global Meteoric Water Line (GMWL) ((Fig. 7 a) that has a slope of 8, and an intercept of 10 (Eq. 5).

$$\delta^{2}H = 8\ \delta^{18}O + 10 \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (5)$$

The intercept is termed as deuterium excess (d) but the value may vary depending on the location and relative humidity, e.g. it was found to be in a range of 4 to 23 for relative humidity variations between 60 and 90 % and for the temperature range of 0 to 20°C (Clark and Fritz 1997; Yurtsever 1994). Due to evaporation, the slope of this linear relation could also change, depending on the temperature and relative humidity (Yurtsever 1994).

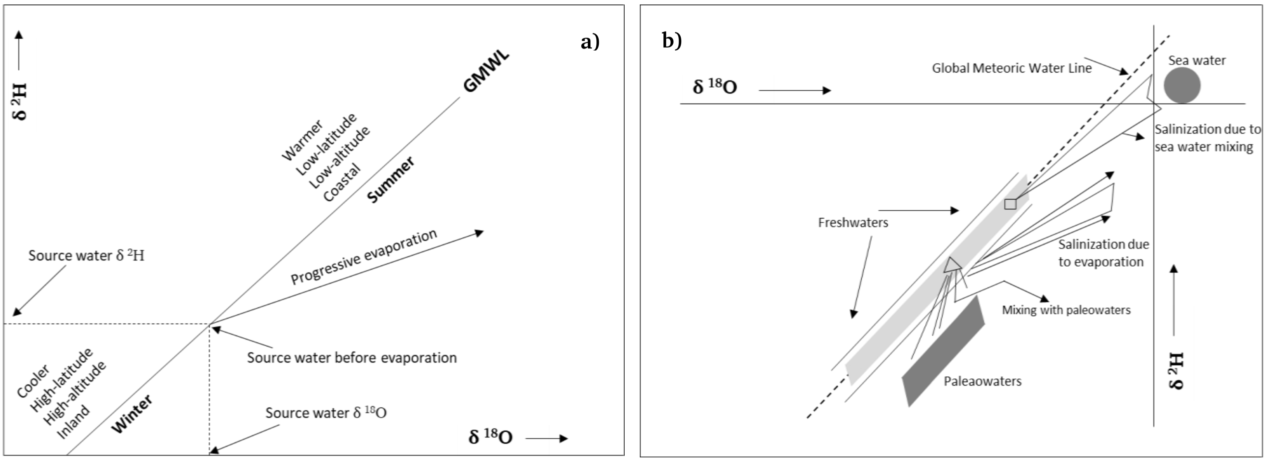

Fig. 7: a) The generalized relationship between $\delta^{2}H$ and $\delta^{18}O$ values measured in precipitation worldwide and processes affecting its isotopic composition (Oerter et al. 2017); b) Evolution of the stable isotopic composition of water for different water salinization processes (Yurtsever 1996).

The isotopic composition of a rainwater sample relative to the global meteoric water line, plotted on a $\delta^{18}O$ and $\delta^{2}H$ graph, can, e.g., reveal different climatic conditions during rainfall. Lighter isotopes would indicate cooler conditions or higher altitude of precipitation, while heavier isotopes would indicate warmer conditions or lower altitude of precipitation. At the same time, linear deviations from the GMWL, i.e. an increase in heavier isotopes with a lower slope compared to the GMWL, would indicate progressive evaporation effects, that could even happen during rainfall (Michelsen et al. 2016) (Fig. 7 a).

Also, different salinization processes in groundwater can be determined, based on the isotopic composition of a water sample compared the GMWL (Fig. 7 b). High salinity paleaowaters, e.g. might substantially deviate from the GMWL. However, the mixing between seawater and freshwater would no result in substantial deviations from the GMWL, as the isotopic composition of seawater is close to the meteoric water line, and at high relative humidity levels, i.e. without significant evaporation, the isotopic composition of the mixed water would move more or less along the GMWL (Clark and Fritz 1997). In such a case, it is problematic to use the stable isotopes of water for investigating seawater intrusion into aquifers.

2.3.5. Sulphate isotopes

Sulfur (^{34}S) and oxygen (^{18}O) isotopes in dissolved sulfate are another tool for identifying seawater influence in groundwater. The international standard for sulfur isotopes is the Vienna Canyon Diablo Troilite (VCDT), having a $\delta^{34}S$ value of 0.3 ‰.

Modern seawater has a very well defined $\delta^{34}S_{SO4}$ and $\delta^{18}O_{SO4}$ isotopic composition and the values are +21‰ VCDT and 9.5‰ VSMOW respectively (Clark and Fritz 1997). Sulphate in groundwater can have various origins and therefore values may be quite different, depending on location. However typically $\delta^{34}S_{SO4}$ and $\delta^{18}O_{SO4}$ values of sulphate in fresh groundwater are significantly lower than in seawater (Elgettafic et al. 2013). Therefore, the isotopic composition of sulphate has been used in several studies to identify and characterize the sources of dissolved SO_4^{2-} in groundwater (Krouse et al. 1999; Dogramaci et al. 2001; Berner et al. 2002).

For analyses, either $\delta^{34}S_{SO4}$ is plotted against $\delta^{18}O_{SO4}$ to distinguish between freshwater and seawater, or $\delta^{34}S_{SO4}$ of a water sample is plotted against the distance of the sample location from the coast (Schulz et al. 2015). In such a plot the sulphur isotope values in groundwater are expected to decrease with increasing distance from the shore, as the seawater impact potentially decreases. However, due to the variability of sulphur isotopes in groundwater, the relation might not necessarily be linear. Similarly, if the fresh groundwater comes to contact with the seawater, there will be a negative linear relationship between $\delta^{34}S$ and SO_4^{2-}/Cl^- mass ratios as the seawater SO_4^{2-}/Cl^- mass ratio is about 0.1 (-). This ratio also helps to identify whether the sulphur isotope (^{34}S) enrichment into the aquifers is from sulphate reduction processes, that would give a positive correlation on such a plot (Freeze and Cherry 1979).

2.4. Seawater-groundwater interaction – definition of risk areas

To consider seawater intrusion in groundwater management concepts is a complicated process, especially in coastal areas. It is therefore important to identify zones with a high potential vulnerability of the groundwater resources, especially in areas of high demand. Assessment of seawater vulnerable zones will assist to produce vulnerability maps that can successfully be used by policymakers in the field of water and environmental management to protect, mitigate and remediate contaminated groundwater resources (Liggett and Talwar 2009; Arthur et al. 2007). In addition to this, groundwater vulnerability assessment methods compile and combine complex hydrogeological and hydrochemical information into maps that will help the decision maker to utilize the limited groundwater resources more sustainably.

Assessment of vulnerability is based on the theory that some areas are less secured by the geological or lithological layers than other areas. Such areas are more prone to contamination by natural processes and human activities (NRC 1993). At the same time, natural conditions in an area of interest can be heterogenous, hence it is practical to enforce restrictions on specific areas rather than all areas.

Researchers around the world hence are using modeling or several types of a vulnerability index, including hydrochemical data, to further assess the extent of seawater intrusion and to manage the limited coastal groundwater resources. Generally, three well-recognized vulnerability techniques are used, (i) overlay or index-based methods, (ii) statistical methods, and (iii) numerical methods (NRC 1993). The most popular method that is widely used is the overly or indexing method (Liggett and Talwar 2009; Beaujean et al. 2013).

The model GALDIT belongs to this group and it is one the few vulnerability indexes approach that are used for assessing seawater intrusion vulnerability in coastal aquifers (Werner et al. 2012; Saidi et al. 2013). The name GALDIT refers to the parameters most important to delineate risk areas, that are **G**roundwater occurrence, **A**quifer hydraulic conductivity, the height of groundwater **L**evel above the sea level, **D**istance from the shore, **I**mpact of existing status of seawater intrusion in the area, and the **T**hickness of the aquifer. The main idea of this approach is to convert the importance of six hydrogeological and hydrochemical parameters into scales of 2.5 to 10 and then combine them to vulnerability scores using weightings (Chachadi and Lobo-Ferreira 2001; Chachadi et al. 2003; Lobo-Ferreira et al. 2007). The resulting map identifies areas that are prone to seawater intrusion or that are already affected by seawater (Saidi et al. 2013; Recinos et al. 2015).

This method has been used in different parts of the world including Greece (Kallioras et al. 2011; Lappas et al. 2016), Florida USA (Tasnim et al. 2016) India (Mahesha et al. 2012; Sophiya and Syed 2013), Tunisia (Saidi et al. 2013; Trabelsi et al. 2016; Gontara et al. 2016), Algeria (Bouderbala et al. 2016; Mehrez et al. 2018), Morocco (Najin et al. 2012), Malaysia (Kura et al. 2015) and Finland (Luoma et al. 2017). However, this approach cannot provide information on the actual water quality as well as loads of contamination. It is based on a combination of the available hydrochemical data and hydrogeological information. The resulting groundwater vulnerability maps can be an effective approach to manage groundwater resources more sustainably.

3. Description of the study area

Cox's Bazar is located in the south-eastern part of Bangladesh at 21.583333°N and 92.016667°E and bounded by Bakkhali river in the north-east and the Bay of Bengal in the west (Fig. 8). The straight coastline with a sandy beach is bound by steep but shallow cliffs and an alluvial plain behind. The maximum elevation of the study area is about 70 m in the east and a few meters above sea level in the west, thus, gently sloping from east to west.

The population in the Cox's Bazar city area is about 459,000 with density a 2,011/km^2 (BBS 2013). The population of this area increased by 111,000 from 2001 to 2011 that indicates an annual growth rate of 3%. Additionally, more than 2 million tourists visit Cox's Bazar every year (Dey et al. 2013).

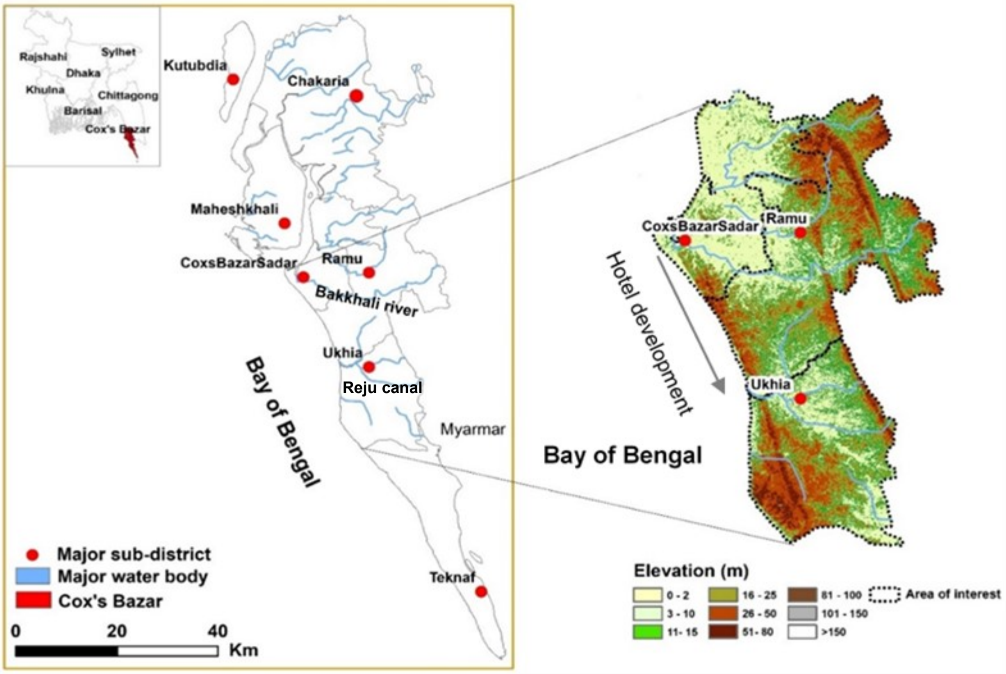

Fig. 8: General map of the area of interest in Cox's Bazar, Bangladesh.

Due to the recent development of the tourist industries and the socio-economic development in the study area, the population is expected to rise to about 620,000 by 2021 and to exceed 1.5 million by 2051, based on the current annual growth rate (Fig. 9). According to the 2013 economic census, the economic numbers have increased in this area by about 7.9%, and the total persons engaged increased by 6.5% annually compared with 2001 and 2003.

Such economic development is turning the rural setting of Cox's Bazar into an urban environment. As a matter of fact, additional stress on the coastal groundwater and other natural resources will further increase in the coming years due to such urban development and growth of population.

For the Cox's Bazar area information on the hydrogeology and resulting available water resources, and even data on groundwater hydraulic heads are rare or absent. Also, groundwater extraction rates are unknown, as wells operated privately or by the touristic centers are not metered and consequently extracted volumes are not charged. Therefore, potential effects of the current water extraction practice on the subsurface hydrogeological and hydrochemical conditions are not known in detail, and further studies are needed for the sustainable management of the coastal resources (Bakari et al. 2012; Cruz et al. 2011).

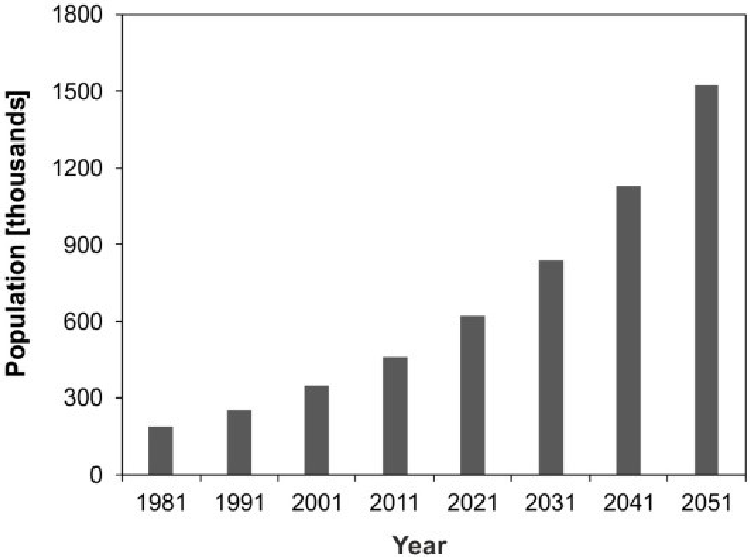

Fig. 9: Projection of population growth in the next 40 years in Cox's Bazar city area, Bangladesh (based on BBS 2013 report).

3.1. Climate

The climate in the area shows a distinct seasonality due to the tropical monsoon with an average yearly rainfall of about 3630 mm, falling mainly between the months of May and October. The rainy season accounts for 90% of the total rainfall. On the other hand, there are some months when there is very little to almost no precipitation especially from November to April.

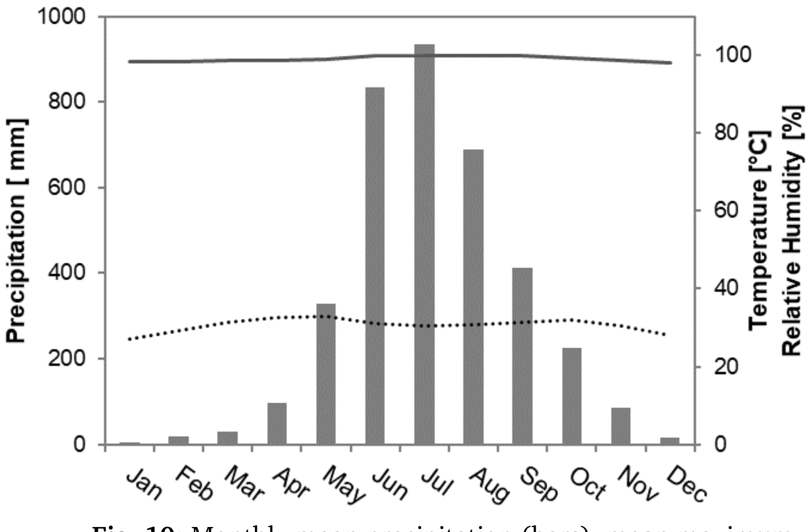

Fig. 10: Monthly mean precipitation (bars), mean maximum temperature (dotted line) and mean maximum relative humidity (solid line) (1980 to 2011) in the Cox's Bazar area.

The monthly mean maximum temperature varies from 25 to 34°C in the Cox's Bazar area. The maximum mean temperature of 34°C is observed in the month of April and May whereas in January the mean minimum temperature is 12°C. The relative humidity in this coastal area is always close to 100% (Fig. 10). All these climatic parameters control not only the quality of water but also the annual regime of water quantity fluctuation.

3.2. Current land use pattern

In general, coastal areas of Bangladesh are diverse with different land uses and Cox's Bazar is not an exception to this. However, Cox's Bazar is known as one of the best-visited tourist destinations in Bangladesh, but it is also one of the sea-based business centers. The tourist sector is the main leading economic factor in this area. As the study area is famous for its long sandy beach, most of the tourist hotel facilities are in Cox's Bazar town and along the coast towards the Tenknaf.

Although the hotel and motel zones are defined in the city development plan, they are growing beyond the planned area of development now. Apart from tourist development, there are also salt and fish cultures, hatcheries, and dry fish production. Few agriculture land-based activities can be found in the area (Fig. 11). Most of the salt and fish cultures are located close to the Moheshkhali channel and along the eastern side of the Bakkhali river. The land use patterns in the region have significantly changed over the last years. In the year 1978, land use for fish and salt culture accounted for 11% whereas, it was about 21% of the total land in 2009 (Alam 2013).

Hills cover a major part of the study area in the eastern part, accounting for about 34% of the total areas (Alam 2013). Most of the human settlements and economic activities are concentrated in the center of the Cox's Bazar town. Most important, the percentage of establishments increased in the urban part of Cox's Bazar by about 7% in 2013 compared to 2001 and 2003 (BBS 2013). The development of Cox's Bazar is still unplanned regarding proper use of the land for the growing population and their economic growth. This unplanned development has an impact on the groundwater recharge during the monsoon season and might have substantially contributed to the stress on the water table in the coastal aquifer together with overexploitation of freshwater, low river discharge, and sea level rise.

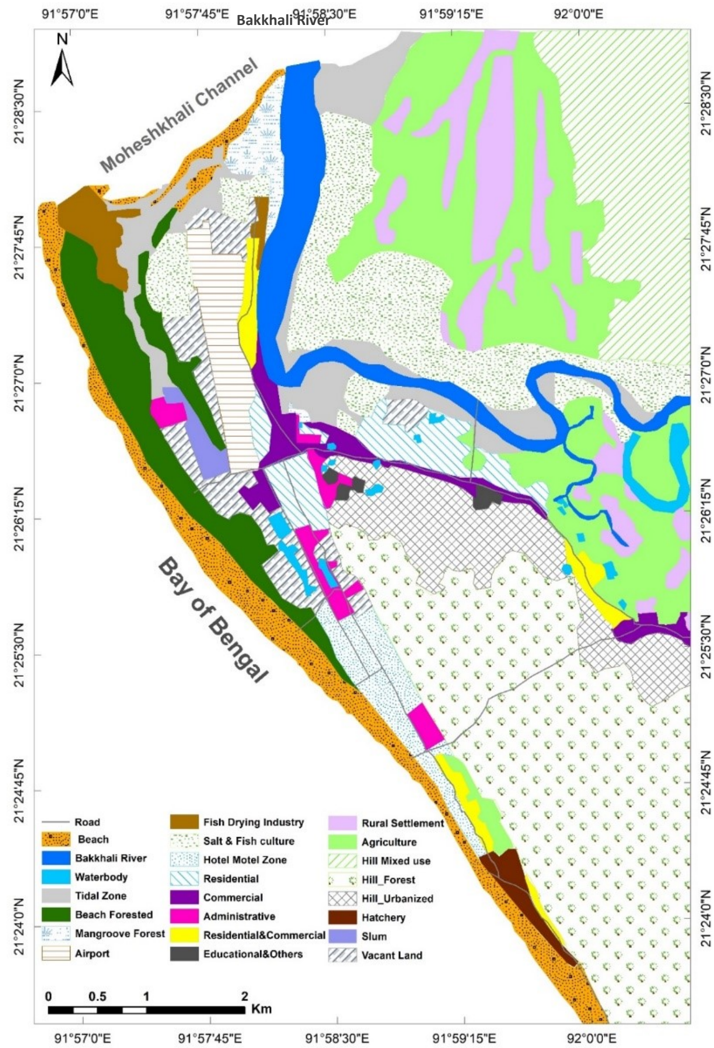

Fig. 11: Land use pattern in and around Cox's Bazar town, Bangladesh.

At the same time, tourist development and the fish culture depend to a large extent on sufficient water availability in good quality. It is reported that forests and rice fields have decreased by 8% and 6%, respectively due to the saltwater intrusion in the Cox's Bazar area (Alam 2013). Meanwhile, mangrove forests in the study area have almost disappeared, due to a lack of proper management and governmental planning. More importantly, land use of the Cox's Bazar has continuously changed during the last ten years, and there is further demand for expansion of industries and touristic centres.

3.3. Geology

3.3.1. Regional geologic setting

Generally, Bangladesh follows two major tectonic divisions. Namely, i) the stable precambrian Rangpur platform in the northwest, and ii) the geosynclinal Bengal basin with rapidly increasing individual formation thicknesses in the southeast. Sediments in the basin are of mesozoic and tertiary age with a maximum thickness of 21 km and are covered by recent alluvium (Khan 1991; Hossain et al. 2018). Due to the north and north-eastern collision of the Indian Plate with the Eurasian Plate and the Burmese Plate, the tectonic evolution of the Bengal Basin is directly related to the development of the Himalaya in the north and the Indo-Burman Ranges (IBR) in the east (Fig. 12) (Curry and Moore 1974; Hossain et al. 2018). The westward propagation part of IBR is known as Tripura-Chittagong Folded Belt TCFB (Fig. 12) (Najman et al. 2016). Low hill tracts to the west of the IBR has been deformed by TCFB (Maurin and Rangin 2009). Tectonically, the Bengal Basin lies within the folded flank of the Bengal Foredeep (Alam et al. 1990; Khan 1991; Reimann 1993; Hossain et al. 2018) and the folded flank occupies the eastern part of Bangladesh.

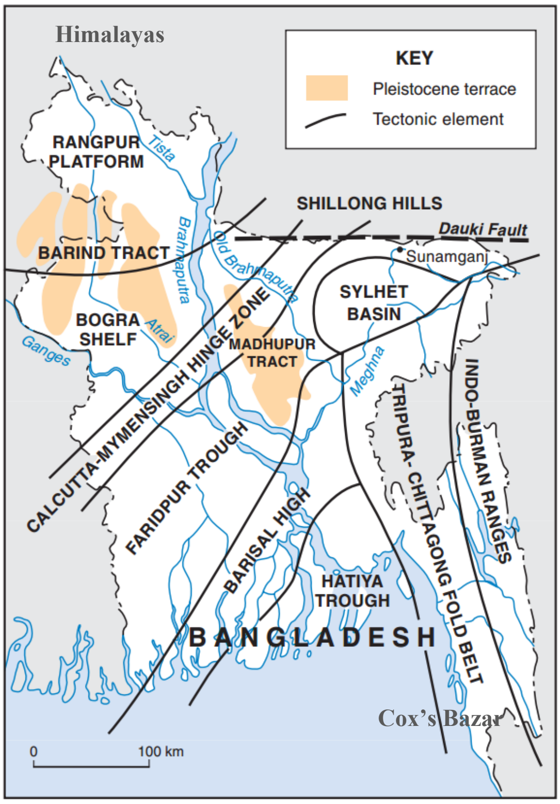

Fig. 12: Tectonic elements of Bangladesh (BGS and DPHE 2001).

3.3.2. General geology of the area

The geological map of Bangladesh (Alam et al. 1990) indicates that the Eastern Coastal Zone and its surroundings are synclines in the Cox's Bazar region and prominent anticlines in the Teknaf region (Fig. 13). In the core of the Cox's Bazar syncline, the Pleistocene to Pliocene Dupi Tila and Dihing Formations are exposed in the south and in the northeast, respectively. (Fig. 13). On the other hand, Miocene

Bhuban, Boka Bil and Plio Pleistocene Tipam Formation are exposed in the core of the Teknaf anticline. Boka Bil Formation also forms the flanks and Tipam Formation forms in the northern plunge in the area.

This coast in the study area has been modified by marine activities during the Mid-Holocene transgression. Coastal morphology and beaches have developed with the gradual retreat of the sea, tidal and fluvial discharges (Fig. 14). Holocene deposits composed of heterogeneous mixture of sand, silt and clay which unconformably overlies the Miocene Boka Bil shale. In the coastal plain pebble beds and boulders are present in between beach deposits and the Tertiary deposits. The beach deposits are elevated just a few centimeters to a meter above the sea level (Khan 1991).

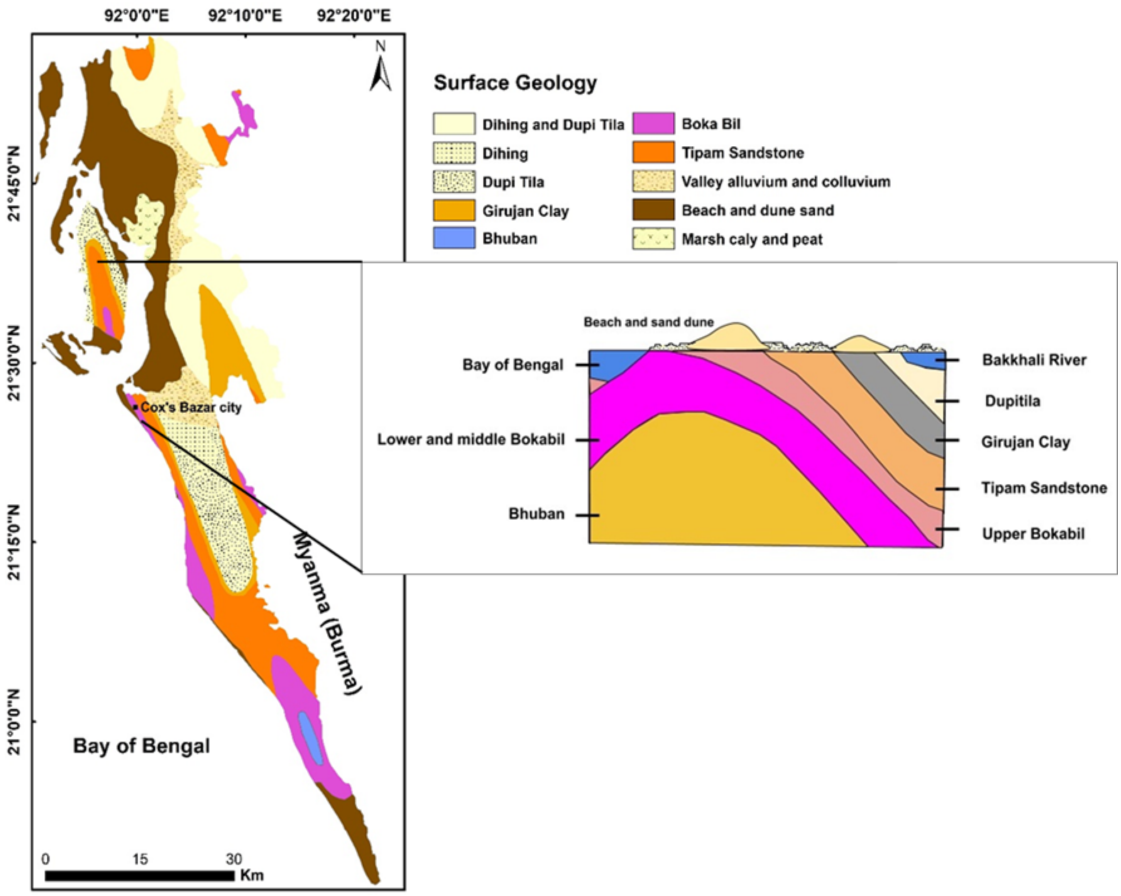

Fig. 13: Surface geology and their possible sequence in the Cox's Bazar city and surround.

Cox's Bazar coastal plain is consisting of sandy beach and sand dunes that is extend up to the foot hill range of the eastern side of the coast. Piedmont plains have been developed in between the hills and the coastal plains by the sediments brought in by the hilly streams and by eroded sand from the Dupi Tila formation. Surrounding rivers and channels of the study area also have contribution to the sediment distribution of all parts of the basin.

Therefore, the coastal deposits of the study area can also be classified into the following succession: i) Beach deposit, ii) Dune deposit, iii) Paleobeach deposit, iv) Paleoshore deposit, v) Tidal Mud deposited, vi) Tidal flat deposit, vii) Intertidal flat deposit, viii) Piedmont and Paleo beach deposit (Fig. 14).

Paleobeach depoists represent the former locations of the beach, and paleoshore deposits are relatively higher in elevation than the beach or tidal flat. Tidal flats are the deposits of materials carried by the Bakkhali river from the upstream hills that are located besides the Bakkhali stream and Moheshkhali channel (Fig. 14). Similarly, intertidal flat deposits are also distributed along the Bakkhali river due to the influence of tidal creeks. Deposits are similar to the tidal flat units with less clayey parts in the sediment (Fig. 14).

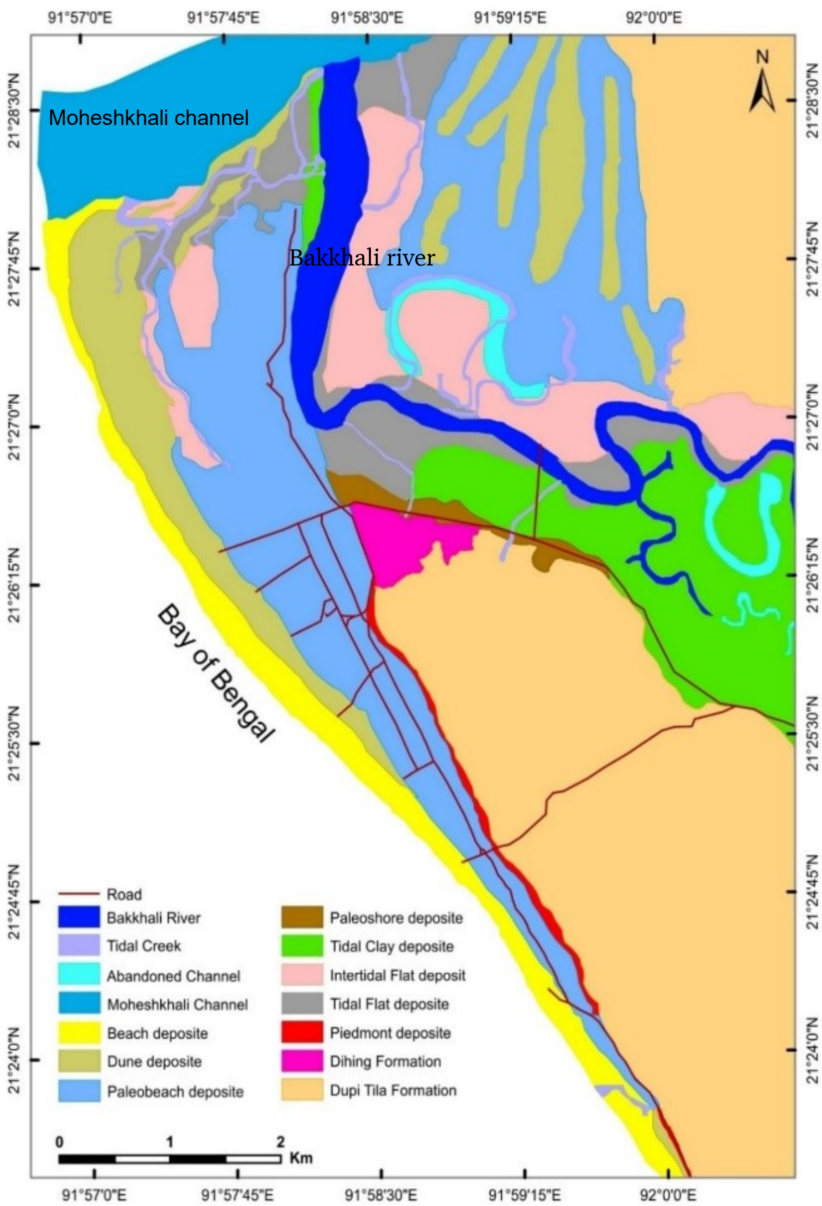

Fig. 14: Geological units of the study area (based on GSB unpublished data).

However, the Dupi Tila sandstone and Tipam sandstone are the primary aquifers of the region (Khan 1991). Rainwater can enter directly into the aquifers and recharge them annually. Also, the floodplains and delta sediments are potential aquifers, although much thinner compared to the sandstones. Thus, stored water volumes are limited in this deposit, making their use primarily in the dry season problematic (Khan 1991).

3.4. Hydrogeological condition and overview of water resources

3.4.1. Groundwater

The coastal aquifer system in Bangladesh has been divided into three major aquifer units where the aquifers are separated by leaky and discontinuous aquitards (Ravenscroft and McArthur 2004). The unconsolidated alluvial sediments of the coastal plain in Cox's Bazar consist of interbedded sand, silt and clay units, with a dominance of fine to coarse sands (Ravencroft et al. 2005). Only a few drilling profiles are available in the study area (Fig. 18) and they reveal mainly sandy deposits with interbedded silt and clay layers (Fig. 15). Layers are laterally discontinuous; thus, correlations are difficult to make. Therefore, sandy layers are assumed to be hydraulically connected (Fig. 15). This is also supported by pumping test results (MPO 1987), and such heterogeneous setup was found to be typical for the fluvial-deltaic deposits of the Bengal Basin (Michael and Voss 2009).

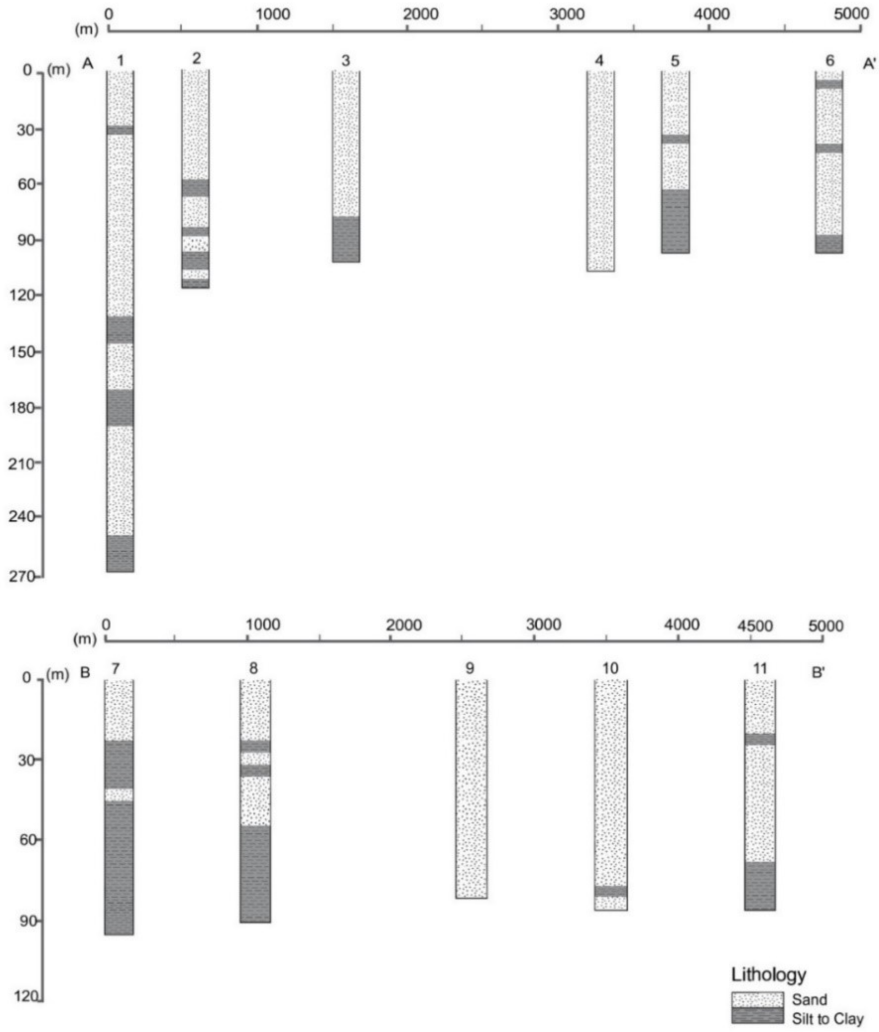

Fig. 15: Major lithological distribution of selected boreholes in the study area. Lithological information was collected from BWDB and DPHE (Fatema et al. 2018).

Because of these heterogeneities, resulting in spatial differences in hydraulic properties, and constant changes of sea level in the past, also the distribution of freshwater and saltwater in the coastal aquifer system is heterogeneous and difficult to predict (Yu et al. 2010). In general, fresh water is found within the upper 25 m of the sediments of the coastal region of Bangladesh (Ravenscroft et al. 2005). Also, the total thickness of the unconsolidated deposits is unknown in this area, but deepest boreholes reach 270 m without reaching basement rocks. The regional groundwater flow follows the local topography with a general direction from the east, north-east to the west, south-west.

3.4.2. Status of groundwater exploitation and use

Currently, local people of the Cox's Bazar town solely depend on the groundwater for the domestic as well as tourist industries as the surface water close to this area is already contaminated by seawater.

Fresh groundwater in the Cox's Bazar area is available already at shallow depths (> 3 m), and most of the water supply in the study area is based on individual wells developed for domestic purposes and the tourist industry.

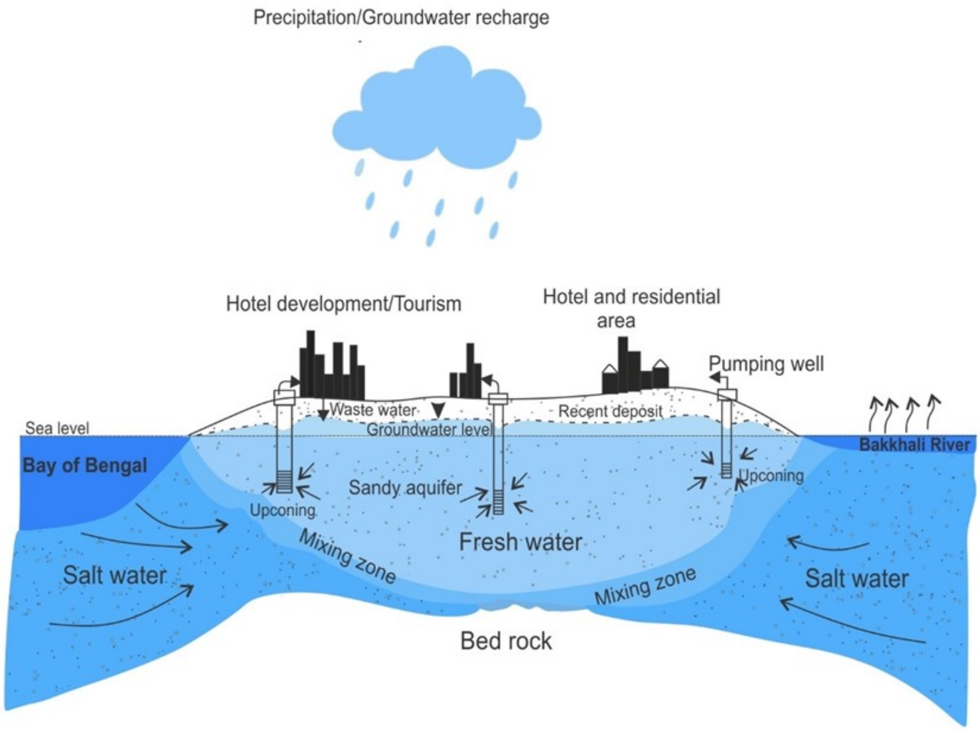

Fig. 16: Current situation of water use and conceptual aquifer system of the Cox's Bazar area, Bangladesh (not to scale).

There is no information about the total number of hand-pumped wells, or wells equipped with pumps, nor on their depths. Typically, a well is drilled to a certain depth and as soon as the yield decreases due to lowering of the groundwater table, the well is deepened, or a new and deeper well is drilled. There is also no information on pumping rates and consequently neither a strategy for optimizing pumping schemes to prevent seawater intrusion (Post 2005) nor a disproportional decline of water levels. A typical water consumption situation in the study area is presented in Fig. 16.

According to the local people and reports, most coastal groundwater is consumed by the tourists and the hotels. The pressure on groundwater is increasing due to this hotel's development and lack of fresh surface water use.

3.4.3. Surface water

Surface water in the Cox's Bazar area is abundant, with the rivers named Bakkhali, Matamuhuri, Rezu, and Naff. Besides these, some complex canals are flowing down to the Bay of Bengal. However, Bakkhali river is the most important from the economical point of view for this study area. It is one of the tidal streams originating from the Arakam mountains and it flows down to the north. The main town of Cox's Bazar is in the downstream of this river. It is the primary source of fresh surface water for the agriculture despite the seawater intrusion from the Moheskhali channel. The Bakkhali river has a broad cross-section with an average width of about 200 m close to the Moheshkhali channel. The riverbed mainly consists of sandy and muddy sediments.

The Bakkhali river is affected by semi-diurnal tides with two high and two low water during a lunar day. The maximum tidal range of this river is above 4 m (Fig. 17). Sometimes, that can bring saltwater up to 50 km upstream. However, there is a local rubber dam that conserves the freshwater upstream and prevents the seawater intrusion, especially in the dry period.

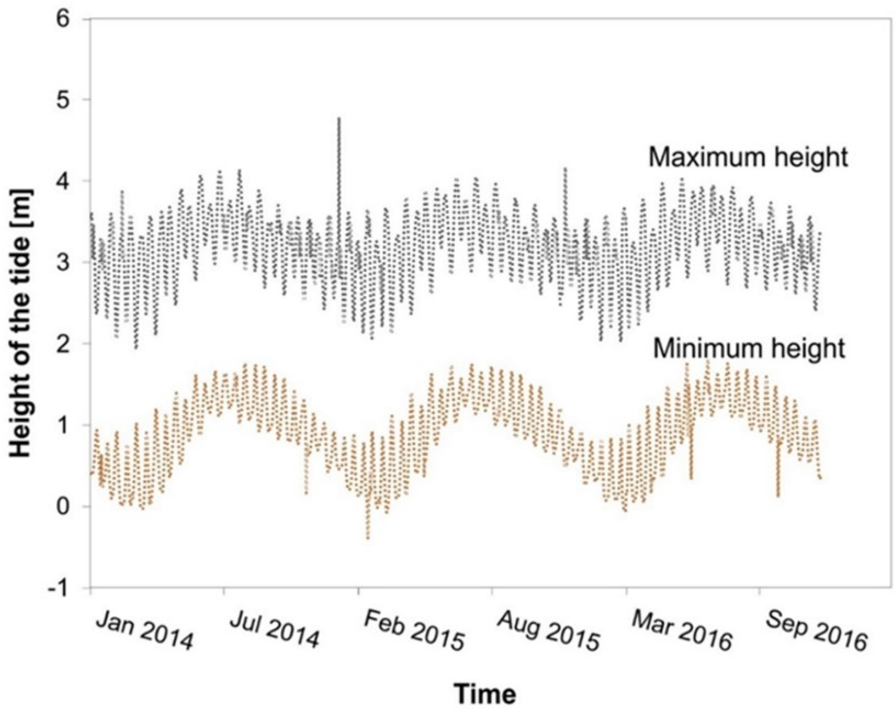

Fig. 17: Maximum and minimum tidal height in the Bakkhali river near Cox's Bazar from 2014 to 2016 (Data source: BIWTA).

Reju canal is located south of Cox's Bazar town at Ukhia sub-district. The downstream section of this canal has an average width of 120 m with a depth of 3 to 6 m. Near the town of Ukhia, the downstream of this canal falls into the Bay of Bengal after meeting with several tributaries. The water of the canal is also profoundly affected by tides from the western side, and it reaches up to several kilometers inland.

Seawater encroachment into the rivers mainly occurs during the dry period as low precipitation in the dry seasion influences the freshwater flow. The flow of these rivers is relatively dominant in the rainy season. More importantly, the porous soils on the hills and valleys store the rainwater and feed some of the streams in the dry period. However, the water of the river and canal close to the Bay of Bengal is saline throughout the year. The electrical conductivity in such a place is close to the seawater value (~49000 μS/cm). Thus, it cannot be used for other domestic and agriculture purposes except aquaculture and salt production.

3.4.4. Current state of water resources management and protection

The Bangladesh government announced the first National Water policy in 1999. Under the policy, there are some initiatives that include the water management plan, guidelines for the participatory water management and allocation of water, to ensure the equal distribution. Several policies and acts were published since then to protect and manage the water resources such as the National Water Policy (1999), Coastal Zone Policy (2005), Coastal Development Strategy (2006), Bangladesh Climate Change Strategy and Action Plan (BCCSAP 2009), the National water management Plan: Development Strategy (2011) and the Bangladesh water Act 2013.

The allocation priority will be given based on specified preferences and depending on the area and the available resources therein, like domestic, municipal use, non-consumptive use, salinity management, recreation and so on. In the policy, it was also mentioned that the government would monitor or restrict the extraction of groundwater in the vulnerable zones for maintaining rechargeable shallow groundwater aquifers. However, they were not formalized. As a result, there are no proper guidelines for actions for the water resources managers and planners. Consequently, the practice of such policy is almost absent in the Cox's Bazar area.

On the other hand, the primary goal of Bangladesh Climate Change Strategy and Action Plan (BCCSAP 2009) is to monitor the variation of quantity and quality of water due to the climate changes in the future. Under this policy the Bangladesh Water Development Board established and accomplished the project of "Establishment of Monitoring Network and Mathematical Model Study to Assess Salinity Intrusion in Groundwater in the Coastal Area of Bangladesh due to Climate Change" funded by the Climate Change Trust Fund (CCTF) of the Ministry of Environment and Forest. They have installed monitoring nested wells as well as five transects of observation wells with a spacing between the wells of 1 km to monitor the encroachment of salinity in the study area. However, there is now a lack of proper maintenance of those wells after finishing the project in 2013.

Moreover, Bangladesh Water Act 2013 is an integrated approach that applied for surface water, groundwater and rainwater throughout Bangladesh. This act gives the provision for development, abstraction, distribution, use, management, protection and conservation of the water resources. However, in practice the Water Act is not implemented properly.

The Department of Public Health Engineering of Bangladesh (DPHE) has installed a lot of wells to provide safe drinking water in the rural and urban parts of Cox's Bazar. They also have the responsibility of planning, designing and implementing water supply and proper sanitation systems in the areas.

At the same time, there are some small-scale surface water resources developments in Cox's Bazar area. One of them is Bakkhali rubber dam, developed by the Local Government Engineering Department (LGED) of Bangladesh in the year of 1995. As Bakkhali river has tidal influence from the downstream Bay of Bengal, hence the dam preserves fresh water in the upstream area and controls the saltwater encroachment from the downstream especially in the dry period of a year. This local dam can retain about 80 million m^3 of water during the months of January to May (Siddque 1996).

According to the project expected outcome, this much of water can irrigate about 6,000 ha rice land. Nevertheless, an apparent mismatch was noticeable between the water need and the maintenance of the dam during the field campaign. During the field campaign in 2015, low maintenance and fault in this rubber dam were noticed; as a result, saline water through Bakkhali river encoarched more than 10 km upstream. Therefore, regular monitoring and, maintenance of such systems is needed to maintain for long-term benefits.

4. Materials and methods

The focus of this chapter is to describe the instruments and methods which have been used during the field campaigns and in the laboratory to generate the data sets. Section 4.1 describes the wells that have been sampled and where level loggers were installed. Survey methods to collect the hotel's data and the calculation of water budget is outlined in section 4.2. The core study of this research includes the hydrochemical characterization of surface and groundwater and a vulnerability assessment of the coastal aquifer in section 4.3 and 4.4 respectively.

4.1. Groundwater level monitoring and equipment

To monitor groundwater dynamics, four automatic water level loggers (Solinst Levelogger©) were installed between October 2014 and February 2016 in monitoring wells constructed by BWDB, three closes to the touristic centers of Cox's Bazar (LW1, PZ1, OW1) and one about 20 km to the south in a less developed area (UK2). The southernmost well served as a reference point for natural water level fluctuations (Fig. 18). The depths of the wells were 49 m, 35 m, 201 m, and 53 m for LW1, PZ1, OW1, and UK2, respectively, each with a screened section along the last 9 m. Selected monitoring wells were already equipped with level loggers between February 2012 and October 2013 in a project of BWDB, and these data were available for comparison. Due to some logger failures, some time series are not complete.

4.2. Survey to identify the hotel location and water balance calculation

As information on water consumption in the area is not available, a field survey was conducted during the month of April in the year 2015. For this, all identified hotels and guest houses, a total number of 281, were categorized into three groups, based on the size and facilities. Then hotels were visited, and responsible persons were interviewed. The questionnaire covered the hotel size, number of employees, water supply system and water storage installations, information on operated wells, and occupancy rates in the peak tourist season and the off-season. Data from a total of 160 facilities could be obtained, for the rest of the facilities either information on the number of guest rooms were obtained from the respective websites or were estimated. The local population of the study area was assumed based on the total population of the Cox's Bazar area, which is about 450,000 (BBS 2013).

4.3. Water sampling and analysis

4.3.1. Sampling for the hydrochemical analysis

Extensive sampling campaigns were performed over two years, covering, therefore, two touristic seasons in two hydrological years. During four field campaigns between October 2014 and April 2016, at the end of the wet periods and the end of the dry periods, respectively, a total of 206 water samples were collected from deep tube-wells (>150 m deep), wells with an intermediate depth (50 m - 150 m), shallow wells (less than 50 m deep), and from surface water, including seawater samples. Sampling locations were chosen to (i) cover the Cox's Bazar area with the large touristic centers and potentially high groundwater extraction rates, (ii) along the coastline and along Bakkhali river, in order to identify the interaction between fresh waters and saline waters, and (iii) within Bakkhali river from the river mouth to several km upstream to analyze tidal effects in the rainy season and the dry season (Fig. 18).

Sampled deep wells with screened sections between 9 m and 30 m were part of the groundwater monitoring network of the Bangladesh Water Development Board (BWDB) and water samples from them were obtained using a submersible pump. Wells with an intermediate depth were either installed by the BWDB as monitoring wells, typically with 9 m of filter screens at the bottom, and sampled according to the deep wells, or used for public and private water supply and therefore equipped with pumps. Typically, no information on the screened sections of these wells was available. The shallow wells were either equipped with hand pumps or operated with submersible pumps by hotels for their water needs. Samples from these wells were typically taken after constant values for electrical conductivity and temperature were recorded.

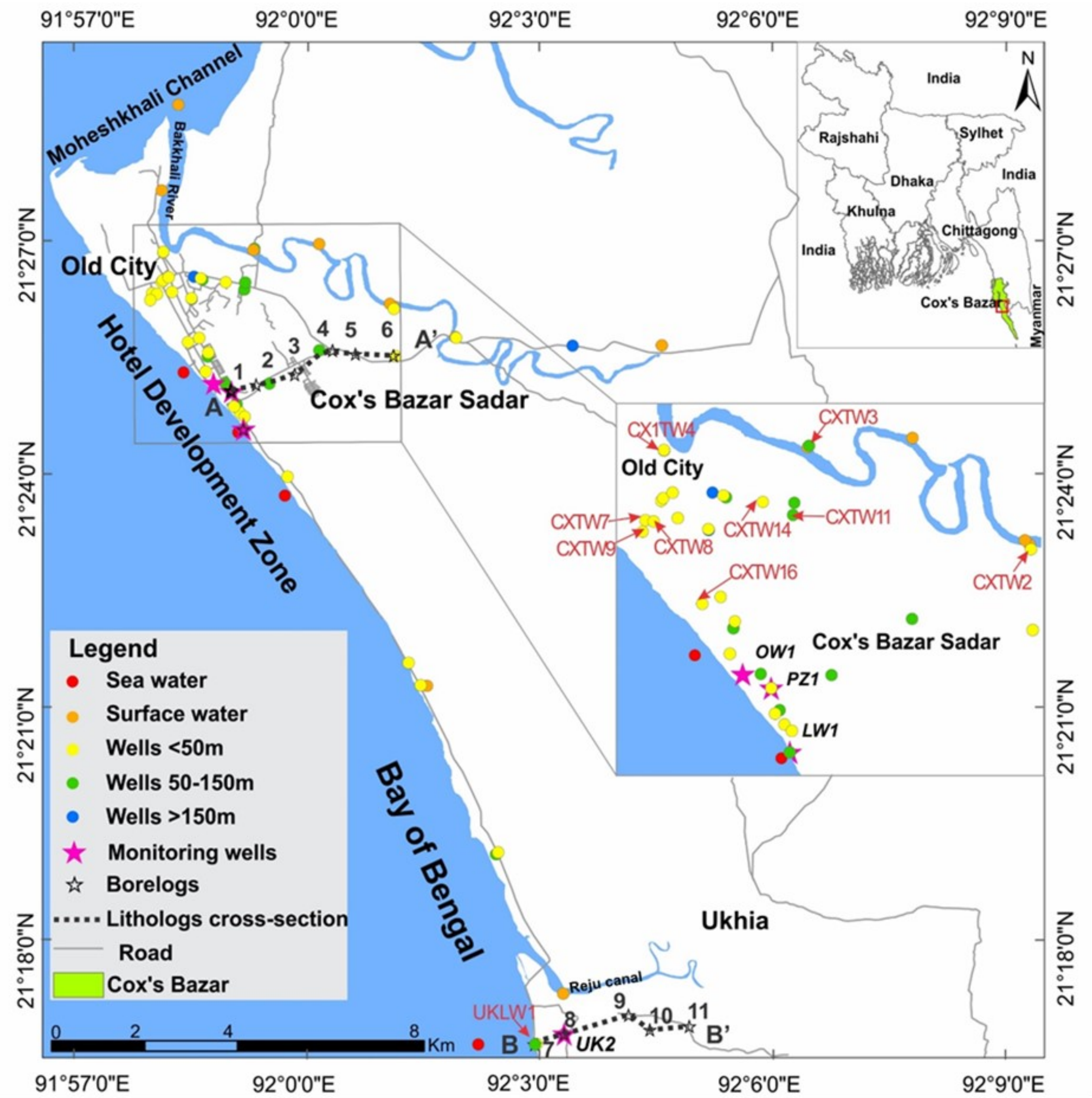

Fig. 18: Location of the study area showing groundwater and surface water sampling locations. In the magnified area the main touristic centers are located (Fatema et al. 2018).

All water samples were filtered in the field using 0.45 μm membrane filters. Basic field parameters (temperature, pH, electrical conductivity, oxygen content) were measured with WTW field probes, and bicarbonate concentrations were determined using a HACH digital titrator. At each sampling location, two samples were then collected in 100 mL polyethylene bottles for in analyses. The sample for cation analyses was acidified by adding concentrated HNO_3 and samples were then stored in a cool box until analysis. Major ions were analyzed by Ion Chromatography (two Metrohm 882 compact IC^{plus} equipped with a Metrosep A Supp 5-250 column for anions and Metrosep C 4-250 column for cations). Relative standard deviations of the analyses were 3%, the ion balances of the samples were typically within ± 7 %.

4.3.2. Sampling for the stable isotopes (δ^2H, $\delta^{18}O$ and $\delta^{34}S$)

Samples for δ^2H and $\delta^{18}O$ in water were collected during each of the four field campaigns. A total of 48 samples from groundwater, surface water, including two seawater samples were collected in each sampling period from Cox's Bazar Bangladesh. A wide cross-section was covered to collect the isotope samples near the shoreline; hotel dominated areas, in residential area, and samples of river water were collected to be influenced by the sea.

The samples were collected in 100 mL vials and stored in a cool place until analysis. The sample bottles were filled carefully to the top without leaving a headspace. Some of the samples were also pre-filtered since small suspended particles were visible.

On the other hand, a total of 11 water samples were collected for stable isotopes of $\delta^{14}S$ and $\delta^{18}O$ analysis in dissolved sulfate, including two sea samples. A certain distance was also followed to collect the samples from the shore to more landward for investigating the influence of saltwater with increasing distance. An estimated volume of water was then collected based on the dissolve SO_4 concentration measured in previous sample analysis. To analysis the $\delta^{14}S$ isotope approximately 20 mg of $BaSO_4$ is required. Therefore, 0.5 M $BaCl_2$ solution was added to precipitate dissolve SO_4 as $BaSO_4$ in the field.

4.3.2.1. Laboratory sample treatment and analysis (δ^2H, $\delta^{18}O$)

In the laboratory, 2 mL of samples were prepared for the analysis. The sample sequence was usually; first deionized water than three lab standards light, heavy, mixed and then a number of ten samples followed by another standards sequence. These stable water isotopes (δ^2H and $\delta^{18}O$) were then analyzed using a Picarro L2130-*i* Cavity Ring Down Spectrometer (CRDS) connected to a Picarro A0211 high precision vaporizer. In each run, the machine first cleans the syringe by using each sample's water after that it measures the samples six times. The average of the last three injections was then used for the final evaluation of the result. All values are expressed in the standard delta (δ) notation in per mil (‰) against Vienna Standard Mean Ocean Water (VSMOW) according to (Coplen, 1996).

$$\delta\ sample\ (permil) = \left(\frac{\text{R sample}}{\text{R reference -1}}\right).1000 \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (6)$$

Where R is the ratio of heavy to light isotopes such as $^2H/^1H$ or $^{18}O/^{16}O$ in sampled water (R_{sample}) and Standard mean ocean water ($R_{standard}$).

All the raw data were first corrected for memory effect and machine drift; then they were calibrated to the VSMOW/SLAP scale. The whole evaluation was done with a program called "SICalib" by Manfred Gröning version 2.16f from 2017. The values of $\delta^{18}O$ and δ^2H for the standard of VSMOW 2 and SLAP 2 are in Tab. 2. Two laboratory standards, which were calibrated directly against VSMOW 2 and SLAP 2, were measured in each run together with deionized water. External reproducibility defined as standard deviation of a control standard during all runs was ± 0.87‰ and ± 0.22‰ for δ^2H and $\delta^{18}O$, respectively. This reproducibility is controlled with standards over a long period. All the analysis results are given in the appendix 11 to 12 .

Tab. 2: Calibration data of standards for $\delta^{18}O$ and $\delta^{2}H$ isotopes

Standard	$\delta^{2}H$ (per mil)	$\delta^{18}O$ (per mil)
VSMOW 2	0	0
SLAP 2	-428	-55.5

4.3.2.2. Analysis of sulphur isotope ($\delta^{34}S$ and $\delta^{18}O$)

Sulphur isotopic compositions were measured after conversion of precipitated $BaSO_4$ to SO_2 using an elemental analyzer (continuous flow flash combustion technique) coupled with a gas isotope ratio mass spectrometer (delta S, ThermoFinnigan, Bremen, Germany). Sulphur isotope measurements were performed with an analytical error of the measurement of better than ± 0.3‰ and results are reported in delta notation ($\delta^{34}S$) as part per thousand (‰) deviation relative to the Vienna Cañon Diablo Troilite (VCDT) standard.

For normalizing the $\delta^{34}S$ data, the IAEA-distributed reference materials NBS 127 ($BaSO_4$) and IAEA-S1 (Ag_2S) were used. The assigned values were +20.3‰ (VCDT) for NBS 127 and 0.3‰ (VCDT) for IAEA-S1.

Oxygen isotope analysis on barium sulfate samples was carried out by high-temperature pyrolysis at 1450 °C in a thermal combustion elemental analyzer (TC/EA) connected to a delta plus XL gas isotope ratio mass spectrometer (ThermoFinnigan, Bremen, Germany) with an analytical error of better than ±0.5‰. Results of oxygen isotope measurements are expressed in delta notation ($\delta^{18}O$) as part per thousand (‰) deviation relative to Vienna Standard Mean Ocean Water (V-SMOW).

The normalization of oxygen isotope data of sulfate was carried out using the reference material NBS 127 with an assigned $\delta^{18}O$ value of +8.7‰ (V-SMOW). All the samples that were considered for this analysis can be found in the appendix 10.

4.4. GALDIT approach for seawater vulnerability assessment of the coastal aquifer

The GALDIT index is a useful tool to predict and identify the coastal groundwater vulnerability zones due to seawater intrusion, and it can also be used for the proper management of such resources (Pedreira et al. 2014; Lobo-Ferreira et al. 2007). For the evaluation of the target area, it combines its hydrogeological, morphological and hydrochemical characteristics. The current status of the aquifer systems under investigation is then evaluated using these relevant parameters that are rated and weighted according to their importance.

To calculate the index knowledge on six different parameters is required which are:

(1) **G**roundwater occurrence: In natural aquifer groundwater bearing layers may be confined, unconfined and/or leaky. In natural condition, unconfined aquifers are more prone to seawater intrusion than the other aquifer types (Chachadi and Lobo-Ferreira 2001). However, confined aquifer is rated as higher due to the large cone of depression during pumping.

(2) **A**quifer hydraulic conductivity: This parameter indicates how easy water can flow through the pore spaces of the aquifers. Usually, aquifers with low hydraulic conductivity are more prone to seawater intrusion, especially in the coastal areas (Sophiya and Syed 2013).

(3) Depth to groundwater **L**evel: This is a very important parameter as it determines the hydraulic pressure to push the saltwater front back.

(4) **D**istance from shore: The impact of seawater intrusion decreases with increasing distance from the shore.

(5) **I**mpact of the existing status of seawater intrusion: This can be determined based on different hydrochemical ratios (Cl^-/ HCO_3^-).

(6) **T**hickness of the aquifer: This parameter plays an essential role in preventing intrusion of saltwater into an aquifer, as the length of seawater intrusion toe depends on the saturated thickness as well hydraulic conductivity. Hence, higher the saturated thickness of the aquifer the more prone it is to seawater intrusion. In this study, the thickness of the aquifer exploited by the wells was calculated based on information on the sampling wells provided by BWDB as well as from the well owners.

The highlighted letters resemble the acronym GALDIT. The first three parameters and parameter number six are static and usually do not change much over time whereas the depth to groundwater may significantly fluctuate, influencing the hydraulic regime in the region.

The most important factors have weights of 4 whereas a weight of 1 is assigned to the less important factors related to seawater intrusion. Data for the six different parameters can in principle be obtained from various sources. Hence, to apply this method for the investigated area of Cox's Bazar, data of water levels and hydrochemistry from the dry period of 2015 have been used. Parameters and their weight, as well as data sources used for this study, are listed in Tab. 3.

Tab. 3: Summary of the data and the methods used to compute the GALDIT vulnerability index and scenario assessment for the Cox's Bazar coastal aquifer

Weights (W)	Parameters	Field methods used to acquire the data	Data
1	**G**	Lithological study from the well logs	32 lithologs from BWDB and DPHE
3	**A**	Pumping and slug test	BWDB
4	**L**	Water level meter and piezometer	Field measurement in 2015 and BWDB
4	**D**	Measured using a topographic map	Google maps
1	**I**	Cl^-/HCO_3^- from the lab and field measurement	Acquired from field and lab in the year of 2015
2	**T**	Bore logs data examination	BWDB and DPHE
Scenario mapping	**Sea level rise**	Value based on IPCC prediction	0.5 m
	Pumping well intensity	Field survey using GPS instrument (Garmin 62s) with real coordinates	332 wells

Also, for each parameter, ratings between 2,5 and 10 are defined based on the respective conditions or values (Tab. 4).

Tab. 4: GALDIT parameters used in the study and their ranks based on the range (Chachadi et al. 2001 with modification)

Groundwater Occurrence		**Aquifer Hydraulic Conductivity (m/day)**		**Height (m) of Groundwater Level (a.s.l)**	
Aquifer Type	Ranking	Range	Ranking	Range	Ranking
Leaky	5.0	7-9	5.0	>2	2.5
Unconfined	7.5			1.5-2	5.0
Confined	10			1-1.5	7.5
				<1	10
Distance from the Shore (m)		**Impact of Existing Status of Seawater Intrusion (Cl^-/HCO_3^-)**		**Thickness of the Aquifer (m)**	
Range	Ranking	Range	Ranking	Range	Ranking
>1000	2.5	<1	2.5	<5	2.5
1000-750	5.0	1-1.5	5.0	5-7.5	5.0
750-500	7.5	1.5-2	7.5	7.5-10	7.5
<500	10	>2	10	>10	10

Finally, the GALDIT Vulnerability Index (GVI) is calculated by multiplying the rating of each parameter by its relative weight and finally by summing up all weights (Lobo-Ferreira et al. 2007; Chachadi and Lobo-Ferreira 2001):

$$\text{GALDIT Index} = \sum_{i=1}^{6}(Wi)Ri / \sum_{i=1}^{6}(Wi) \quad \text{.............................. (7)}$$

$$= (1 * G + 3 * A + 4 * L + 4 * D + 1 * I + 2 * T) / 15 \quad \text{.............................. (8)}$$

where W_i is the weight of the i^{th} indicator and R_i is the significance rating of the i^{th} indictor. G, A, L, D, I and T are the rating factors of the parameters in the GALDIT index method. The numerical values are the weights that are set for these six indicators.

The GALDIT vulnerability index usually provides a relative assessment of the area and the higher the index, the greater the seawater intrusion potential of the coastal area of interest. Computed results are then evaluated based on vulnerability index classes (Tab. 5) (Lobo-Ferreira et al. 2007; Chachadi and Lobo-Ferreira 2001)

Tab. 5: Index of vulnerability to seawater intrusion

GVI* Range	Vulnerability Class
≥7.5	Highly vulnerable
5 to 7.5	Moderately vulnerable
<5	Low vulnerable

GVI* represents GALDIT Vulnerability Index

With this, the current vulnerability of the aquifers in the study area to seawater intrusion was evaluated, and the anticipated changes in vulnerability due to sea level rise were predicted. As Luoma et al. (2017) mentioned in their work that sea level rise caused coastal flooding which may expand the extension of seawater intrusion, resulting in saltwater pollution of the aquifers. Finally, the results were compared to current pumping well locations and hotel distribution patterns (Tab. 3).

5. Results and discussion

All the results and their discussion are ordered according to the methodology chapter. The water level fluctuation, water budget, hydrochemical and isotopes results are obtained from data which acquired during the project period. On the other hand, the vulnerability index mapping results are a combination of secondary and primary data.

5.1. Groundwater dynamics over the study period

Fig. 19 shows monthly rainfall data from the Cox's Bazar rainfall station (Station ID 11927) between February 2012 and February 2016 and the groundwater levels recorded by the data logger installed in the monitoring wells of BWDB. Rainfall data show the typical seasonality of the monsoon climate with peak rainfall between June and August and monthly precipitation depths of up to 1600 mm.

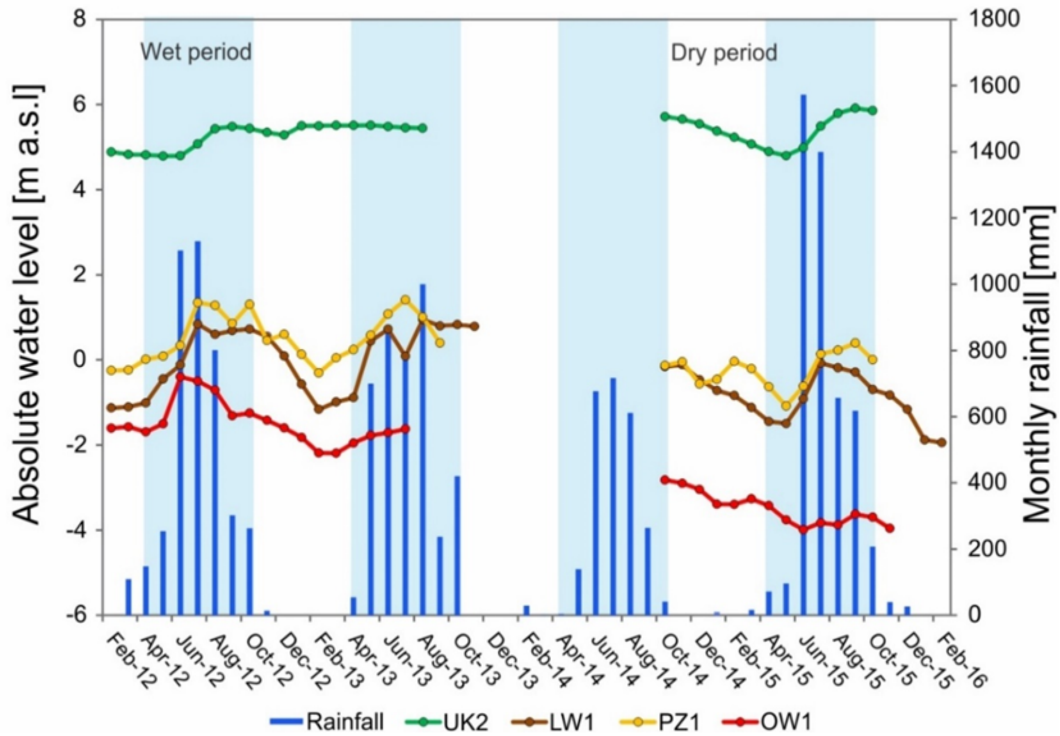

Fig. 19: Rainfall and groundwater level fluctuations in selected piezometers from 2012 to 2016. Data from the year 2012 and 2013 were collected by the Bangladesh Water Development Board (Fatema et al. 2018).

Groundwater level fluctuations in the reference well UK2 in the small village of Ukhia about 1.5 km away from the coast showed water levels influenced by seasonal effects with a decline in water level in the dry season and, with some lag-time, recovery in the wet season. Absolute water levels are well above sea level (~ 5 m) and showed no declining trend over the observation time.

The three monitoring wells close to the Cox's Bazar touristic centers also reflected the seasonal variations, but showed much more pronounced water level fluctuations, especially during the dry season (November – March) which has the peak season in tourism and therefore the season with higher water demand. Overall, a declining trend of water levels was observed over the last four years with absolute water levels of the three wells at (PZ1), or well below sea level (LW1, OW1). For OW1 a decline in water levels of about 2.2 m from the year 2012 to 2016 was observed with the water level now at 4 m below sea-level. This well is closest to the touristic centers where the large hotels operate their own production wells in the same aquifer at a similar depth. Although there are missing well distributed water level data that hinder to draw groundwater counter map for actual groundwater flow pattern here. However, the water level fluctuations of the three wells show clearly the effect of groundwater abstraction and water levels already below sea level indicate the potential for seawater intrusion.

5.2. Estimation of water consumption and water balance

The field survey revealed that there is a total of 281 hotels and guest houses in the study area, all operating their own groundwater wells. The calculated total number of rooms is about 12,000. In the peak touristic season (November to March), occupancy rates for the large hotels were reported to be on average at 60%, whereas smaller hotels and guest houses had an occupancy rate of 70%. These rates dropped to about 20% for the large hotels and 30% for the smaller hotels and guest houses in the off-season.

Total numbers of tourist were taken, and a double occupancy of the rooms assumed to calculate the water demand of the tourists, together with water consumption of 200 L/day and tourist (Gössling 2001), total water demand of 0.7 Mio m^3/a was calculated, with roughly 70% consumed in the peak season. Based on the total population in the Cox's Bazar region of 450,000 (BBS 2013), the local population in the Cox's Bazar touristic area is assumed to be about 200,000. Assuming a water consumption of 100 L/day which is typical for the population in urban areas in Bangladesh (Ahmed 2000), the water demand is about 7.3 Mio m^3, resulting in total public water demand of 8 Mio m^3/a. Although the water demand of the tourists is small compared to the demand of the local population, both numbers are connected, as the touristic sector is the main driver for the local economy and the population growth in the region. This demand is covered to the largest extent by local groundwater abstraction and any agricultural or industrial water demand in the region is further increasing abstraction.

Although the yearly precipitation in the eastern part of Bangladesh is comparatively high (3,630 mm), groundwater recharge is limited, due to the pronounced seasonality of rainfall and the thin unsaturated zone available for storage (Ravenscroft et al. 2005). Several methods have been used in Bangladesh to estimate net groundwater recharge, e.g. the water-table fluctuation (WTF) technique (Todd 1959; Healy and Cook 2002) that assumes that rises in the water level of an unconfined aquifer result from recharge arriving at the water table. For this, however, observation wells that are not influenced by abstraction are needed, which are rare in the Cox's Bazar region, and some estimates on specific yield. Shamsudduha et al. (2011) interpolated water table fluctuations derived from wells all over Bangladesh and analyzed pumping tests for specific yield determination. For the Cox's Bazar region, an annual mean recharge of about 100 mm only was estimated. Taking the water level fluctuations in the reference well UK2 of about 1 m and an average specific yield of 0.1 that was derived from pumping test data in the region, this number seems to be realistic. The calculated net groundwater recharge (0.1 Mio $m^3/(a\ km^2)$) is substantially lower than values derived from empirical correlations with precipitation for Bangladesh (Islam et al. 2014), and southeast Asian monsoon climatic conditions (Adeleke et al. 2015), of 305 and 381 mm/a, respectively. One reason for this difference can be the fact that the shallow unsaturated zone leads to frequent 'aquifer full' conditions in the monsoon period, and potential recharge water contributes to surface runoff (Ravenscroft 2003; Shamsudduha et al. 2011).

Although the database on groundwater fluctuations in the Cox's Bazar region is weak and local conditions can deviate largely from regional averages, it is obvious that the estimated low groundwater recharge (0.1 Mio m³/a km²) is unable to replenish the local water abstraction in the Cox's Bazar touristic area. In addition, most hotels are located close to the shoreline in low-lying regions just a few meters above sea-level. This leads to the declining trend in water levels as shown in Fig. 19 with groundwater levels in various wells constantly below sea level.

5.3. Hydrochemical characteristic of coastal water resources

Hydrochemical data can be used to analyze the effects of seawater intrusion into coastal aquifers, and chlorine/bromine ratios are widely used as a simple method to identify saltwater encroachment (Freeman 2007; Dror et al. 1999; Davis et al. 1998). The Cl^-/Br^- mass ratio of seawater is typically around 300 (Nair et al. 2013; Katz et al. 2011; Bear et al. 1999), and in the Cox's Bazar area a ratio of 295 was found. Also, the background ratio of unaffected groundwater has to be determined and in the study area samples were selected based on the distance from the coast and low concentration of chloride (< 5 mg/L). This was done using fresh water from a deep well (CX2PZ4), a well with intermediate depth (CXCXLW3), and a shallow well (CXCXTW3) that are 11 km, 4 km and 15 km away from the coast, respectively. The average Cl^-/Br^- ratio was found to be around four. With these two values a mixing line between groundwater and seawater can be established (Fig. 20). Results show that most of the groundwater samples are following the trend of the seawater mixing line suggesting that most of the samples were affected by seawater intrusion. Also, surface water from the mouth of Bakkhali River, where it flows to Moheshkhali Channel (Fig. 21), showed the Cl^-/Br^- ratio similar to the seawater. Those samples also have higher electrical conductivities (EC) values (46000 μS/cm) during the dry period.

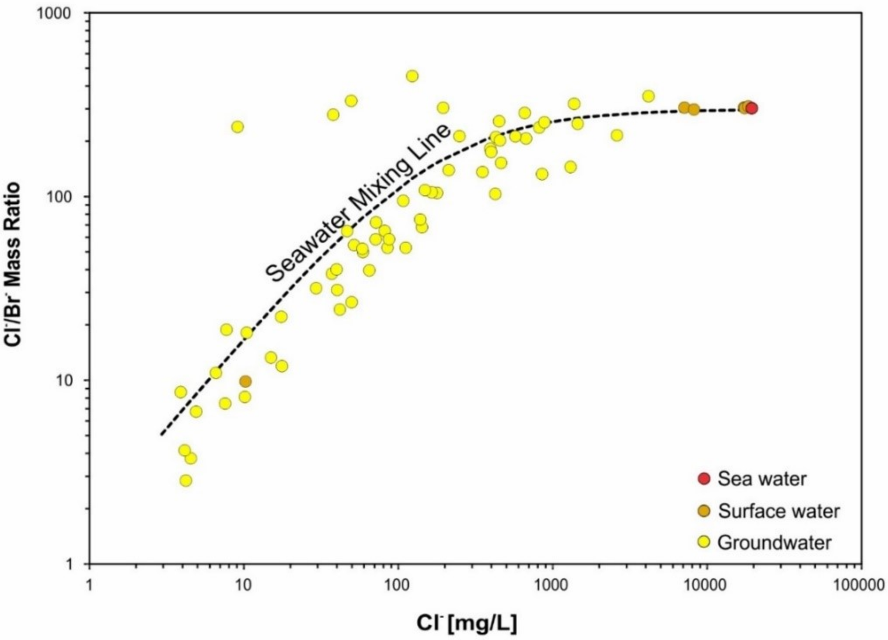

Fig. 20: Cl^-/Br^- against Cl^- concentration of the dry period of 2015 indicating mixing between seawater and groundwater as well as anthropogenic contamination (Fatema et al. 2018).

Several data points plot well above the seawater mixing line in Fig. 20, which might indicate the effects of contamination. Field investigations showed that the wells with high Cl^-/Br^- are located next to latrines or open wastewater draining channels. The drainage channels carry untreated wastewater from households as well as waste from nearby open markets. Improper disposal of untreated domestic waste can be the source for high Cl^-/Br^- ratios, as it has been shown by previous studies (Nair et al. 2013;

McArthur et al. 2012; Katz et al. 2011). These wells also contain elevated concentrations of NO_3^- and SO_4^{2-}, reaching 68 mg/L and 163 mg/L respectively. NO_3^-/Cl^- mass ratios > 0.0002 and SO_4^{2-}/Cl^- mass ratios > 0.14 can serve as an indicator of groundwater contamination by wastewater (Mtoni et al. 2013; McArthur et al. 2012; Hudak 2003). The data points located above the seawater mixing line have values of NO_3^-/Cl^- and SO_4^{2-}/Cl^- from 0.1 to 0.29 and from 0.2 to 0.6 respectively, supporting the assumption of infiltrating wastewater. In addition, most of the hotels do not have proper waste-water treatment systems, which can be a further source of wastewater infiltration.

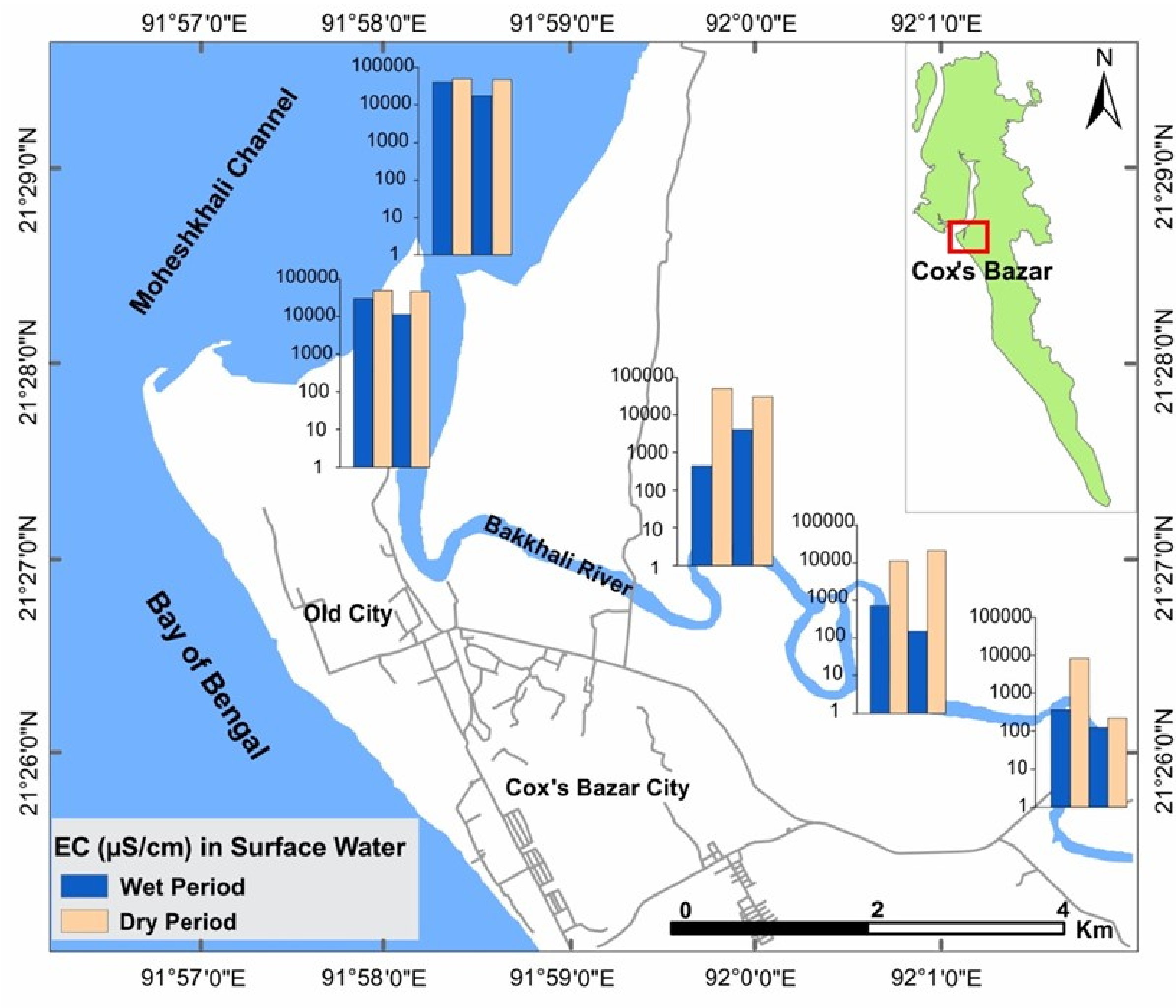

Fig. 21: Variation of electrical conductivity of surface water samples between the wet and dry period in the investigated area (Fatema et al. 2018).

The coastal aquifers in Cox's Bazar area are not only threatened by seawater intrusion from the west, but also by the intrusion of saline water from the Bakkhali river in the north and east, especially during the dry season. This is indicated by large variations in EC for surface water samples from Bakkhali river between the two wet and two dry periods covered and with distance from the river mouth (Fig. 21). The salinity in the river is heavily influenced by tidal effects, more pronounced close to the river mouth, as well as by seasonality of rainfall. Although the locals are using special rubber dams to prevent saltwater movement upstream during the dry season, effects can still be detected up to 10 km inland. The increase in salinity is typically more than an order of magnitude between seasons, with maximum EC values around 10000 μS/cm in the most upstream sampling points. Besides the absence of rainfall in the dry seasons resulting in reduced gradients between the sea and the river, the enhanced salinities during that times can also be partly due to evaporation effects and, more pronounced in the upstream part of the river, due to an increase of groundwater base flow in the total runoff.

Processes in the aquifer system can also be analyzed using the Piper diagram (Fig. 22). Symbol sizes of groundwater samples indicate their TDS, which was omitted for seawater and surface water samples due to their high TDS contents. For samples from shallow wells (< 50 m) and some samples from wells of intermediate depth (50 – 150 m), a typical Ca^{2+}-HCO_3^- fresh groundwater composition with comparably low TDS content can be delineated in the left corner of the Piper diamond. This groundwater type is reported to be typical for most alluvial aquifers in Bangladesh (Shamsudduha et al. 2008; Martinez and Bocanegra 2002). Several water samples from wells with intermediate depths and also some samples from deep wells (> 150 m) classify mostly as Na^+-HCO_3^- type. These are most likely influenced by pore water which was trapped during Holocene marine flooding in the sandy aquifers, confined by low permeable clay or silty clay layers and which went through refreshing processes together with cation exchange (Ravenscroft and McArthurb 2004; Yu et al. 2010). Therefore, those baseline waters appear in the lower corner of the diamond in the piper plot. Seawater composition as the third end member plots close to the right corner in the Piper diagram (Fig. 22 a and 22 b).

The interaction between these end members can either occur along a simple mixing line or along a path with cation exchange processes (Fig. 22), indicating either seawater intrusion or freshening. The chemistry of the water samples than either follow the mixing line or the path of freshening with cation exchange, leading to a Na^+-HCO_3^- water type (Appelo and Postma 1999; Hounslow 1995), or saline intrusion leading to a Ca^{2+}-Cl^- water type. All these processes can be identified in the Piper plot, while an upward shift of samples in the diamond of the Piper diagram indicates cation exchange and a shift towards the seawater chemistry indicates a simple mixing process. The scattered distribution of the samples mainly in between the two baseline water chemistries in the Piper plot indicates the highly dynamic coastal aquifer system and also indicates its vulnerability related to changes in hydraulic heads.

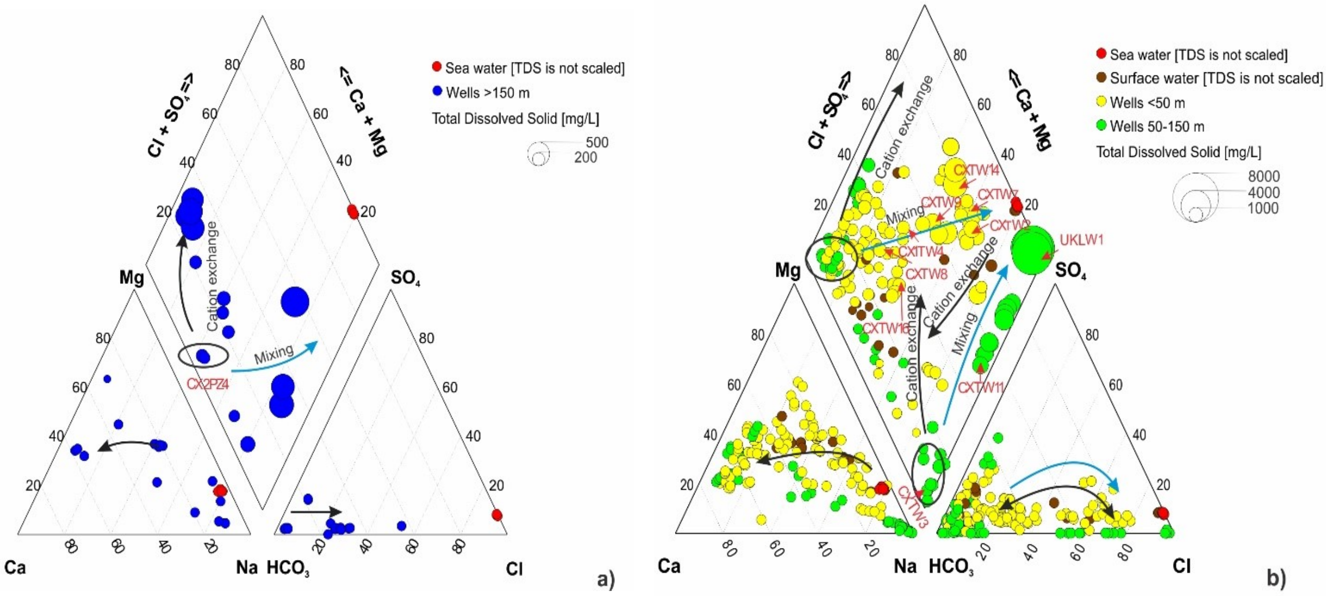

Fig. 22: Piper diagram including all samples collected. a) shallow wells (<50m), intermediate wells(50-150m) and surface water samples, b) deep wells (>150m) samples, and. The symbol size in the diamond (note the different scale for 'a' and 'b') represents the TDS value excluding the extreme values of seawater and surface water (Fatema et al. 2018).

For the surface waters from the Bakkhali river, the samples with the lowest TDS values taken upstream at the end of the rainy season plot close to the left corner in the Piper diagram. This might indicate at least a contribution of baseflow from the fresh shallow aquifers to total runoff. Samples with higher TDS values are typically taken more downstream and in the dry season plot towards the seawater corner, indicating simple mixing processes.

To analyze the dynamics of water chemistry changes between dry and wet seasons a scatter plot of Na^+/Cl^- molar ratios against Na^+ concentrations was established (Fig. 23) (EL Moujabber et al. 2006; Shanyengana et al. 2004; Mercado 1985). A Na^+/Cl^- molar ratio of 0.86 (McCaffrey et al. 1987; Mercado 1985), independent on Cl^- concentrations, would indicate simple mixing between seawater, as one end member, and freshwater, i.e. rainwater or fresh groundwater as the other end-member, having typically also a similar molar ratio close to 1 (Shanyengana et al. 2004; Mercado 1985). Samples located above the mixing line at low Cl^- concentrations would indicate dissolution effects in the aquifer, or, at higher Cl^- concentrations, could also indicate freshening effects with cation exchange. Samples below the mixing line could indicate cation exchange during seawater intrusion. For each sample point, the head indicates the location of the water sample composition in the plot (Fig. 23) at the end of the dry season in the year 2016, and the tail the location at the end of the wet season in the year 2014, thus covering the whole observation time. Both processes, freshening and seawater intrusion can be identified, while the longer the tail of the data points, the more dynamic the changes in hydrochemistry at a single location between seasons. Even for shallow wells located within the old city center (CXTW7, CXTW8, CXTW9, CXTW14; Fig. 18, Fig. 22 a, and Fig. 23) having a long history of pumping, and wells located close to the Bakkhali river (CXTW2, CXTW3) all different processes with varying intensity can be observed. It also has to be considered, that potentially a large temporal offset between changing gradients and the resulting hydrochemical effect at a specific location occurs, further complicating interpretation. Results were compared with the Base Exchange Index (BEX) proposed by Stuyfzand (2008) to distinguish between salinization and freshening process between the seasons. In all cases but one the BEX matched the processes proposed by the Na^+/Cl^- ratios, supporting the findings based on this ratio.

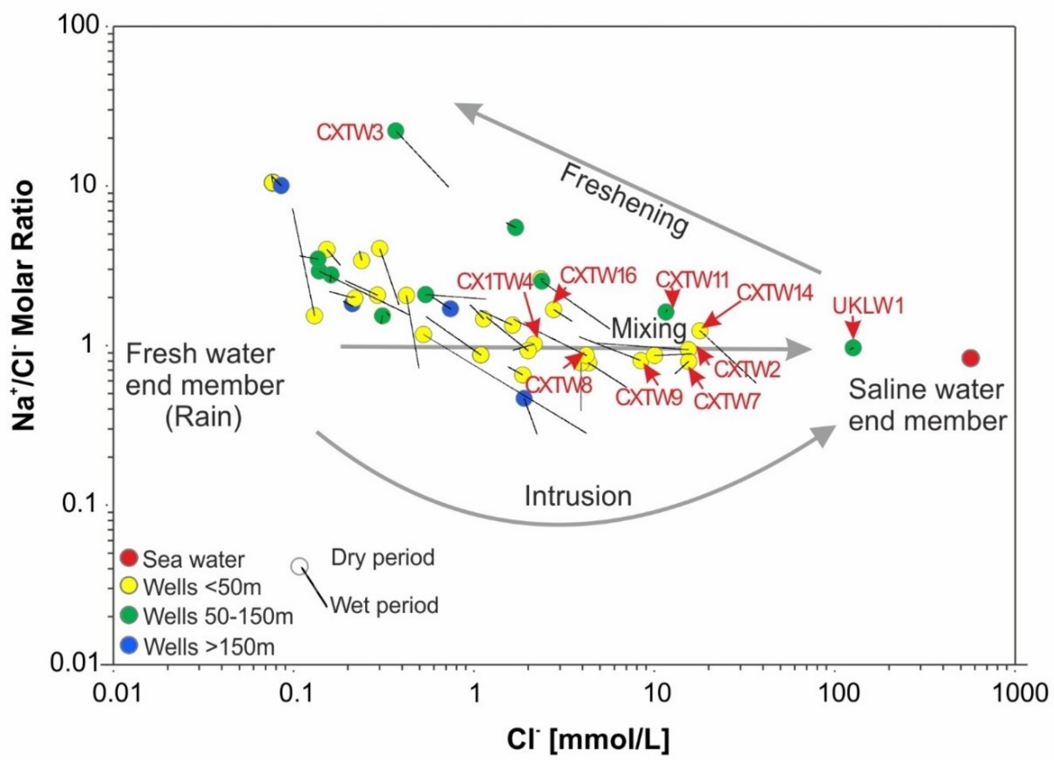

Fig. 23: Change in Na^+/Cl^- molar ratios and Cl^- concentration of water samples from the end of the wet period in 2014 to the end of the dry period in 2016. The tail of the data points represents wet period samples whereas the head depicts dry period samples (Fatema et al. 2018).

The shown strong seasonal variations in EC and hydrochemistry are typical for surface waters and groundwater in coastal regions, especially in the monsoon climate. In aquifer systems not affected by groundwater pumping, a dynamic equilibrium should be established between changes in water chemistry in the dry seasons and wet seasons, respectively. Analyzing the hydrochemical data of the two years of this study show, however, that a trend for an increased salinity of the overall groundwater can be deduced. Tab. 6 shows that, as an average of chemical analyses of all groundwater samples, all indicating parameters, i.e. concentrations of sodium and chloride as well as EC and TDS values, increase significantly from the first sampling campaign at the end of wet period 2014 to the last sampling campaign at the end of dry period 2016. This clearly demonstrates the effects of the large pumping rates leading to a gradual increase in the overall salinity of the coastal aquifers.

Tab. 6: Statistical distribution of fundamental physical and chemical parameters of collected groundwater samples over the time of 2014-2016 (Fatema et al. 2018)

Year	Parameters (mg/L)	Na^+	Cl^-	TDS(calculated)	EC(μS/cm)
2014 (wet period)	Min.	7.5	2.68	121	177
	Max.	696.7	1305	2935.7	4320
	Med.	39.5	56.2	577.8	671
	Avg.	**123** [a]	**113** [a]	**750** [a]	**920** [a]
2015 (dry period)	Min.	8.4	3	170	197
	Max.	2588.6	4265.7	71561.3	12650
	Med.	31.1	42.7	595.2	717
	Avg.	**152** [a]	**226** [a]	**852** [a]	**1176**[a]
2015 (wet period)	Min.	7.9	2.7	130.1	188
	Max.	2476.9	4176.6	7188.3	11870
	Med.	28.5	40.8	575	707
	Avg.	**147** [a]	**220.6** [a]	**843** [a]	**1112** [a]
2016 (dry period)	Min.	5.09	2.7	75.82	195
	Max.	2819	4496.3	7760	13120
	Med.	30	42.2	582.5	802
	Avg.	**167** [a]	**227** [a]	**844** [a]	**1322** [a]

[a] Indicates the increasing trend of selected parameters over the study period. Where Min. Max. Med. and Avg. indicates minimum, maximum, median and average value respectively

5.4. Assessment of groundwater recharge and seawater intrusion using stable isotopes

The stable isotopes of $\delta^{18}O$, $\delta^{2}H$ and $\delta^{34}S$ of dissolved sulfate in water are discussed in this section. They are used as a tracer to determine the seasonal variations regarding isotopic composition and to investigate the seawater intrusion in the coastal aquifer of Cox's Bazar Bangladesh. Meanwhile, another main objective is to study stable isotopes in this project to compare the results of stable isotopes with hydrochemical results in terms of saltwater investigation in the coastal aquifers of Bangladesh, as hydrochemical results of the project proved that the coastal aquifer of Cox's Bazar already prone to seawater intrusion. The results of the analysis are compared with regards to seasonality, seawater intrusion, and finally, a conclusion was made based on the interpretation of the results.

5.4.1. Isotopic composition of $\delta^{18}O$, $\delta^{2}H$ of the surface water and groundwater and it's sensitivity for freshwater and seawater interaction

The stable isotope composition of $\delta^{18}O$ and $\delta^{2}H$ were determined in the coastal area of Cox's Bazar over the period of 2014 to 2016. Comparison between the wet period (post-monsoon) and dry season (pre-monsoon) isotopic composition of the water samples were examined in this study. The $\delta^{18}O$ and $\delta^{2}H$ values of surface water ranged from 0 ‰ to -5.11 ‰ and from 0.9 ‰ to -26.54 ‰ at the end of the dry period and from -0.81 ‰ to -6.5 ‰ and from -3.28 ‰ to -42.41 ‰ at the end of wet period respectively. The groundwater isotope signature ranged from -1.1‰ to -6‰ and from -2.1‰ to -34.2‰ for the shallow wells (<50 m depth) and from -3.22‰ to -5.5‰ and from -14.41‰ to -31.3‰ for the intermediate wells (depth 50-150 m) in the period of dry month, respectively; whereas at the end of the wet period the values ranged from -2.52‰ to -6.43‰ and from -16.85‰ to -39.62‰ for the shallow wells and from -3.18‰ to -6.92‰ and from -13.39‰ to -40.97‰ for the wells depth of 50-150 m respectively (Tab. 7). The precipitation-weighted mean of rainwater ($\delta^{18}O$: -5.35 ‰ and $\delta^{2}H$: -33.92‰) is comparable with the average isotopic composition of the groundwater (Tab. 7). The resulting rainwater isotope values are also used as a freshwater end member in this research.

Tab. 7: Seasonal range of $\delta^{18}O$ (‰) and $\delta^{2}H$ (‰) of the water samples

Sampling period		Shallow wells			Intermediate wells			Deep wells			Surface water		
		Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.
2014 (Wet)	$\delta^{18}O$ (‰)	-6.43	-3.73	-4.84	-5.14	-3.18	-4.4	-5.32	-3.24	-4.38	-4.65	-0.81	-3.46
	$\delta^{2}H$ (‰)	-39.62	-19.62	-27.45	-28.35	-13.39	-23.4	-28.0	-11.45	-22.26	-26.23	-3.28	-19.6
	d-excess (‰)	9.6	13.57	11.26	9.28	13.12	12.10	11.0	14.52	12.76	Avg. 8.12		
2015 (Dry)	$\delta^{18}O$ (‰)	-6.0	-1.1	-4.41	-5.5	-3.6	-4.4	-5.6	-3.2	-4.6	-2.80	0.18	-0.81
	$\delta^{2}H$ (‰)	-34.2	-2.1	-23.4	-31.3	-15.3	-23.4	-31.9	-11.7	-23.6	-10.73	3.55	-2.43
	d-excess (‰)	7.0	14.4	11.8	9.2	13.8	12.2	12.6	14.3	13.3	Avg. 4.0		
2015 (Wet)	$\delta^{18}O$ (‰)	-5.46	-2.52	-4.76	-6.92	-3.55	-4.85	-5.67	-3.83	-5.13	-6.50	-2.54	-5.37
	$\delta^{2}H$ (‰)	-31.7	-16.85	-26.35	-40.97	-14.38	-25.52	-30.1	-19.90	-27.45	-42.41	-16.69	-33.93
	d-excess (‰)	9.11	13.57	11.81	9.84	14.70	13.31	10.76	16.30	13.61	Avg. 9.01		
2016 (Dry)	$\delta^{18}O$ (‰)	-5.48	-2.22	-4.47	-5.42	-3.22	-4.33	-7.60	-3.67	-5.07	-5.11	-0.12	-1.75
	$\delta^{2}H$ (‰)	-33.68	-16.89	-26.29	-31.11	-14.41	-23.73	-46.2	-16.74	-27.69	-26.54	-0.68	-9.91
	d-excess (‰)	7.29	12.34	9.46	8.96	13.22	10.91	9.06	14.59	12.87	Avg. 4.08		

Where Min. Max. and Avg. indicates minimum, maximum and average value respectively

The stable isotope composition of the surface water samples collected from the Bakkhali river and Reju channel are shown in Fig. 24 together with the Global Meteoric Water Line (GMWL) derived from the equation of $\delta^{2}H = 8\ \delta^{18}O + 10‰$ (Craig 1961) and the Precipitation Weighted Least Squares Regression (PWLSR) that represents the Local Meteoric Water Line (LMWL) of Cox's Bazar. Rainwater data were collected from the IAEA, Global Network for Isotopes in Precipitation (GNIP) from 2014 to 2016. Symbol sizes indicate the amount of rain in millimetre (Fig. 24). Precipitation data are further divided into pre-monsoon, monsoon, and post-monsoon. Pre-monsoon precipitation data are isotopically more enriched compared to the monsoon and post-monsoon data (Fig. 24). During the pre-monsoon period warm airmasses travel from the Bay of Bengal towards inland that might be the reason for this isotopic enrichment. In addition, four seawater samples from the Bay of Bengal were collected to determine the isotope values for the seawater end member. The average $\delta^{18}O$ and $\delta^{2}H$ value of seawater is 0‰ and -0.2‰, respectively (Fig. 24) which is close to the VSMOW standard seawater ($\delta^{18}O$=0‰ and $\delta^{2}H$=0‰) value.

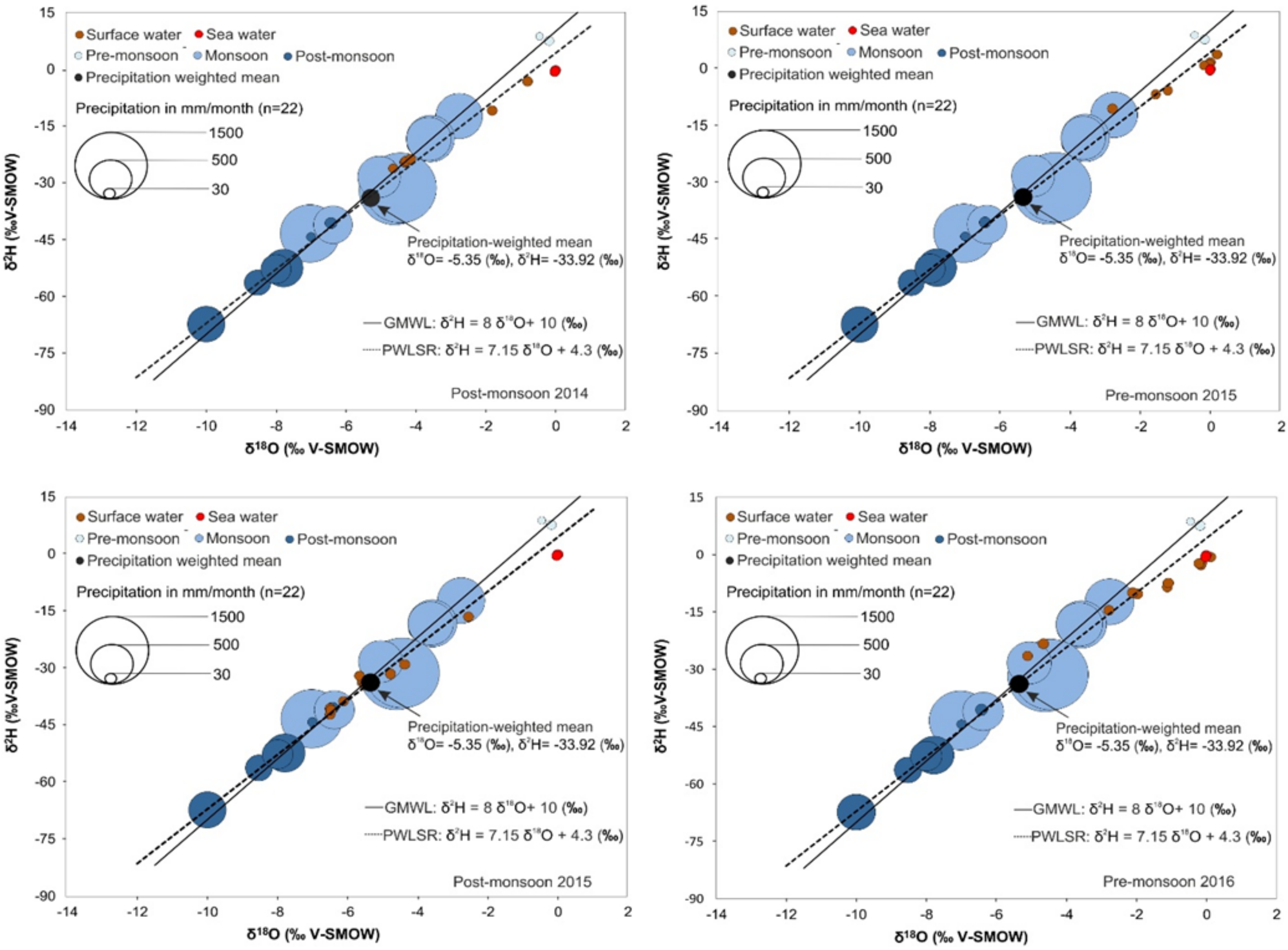

Fig. 24: Distribution of $\delta^{18}O$ and $\delta^{2}H$ isotopes in surface water between 2014 to 2016, GMWL (Craig 1961) and PWLSR from GNIP station of Cox's Bazar. Symbol size indicates precipitation values.

In Fig. 24, surface water samples plot well along the LMWL, both, for the end of wet and the end of the dry months of the study period. In the dry period, surface water samples close to the mouth of Moheskhali channel (Fig. 18) showed considerable differences in the stable isotope compositions ($\delta^{18}O$= -2.38‰; $\delta^{2}H$= -0.2‰) which can be explained by the combined effects of low precipitation in the dry period and the tidal influence. In the case of simple mixing of freshwater that has not undergone significant evaporation with seawater, samples should plot along the mixing line of two end members (freshwater and seawater). Indeed, there is no indication of evaporation effects in the isotope values of those water samples. In the period of pre-monsoon 2015 and 2016 (dry months) samples are shifted far towards the direction of seawater, indicating a strong enrichment of isotope values that show the seawater intrusion in the surface water body. The increasing trend of electrical conductivity between the dry and wet season confirms this assumption (Fig. 25). On the other hand, river discharge and relatively high precipitation reduces the effect of seawater mixing in river water and explains why the isotope values of the post-monsoon 2015 (end of wet period) are more negative (Fig. 24). In addition to this, few samples are located close to the precipitated weighted mean as the local rubber dam was closed during the sampling period which might prevent seawater encroachment more upstream.

On the other hand, the isotopic composition of groundwater samples of shallow wells (depth <50 m), intermediate depth wells (50-150 m) and deep wells (>150 m) show little differences between dry and wet season. Although the EC values of the groundwater samples between wet and dry period showed an increasing trend (Fig. 25), the values are scattered along the LMWL as well as the weighted mean value of precipitation (Fig. 26). This indicates that there might be negligible mixing of groundwater with the seawater. In addition, the scattered isotopic signatures of the groundwater samples might be due to the scattered isotopic composition of the rainwater. However, it might be also due to seawater mixing with freshwater or because of evaporation effects in the samples. The similar patterns of isotopic composition between shallow wells and deep wells (Tab. 7) is also suggesting that the water was recharged under similar conditions.

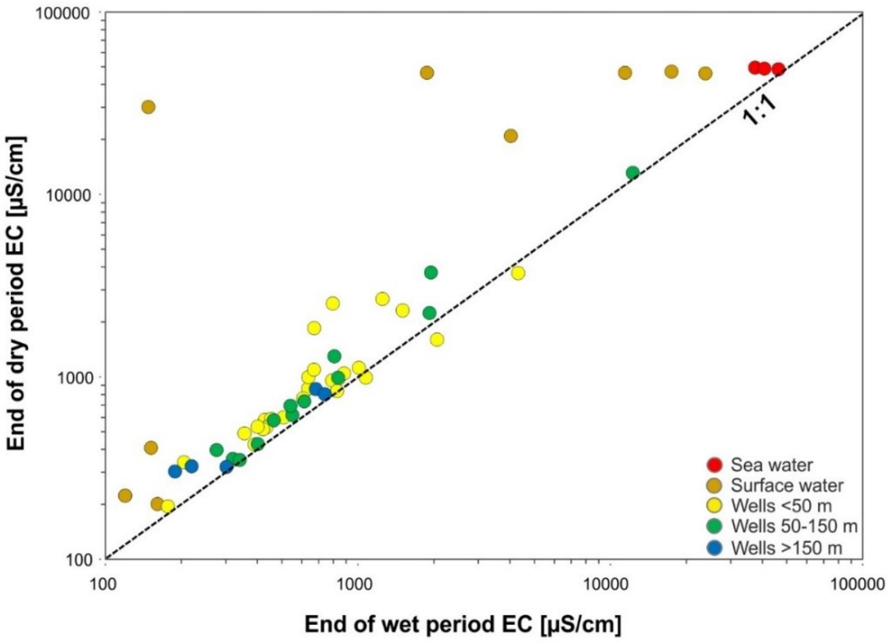

Fig. 25: Distribution of electrical conductivity between the wet and the dry period of 2014-2015.

However, opposed to the isotope results, hydrochemical results, especially the Cl^-/Br^- ratios presented in the previous section and EC values in Fig. 25 show that there is a clear influence of seawater in the aquifer. Therefore, a trend of the stable isotope composition of the groundwater towards the seawater end member was expected but was not found on the groundwater samples (Fig. 26).

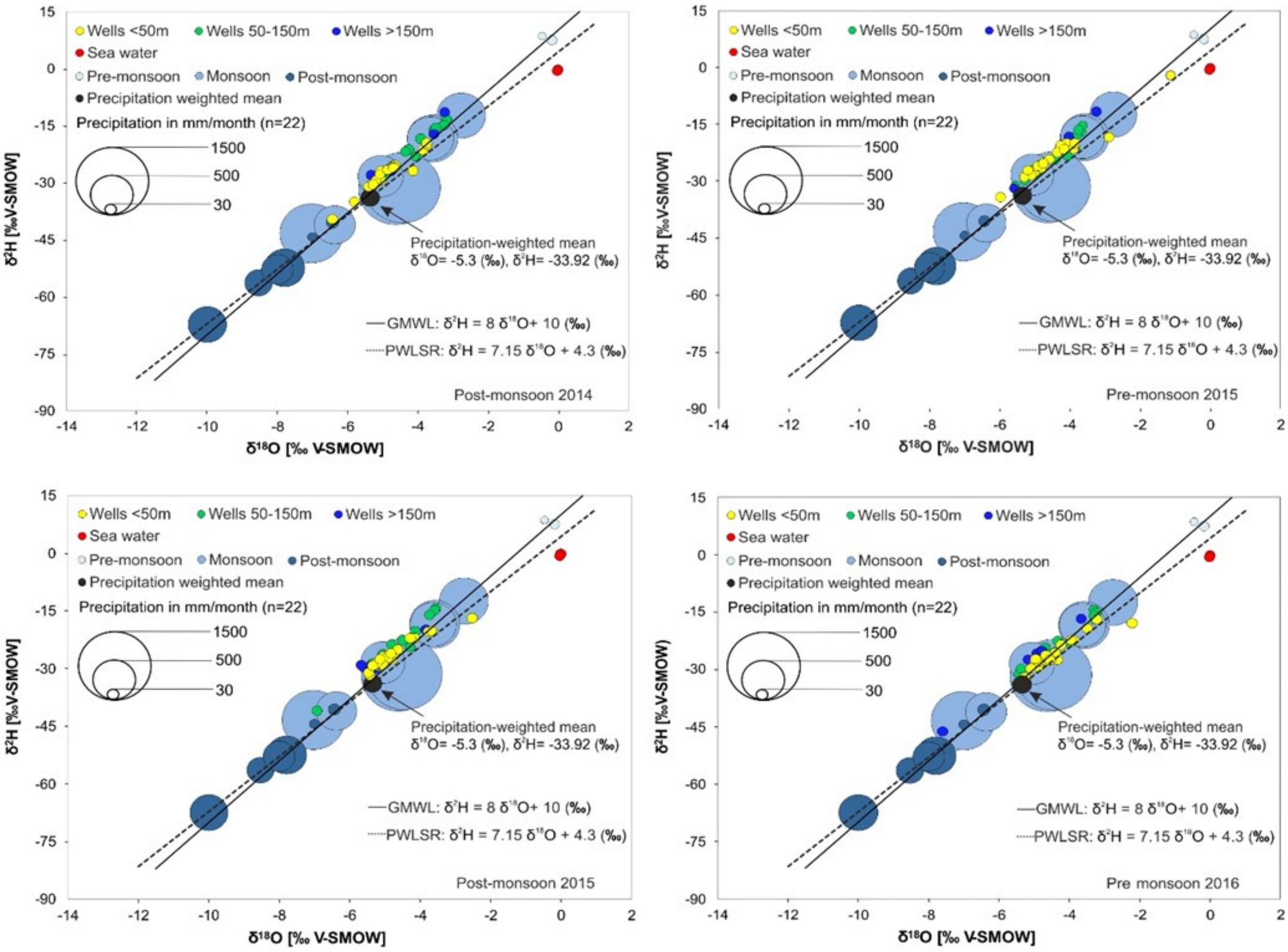

Fig. 26: Cross plot of the δ^2H and $\delta^{18}O$ of all groundwater samples from 2014 to 2016, GMWL (Craig 1961) and PWLRS from GNIP station of Cox's Bazar. Symbol size indicates precipitation values.

As hydrochemical data proves that this coastal aquifer is affected by seawater intrusion to some extent, an apparent seawater contribution (f_{sea}) was calculated based on the chloride concentrations in the samples. This is a simple method widely used to investigate seawater intrusion (Appelo and Postma, 2005) into aquifers. Based on the chloride concentrations, the apparent seawater contribution (f_{sea}) varies from 1 to 25 % in groundwater and 4 to 99% in surface water, depending on season and distance. However, a maximum of about 25% seawater contribution would cause an $\delta^{18}O$ enrichment by 1.3‰ only. Therefore, the water stable isotopes are not a sensitive indicator for seawater intrusion as expected changes are within the data scatter of the samples (Fig. 26).

In Fig. 27, samples CXTW7 and CXUKTW1 are displaying seawater contributions of ~5% and ~3% respectively, based on the EC-values, however, they are plotted along the local meteoric water line. Although both samples indicate the same amount of seawater contribution, they are located quite apart from each other, which might be a result of different initial isotopic compositions, due to differences in the time the water was recharged. Therefore, the influence of seawater is difficult to identify in this aquifer by using the stable isotopes of $\delta^{18}O$ and $\delta^{2}H$.

Another possible reason could be that the stable isotopic compositions of the two end members (fresh water and seawater) are not different enough. As it is shown in Fig. 26, the isotopic composition of the seawater plots quite close to the LMWL. Therefore, the mixtures between freshwater and seawater do not significantly plot away from the LMWL and might therefore not be noticable. At the same time, the slope of the evaporation line in humid regions is also close to the LMWL (Clark and Fritz 1997), and the isotopic signatures of rainwater througout the year scatter over a large part of the LMWL. Therefore, the stable isotopes of $\delta^{18}O$ and $\delta^{2}H$ may not be sensitive enough to indicate mixing of seawater and freshwater in a humid coastal area like Cox's Bazar.

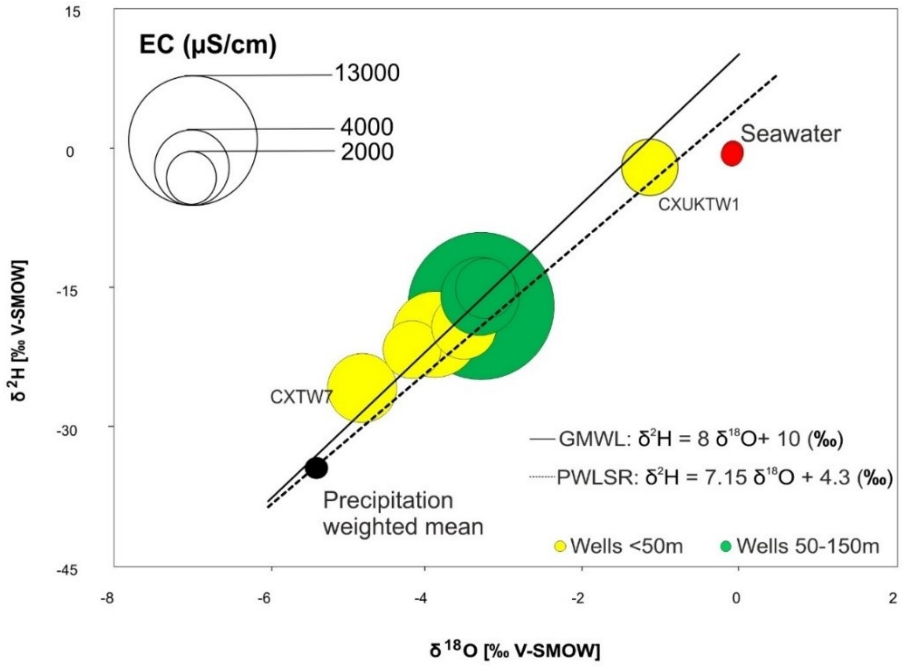

Fig. 27: Isotopic composition of selected groundwater samples in compare with EC contribution. The symbol size indicates the EC of the samples.

5.4.2. Sulphur isotopes to identify seawater intrusion

Fig. 28a shows the distribution of $\delta^{34}S$ and $\delta^{18}O$ in sulphate of the selected groundwater samples and in seawater. Sulphur isotope values are varying significantly from 2.2 to17.66‰. Due to the low variation in $\delta^{18}O$ values no clear trend between $\delta^{34}S$ and $\delta^{18}O$ values can be obtained. However, plotting the isotopic composition of $\delta^{34}S$ over the distance from the coast, a clear trend can be seen, with sulphur isotope values getting more negative with increasing distance (Fig. 28 b). The isotopic signature of $\delta^{34}S$ of the seawater end member from the Bay of Bengal has the highest value of 20.42‰. The symbol size represents the mass ratio of SO_4^{2-}/Cl^-, and also here a clear trend of increased values can be seen with distance from the coast.

CXUKTW1 is a shallow hand pump well located ~100 m from the coast of Bay of Bangel (Fig. 28 b). The $\delta^{34}S$ isotopic composition (~18‰) of the water from this well quite closely reflects that of the Bay of Bengal water (20,42‰), although, based on EC values, the seawater contribution is only 3 %. This shows how sensitive the sulphur isotopes are, as the sulphate concentrations in seawater greatly exceed the sulphate concentrations in the freshwater. Similarly, well CXTW7 is located ~600 m from the shore (Fig. 28 b) suggesting that also this water contains a significant amount of dissolved sulphate from seawater. The nice negative liner correlation between $\delta^{34}S$ and SO_4^{2-}/Cl^- mass ratios further indicates the sweater influence in the groundwater samples (IAEA 2000).

In addition, CXTW7 plots in the lower part of the local meteoric water line (Fig. 27), suggesting that this water has not been significantly affected by seawater. This in contrast to the results of the $\delta^{34}S$ (Fig. 28 b) and Na^+/Cl^- data (Fig. 23), and also the SO_4^{2-}/Cl^- mass ratio of 0.2 is close to the seawater (0.1). The apparent contribution of seawater based on chloride concentration varies between 3% to 5% in the CXTW7 as well, and this small seawater contribution cannot significantly change the water isotopic composition, as still 95% to 97% of the water is freshwater. The contribution of seawater in the well may be a result of groundwater extraction, since the well is located close to the coast in the old city centre of Cox's Bazar where most of the hotels are situated (Fig. 18) and can further be a result of low rainfall in dry periods with low recovery of water levels.

In line with these two samples, results of the other selected samples are confirming that the $\delta^{34}S$ composition in dissolved sulphate decreases with increasing distance, and SO_4^{2-}/Cl^- mass ratios also increase from 0.1 to 0.5 with increasing distance from the coast of Cox's Bazar, indicating that seawater influence with distance from the coast decreases.

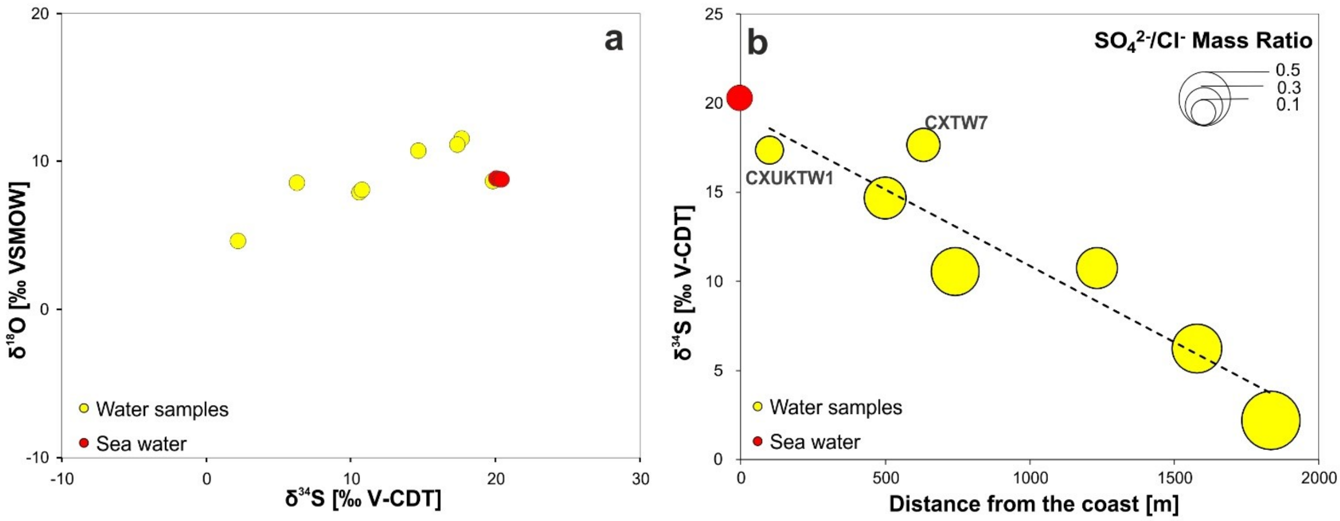

Fig. 28: Cross plot of $\delta^{34}S$ and $\delta^{18}O$ of selected water samples. On the right, the relationship between the $\delta^{34}S$ and the distance from the coast of Cox's Bazar. The symbol size represents the mass ratio of SO_4^{2-}/Cl^-.

Conclusions drawn from the sulfur isotopes are consistent with the hydrochemical and hydrological data indicating seawater intrusion into the coastal aquifer in Cox's Bazar. In addition, sulfur isotopes were found to be much more sensitive to show this, compared to, e.g. the stable isotopes of water.

5.5. Assessment of seawater intrusion potential in coastal aquifers using GALDIT vulnerability index

The geological, hydrological and hydrochemical data summarized in the previous sections allow a qualitative assessment of current aquifer vulnerability as well as of potential vulnerability in the future due to changes in the hydrological system. These can be triggered i.e. by the increasing water demand of the tourist industries as well as by a growing population, leading to increased groundwater abstraction in the coastal zone. Furthermore, expected sea level rise due to climate change will also have an impact on the hydraulic conditions in the study area.

5.5.1. GALDIT groundwater vulnerability mapping

The GALDIT approach was applied in the hotel dominated area as there is a high-water demand in a relatively small area, which is satisfied by local groundwater abstraction. There is also a high likelihood of increasing water demand due to the expansion of the tourist sector. The area is surrounded by the Bay of Bengal on the west and Bakkhali River on the east, enabling seawater intrusion from both sides as already proved by the hydrochemical data.

The sandy aquifer in the study area is mostly unconfined in the eastern part with some confined and leaky parts in the west. It is recharged mainly by infiltration. According to Chachandi et al. (2001), an unconfined aquifer has a rating of 7.5, as under natural condition an unconfined aquifer is in principle more affected by seawater intrusion. (Fig. 29).

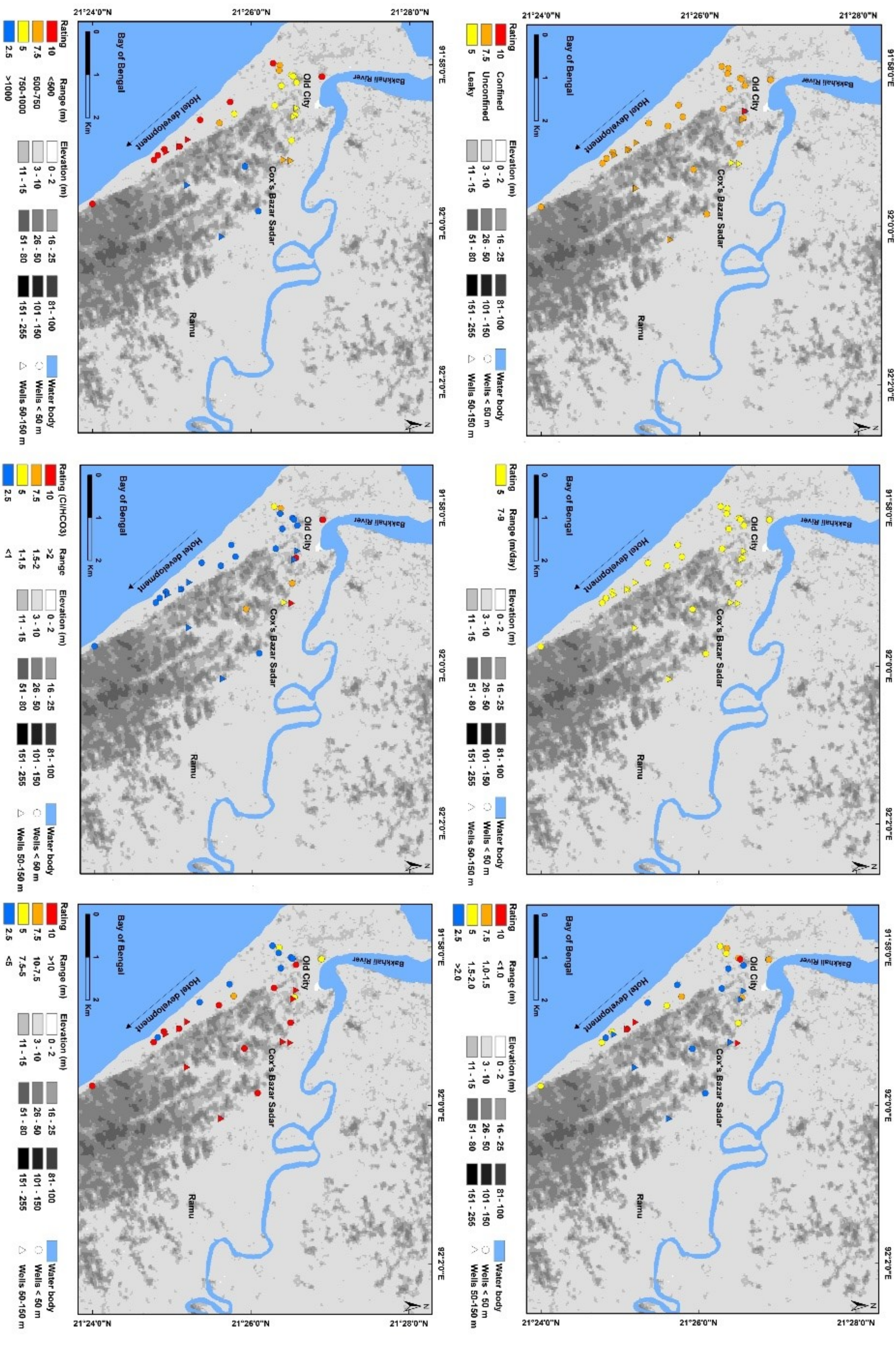

Fig. 29: Parameters of GALDIT method for the Cox's Bazar coastal aquifers.

The hydraulic conductivity data for the aquifer were collected from the pumping and slug test data from BWDB. Values for the hydraulic conductivities do not vary much over the study area and range from 7 to 9 m/day.

The height of the groundwater above means sea level was calculated from the groundwater level measurements in the dry month of the year 2015. The wells which are closest to the shore line, as well as wells that are located close to large hotels, have water levels ranging from -8 to 5 m. On the other hand, wells located in the old city center have values ranging from -3 to 6.5 m. Most of the hotels were earlier located in the old city center, and now they are expanding along the coast. Therefore, some of the wells that are in the old city area and next to the big hotels have water levels below or close to sea level.

Wells that are close to the coastline and near to the Bakkhali river in the north eastern part of the study area are typically more affected by seawater intrusion compared to wells further away. The minimum distance of wells to surface waters is 20 m. For the GALDIT vulnerability calculations distances ≤ 500 m were ranked as 10 whereas distances ≥ 1000 m were ranked as 2.5, indicating the decreasing risk that these wells are affected by seawater intrusion.

Also, existing hydrochemical data can be evaluated, rated, and implemented in the GALDIT calculations, as the fresh water has a different chemical composition compared to seawater. As fresh water is dominated by Ca^+ and HCO_3^- (Richter and Kreitler 1993) and Cl^- dominates seawater$^-$ and Na^+, it was suggested by Chachadi and Lobo-Ferreira (2001) to use the ratio between Cl^- and HCO_3^- to account for the current status of seawater intrusion in a study area. Minimum values of the Cl^-/HCO_3^- ratio (0.01) were recorded in the south-eastern part of the study area, indicating minor or no current seawater intrusion, while in the old city area with hotels that are operating for extended periods values greater than 1 are present. These areas were consequently ranked as 10 in the GALDIT calculations.

The six defined parameters are then implemented into a GIS, and the spatial distribution of the GALDIT index is computed (Fig. 30). According to Chachandi and Lobo-Ferreira (2001) the higher the GALDIT index, the greater the vulnerability to seawater intrusion in the area.

The GALDIT model of Cox's Bazar indicates that the highest potential for seawater intrusion is present in the western part, particularly along the shoreline of Cox's Bazar (GVI ≥ 7.5) where most of the hotels are located. The negative values of the groundwater head, -2 to -8 m about the sea-water level, are also a clear indication of overexploitation of the groundwater resources.

In the northern part of the study area especially close to the Bakkhali river and the old city center, the vulnerability to saltwater encroachment is moderate (GVI value 5 to 7.5) due to the influence of tide, water consumption from the local population and old hotels. Likewise, electrical conductivity (>1000 to 4540 μS/cm) and negative piezometric head in a hotel development zone in Cox's Bazar include the possible seawater intrusion which can be explained by the high-water demand in the dry period, low precipitation and flat elevation of this coastal area. More than that, Cl^-/HCO_3^- the value of the wells is ≥ 1 indicating the existing impact of saltwater in the aquifer. More importantly, the results for the shallow wells (<50 m) showed that two out of 23 wells in the study area were classified as highly vulnerability group of GALDIT index model and 18 of them as a moderately vulnerable group. This research results also revealed that 9% and 78% of shallow wells is highly and moderately vulnerable to seawater intrusion respectively and 13% is potentially at low risk under the present condition. Whereas, three intermediate depth wells (50-150 m) were identified as highly vulnerable out of 9 monitoring wells. Some wells in the old city center area show low levels of vulnerability (GVI value ≤5), which is related to the limited wells' depth and the distance from the saline surface waters.

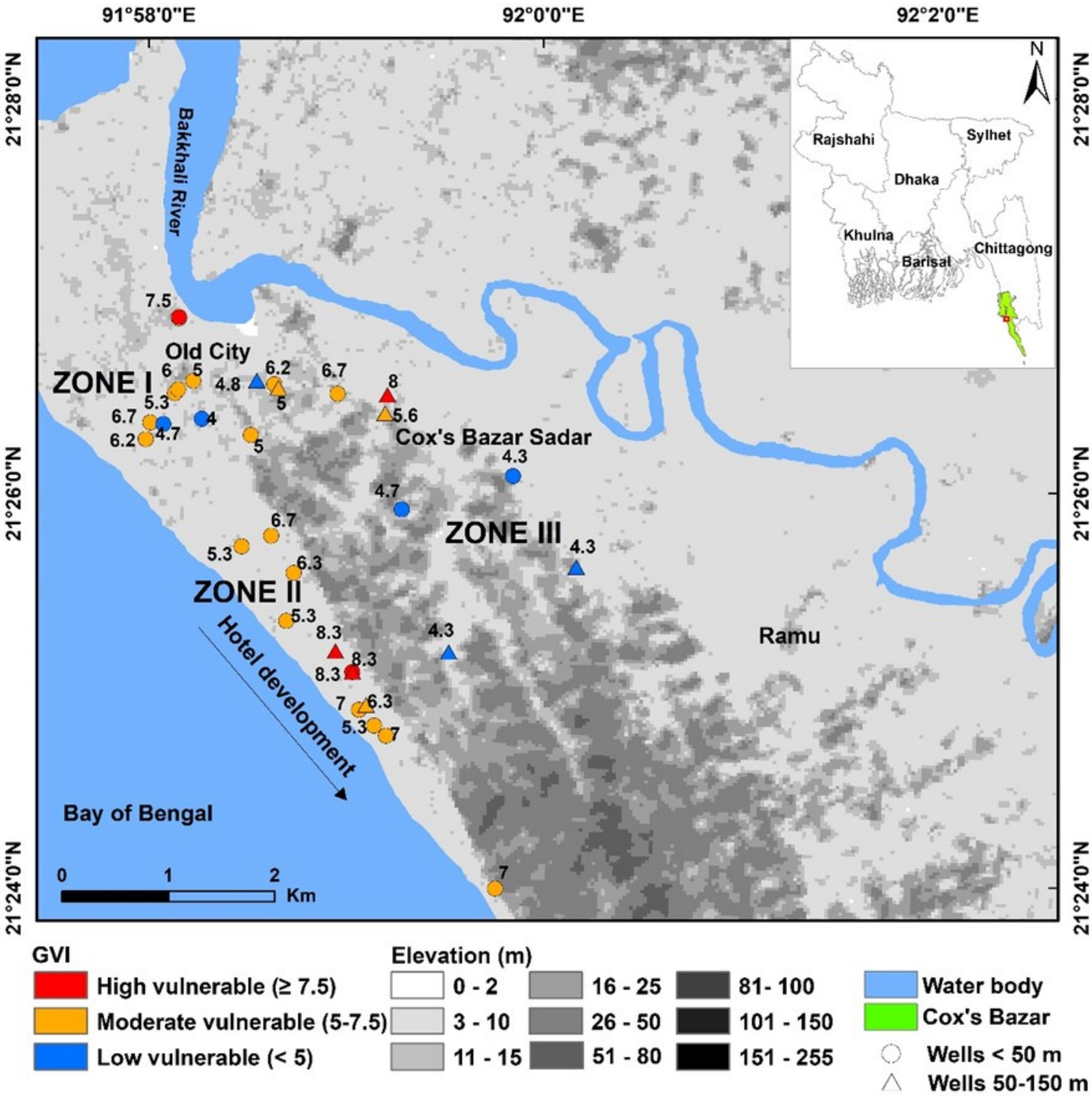

Fig. 30: GALDIT vulnerability map of the Cox's Bazar coastal aquifer. Zone I, II and III represent the locality, hotel development and less exploitation of groundwater zones respectively.

In the south-eastern part which is relatively elevated (>20 m) and where wells are typically further away from the shore compared to other parts of the study area, low vulnerabilities (GVI value ≤5) to seawater intrusion are calculated. This is also reflected by the low electrical conductivities (~ 300 μS/cm) of the groundwater in this region.

The differences in the vulnerability index in this research indicate three distinct zones. Zone I and II, the old town of Cox's Bazar (I) and the shoreline with rapid hotel development (II), are highly vulnerable as expected, while zone III in the south-east is currently not at risk, due to the higher elevation and more sparse population. As the population and tourism industries are increasing rapidly in zones I and II, the situation is likely to get worse, if no actions are taken.

5.5.2. Risk and scenario assessment of seawater intrusion in the Cox's Bazar coastal aquifer

5.5.2.1. Scenario 1: Seawater hazard based on the pumping wells distribution

In future scenarios, two main factors might influence the risk of seawater intrusion in this area, (i) increasing water consumption by the growing tourist industry and a connected growing local population with increased water demand and (ii) sea level rise due to the climate change, especially considering the flat topography of the study area.

Fig. 31 shows the distribution of pumping wells which were active during the study period. These are 332 wells including the sampling wells used in this study and identified hotels' wells. Other private wells were not considered. The highest density of pumping wells is in the western and the north-eastern part of Cox's Bazar city (Fig. 31), representing the areas with the largest volume of water extraction. According to Trabelsi et al. (2016) areas with 7 to 12 wells per km^2 are highly hazarded zone compared to zones with less than 2 wells per km^2. In the study area, the density of the wells is more intense as shown in Fig. 31. The area of interest for this modelling belongs to the Jhilwanja union of Cox's Bazar Sadar upazila. Considering the total area of 29 km^2 of Jhilwanji union, an average density of the wells is 11 per km^2. In addition, distribution of the wells varies between 3 to 114 per km^2 only considering the areas along the shoreline and old city center of Cox's Bazar. Although the wells are not evenly distributed it already shows the area is highly hazarded zone to saltwater intrusion. Total households of the Jhilwanji union are 7406 (BBS 2013) if all the households consist of one well; the intensity of vulnerability would be more intense in this coastal aquifer.

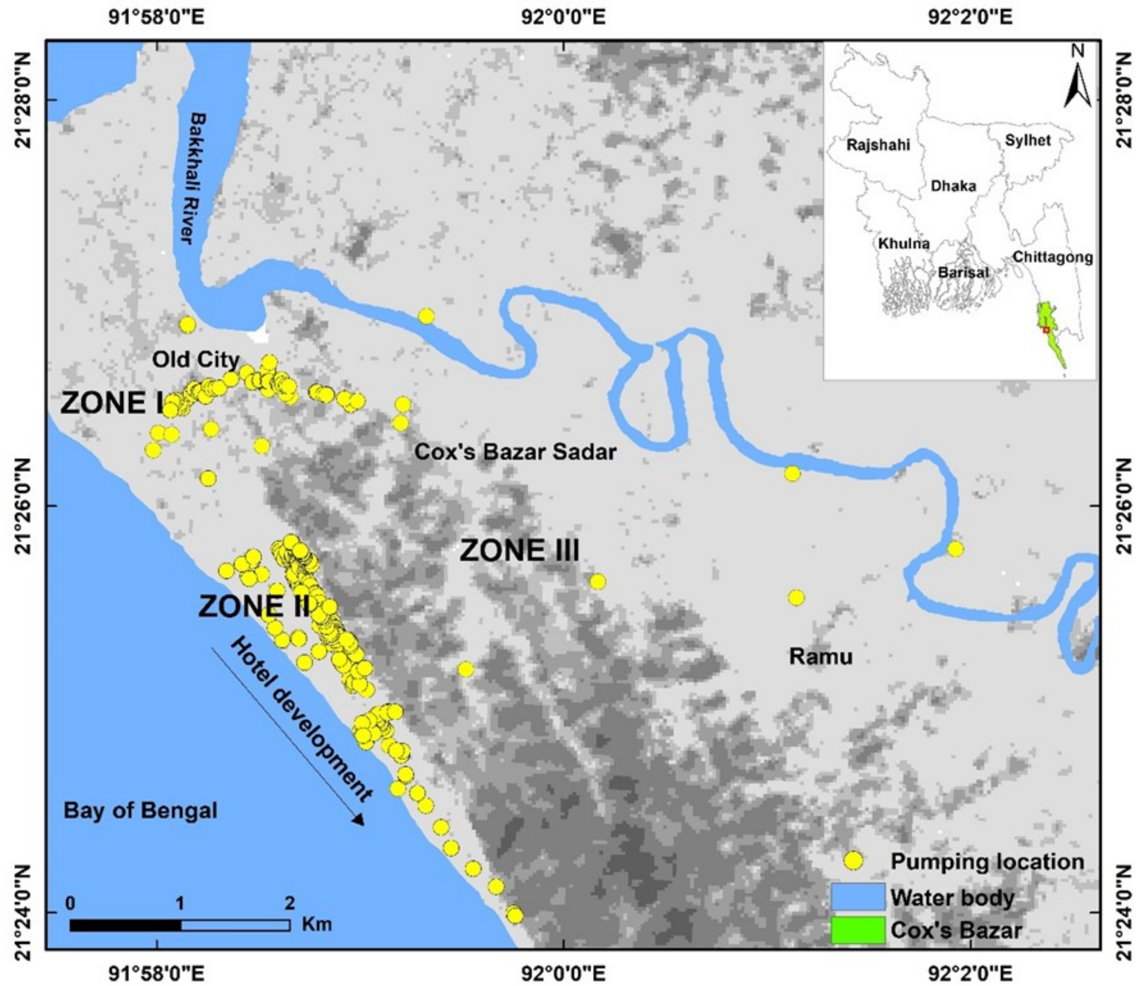

Fig. 31: Distribution of the pumping wells in the study area.

More importantly, if the distribution of the pumping wells is compared with the GALDIT vulnerability index (Fig. 30), the zones of vulnerability correspond well with the pumping wells distribution (Fig. 31) in the area. Both the vulnerability index map and pumping well density map indicating that the area along the shore and the old city center are high-risk zones compared to the other parts of the coastal aquifer. This confirms that the main reason for seawater intrusion in this reason due to the over-extraction of wells for the increasing tourists and population water demand. Likewise, it is mentioned in the previous section, that the calculated recharge and the water consumption based on the tourist and local population demand do not balance for the long run. Therefore, the further lowering of water level in this tourist area enhanced the seawater intrusion if more attention is not taken from now on the vulnerable zones especially zone I and II respectively.

5.5.2.2. Scenario 2: Computation of vulnerability index in the context of sea level rise

Sea level rise in principal has the same effect as lowering the water level in the aquifer due to pumping, as gradients are influenced. As Bangladesh considered one of the more vulnerable countries to sea level rise, a sea level rise of 0.5 m (based on IPCC 5th assessment report, sea level rise in Bay of Bengal 20-90 cm by 2100) was considered in the GALDIT model (Fig. 32).

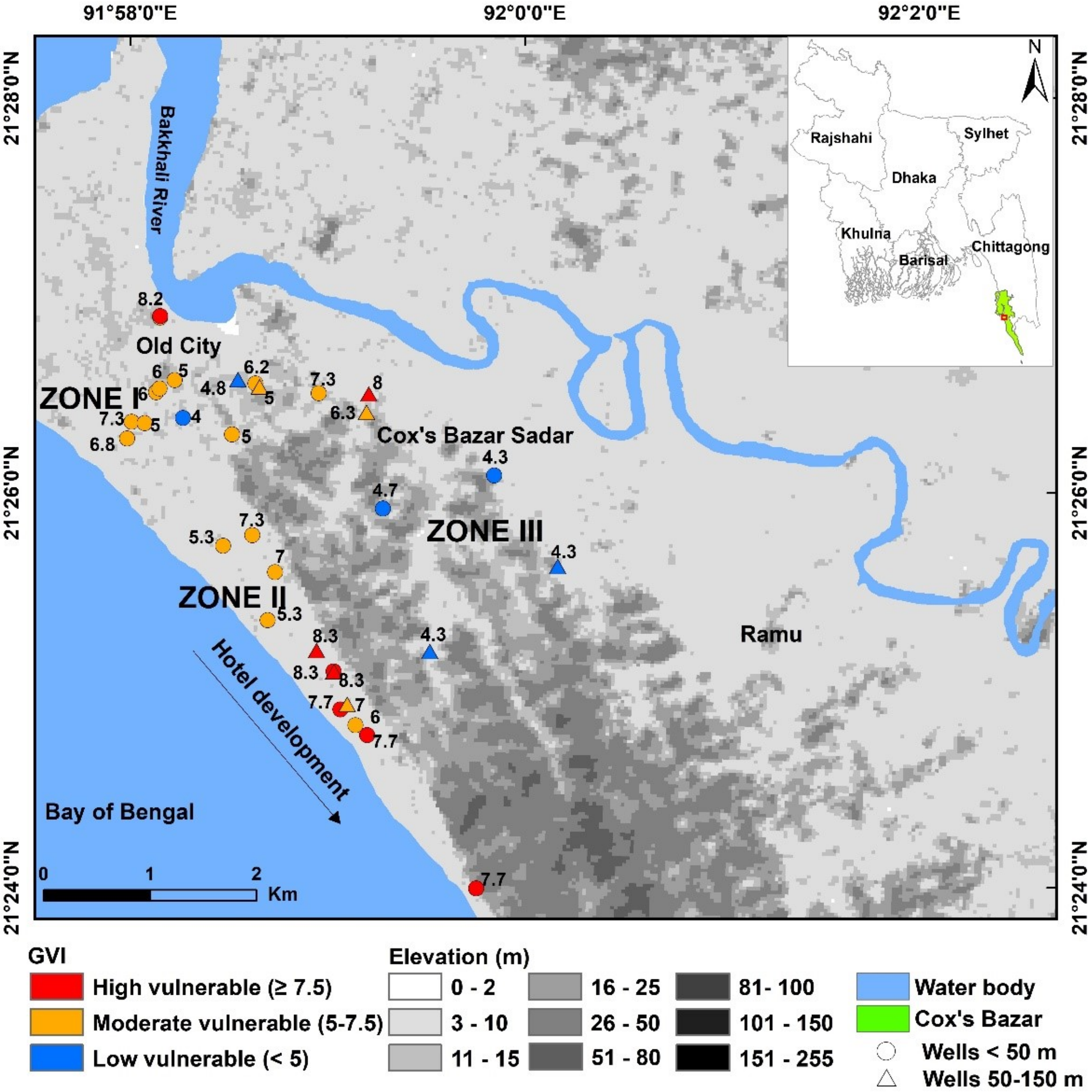

Fig. 32: Computed GALDIT vulnerability Index (GVI) of the Cox's Bazar coastal aquifer for the scenario of sea level rises 0.5 m.

In this case, the groundwater level above MSL was changed based on the sea level rise (SLR) scenario of 0.5 m. So, SLR of 0.5 m scenario resulted in a 0.5 m reduction in groundwater level above mean sea level (MSL). This evaluation shows that the wells which are not currently affected by seawater (Fig. 30), sea level rise of 0.5 m has intensified the extent of saltwater in the aquifer (Fig. 32) and could be more intense than the GALDIT approach predicted in Cox's Bazar coastal aquifer. Fig. 32 also illustrates that the area of highest risk of seawater intrusion remained same with regards to current water level, i.e. area close to Bay of Bengal and eastern part of the Bay; however, with greater risk. The GALDIT vulnerability index for some of the wells located close to the Bakkhali river as well as close to the Bay of Bengal changed from moderate to highly vulnerable, and the values raise from 5 to 7.7 in some cases.

The simulation results also show that about 22% of the shallow wells (<50 m) are highly vulnerable to saltwater where it was only about 9% based on the current sea level. The extent of saltwater vulnerabilities could be more intense in this coastal aquifer if GALDIT index model would consider sea level rise of 1 m and 1.5 m for simulation of saltwater intrusion vulnerabilities. As the sea level increased, the areas of highest saltwater intrusion vulnerability expanded and intensified. However, this figure is also important for considering in GALDIT model for the future risk assessment with pumping factor on coastal groundwater.

Additionally, some zones require basic recommendations due to the change in the natural system. This characteristic of the study area needs to be considered for sustainable groundwater management. Consequently, special attention is required in the western part as well as north-eastern part of the Cox's Bazar which is characterized moderate to highly vulnerable based on GALDIT vulnerability index model. Additional risk activities should not be allowed to protect coastal resources and the economic advantages of the tourism sector. The high distance of pumping wells installation should be maintained both in the hotels and domestic sector around highly vulnerable areas. Meanwhile, excessive exploitation of groundwater and installation of wells in the low vulnerable zone should not be considered for the shake of conservation and protecting the coastal resources.

Although, there is a lack of well distribution of sampling wells and lithological information that restricts GALDIT method to calculate the area of the aquifer affected by seawater intrusion. This might be a drawback of the method in such a case of Cox's Bazar area. However, the visual overview of seawater intrusion vulnerabilities of GALDIT model can be a qualitative indicator of rational decision making for the water resources management of coastal aquifers like Bangladesh.

6. Conclusion and outlook

6.1. General conclusion

In the coastal area of Bangladesh, the multi-layered aquifers system represents a complex hydrogeological environment. Exploitation of the fresh groundwater as a result of the increasing water demand, due to the growing population and the tourist industry, is of great concern, as the aquifer is especially vulnerable to seawater intrusion from the Bay of Bengal in the west. Besides the groundwater abstraction, this is also due to natural reasons, e.g. the low hydraulic gradients between seawater and groundwater, and the pronounced seasonality of rainfall. In addition, the Bakkhali river enables the intrusion of saline water from the north, as seawater encroachment was observed up to 10 km inland. These natural and man-made conditions result in highly dynamic hydraulic conditions in the aquifer system. Due to the sole dependency on groundwater, however, water levels in some touristic centers have gone already below sea level, and a persistent trend of declining water levels has been observed.

Such a condition can drive the system out of an assumed long-term steady state condition, which is consistent with an overall trend of increasing salinity of the groundwater over time.

Besides water table information, hydrochemical parameters, i.e. stable water isotopes (^{18}O and ^{2}H) and stable isotopes of ^{34}S and ^{18}O in dissolved sulphate, have been used to investigate the potential sources of salinity in Cox's Bazar coastal aquifers. The stable isotopic composition of ^{34}S in sulphate turned out to be more effective, compared to the stable isotopes of ^{18}O and ^{2}H, for identifying mixing of freshwater with seawater, especially in the humid climate of Bangladesh. The results of sulphate isotopes are also consistent with major ion chemistry and physical parameter of the water samples. This indicates that the simple to measure physical and chemical parameters EC, Cl^-/Br^- molar ratios and SO_4^{2-}/Cl^- mass ratios can be an inexpensive and handy tool in special climatic condition to investigate the saltwater intrusion, as compared to other more expensive methods. However, in some cases combined approach of hydrochemical and isotope methods can be a useful tool to understand the coastal aquifers system in a better way.

The GALDIT approach was found to be a practical method for identifying the current state of risk and future potential risks of saltwater contamination in the coastal aquifer of Cox's Bazar, as a result of over-exploitation and climate change effects. The results of this model identified zones that are more prone to seawater encroachment and therefore are in need for specific attention in the management of the resources. The final map revealed that the aquifers in the hotel dominated area and the old city center are suffering from elevated seawater intrusion vulnerability, compared to the south-east part of the study area. Expected sea level rise will substantially enlarge the extent of vulnerable areas.

However, Cox's Bazar is economically of major importance for Bangladesh, and therefore a strategic planning especially related to the management of the water resources is needed. However, up to now this issue has received little attention or intervention from responsible water management authorities Moreover, the dense population and the growing tourism in Cox's Bazar area contradicts with both, the water quality and quantity available in the area. Water supply and storage problems are already obvious and will be more severe in the future, demanding an improvement of local water resources management. To ensure sustainable development of the Cox's Bazar touristic region, strategies for water management and a regulatory framework need to be implemented, keeping the specific conditions of the area in mind. National and regional water laws are a necessity for proper water budgeting. However, currently there is virtually no monitoring of abstraction rates in the area, and poor water management by the tourist sector may result in a disaster for future operations. This is especially true as a significant increase in the water demand can be expected in the years to come, due to the anticipated growth of population, the tourist sector, and agricultural activities in Cox's Bazar are. There are no hard numbers on the costs associated with the unsustainable water use in the region, but there is no doubt that efficient measurements that can reduce water use will be economical. If seawater intrusion will increase in the future it will be almost impossible to reverse this. Thus, investment and regulations on water use will give a chance for sound and sustainable future in Cox's Bazar area of Bangladesh.

Additionally, to meet the water demand in the future, a well-designed conjunctive development of surface and groundwater resources is necessary. Thus, increased use of surface water, concepts of managed aquifer recharge (MAR), aquifer storage and recovery (ASR), rainwater harvesting, water reuse, or seawater desalination might provide solutions for the future.

6.2. Outlook

The water demand in Cox's Bazar will increase in the future. In principle, however, water is not a scarce resource in the region. With a yearly precipitation of 3,630 mm, falling almost exclusively in the monsoon season, problems arise mainly due to the mismatch between water availability and demand. Therefore, methods can be considered that make use of the excess available water in winter through temporal storage.

In the monsoon period, rainwater flows from the steep hilly southeastern part of Cox's Bazar into the Bay of Bengal. Due to the heavy rainfall and steep slopes and low recharge, a substantial amount of the water is lost to the sea. Thus, the use of retention ponds with small connecting channels can also be a solution to store the rainwater flows from the hilly area in the dry season for domestic as well as agricultural use. Also, rainwater harvesting could be an effective choice for future use and a source for artificial groundwater recharge to reduce the stress on the coastal groundwater resources. These possible options can alleviate the potable water in the area where groundwater is affected by saltwater contamination especially in the old city area of Cox's Bazar.

Furthermore, usage of domestic water must be guaranteed by a stable centralized water supply system. A complete guideline is also needed to switch from the private wells to centralized tap water, with an appropriate pricing. Most importantly, fresh coastal groundwater should be reserved for the production of drinking water, and not for aquaculture, hatchery and even agricultural activity. Instead, people can use surface water during the low tide to minimize the tidal influence.

During the study period, it was noticeable that the status of hydrological, hydrogeological and meteorological data in Cox's Bazar area was relatively weak compared to the the southwestern part of Bangladesh, although Bangladesh Water Development Board has some monitoring wells for groundwater level observation. There is a lack of continuous monitoring data for the future management concepts, thus, the government and responsible authorities should put stress on the necessity of continuous data gathering for the evaluation of groundwater resources in such a tourist development area.

Additionally, a model is highly recommended to idealize the actual system of the study area. For a well calibrated model, data on actual groundwater recharge, uniformly distributed water level data, river discharge and obviously well distributed lithological information should be collected. Moreover, groundwater dating that will also be useful for the identification of modern or ancient saltwater mixing with the freshwater system, such as seawater, brackish or brine water in the area.

Recently a long marine drive of 80 km from Cox's Bazar to Teknaf has been opened along the Bay of Bengal. One side of the marine drive displays beautiful mountains, the other side is the scenic Bay of Bengal. This unique landscape of Cox's Bazar will unlock the door for more tourism and hotels development and every effort has to be made to preserve this for future generations.

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Appendix

Fig.- App.1: Impact of growing tourist industries in the study area of Cox's Bazar, Bangladesh. A) Unplanned hotels development along coast, B) Waste dumping in the water body by tourists, C) Improper waste management.

Fig.- App.2: Measurement of field parameters during field campaign in Cox's Bazar.

Fig.- App.3: Preparation of sulphur isotope samples in the field (precipitated $BaSO_4$).

Monitoring well

Sample collection

Installation of data logger

Fig.- App.4: Sample collection and installation of data logger for the water level measurement.

Tab.- App. 1: Current population of the Cox's Bazar Sadar and the projected population in the coming year (Based on BBS 2011 data)

Years	1981	1991	2001	2011	2021	2031	2041	2051
Population	186000	254000	348000	459000	619585	836352	1128957	1523932

Tab.- App. 2: Maximum relative humidity, temperature, and the precipitation over the period of 1980 to 2011

Months	**Relative humidity in % (monthly avg.)**	**Temperature in ℃ (monthly avg.)**	**Rainfall in mm (monthly avg.)**
January	98	27	5
February	98	29	20
March	99	32	31
April	99	33	96
May	99	33	330
June	100	31	835
July	100	30	935
August	100	31	689
September	100	31	411
October	99	32	226
November	99	31	86
December	98	28	15

Tab.- App. 3: Chemical parameters of the collected water samples in the study period of 2014 (end of wet period)

Sample ID	Date	Na (mg/L)	K (mg/L)	Mg (mg/L)	Ca (mg/L)	Cl (mg/L)	Br (mg/L)	NO_3 (mg/L)	SO_4 (mg/L)	HCO_3 (mg/L)	Wells Depth (m)
CXTW1	Oct-14	20.25	2.10	1.38	1.78	2.68	0.49	1.84	5.19	85.4	<50
CXTW2	Oct-14	110.57	16.22	13.93	1.62	164.40	1.56	3.56	31.93	151.28	<50
CXTW4	Oct-14	35.14	3.20	37.31	99.26	138.89	1.86	2.71	24.41	334.28	<50
CXTW5	Oct-14	27.26	5.96	31.31	23.69	148.63	1.37	5.97	31.48	209.84	<50
CXTW6	Oct-14	41.24	10.05	29.20	26.53	38.35	0.79	54.02	23.74	236.68	<50
CXTW7	Oct-14	199.49	16.62	53.72	46.50	462.59	3.03	4.96	58.32	229.36	<50
CXTW8	Oct-14	55.89	12.03	31.18	31.58	59.02	1.19	7.05	26.07	358.68	<50
CXTW9	Oct-14	100.18	16.50	91.71	57.93	136.27	2.67	1.45	42.72	592.92	<50
CXTW10	Oct-14	40.67	10.22	3.46	64.73	41.57	1.10	34.88	18.86	407.48	<50
CXTW12	Oct-14	20.83	1.74	13.37	21.76	8.21	0.91	1.13	7.17	173.24	<50
CXTW13	Oct-14	146.04	2.16	9.53	27.76	87.07	1.49	1.75	20.63	422.12	<50
CXTW14	Oct-14	490.87	9.56	114.39	329.21	1305.24	9.03	9.38	99.53	568.52	<50
CXTW16	Oct-14	106.93	23.34	42.32	48.26	98.24	1.98	1.08	29.54	468.48	<50
CX1TW4	Oct-14	35.41	15.56	33.40	60.25	58.51	1.13	20.85	18.79	329.4	<50
CXCXTW1	Oct-14	18.95	4.62	19.28	50.43	19.36	0.87	0.63	28.00	239.12	<50
CXCXTW3	Oct-14	16.36	4.37	2.39	2.38	3.50	0.52	2.85	3.32	129.32	<50
CXCXTW5	Oct-14	120.33	19.49	131.73	299.09	659.59	2.32	50.65	55.74	226.92	<50
CXCXTW6	Oct-14	39.48	10.82	43.32	34.62	33.76	1.31	1.48	30.49	314.76	<50
CXCXTW8	Oct-14	88.35	10.14		43.23	249.10	1.17	58.45	75.48	70.76	<50
CXHTW1	Oct-14	18.07	2.20	8.96	7.48	56.20	0.74	3.61	22.24	187.88	<50
CXUKTW1	Oct-14	328.92	14.99	54.35	71.35	573.72	2.70	5.19	63.55	341.6	<50
CXCX1PZ1	Oct-14	23.80	3.16	29.00	169.37	34.88	1.32	0.10	114.42	395.28	<50
CXTW3	Oct-14	165.28	1.03	0.15	0.27	5.87	1.53	0.84	0.25	402.6	50-150
CXTW11	Oct-14	448.61	2.37	6.06	12.01	424.94	4.11	7.67	0.24	561.2	50-150
CXTW15	Oct-14	696.75	3.01	8.83	18.26	854.46	6.46	5.23	0.30	561.2	50-150
CXCXTW7	Oct-14	204.21	0.94	0.13	0.56	49.88	1.88	1.84	0.93	417.24	50-150
CXCXLW1	Oct-14	11.20	1.86	11.12	49.79	5.44	0.85	1.04	7.28	219.6	50-150
CXCXLW2	Oct-14	11.54	2.33	4.54	10.34	9.57	0.77	1.08	0.73	204.96	50-150
CXCXLW3	Oct-14	8.70	2.50	23.49	68.88	3.49	1.22	2.60	17.94	380.64	50-150
UKLW2	Oct-14	589.51	2.52	3.55	27.83	549.57	5.58	2.53	0.28	624.64	50-150
CXCX1PZ2	Oct-14	7.51	2.72	13.93	38.45	3.66	0.72	0.17	14.08	366	50-150
CXHoTW1	Oct-14	17.66	2.81	27.62	148.31	40.26	1.30	2.39	160.43	463.6	50-150
CXDTW1	Oct-14	12.26	2.60	61.04	47.37	82.97	1.46	5.95	9.19	309.88	>150
CX2PZ4	Oct-14	20.82	8.81	3.48	2.50	2.94	0.58	1.84	2.35	104.92	>150
CXCX1PZ4	Oct-14	8.81	2.84	10.06	12.68	7.21	0.35	2.71	19.65	134.2	>150
CXBKR1	Oct-14	36.63	3.36	9.72	6.61	47.29	0.69	2.35	7.52	65.88	SW
CXBKR2	Oct-14	119.87	6.37	13.74	4.18	205.20	0.94	2.32	24.28	117.12	SW
CXBKR3	Oct-14	64.11	4.38	7.61	7.01	99.51	0.75	2.00	12.53	90.28	SW
CXBKR4	Oct-14	404.63	17.09	53.82	26.54	734.36	2.50	6.61	79.81	126.88	SW
CXCXSW1	Oct-14	6300.05	230.90	750.70	245.67	11218.63	40.81	36.77	1286.84	109.8	SW
CXMKC2	Oct-14	9193.13	347.82	1096.48	370.89	18024.79	62.75	101.09	2003.59	139.08	SW
Sea water	Oct-14	9773.71	367.72	1178.15	589.51	17258.71	60.09	11.44	1916.83	109.8	Standard
Sea water	Oct-14	8995.23	337.65	1078.06	363.77	17136.83	60.68	22.58	1894.53	129.32	Standard

Where SW=Surface water

Tab.- App. 4: Physical parameters of the collected water samples in the study period of 2014 (end of wet period)

Sample ID	Date	TDS (calculated)	EC (μS/cm)	pH	Temp^{0}C	Wells Depth (m)
CXTW1	Oct-14	121.09	177	5.5	25.9	<50
CXTW2	Oct-14	495.06	796	5.5	25.9	<50
CXTW4	Oct-14	677.05	882	6.56	25.8	<50
CXTW5	Oct-14	485.51	454	7.55	27.5	<50
CXTW6	Oct-14	460.59	607	7.53	30.1	<50
CXTW7	Oct-14	1074.58	1506	7.85	27.6	<50
CXTW8	Oct-14	582.69	638	7.86	27.3	<50
CXTW9	Oct-14	1042.35	1253	7.35	28.3	<50
CXTW10	Oct-14	622.98	671	7.26	27.2	<50
CXTW12	Oct-14	248.36	356	7.74	26.6	<50
CXTW13	Oct-14	718.54	790	5.75	28.3	<50
CXTW14	Oct-14	2935.71	4320	7.11	27.1	<50
CXTW16	Oct-14	820.17	1010	7.35	27.7	<50
CX1TW4	Oct-14	573.29	672	7.09	27.8	<50
CXCXTW1	Oct-14	381.24	429	7.5	27.9	<50
CXCXTW3	Oct-14	165.00	205	6.51	26.2	<50
CXCXTW5	Oct-14	1565.86	2250	5.5	27.4	<50
CXCXTW6	Oct-14	510.04	636	7.71	29.4	<50
CXCXTW8	Oct-14	596.68	1076	6.08	27.0	<50
CXHTW1	Oct-14	307.38	358	6.58	27.2	<50
CXUKTW1	Oct-14	1456.36	2190	7.23	28.0	<50
CXCX1PZ1	Oct-14	771.34	837	7.11	27.3	<50
CXTW3	Oct-14	577.82	614	8.54	30.2	50-150
CXTW11	Oct-14	1467.20	1925	8.2	27.0	50-150
CXTW15	Oct-14	2154.51	2950	8.01	27.0	50-150
CXCXTW7	Oct-14	677.61	808	8.06	28.1	50-150
CXCXLW1	Oct-14	308.16	320	7.67	27.7	50-150
CXCXLW2	Oct-14	245.85	276	6.24	26.8	50-150
CXCXLW3	Oct-14	509.45	551	7.41	26.9	50-150
UKLW2	Oct-14	1806.01	402	6.07	26.7	50-150
CXCX1PZ2	Oct-14	447.23	303	6.3	28.3	50-150
CXHoTW1	Oct-14	864.37	836	7.44	28.6	50-150
CXDTW1	Oct-14	532.71	682	7.25	24.5	>150
CX2PZ4	Oct-14	148.23	189	6.66	26.9	>150
CXCX1PZ4	Oct-14	198.52	220	6.27	27.7	>150
CXBKR1	Oct-14	180.04	368	7.44	26.3	SW
CXBKR2	Oct-14	494.02	720	7.46	26.9	SW
CXBKR3	Oct-14	288.17	437	7.54	27.3	SW
CXBKR4	Oct-14	1452.24	2740	7.58	27.9	SW
CXCXSW1	Oct-14	20220.16	29600	8.22	30.5	SW
CXMKC2	Oct-14	31339.62	40500	8.18	27.5	SW
Sea water	Oct-14	31265.95	37500	8.31	29.8	Standard
Sea water	Oct-14	30018.66	40800	8.2	25.5	Standard

Where SW= Surface water

Tab.- App. 5: Chemical parameters of the collected water samples in the study period of 2015 (end of dry period)

Sample ID	Date	Na (mg/L)	K (mg/L)	Mg (mg/L)	Ca (mg/L)	Cl (mg/L)	Br (mg/L)	NO_3 (mg/L)	SO_4 (mg/L)	HCO_3 (mg/L)	Wells Depth (m)
CXTW1	Apr-15	17.81	2.52	2.04	2.05	10.43	0.58	0.37	5.88	136.64	<50
CXTW2	Apr-15	346.43	51.72	71.48	28.26	671.16	3.25	3.09	149.91	422.12	<50
CXTW4	Apr-15	30.15	28.06	35.86	97.16	142.31	2.09	2.30	19.34	505.08	<50
CXTW5	Apr-15	66.17	5.27	20.84	48.34	107.55	1.14	1.64	5.70	346.48	<50
CXTW6	Apr-15	45.70	11.23	30.90	58.13	51.70	0.95	43.72	31.48	270.84	<50
CXTW7	Apr-15	417.56	22.15	92.86	74.80	816.02	3.44	4.96	106.01	409.92	<50
CXTW8	Apr-15	74.24	12.01	47.61	36.16	123.24	0.27	14.15	31.51	402.60	<50
CXTW9	Apr-15	227.17	28.16	105.73	57.38	427.82	2.03	7.73	60.18	529.48	<50
CXTW10	Apr-15	39.93	13.12	28.78	73.04	71.79	0.99	54.01	25.87	348.92	<50
CXTW12	Apr-15	19.24	1.71	9.72	46.39	7.54	1.01	1.29	6.36	246.44	<50
CXTW13	Apr-15	178.79	2.18	8.21	18.94	85.18	1.62	2.15	21.17	390.40	<50
CXTW14	Apr-15	568.10	10.53	121.79	334.17	1376.07	4.31	9.81	109.92	719.80	<50
CXTW16	Apr-15	97.15	22.29	41.05	48.26	111.76	2.12	1.25	26.34	488.00	<50
CXTW20	Apr-15	14.03	3.17	34.55	64.10	9.71	1.51	2.41	78.11	392.84	<50
CX1TW4	Apr-15	36.27	12.32	25.52	36.93	29.33	0.93	37.94	26.64	261.08	<50
CXCXTW1	Apr-15	17.49	8.79	19.35	51.92	37.07	0.98	9.74	34.88	207.40	<50
CXCXTW3	Apr-15	15.70	2.68	2.02	2.63	3.04	0.01	0.87	1.94	100.04	<50
CXCXTW5	Apr-15	54.53	14.60	43.29	62.10	71.36	1.22	126.26	37.99	273.28	<50
CXCXTW6	Apr-15	37.38	12.31	51.56	36.75	39.84	1.00	1.17	34.94	409.92	<50
CXCXTW8	Apr-15	79.36	9.93	42.40	39.87	195.00	0.70	56.99	70.95	85.40	<50
CXCX1PZ1	Apr-15	26.81	3.46	27.40	139.00	41.79	1.72	2.75	140.95	441.64	<50
CXUKTW1	Apr-15	301.82	16.69	55.85	52.96	455.14	2.26	24.10	65.04	353.80	<50
CXHO2	Apr-15	21.70	3.29	22.04	105.45	66.17	1.42	1.69	40.29	309.88	<50
CXHO4	Apr-15	17.00	3.92	15.48	53.51	14.97	1.13	2.08	17.56	322.08	<50
CXHO5	Apr-15	8.39	2.60	15.03	43.18	5.73	1.07	1.55	29.15	195.20	<50
CXHO6	Apr-15	13.86	2.40	9.51	59.26	4.52	1.21	1.43	13.27	324.52	<50
CXHH1	Apr-15	13.15	2.13	11.98	16.60	6.04	0.79	0.94	24.00	143.96	<50
CXTW3	Apr-15	161.26	0.96	0.46	1.09	17.65	1.48	1.49	1.75	373.32	50-150
CXTW11	Apr-15	470.22	2.56	6.38	12.09	449.40	1.75	4.23	1.00	500.20	50-150
CXTW19	Apr-15	119.90	1.08	3.02	7.14	37.90	0.14	1.48	9.37	351.36	50-150
CXCXTW7	Apr-15	190.59	0.80	0.87	1.31	49.64	0.15	2.95	0.47	453.84	50-150
CXCXLW1	Apr-15	10.69	2.04	10.31	51.24	4.90	0.08	35.66	8.28	192.76	50-150
CXCXLW2	Apr-15	9.11	1.05	2.74	7.19	9.10	0.04	1.01	0.70	178.12	50-150
CXCXLW3	Apr-15	8.62	2.46	26.32	74.33	4.22	1.48	3.34	20.26	405.04	50-150
UKLW1	Apr-15	2476.91	9.78	33.29	72.88	4176.59	11.89	40.24	4.54	129.32	50-150
UKLW2	Apr-15	12.29	1.74	1.35	3.91	6.59	0.60	0.20	1.24	143.96	50-150
UKLW3	Apr-15	10.76	2.57	16.98	34.82	5.37	0.04	3.50	12.16	251.32	50-150
CXCX1PZ2	Apr-15	12.29	1.97	2.15	7.57	3.90	0.45	1.25	11.10	222.04	50-150
CXHO3	Apr-15	9.46	2.16	13.44	62.54	10.14	1.25	1.12	10.53	168.36	50-150
CXHoTW1	Apr-15	18.44	3.15	28.96	168.05	46.63	0.72	6.46	163.86	492.88	50-150
CXTW18	Apr-15	138.74	0.87	3.91	12.04	81.66	1.26	4.35	7.95	366.00	>150
CX2PZ4	Apr-15	26.10	3.28	2.34	1.74	6.73	0.02	4.54	4.59	226.92	>150

Rest of the samples data in the following page

Tab.- App. 5: Chemical parameters of the collected water samples in the study period of 2015 (end of dry period)

Sample ID	Date	Na (mg/L)	K (mg/L)	Mg (mg/L)	Ca (mg/L)	Cl (mg/L)	Br (mg/L)	NO_3 (mg/L)	SO_4 (mg/L)	HCO_3 (mg/L)	Wells Depth (m)
CXDTW1	Apr-15	11.31	2.63	27.21	76.33	64.86	1.64	1.43	8.02	324.52	>150
CXCX1PZ4	Apr-15	8.89	2.33	2.04	4.67	7.71	0.41	0.60	19.85	139.08	>150
CXHSTREAM	Apr-15	9.22	2.66	4.61	4.05	6.14	0.51	0.09	16.67	95.16	SW
CXBKR1	Apr-15	1455.03	56.81	181.68	76.17	2706.35	8.25	7.97	283.83	126.88	SW
CXBKR2.1	Apr-15	4595.15	176.55	596.58	214.99	8207.96	27.60	8.79	954.63	141.52	SW
CXBKR3	Apr-15	11746.33	429.17	1391.91	427.90	18708.49	57.07	21.22	2092.88	90.28	SW
CXBKR4	Apr-15	12040.39	444.66	1429.17	645.95	19427.76	59.33	16.88	2219.47	153.72	SW
CXCXSW1	Apr-15	11799.20	433.10	1401.16	428.67	19600.63	60.36	13.89	2199.00	202.52	SW
CXMKC2	Apr-15	10807.66	395.52	1283.69	397.65	18371.79	59.50	20.09	2056.34	112.24	Standard
Sea water	Apr-15	12399.13	447.64	1463.03	445.03	19102.14	59.42	22.22	2169.90	156.16	Standard
Sea water	Apr-15	11231.83	428.73	1325.60	412.22	17763.00	55.53	129.25	1983.69	131.76	Standard

Where SW=Surface water

Tab.- App. 6: Physical parameters of the collected water samples in the study period of 2015 (end of wet and dry period)

Sample ID	Date	TDS (calculated)	EC (μS/cm)	pH	Temp^{0}C	Wells Depth (m)
CXTW1	Apr-15	178.32	203	6.55	26.6	<50
CXTW2	Apr-15	1747.42	796	7.26	27.3	<50
CXTW4	Apr-15	862.35	990	6.6	27	<50
CXTW5	Apr-15	603.11	729	7.87	27.3	<50
CXTW6	Apr-15	544.64	737	7.46	30.5	<50
CXTW7	Apr-15	1947.71	2930	7.87	26.9	<50
CXTW8	Apr-15	741.79	930	8.6	27.2	<50
CXTW9	Apr-15	1445.68	2080	7.55	26.8	<50
CXTW10	Apr-15	656.45	812	7.41	27.8	<50
CXTW12	Apr-15	339.70	377	7.77	28.2	<50
CXTW13	Apr-15	708.64	863	7.3	28.4	<50
CXTW14	Apr-15	3254.51	4540	7.2	27.3	<50
CXTW16	Apr-15	838.22	1092	7.57	28.5	<50
CXTW20	Apr-15	600.43	631	7.35	27.7	<50
CX1TW4	Apr-15	466.95	630	7.46	28.3	<50
CXCXTW1	Apr-15	387.62	570	7.25	27	<50
CXCXTW3	Apr-15	128.94	215	6.62	26.3	<50
CXCXTW5	Apr-15	684.61	999	7.39	28	<50
CXCXTW6	Apr-15	624.86	808	7.59	27.7	<50
CXCXTW8	Apr-15	580.60	1090	6.6	27	<50
CXCX1PZ1	Apr-15	825.52	1022	7.36	28.3	<50
CXUKTW1	Apr-15	1327.65	2060	7.5	27.9	<50
CXHO2	Apr-15	571.91	799	7.44	27.5	<50
CXHO4	Apr-15	447.73	477	7.2	32.2	<50
CXHO5	Apr-15	301.89	405	7.63	25.6	<50
CXHO6	Apr-15	429.98	416	7.65	27.8	<50
CXHH1	Apr-15	219.60	309	6.96	27.4	<50
CXTW3	Apr-15	559.48	668	8.6	30.6	50-150
CXTW11	Apr-15	1447.84	2100	8.25	27.2	50-150
CXTW19	Apr-15	531.38	534	8.11	27.5	50-150
CXCXTW7	Apr-15	700.62	791	8.5	28.2	50-150
CXCXLW1	Apr-15	315.95	351	7.77	27.5	50-150

Rest of the samples data in the following page

Tab.- App. 6: Physical parameters of the collected water samples in the study period of 2015 (end of dry period)

Sample ID	Date	TDS (calculated)	EC (μS/cm)	pH	Temp^{0}C	Wells Depth (m)
CXCXLW2	Apr-15	209.06	292	6.6	27	50-150
CXCXLW3	Apr-15	546.07	605	7.26	26.7	50-150
UKLW1	Apr-15	6955.45	11870	7.8	31.5	50-150
UKLW2	Apr-15	171.87	197	7.24	26.8	50-150
UKLW3	Apr-15	337.51	334	7.7	27.1	50-150
CXCX1PZ2	Apr-15	262.71	269	7.47	27.4	50-150
CXHO3	Apr-15	279.00	457	7.45	27.7	50-150
CXHoTW1	Apr-15	929.15	959	7.3	27	50-150
CXTW18	Apr-15	616.75	825	8.35	28.5	>150
CX2PZ4	Apr-15	276.25	268	6.5	26.5	>150
CXDTW1	Apr-15	517.94	686	6.78	27.4	>150
CXCX1PZ4	Apr-15	185.58	229	7.26	28.4	>150
CXHSTREAM	Apr-15	139.11	212	7.74	26.6	SW
CXBKR1	Apr-15	4902.97	8240	8.54	32.3	SW
CXBKR2.1	Apr-15	14923.76	30100	7.47	32.3	SW
CXBKR3	Apr-15	34965.26	49600	7.85	31.2	SW
CXBKR4	Apr-15	36437.32	48600	7.96	31.6	SW
CXCXSW1	Apr-15	36138.54	49400	7.71	31.4	SW
CXMKC2	Apr-15	33504.49	48500	8.06	30.6	Standard
Sea water	Apr-15	36264.67	49200	8.14	29	Standard
Sea water	Apr-15	33461.61	47400	8.23	29.7	Standard

Where SW= Surface water

Tab.- App. 7: Chemical parameters of the collected water samples in the study period of 2015 (end of wet period)

Sample ID	Date	Na (mg/L)	K (mg/L)	Mg (mg/L)	Ca (mg/L)	Cl (mg/L)	Br (mg/L)	NO_3 (mg/L)	SO_4 (mg/L)	HCO_3 (mg/L)	Wells Depth (m)
CXTW1	Oct-15	18.10	2.18	4.90	5.65	5.01	0.59	0.70	5.85	200.08	<50
CXTW2	Oct-15	278.43	45.46	70.92	27.46	484.37	2.61	1.40	121.73	392.84	<50
CXTW4	Oct-15	36.81	3.63	33.61	86.53	132.92	1.62	0.47	22.56	378.20	<50
CXTW5	Oct-15	17.89	6.69	24.24	41.01	32.79	1.19	17.02	20.29	324.52	<50
CXTW6	Oct-15	35.00	9.09	25.91	45.89	43.88	1.37	36.85	26.69	295.24	<50
CXTW7	Oct-15	118.38	12.19	38.59	30.98	217.84	0.98	7.82	37.24	283.04	<50
CXTW8	Oct-15	56.31	10.56	42.03	29.19	85.50	1.11	8.53	30.11	341.60	<50
CXTW4	Oct-15	36.81	3.63	33.61	86.53	132.92	1.62	0.47	22.56	378.20	<50
CXTW5	Oct-15	17.89	6.69	24.24	41.01	32.79	1.19	17.02	20.29	324.52	<50
CXTW6	Oct-15	35.00	9.09	25.91	45.89	43.88	1.37	36.85	26.69	295.24	<50
CXTW7	Oct-15	118.38	12.19	38.59	30.98	217.84	0.98	7.82	37.24	283.04	<50
CXTW8	Oct-15	56.31	10.56	42.03	29.19	85.50	1.11	8.53	30.11	341.60	<50
CXTW9	Oct-15	290.33	35.37	111.92	57.01	540.73	2.60	22.15	91.27	675.88	<50
CXTW10	Oct-15	47.64	13.73	35.45	87.31	81.28	0.72	132.92	36.69	278.16	<50
CXTW12	Oct-15	17.61	1.64	9.02	42.23	8.59	0.79	2.31	7.73	185.44	<50
CXTW13	Oct-15	150.99	2.27	9.14	23.43	86.17	1.49	8.12	22.44	383.08	<50
CXTW14	Oct-15	419.31	6.90	77.02	182.56	831.67	3.53	22.57	74.29	841.80	<50
CXTW16	Oct-15	96.36	21.68	39.61	42.83	104.42	1.77	1.95	27.77	534.36	<50
CXTW20	Oct-15	11.36	2.41	24.10	49.30	6.89	0.85	3.86	32.31	302.56	<50
CX1TW4	Oct-15	92.58	20.82	45.43	75.95	150.67	1.22	111.09	55.49	370.88	<50
CXCXTW1	Oct-15	22.46	5.64	17.97	45.64	26.45	0.16	9.88	32.89	204.96	<50
CXCXTW6	Oct-15	37.77	14.08	48.55	23.29	39.47	1.99	4.28	3.27	497.76	<50
CXCXTW8	Oct-15	74.35	9.56	36.87	34.30	153.47	0.56	65.72	78.93	117.12	<50
CXCX1PZ1	Oct-15	26.97	3.17	27.12	129.62	37.78	0.32	3.20	109.94	478.24	<50

Rest of the samples data in the following page

Tab.- App. 7: Chemical parameters of the collected water samples in the study period of 2015 (end of wet period)

Sample ID	Date	Na (mg/L)	K (mg/L)	Mg (mg/L)	Ca (mg/L)	Cl (mg/L)	Br (mg/L)	NO_3 (mg/L)	SO_4 (mg/L)	HCO_3 (mg/L)	Wells Depth (m)
CXUKTW1	Oct-15	209.61	18.85	37.83	32.66	401.78	1.56	15.22	49.68	146.40	<50
CXHO2	Oct-15	26.17	4.35	29.20	94.61	54.83	1.10	5.72	42.40	439.20	<50
CXHO4	Oct-15	8.24	3.51	13.41	45.63	17.56	0.54	10.72	11.04	161.04	<50
CXHO5	Oct-15	7.93	2.44	17.72	45.84	5.62	1.01	3.69	35.57	261.08	<50
CXHO6	Oct-15	13.30	1.84	9.78	57.22	6.42	1.14	2.60	14.82	312.32	<50
CXHH1	Oct-15	15.92	2.53	18.33	23.70	13.60	0.56	3.67	33.23	204.96	<50
CXTW3	Oct-15	163.72	0.93	0.55	2.50	25.71	1.51	5.79	1.36	585.60	50-150
CXTW11	Oct-15	432.29	2.10	5.74	10.88	411.67	2.24	5.24	0.02	651.48	50-150
CXTW15	Oct-15	674.40	3.08	7.54	14.03	800.88	3.76	92.28	0.35	558.76	50-150
CXTW19	Oct-15	114.83	1.07	3.24	8.99	14.19	0.13	16.80	9.28	285.48	50-150
CXCXTW7	Oct-15	204.15	0.94	1.17	2.19	53.54	1.45	9.16	0.01	546.56	50-150
CXCXLW1	Oct-15	9.20	1.50	7.84	38.97	5.65	1.10	5.09	8.86	202.52	50-150
CXCXLW2	Oct-15	9.65	1.36	1.60	6.61	10.81	0.74	2.85	1.19	158.60	50-150
CXCXLW3	Oct-15	15.76	2.23	20.21	63.53	15.68	0.28	7.54	34.36	285.48	50-150
UKLW1	Oct-15	2588.55	11.61	36.45	79.64	4265.65	20.20	26.69	1.41	290.36	50-150
UKLW2	Oct-15	52.57	1.70	4.85	20.17	41.47	0.25	58.97	0.25	285.48	50-150
UKLW3	Oct-15	9.07	1.88	15.57	26.42	3.84	0.71	5.20	11.76	134.20	50-150
CXCX1PZ2	Oct-15	11.36	1.93	18.06	52.06	91.60	0.51	2.14	21.73	373.32	50-150
CXHO3	Oct-15	8.96	1.92	13.77	60.81	9.83	1.27	4.27	12.44	258.64	50-150
CXHoTW1	Oct-15	18.11	2.61	27.05	139.86	27.64	1.04	2.56	176.00	461.16	50-150
CXTW18	Oct-15	165.63	1.05	11.03	39.30	201.18	0.99	0.89	18.00	285.48	>150
CX2PZ4	Oct-15	20.05	2.62	8.66	7.79	2.69	0.65	0.99	2.71	122.00	>150
CXDTW1	Oct-15	14.28	2.70	32.15	86.32	79.50	1.92	12.23	11.00	353.80	>150
CX2TW17	Oct-15	27.18	3.86	12.27	11.48	20.86	0.65	0.19	0.12	119.56	>150
CXCX1PZ4	Oct-15	12.18	1.05	4.18	6.83	48.23	0.18	1.81	23.46	119.56	>150
CXS1	Oct-15	7.23	1.72	2.91	2.02	5.48	0.04	2.51	9.17	139.08	SW
CXHSTREAM	Oct-15	10.24	2.35	2.96	2.26	5.32	0.21	1.27	13.86	122.00	SW
CXBKR1	Oct-15	6.98	4.40	4.53	6.75	3.58	0.19	0.39	4.10	112.24	SW
CXBKR2.1	Oct-15	10.32	2.30	5.15	7.37	9.35	0.07	5.75	4.80	109.80	SW
CXBKR3	Oct-15	554.51	21.28	68.72	27.27	996.38	3.49	2.85	124.15	175.68	SW
CXBKR4	Oct-15	2882.40	107.47	344.42	112.40	5209.45	17.77	262.92	636.84	75.64	SW
CXCXSW1	Oct-15	2122.92	79.42	257.12	90.69	4068.32	15.46	124.83	504.63	207.40	SW
CXMKC2	Oct-15	3098.84	112.14	367.42	114.94	5535.73	21.03	5.64	698.14	209.84	SW
CXUKRE1	Oct-15	4343.13	160.32	519.73	162.09	8078.65	27.63	324.36	1017.20	136.64	SW
Sea water	Oct-15	11261.59	406.14	1338.69	463.93	19843.81	66.74	824.33	2452.27	161.04	Standard
Sea water	Oct-15	9273.86	335.31	1105.70	339.30	17376.54	66.42	21.95	2112.07	107.36	Standard
Sea water	Oct-15	9098.32	331.74	1089.60	330.02	16547.00	65.55	32.76	2012.14	146.40	Standard

Where SW= Surface water

Tab.- App. 8: Physical parameters of the collected water samples in the study period of 2015 (end of wet period)

Sample ID	Date	TDS (calculated)	EC (μS/cm)	pH	Temp^{0}C	Wells Depth (m)
CXTW1	Oct-15	243.04	188	6.18	26.2	<50
CXTW2	Oct-15	1425.22	2210	7.4	27.4	<50
CXTW4	Oct-15	696.36	1020	6.5	26.2	<50
CXTW5	Oct-15	485.64	522	7.66	27.6	<50
CXTW6	Oct-15	519.91	693	7.33	28.8	<50
CXTW7	Oct-15	747.06	1123	7.54	27.9	<50
CXTW8	Oct-15	604.93	789	7.81	27.9	<50
CXTW4	Oct-15	696.36	1020	6.5	26.2	<50
CXTW5	Oct-15	485.64	522	7.66	27.6	<50
CXTW6	Oct-15	519.91	693	7.33	28.8	<50
CXTW7	Oct-15	747.06	1123	7.54	27.9	<50
CXTW8	Oct-15	604.93	789	7.81	27.9	<50
CXTW9	Oct-15	1827.27	2660	7.69	28.6	<50
CXTW10	Oct-15	713.90	1030	7.22	27.7	<50
CXTW12	Oct-15	275.36	390	7.64	27.4	<50
CXTW13	Oct-15	687.12	863	7.1	28.6	<50
CXTW14	Oct-15	2459.64	3560	7.09	27.7	<50
CXTW16	Oct-15	870.73	1072	7.3	28	<50
CXTW20	Oct-15	433.62	508	7.02	28.2	<50
CX1TW4	Oct-15	924.13	1260	6.9	28.4	<50
CXCXTW1	Oct-15	366.05	508	7.24	27.7	<50
CXCXTW6	Oct-15	670.44	855	7.43	29.4	<50
CXCXTW8	Oct-15	570.87	970	5.95	27.1	<50
CXCX1PZ1	Oct-15	816.35	931	7.14	27.7	<50
CXUKTW1	Oct-15	913.58	1592	7.02	28.1	<50
CXHO2	Oct-15	697.58	829	7.25	27.6	<50
CXHO4	Oct-15	271.70	401	7.11	28.1	<50
CXHO5	Oct-15	380.90	422	7.49	25.5	<50
CXHO6	Oct-15	419.45	434	7.41	27.7	<50
CXHH1	Oct-15	316.50	390	6.53	27.5	<50
CXTW3	Oct-15	787.66	688	8.61	29.8	50-150
CXTW11	Oct-15	1521.64	2070	8.27	27.3	50-150
CXTW15	Oct-15	2155.09	3260	8.16	27.7	50-150
CXTW19	Oct-15	454.00	542	8.2	25	50-150
CXCXTW7	Oct-15	819.15	1216	8.51	28.5	50-150
CXCXLW1	Oct-15	280.73	353	7.6	27.3	50-150
CXCXLW2	Oct-15	193.41	300	6.45	26.5	50-150
CXCXLW3	Oct-15	445.06	503	6.84	26.5	50-150
UKLW1	Oct-15	7320.58	12650	7.51	27.5	50-150
UKLW2	Oct-15	465.71	402	7.26	25.8	50-150
UKLW3	Oct-15	208.63	341	7.8	27	50-150
CXCX1PZ2	Oct-15	572.70	497	6.48	25	50-150
CXHO3	Oct-15	371.90	465	7.33	27	50-150
CXHoTW1	Oct-15	856.02	944	7.12	26.6	50-150
CXTW18	Oct-15	723.55	741	8.18	28.1	>150
CX2PZ4	Oct-15	168.16	212	6.62	27	>150
CXDTW1	Oct-15	593.89	798	6.53	26.7	>150

Rest of the samples data in the following page

Tab.- App. 8: Physical parameters of the collected water samples in the study period of 2015 (end of wet period)

Sample ID	Date	TDS (calculated)	EC (μS/cm)	pH	Temp^{0}C	Wells Depth (m)
CX2TW17	Oct-15	196.16	302	6.78	26.4	>150
CXCX1PZ4	Oct-15	217.48	220	6.44	27.4	>150
CXS1	Oct-15	170.16	152	6.6	26.1	SW
CXHSTREAM	Oct-15	160.46	161	7.57	26	SW
CXBKR1	Oct-15	143.17	120	7.17	29	SW
CXBKR2.1	Oct-15	154.90	148	7.31	29.2	SW
CXBKR3	Oct-15	1974.32	4040	7.04	29.2	SW
CXBKR4	Oct-15	9649.29	1880	7.45	29.2	SW
CXCXSW1	Oct-15	7470.79	11450	7.42	28.4	SW
CXMKC2	Oct-15	10163.72	17480	7.75	28.3	SW
CXUKRE1	Oct-15	14769.75	23800	8.12	25.7	SW
Sea water	Oct-15	36818.54	47100	8.12	27.2	Standard
Sea water	Oct-15	30738.50	46400	8.16	26.5	Standard
Sea water	Oct-15	29653.53	46300	8.16	26.2	Standard

Where SW= Surface water

Tab.-App. 9: Chemical parameters of the collected water samples in the study period of 2016 (end of dry period)

Sample ID	Date	Na (mg/L)	K (mg/L)	Mg (mg/L)	Ca (mg/L)	Cl (mg/L)	Br (mg/L)	NO_3 (mg/L)	SO_4 (mg/L)	HCO_3 (mg/L)	Wells Depth (m)
CXTW1	Apr-16	18.49	2.22	5.22	6.24	2.72	0.01	0.04	5.67	107.36	<50
CXTW2	Apr-16	334.83	52.38	85.95	36.86	548.25	1.77	0.43	168.10	356.24	<50
CXTW4	Apr-16	70.27	4.38	32.71	87.40	139.35	0.20	0.28	20.53	390.40	<50
CXTW5	Apr-16	14.15	5.49	18.44	36.35	18.63	0.05	1.87	11.54	183.00	<50
CXTW6	Apr-16	50.58	10.81	31.20	57.73	58.13	0.07	44.15	37.63	307.44	<50
CXTW7	Apr-16	283.08	19.11	76.78	68.46	550.10	1.77	0.87	77.46	329.40	<50
CXTW8	Apr-16	83.59	12.48	50.43	40.92	148.89	0.42	11.92	36.37	375.76	<50
CXTW9	Apr-16	155.93	22.75	76.52	59.12	298.89	0.96	1.37	59.20	463.60	<50
CXTW10	Apr-16	42.64	17.29	35.88	91.70	70.87	0.12	86.42	38.78	390.40	<50
CXTW12	Apr-16	18.72	1.84	9.82	48.08	8.47	0.04	0.08	7.85	378.20	<50
CXTW13	Apr-16	141.18	2.36	9.98	28.69	83.26	0.15	0.05	21.08	414.80	<50
CXTW14	Apr-16	510.16	5.08	29.46	66.35	636.28	2.43	0.56	16.23	602.68	<50
CXTW16	Apr-16	114.10	22.03	44.31	50.63	124.38	0.34	1.18	24.95	480.68	<50
CXTW20	Apr-16	13.87	2.93	33.21	64.38	10.35	0.03	0.71	73.57	309.88	<50
CX1TW4	Apr-16	50.77	16.22	35.07	54.96	76.66	0.09	47.23	39.69	290.36	<50
CXCXTW1	Apr-16	21.93	7.00	22.35	122.48	38.77	0.07	44.72	33.55	200.08	<50
CXCXTW6	Apr-16	38.22	14.86	56.95	28.18	40.14	0.13	0.23	5.84	453.84	<50
CXCXTW8	Apr-16	77.29	9.28	37.93	35.71	153.40	0.37	68.35	80.86	141.52	<50
CXUKTW1	Apr-16	200.01	19.47	52.55	46.90	355.88	1.14	63.45	56.69	241.56	<50
CXCX1PZ1	Apr-16	30.13	3.56	27.53	139.58	42.22	0.10	0.83	114.29	463.60	<50
CXHO2	Apr-16	28.02	4.26	27.03	110.97	66.17	0.22	0.29	50.25	295.24	<50
CXHO4	Apr-16	19.98	4.39	19.15	65.13	14.97	0.08	6.94	15.41	324.52	<50
CXHO5	Apr-16	9.93	2.74	18.48	50.89	7.75	0.02	0.45	34.46	226.92	<50
CXHO6	Apr-16	14.09	1.95	10.26	63.80	5.43	0.02	0.44	15.41	268.40	<50
CXHH1	Apr-16	28.02	4.26	27.03	110.97	66.17	0.22	0.29	50.25	295.24	<50

Rest of the samples data in the following page

Tab.-App. 9: Chemical parameters of the collected water samples in the study period of 2016 (end of dry period)

Sample ID	Date	Na (mg/L)	K (mg/L)	Mg (mg/L)	Ca (mg/L)	Cl (mg/L)	Br (mg/L)	NO_3 (mg/L)	SO_4 (mg/L)	HCO_3 (mg/L)	Wells Depth (m)
CXTW3	Apr-16	187.66	1.10	0.98	2.73	13.07	0.06	0.39	0.25	497.76	50-150
CXTW11	Apr-16	451.88	2.42	6.64	13.61	417.44	1.65		0.15	575.84	50-150
CXTW15	Apr-16	700.08	3.09	9.38	18.60	859.71	3.52		0.74	505.08	50-150
CXTW19	Apr-16	135.05	1.41	3.60	11.43	37.90	0.14	0.68	9.40	317.20	50-150
CXCXTW7	Apr-16	214.62	1.06	2.02	4.71	60.39	0.24	0.07	0.34	497.76	50-150
CXCXLW1	Apr-16	10.26	1.75	10.83	48.60	5.71	0.02	0.04	8.80	224.48	50-150
CXCXLW2	Apr-16	10.95	1.71	7.87	38.15	11.03	0.05	0.02	1.08	170.80	50-150
CXCXLW3	Apr-16	9.34	2.51	27.19	87.35	4.93	0.11	0.24	37.87	366.00	50-150
UKLW1	Apr-16	2819.02	11.42	58.74	98.52	4496.26	21.13	0.63	0.95	253.76	50-150
UKLW2	Apr-16	25.89	1.84	4.80	24.00	19.16	0.08	0.02	0.10	141.52	50-150
UKLW3	Apr-16	10.94	2.25	18.32	34.14	4.85	0.02	0.06	13.36	185.44	50-150
CXHO3	Apr-16	10.45	2.32	15.26	70.26	10.14	0.10	0.23	13.87	368.44	50-150
CXHoTW1	Apr-16	20.17	2.95	29.99	162.11	27.84	0.10		208.85	383.08	50-150
CXTW18	Apr-16	138.34	1.18	4.71	15.88	84.37	0.27	0.74	9.91	307.44	>150
CXDTW1	Apr-16	20.32	2.70	27.38	78.02	67.31	0.10	2.15	9.84	336.72	>150
CX2PZ4	Apr-16	19.73	2.54	8.74	8.70	3.03	0.01	0.03	2.82	148.84	>150
CX2TW17	Apr-16	28.96	4.11	14.02	14.28	26.30	0.09	2.46	7.27	151.28	>150
CXCX1PZ4	Apr-16	5.09	2.66	3.46	7.90	7.41	0.02	2.83	7.41	39.04	>150
CXHSTREAM	Apr-16	9.44	1.86	10.90	12.20	69.33	0.24	0.04	26.31	122.00	SW
CXBKR1	Apr-16	17.28	3.06	9.57	12.60	10.25	1.04	0.02	4.32	170.80	SW
CXBKR2.1	Apr-16	4595.15	176.55	596.58	214.99	8207.96	27.60	8.79	954.63	141.52	SW
CXBKR3	Apr-16	4016.00	145.71	492.89	210.62	7136.22	23.43	96.93	877.22	143.96	SW
CXBKR4	Apr-16	9775.54	364.19	1239.49	443.41	17539.17	57.98	12.66	2060.36	170.80	SW
CXCXSW1	Apr-16	9774.08	367.72	1190.68	473.79	17352.55	56.90	56.03	2041.02	178.12	SW
CXMKC2	Apr-16	10264.48	373.84	1306.52	447.42	18518.93	59.89	8.79	2183.63	97.60	SW
CXUKRE1	Apr-16	10378.74	384.53	1253.04	467.67	18138.19	59.77	2.88	2123.51	141.52	SW
Sea water	Apr-16	10353.48	388.06	1303.79	443.60	18872.48	62.06	3.08	2220.36	231.80	Standard
Sea water	Apr-16	10311.37	386.32	1307.19	442.19	18538.10	60.42	1.32	2182.22	202.52	Standard
Sea water	Apr-16	10401.28	401.63	1311.94	446.92	18320.07	59.46		2170.73	170.80	Standard

Where SW= Surface water

Tab.-App. 9: Physical parameters of the collected water samples in the study period of 2016 (end of dry period)

Sample ID	Date	TDS (calculated)	EC (μS/cm)	pH	Temp^{0}C	Wells Depth (m)
CXTW1	Apr-16	147.97	195	6.59	26.6	<50
CXTW2	Apr-16	1584.81	2520	7.43	27.3	<50
CXTW4	Apr-16	745.51	1043	7.03	26.6	<50
CXTW5	Apr-16	289.51	588	8.09	27	<50
CXTW6	Apr-16	597.74	761	7.55	30.1	<50
CXTW7	Apr-16	1407.01	2310	7.85	27.1	<50
CXTW8	Apr-16	760.76	996	7.99	27.1	<50
CXTW9	Apr-16	1138.35	2672	7.48	27.2	<50
CXTW10	Apr-16	774.09	1096	7.32	27.2	<50
CXTW12	Apr-16	473.09	490	7.93	27.4	<50

Rest of the samples data in the following page

Tab.-App. 9: Physical parameters of the collected water samples in the study period of 2016 (end of dry period)

Sample ID	Date	TDS (calculated)	EC (μS/cm)	pH	Temp^{0}C	Wells Depth (m)
CXTW13	Apr-16	701.55	955	7.27	28.7	<50
CXTW14	Apr-16	1869.23	3700	7.78	28.8	<50
CXTW16	Apr-16	862.60	1120	7.59	26.9	<50
CXTW20	Apr-16	508.92	599	7.23	27.9	<50
CX1TW4	Apr-16	611.04	1847	7.4	27.6	<50
CXCXTW1	Apr-16	490.94	581	7.29	27.1	<50
CXCXTW6	Apr-16	638.39	861	7.84	27.1	<50
CXCXTW8	Apr-16	604.72	991	6.2	27	<50
CXUKTW1	Apr-16	1037.65	1600	7.18	27.1	<50
CXCX1PZ1	Apr-16	821.83	972	7.24	27.7	<50
CXHO2	Apr-16	582.46	835	7.54	27.5	<50
CXHO4	Apr-16	470.57	532	7.14	28.5	<50
CXHO5	Apr-16	351.64	517	7.69	26.1	<50
CXHO6	Apr-16	379.80	528	7.85	28.7	<50
CXHH1	Apr-16	582.46	426	6.88	27.7	<50
CXTW3	Apr-16	704.01	733	8.61	31.4	50-150
CXTW11	Apr-16	1469.62	2234	8.32	27.8	50-150
CXTW15	Apr-16	2100.21	3730	8.27	27.3	50-150
CXTW19	Apr-16	516.81	694	8.3	27.6	50-150
CXCXTW7	Apr-16	781.21	1296	8.66	28.1	50-150
CXCXLW1	Apr-16	310.49	355	7.83	27.5	50-150
CXCXLW2	Apr-16	241.65	397	6.58	27	50-150
CXCXLW3	Apr-16	535.54	617	7.21	26.5	50-150
UKLW1	Apr-16	7760.44	13120	8.07	29.6	50-150
UKLW2	Apr-16	217.41	428	7.72	28.5	50-150
UKLW3	Apr-16	269.37	350	7.93	27.2	50-150
CXHO3	Apr-16	491.07	578	7.47	29.2	50-150
CXHoTW1	Apr-16	835.10	989	7.29	26.9	50-150
CXTW18	Apr-16	562.83	802	8.55	28.4	>150
CXDTW1	Apr-16	544.55	856	7.21	29.1	>150
CX2PZ4	Apr-16	194.45	303	6.85	26.8	>150
CX2TW17	Apr-16	248.76	321	6.88	26.5	>150
CXCX1PZ4	Apr-16	75.82	323	6.94	28.8	>150
CXHSTREAM	Apr-16	252.32	201	8.17	31.9	SW
CXBKR1	Apr-16	228.95	223	8.49	32.2	SW
CXBKR2.1	Apr-16	14923.76	30100	7.47	32.3	SW
CXBKR3	Apr-16	13142.98	20900	7.9	32.8	SW
CXBKR4	Apr-16	31663.60	46300	7.77	31.1	SW
CXCXSW1	Apr-16	31490.88	46400	7.75	32.2	SW
CXMKC2	Apr-16	33261.09	47000	7.84	30.2	SW
CXUKRE1	Apr-16	32949.85	46000	8.14	30.2	SW
Sea water	Apr-16	33878.72	49500	8.1	30.2	Standard
Sea water	Apr-16	33431.65	48500	8.21	31	Standard
Sea water	Apr-16	33282.82	48800	8.18	31	Standard

Where SW=Surface water

Tab.- App. 10: Sulphur isotopic composition of dissolve sulphate in water and SO_4^{2-}/Cl^- mass ratio of the selected samples

Sample ID	$\delta^{34}S$ (‰ V-CDT)	$\delta^{18}O$ (‰ V-SMOW)	Distance from shore (m)	SO_4^{2-}/Cl^-
CXTW8	10.56	7.92	743	0.4
CXTW16	14.68	10.75	500	0.3
CXCXTW8	2.19	4.16	1835	0.5
CXTW13	10.76	8.12	1234	0.3
CXCXTW4	6.23	8.56	1579	0.4
CXTW7	17.66	11.54	633	0.2
CXUKTW1	17.36	11.13	100	0.1
Sea water	20.25	8.82	0	0.12

Tab.- App. 11: Stable isotopic composition of ^{18}O and ^{2}H of the water samples between 2014 (wet period) and 2015 (dry period)

Sample ID	^{18}O (‰) _2014	^{2}H (‰) _2014	^{18}O (‰) _2015	^{2}H (‰) _2015	Wells Depth (m)
CXCX1PZ1	-5.06	-26.94	-5.0	-27.3	<50
CXCXTW1	-5.05	-29.45	-4.8	-25.7	<50
CXCXTW4	-6.43	-39.62	-4.08	-20.08	<50
CXCXTW6	-4.13	-26.87	-2.9	-18.4	<50
CXCXTW8	-5.19	-29.43	-5.1	-28.4	<50
CXTW1	-5.08	-27.78	-5.3	-28.9	<50
CXTW2	-4.65	-25.55	-3.9	-21.4	<50
CXTW4	-4.76	-26.14	-4.58	-24.21	<50
CXTW5	-5.40	-31.07	-4.25	-20.55	<50
CXTW6	-4.87	-26.62	-4.36	-22.40	<50
CXTW7	-4.67	-26.08	-4.8	-25.8	<50
CXTW8	-4.69	-26.22	-4.8	-26.5	<50
CXTW9	-3.85	-21.46	-4.2	-21.6	<50
CXTW10	-5.81	-35.09	-6.0	-34.2	<50
CXTW12	-4.86	-26.65	-5.2	-27.1	<50
CXTW13	-4.68	-26.14	-4.9	-26.1	<50
CXTW14	-3.73	-20.23	-3.9	-20.0	<50
CXTW16	-5.26	-30.53	-4.76	-25.34	<50
CXUKTW1	-3.76	-19.62	-1.13	-2.06	<50
CXCKPZ1	-3.92	-18.48	-3.7	-17.0	50-150
CXCXLW1	-4.93	-27.06	-5.1	-27.8	50-150
CXCXLW2	-4.06	-23.17	-4.4	-24.4	50-150
CXCXLW3	-5.05	-27.28	-5.0	-27.7	50-150
CKLW1	-4.83	-26.66	-3.8	-21.1	50-150
CKLW2	-5.14	-28.35	-4.9	-27.1	50-150
CKLW3	-4.70	-25.54	-4.1	-23.2	50-150
UKLW1	-3.55	-16.20	-5.54	-31.28	50-150
UKLW2	-4.26	-21.28	-5.05	-27.12	50-150
CXTW7	-4.35	-21.87	-4.3	-21.8	50-150
CXTW3	-3.18	-13.39	-3.8	-17.7	50-150
CXTW11	-3.26	-14.96	-3.6	-15.3	50-150
CXTW15	-3.48	-15.55	-3.7	-16.4	50-150
CXCXHoTW1	-4.94	-28.07	-5.3	-29.8	50-150

Rest of the samples data in the following page

Tab.- App. 11: Stable isotopic composition of ^{18}O and ^{2}H of the water samples between 2014 (wet period) and 2015 (dry period)

Sample ID	^{18}O (‰) _2014	^{2}H (‰) _2014	^{18}O (‰) _2015	^{2}H (‰) _2015	Wells Depth (m)
CXCX1PZ4	-3.24	-11.45	-3.2	-11.7	>150
CXCX2PZ4	-5.32	-28.05	-5.2	-28.1	>150
CXCKPZ2	-5.04	-27.54	-5.1	-28.1	>150
CXCKPZ3	-3.54	-17.23	-4.0	-18.3	>150
CXDTW1	-4.75	-27.02	-5.6	-31.9	>150
CXCXSW1	-1.82	-10.97	-0.01	1.51	SW
CXBKR1	-4.31	-24.55	-1.6	-6.9	SW
CXBKR2	-4.23	-24.21	-1.2	-6.0	SW
CXBKR3	-4.29	-24.27	0.2	3.5	SW
CXBKR4	-4.14	-23.69	0.0	0.9	SW
CXCKSW3	-4.65	-26.23	-2.8	-10.7	SW
CXMKC2	-0.81	-3.28	-0.2	0.7	SW
Sea water	0.00	-0.2	0.00	-0.2	Standard
Sea water	-0.02	-0.6	-0.02	-0.6	Standard

Where SW= Surface water

Tab.- App. 12: Stable isotopic composition of ^{18}O and ^{2}H of the water samples between 2015 (wet period) and 2016 (dry period)

Sample ID	^{18}O (‰) _2015	^{2}H (‰) _2015	^{18}O (‰) _2016	^{2}H (‰) _2016	Wells Depth (m)
CXCX1PZ1	-4.97	-27.58	-4.35	-27.46	<50
CXCXTW1	-4.78	-27.63	-4.54	-26.69	<50
CXCXTW2	-5.04	-26.76	-4.53	-27.36	<50
CXCXTW4	-4.75	-26.06	-5.48	-33.68	<50
CXCXTW6	-2.52	-16.85	-2.22	-17.88	<50
CXCXTW8	-5.19	-29.18	-4.90	-29.35	<50
CXTW1	-5.03	-27.69	-4.98	-28.11	<50
CXTW2	-3.77	-20.36	-3.49	-19.21	<50
CXTW4	-4.74	-26.05	-4.24	-23.58	<50
CXTW5	-5.18	-28.82	-5.26	-32.10	<50
CXTW6	-5.42	-31.70	-4.58	-27.38	<50
CXTW7	-4.90	-26.92	-4.40	-25.64	<50
CXTW8	-5.14	-28.66	-4.61	-27.55	<50
CXTW9	-4.16	-22.07	-3.89	-22.29	<50
CXTW10	-4.64	-25.10	-4.61	-27.81	<50
CXTW12	-5.19	-28.51	-4.53	-27.44	<50
CXTW13	-5.07	-27.12	-4.66	-26.61	<50
CXTW14	-3.67	-20.21	-3.22	-16.89	<50
CXTW16	-4.93	-27.23	-4.71	-27.59	<50
CXUKTW1	-4.28	-22.06	-3.95	-22.37	<50
CXTW20	-5.04	-29.08	-4.86	-27.84	<50
CXHO6	-5.23	-28.54	-4.91	-27.83	<50
CXHO5	-5.13	-27.60	-4.96	-27.30	<50
CXHO4	-5.46	-31.04	-5.09	-29.72	<50

Rest of the samples data in the following page

Tab.- App. 12: Stable isotopic composition of ^{18}O and ^{2}H of the water samples between 2015 (wet period) and 2016 (dry period)

Sample ID	^{18}O (‰) _2015	^{2}H (‰) _2015	^{18}O (‰) _2016	^{2}H (‰) _2016	Wells Depth (m)
CXHO2	-4.82	-26.05	-4.67	-26.34	<50
CXHH1	-5.34	-29.24	-4.56	-27.48	<50
CXCXLW1	-5.37	-28.74	-4.90	-28.02	50-150
CXCXLW2	-4.29	-24.46	-4.41	-25.46	50-150
CXCXLW3	-5.31	-29.59	-4.85	-28.26	50-150
UKLW1	-4.14	-20.27	-3.28	-16.96	50-150
UKLW2	-5.36	-29.66	-4.57	-26.22	50-150
UKLW3	-5.24	-29.20	-5.37	-29.73	50-150
CXCXTW7	-4.50	-22.61	-4.33	-22.60	50-150
CXTW3	-3.55	-14.38	-3.30	-14.41	50-150
CXTW11	-3.59	-14.85	-3.22	-15.06	50-150
CXTW15	-3.73	-16.01	-3.29	-15.96	50-150
CXCXHoTW1	-5.46	-29.79	-4.90	-28.66	50-150
CXTW19	-4.81	-23.76	-4.02	-22.97	50-150
CXHO3	-5.06	-26.21	-4.41	-26.28	50-150
CKLW1	-5.40	-29.66	-4.69	-24.32	50-150
CKLW3	-6.92	-40.97	-5.42	-31.11	50-150
CXCX2PZ4	-5.61	-29.59	-4.54	-27.26	>150
CXCX2TW17	-5.67	-29.09	-5.18	-27.46	>150
CXDTW1	-5.38	-29.25	-4.80	-25.10	>150
CXTW18	-5.04	-26.74	-4.78	-25.14	>150
CKPZ2	-5.26	-30.11	-4.92	-25.87	>150
CKPZ3	-3.83	-19.90	-3.67	-16.74	>150
CXUKRE1	-2.54	-16.69	0.12	-0.68	SW
CXCXSW1	-5.34	-32.83	-0.16	-2.77	SW
CXBKR1	-6.11	-38.85	-1.97	-10.33	SW
CXBKR2	-6.50	-40.79	-2.10	-10.04	SW
CXBKR3	-6.50	-42.41	-1.11	-8.53	SW
CXBKR4	-4.51	-30.59	-0.14	-2.25	SW
CXCKSW3	-5.54	-33.91	-2.79	-14.61	SW
CXMKC2	-4.37	-29.17	-0.22	-2.38	SW
CXHSTREAM	-5.66	-32.17	-5.11	-26.54	SW
CXBKR2.1	-6.47	-41.15	-1.09	-7.46	SW
CXS1	-5.51	-34.66	-4.66	-23.36	SW
Sea water	-0.17	-2.16	0.00	-0.2	Standard
Sea water	-0.37	-3.33	-0.02	-0.6	Standard

Where SW= Surface water

Tab.- App. 13: Hotels and their rooms that are used to calculate water budget in the study area of Cox's Bazar, Bangladesh.

Big Hotel	Total Room	Medium Hotel	Total Room	Small Hotel	Total Room
seagull	181	Blue moon resort	30	Nilima Resort	9
sayeman	228	Unity Inn	30	Mermaid Eco Resort	15
long beach	104	Resort Islandia	35	Sampan Resort (7villas)	7
Mishuk	100	Alfa Wave	36	Shaibal	15
Ocean paradise	296	Cox's Hilton	42	Favour Inn COX international	15
Sea crown	100	Amin Interntional	30	Marine Bird	18
The Cox Today	276	Renaissance	31	Crystal Bay Resort	12
Sea palace	50	Nitol Bay Resort	37	Al Haramayn resort	10
White orchid	64	Daimond Palace	38	Fu wang Dommons resort	19
Coastal Peace	60	Shumudro Bilass	40	Crystal Bay resort	15
Ocean Palace	100	Water orchid	40	Alamin	20
Praasad paradise	83	marine plaza	35	Jinia apartment and hotel	20
sea Alif	100	shugondha guest house	38	Sea knight resort	28
Prime Park	50	Sea-sun resort	40	3star	15
Silver Shine	87	Galaxy resort	41	sea place	25
Western Plus Heritage	236	Iqra beach hotel	40	Nilime beach	12
Albatross Resort	57	Hotel sams Plaza	43	Stone forest	10
Sea world	200	sea welcome resort	48	Shohan resort	14
Resort Beach View	62	sea point resort	36	Mom's resort	11
Uni resort	50	Hiperion sea wave	44	Cox Ocean resort	15
Bay Touch	50	Shwapno Bilas	36	Taher Bhaban gust house	22
Beach way	158	Cox-Inn	38	kalim resort	12
Media international	253	Zia guest house	38	B.M. resort	10
Suite Sadaf	68	Zia guest Inn	35	Siddik guest house	15
Neeshorgo hotel and resort	150	Lemis resort	49	sea shark resort	17
Allegro holiday Suites	50	land sea resort	35	Al-zia guest house	21
Saint martin Resort	66	G.M. guest house	31	Al mahmud Guest house	18
Needs Bay watch	56	Nisan guest house	40	faisal hotel	23
Coral reef	59	Sea Arafat resort	32	Ramjan cottage	13
Muscat Holiday Resort	65	Sea havean guest house	38	Shumudro Nibas	10
Sea princess	80	amari resort	36	Jainal resort	12
Bashati Bay resort	77	Comfort sea star	42	Hill crest guest house	14
Zaman Sea Heights	50	Hotel lodge residential	43	Sea home	18
Windy Terrace Boutique	60	Hotel sky line	38	Hhiman resort	15
Honeymoon Resort	50	grand pacific	45	Hoque garden resort	14
Vista Bay resort	60	rain view resort	36	Sakil guest house	16
Mohammadia gust house	60	Dynamic hotel	46	Sopno bilass guest house	22
D'Oceania	126	noor plaza	35	Shaiiad cottage	13

Rest of the hotels data in the following page

Tab.- App. 13: Hotels and their rooms that are used to calculate water budget in the study area of Cox's Bazar, Bangladesh

Big Hotel	Total Room	Medium Hotel	Total Room	Small Hotel	Total Room
Holiday	96	hyperion bay queen	44	Dream guest house	19
Banu Plaza	52	fercem inn and suites	30	Sea green resort	11
Hotel D'Oceania	80	niribili petal	40	M. Aziz resort	10
Bay view gust house	65	My resort	36	Sea Angel College	12
sea hill	95	sea king guest house	30	Beach Gargen	11
Urmi guest house	67	sea breez resort	40	Beach city resort	9
sea cox resort	50	beach holiday guest house	33	Ragion cottage	7
Kollol	95	marine plaza	35	S.A. Guest INN	9
Motel laboni	78	Hotel sand beach	30	Light house resort	12
Sea Park resort	60	hotel jhowtola	35	Shumudro kanta guest house	14
Sea view	56	dhaka hotel	39	Arman cottage	9
Grand Beach resort	52	zia hotel	33	Dar-al-ahsan guest house	17
Sony Silver Ocean	87	hotel palonki	44	Sea garden cottage	8
Hotel king palace	51	hotel bilkis	35	Diamond angel	22
Hotel Aristocrat	120	hotel cox's bazar	40	M.Ali guest house	15
Hotel sandy land	210	hotel prince	39	Fahim cottage	11
hotel sea shine	55	zilani hotel	32	Beach Noor resort	19
world beach resort	180	al foisal	43	Shahed guest house	13
bay one touch	50	dreamland	31	Beach park cottage	16
hotel sea uttara	80	nisitha	35	Al Shahab resort	20
grand marina beach	132	saint martin resort	32	Little moon cottage	15
Hotel bay beach	75			Shagor Bilass	17
hotel zaman sea heights	50			Al Hossain cottage	12
laguna beach	68			Quality home	9
regal place	80			Haque guest Inn	12
Royal beach resort	98			sweet home resort	10
hyperian hotel sun coast	78			R.M. resort	10
Esplanacle hotel	56			Sea land guest house	20
marmaid bay watch resort	81			Blue water cottage	10
ocean green	132			Sunset resort	25
sealand	60			Dhaka cottage	9
hotel sunmoon	56			Ilhum cottage	10
Hotel bay beach	75			Rongdhonu resort	17
hotel paradise	51			Sead sand resort	21
hotel sagargaon	60			Dhakar bari cottage	9
hotel sea queen	106			Richan guest house	17
hotel bay ampair	52			Prince resort	22
golden inn	102			Beach light	23
best western plus	236			Hill side resort	12
Avisar	55			Bellavumi guest house	13
Auster echo	65			Classic guest Inn	15

Rest of the small hotel's information in the following page

Tab.- App. 13: Hotels and their rooms that are used to calculate water budget in the study area of Cox's Bazar, Bangladesh

Small Hotel	Total Room
Hamdam cox resort	20
Al kafi cottage	9
Himchori holiday inn	16
PHP palican tarzia	10
Afreen Inn	15
modern sea resort	20
hotel falcon beach	25
blue sea cottage	12
shahjadi resort	10
Dynamic cox kingdom	11
shaim cottage	9
Digonto guest house	22
sea gazipur resort	21
sha aman guest house	17
sea star cottage	11
blue ocean	16
Ahmdia resort	17
shohag guest house	24
Alam guest house	22
cox view resort	18
mission hill bay	15
silvia resort	27
A.R. guest house	25
camellia house	12
Fahima cottage	10
Holiday mark hotel resort	22
kabir guest house	15
taleb guest house	18
ocean view resort	23
ocean ampaire cottage	15
sea nice guest house	22
sea kanon resort	18
kanima resort	17
soikoiawt bilass	20
south beach resort	25
Hotel soiball	22
hotel Alin park	13
Hotel sea view	22
sealand guest house	22
hotel alam	20
saleh noor guest house	12

Rest of the small hotel's information in the following page

Tab.- App. 13: Hotels and their rooms that are used to calculate water budget in the study area of Cox's Bazar, Bangladesh

Small Hotel	Total Room
sagorika guest house	23
hotel bijoy sharani	13
hotel kakoly	11
hotel jawbithi	17
hotel al-hera	12
hotel al-amin	16
M.S guest care	16
pachtara boading	15
amena guest house	15
hotel paynoya	24
nid mohol	13
zilani resort	14
hotel razmoni	15
Hotel Al Nizam	20
al mubin	15
seastar	15
hotel sea heart	9
Al Hossain cottage	11
shaheraz	25
asia	12
sopnil resort(ukhia)	15
sarmom guest house	24
La Bella resort	20

Tab.-App. 14: Values for GALDIT six parameters including sea level rise (water level) of 0.5 m used in the study and the results of groundwater vulnerabilitz index for shallow wells (<50m depth)

Well ID	X	Y	G	A (m/day)	L (m)	D (m)	I Ratio	T (m)	GVI	GVI Index	L (m)_SLR (0.5 m)	GVI	GVI Index
CXCX1PZ1	91.98383	21.41826	Unconfined	8.53	-2.43	411	0.09	15	8.3	High	-2.93	8.3	High
CXCXTW1	91.98568	21.413722	Unconfined	8.60	2.47	219	0.18	2	5.3	Moderate	1.97	6.0	Moderate
CXCXTW4	91.96918	21.448143	Unconfined	8.68	3.67	255	0.25	5	5.7	Moderate	3.17	5.7	Moderate
CXCXTW5	91.96918	21.448246	Unconfined	8.68	1.47	250	2.91	5	7.5	High	0.97	8.2	High
CXCXTW6	91.97825	21.422579	Unconfined	8.63	5.37	346	0.10	2.5	5.3	Moderate	4.87	5.3	Moderate
CXCXTW8	91.97723	21.442565	Unconfined	8.62	1.37	900	2.28	6	6.2	Moderate	0.87	6.8	Moderate
CXTW4	91.97526	21.438273	Unconfined	8.67	6.47	850	0.28	20	5.0	Moderate	5.97	5.0	Moderate
CXTW5	91.96884	21.441814	Unconfined	8.63	1.47	859	0.31	4.5	5.3	Moderate	0.97	6.0	Moderate
CXTW6	91.96912	21.44214	Unconfined	8.56	-0.33	900	0.19	4	6.0	Moderate	-0.83	6.0	Moderate
CXTW7	91.96676	21.439336	Unconfined	8.64	1.17	520	1.99	5.5	6.7	Moderate	0.67	7.3	Moderate
CXTW8	91.96787	21.439207	Unconfined	8.60	8.07	605	0.31	1	4.7	Low	7.57	4.7	Low
CXTW9	91.96638	21.437928	Unconfined	8.50	1.67	392	0.81	1	6.2	Moderate	1.17	6.8	Moderate
CXTW10	91.97111	21.439652	Unconfined	7.85	9.67	906	0.21	3.5	4.0	Low	9.17	4.0	Low
CXTW12	91.97697	21.429758	Unconfined	8.49	1.07	674	0.03	10	6.7	Moderate	0.57	7.3	Moderate
CXTW13	91.97039	21.442858	Unconfined	7.85	5.80	880	0.22	11	5.0	Moderate	5.30	5.0	Moderate
CXTW14	91.98258	21.441756	Unconfined	7.89	1.37	839	1.91	23	6.7	Moderate	0.87	7.3	Moderate
CXTW16	91.97449	21.428873	Unconfined	8.56	5.37	432	0.23	4	5.3	Moderate	4.87	5.3	Moderate
CXHo4	91.98668	21.412878	Unconfined	8.61	1.90	231	0.05	17	7.0	Moderate	1.40	7.7	High
CXHo5	91.99589	21.399942	Unconfined	8.56	2.00	197	0.03	20	7.0	Moderate	1.50	7.7	High
CXHo6	91.9844	21.415055	Unconfined	8.23	1.80	199	0.01	22	7.0	Moderate	1.30	7.7	High
CXHo2	91.97888	21.426632	Unconfined	8.45	1.90	678	0.21	23	6.3	Moderate	1.40	7.0	Moderate
Well1	91.988	21.432	Unconfined	7.85	5.50	1766	1.90	15	4.7	Low	5.00	4.7	Low
Well2	91.9974	21.4348	Unconfined	7.85	4.60	2723	0.01	17	4.3	Low	4.10	4.3	Low

Tab.- App. 15: Values for GALDIT six parameters including sea level rise (water level) of 0.5 m used in the study and results of groundwater vulnerability index for intermediate depth wells (50-150 m)

Well ID	X	Y	G (Type)	A (m/d)	L (m)	D (m)	I Ratio	T (m)	GVI	GVI Index	L (m)_ SLR (0.5 m)	GVI	GVI Index
CXCX1PZ2	91.98387	21.41827	Uncon.	8.66	-7.79	409	0.02	22	8.3	High	-8.29	8.3	High
CXCXLW2	91.99198	21.41995	Uncon.	8.70	3.34	1147	0.05	18	4.3	Low	2.84	4.3	Low
CXCXLW3	92.00278	21.42713	Uncon.	8.64	5.05	2560	0.01	20	4.3	Low	4.55	4.3	Low
CXCXTW7	91.9776	21.4423	Uncon.	8.70	6.67	910	0.11	35	5.0	Moderate	6.17	5.0	Moderate
CXTW11	91.98663	21.44014	Leaky	7.85	2.17	750	0.90	25	5.7	Moderate	1.67	6.3	Moderate
CXTW15	91.98682	21.44168	Leaky	7.85	-3.00	600	2.02	30	8.0	High	-3.50	8.0	High
CXCXHoTW1	91.98242	21.42004	Uncon.	8.63	0.60	446	0.09	25	8.3	High	0.10	8.3	High
CXHo3	91.985	21.41548	Uncon.	8.62	2.50	278	0.06	23	6.3	Moderate	2.00	7.0	Moderate
CXTW18	91.97577	21.4429	Leaky	7.85	3.10	900	0.22	35	4.8	Low	2.60	4.8	Low

Where Uncon. =unconfined, SLR= Sea level rise

Tab.-App. 16: Rating for GALDIT six parameters including sea level rise (water level) of 0.5 m used in the study to calculate groundwater vulnerability index for shallow wells (<50 m depth)

Well ID	X	Y	G (Type)	A (m/day)	L (m)	D (m)	I (Ratio)	T (m)	L (m)_SLR (0.5 m)
CXCX1PZ1	91.98383	21.41826	7.5	5	10	10	2.5	10	10
CXCXTW1	91.98568	21.41372	7.5	5	2.5	10	2.5	2.5	2.5
CXCXTW4	91.96918	21.44814	7.5	5	2.5	10	2.5	5	2.5
CXCXTW5	91.96918	21.44825	7.5	5	7.5	10	10	5	10
CXCXTW6	91.97825	21.42258	7.5	5	2.5	10	2.5	2.5	2.5
CXCXTW8	91.97723	21.44257	7.5	5	7.5	5	10	5	10
CXTW4	91.97526	21.43827	7.5	5	2.5	5	2.5	10	2.5
CXTW5	91.96884	21.44181	7.5	5	7.5	5	2.5	2.5	10
CXTW6	91.96912	21.44214	7.5	5	10	5	2.5	2.5	10
CXTW7	91.96676	21.43934	7.5	5	5	7.5	7.5	5	10
CXTW8	91.96787	21.43921	7.5	5	2.5	7.5	2.5	2.5	2.5
CXTW9	91.96638	21.43793	7.5	5	5	10	5	2.5	7.5
CXTW10	91.97111	21.43965	7.5	5	2.5	5	2.5	2.5	2.5
CXTW12	91.97697	21.42976	7.5	5	7.5	7.5	2.5	7.5	10
CXTW13	91.97039	21.44286	7.5	5	2.5	5	2.5	10	2.5
CXTW14	91.98258	21.44176	7.5	5	5	2.5	7.5	10	10
CXTW16	91.97449	21.42887	7.5	5	2.5	10	2.5	2.5	2.5
CXHo4	91.98668	21.41288	7.5	5	5	10	2.5	10	7.5
CXHo5	91.99589	21.39994	7.5	5	5	10	2.5	10	7.5
CXHo6	91.9844	21.41506	7.5	5	5	10	2.5	10	7.5
CXHo2	91.97888	21.42663	7.5	5	5	7.5	2.5	10	7.5
well1	91.988	21.432	7.5	5	2.5	2.5	7.5	10	2.5
well2	91.9974	21.4348	7.5	5	2.5	2.5	2.5	10	2.5

Tab.- app. 17: Rating for GALDIT six parameters including sea level rise (water level) of 0.5 m used in the study to calculate groundwater vulnerability index for intermediate depth wells (50-150 m)

Well ID	X	Y	G (Type)	A (m/day)	L (m)	D (m)	I (Ratio)	T (m)	L (m)_SLR (0.5 m)
CXCXLW2	91.99198	21.41995	7.5	5	2.5	2.5	2.5	10	2.5
CXCXLW3	92.00278	21.42713	7.5	5	2.5	2.5	2.5	10	2.5
CXCXTW7	91.9776	21.4423	7.5	5	2.5	5.0	2.5	10	2.5
CXTW11	91.98663	21.44014	5	5	2.5	7.5	5	10	5
CXTW15	91.98682	21.44168	5	5	10.0	7.5	10	10	10
CXCXHoTW1	91.98242	21.42004	7.5	5	10.0	10.0	2.5	10	10
CXHo3	91.985	21.41548	7.5	5	2.5	10.0	2.5	10	5
CXTW18	91.97577	21.4429	5	5	2.5	5.0	2.5	10	2.5