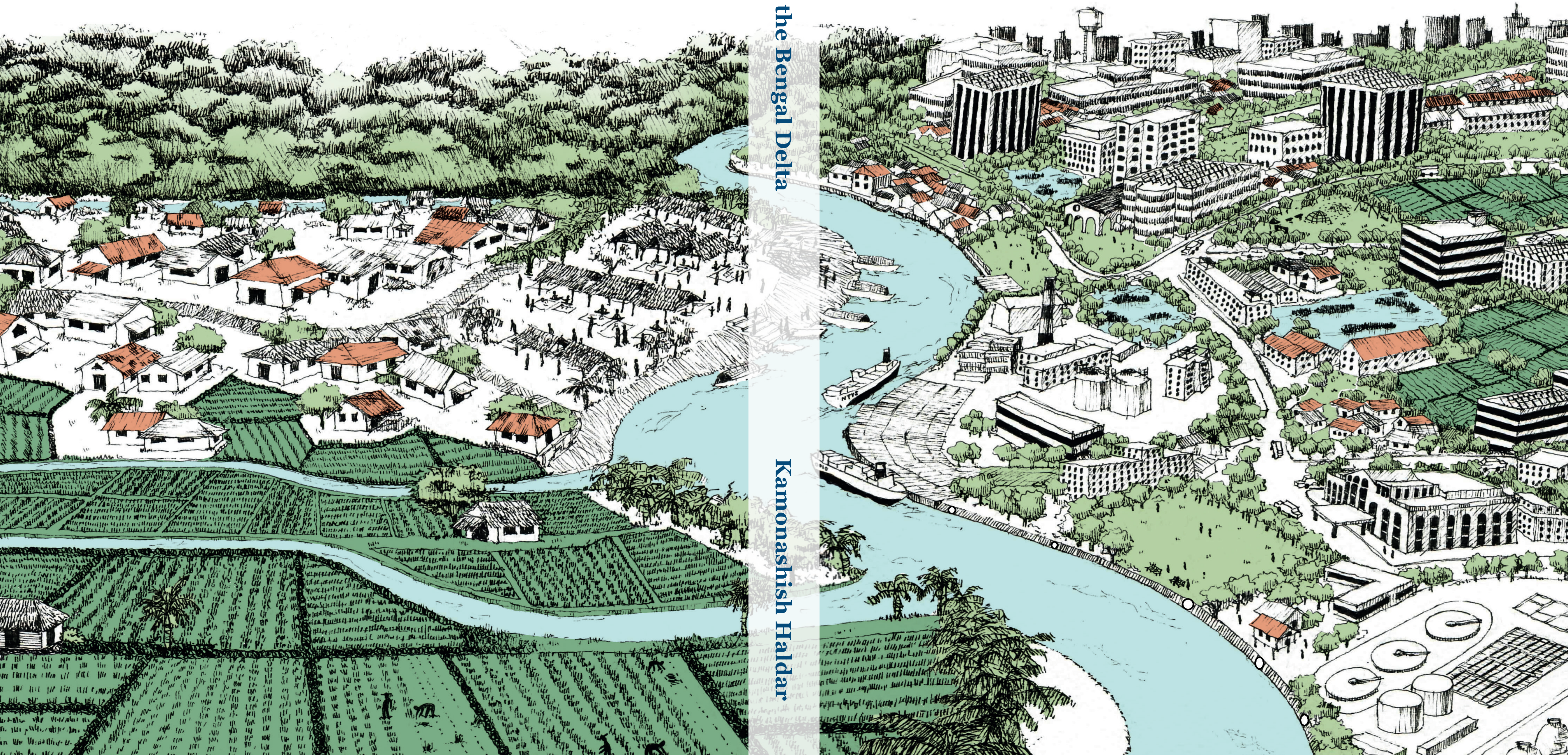
Urban Water Reuse in the Bengal Delta

Prospects, Challenges and Socio-Technological Solutions

Kamonashish Haldar



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Propositions

1. Proper urban planning and water management is pivotal in improving surface water quality in the deltas of the global South.
(this thesis)

2. Assigning single responsibilities to water governance organizations hinder the facilitation of urban water reuse.
(this thesis)

3. To accomplish science for impact, it is necessary to provide easy access of research findings to the public.

4. Valuing the opinion of social scientists would have resulted in better management of the pandemic.

5. Money spent for the exploration of other planets are not justifiable when that same amount could reduce the damages to our planet.

6. Automation will invoke a universal basic income for all.

Propositions belonging to the thesis, entitled

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to my family

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Summary

Water is indispensable for sustaining life on Earth and the uneven distribution of freshwater resources is impacting water availability. Additionally, climate change and rapid urbanization restrict water availability, causing global water scarcity. Being in proximity to the sea, delta areas are most vulnerable to rapidly increasing water scarcity. The Bengal delta is the largest delta in the world and is suffering from economic water scarcity due to the lack of water infrastructure even though the abundance of water in nature. Sea level rise, salinity intrusion, discharge of untreated or insufficiently treated wastewater degrade surface water quality and threaten the availability and quality of drinking and irrigation water. Urban water is defined here as a combination of greywater and sealed surface runoff often collected in the same infrastructure and significantly less polluted than blackwater. Urban water is used in agriculture as an alternative source of irrigation but requires quality up-grade for safe application. Reuse of urban water offers a cost-effective solution by enhancing the socio-environmental sustainability of water resources. However, adequate planning and in-depth understanding of the socio-economic, health and technological (collection, treatment, distribution) aspects are necessary for successfully implementing reuse projects.

Considering the growing demand for quality irrigation water in the Bengal delta, this research explored the possibilities and barriers related to safe urban water reuse in agriculture. Given the complexity of the topic, following objectives were articulated covering socio-technical aspects related to urban water reuse: (i) to match the peri-urban irrigation demand with potential urban water supply, (ii) to understand the spatio-temporal variability of surface water quality influencing its use in agriculture in the delta, (iii) to analyze the microbial and heavy metal contamination of surface water and assess the health risks for peri-urban farmers practicing indirect wastewater irrigation, (iv) to explore the existing institutional arrangement and stakeholders' perception towards planned water reuse in agriculture, and finally (v) to develop scenarios of socio-technological solutions for the management and treatment of urban water facilitating safe reuse.

Khulna, the coastal city in Bangladesh, the most vulnerable to climate change, has been taken as a case study. The core urban area and the peri-urban area were delineated as the boundary of this research. The following research questions guided the overall aim of the research, dealt in several chapters:

1. To what extent can urban water contribute to peri-urban agricultures' irrigation demand during the dry season?
2. Does the existing surface water quality affect the reuse potential in agriculture?
3. What are the health risks among farmers related to indirect wastewater irrigation?
4. Is the existing state of governance arrangement and stakeholders' perception conducive to the facilitation of the urban water reuse plan?

Chapter 1 starts with the global overview on water availability and narrows down to the negative impact of climate change and rapid urbanization on growing water scarcity in different regions. Literature was consulted to illustrate the history, major trends and achievements in urban water reuse worldwide. Sanitation, drinking water supply and irrigation water for agriculture were discussed next to indicate the growing challenges and needs in the Bengal delta. Finally, the chapter defined the scope of the research by identifying the existing knowledge gap and research needs in the study region.

Several quantitative and qualitative research methods were employed to gather data from the study area. Data collection focused on water volumes generated at various urban resources and needed for irrigation (Chapter 2), macro-chemical salinity and wastewater related parameters (Chapter 3), and micro-chemical (heavy metals) and microbiological (Coliform and Enterococci) pollutants (Chapter 4) and stakeholder perception towards reuse (Chapter 5).

In **Chapter 2,** the urban water reuse potential in peri-urban agriculture was quantitatively assessed. Firstly, the irrigation water requirement of Boro rice as a prevailing crop during the dry season was assessed using the FAO AquaCrop model. Then the greywater and sealed surface runoff generation were calculated based on drinking water consumption, annual rainfall of 2018 in different land uses, respectively. The average irrigation demand of 2018 was evaluated against urban water generation scenarios. The analysis indicated that the urban water could positively contribute to the irrigation water demand of peri-urban agriculture while the net irrigation requirement of Boro rice has declined over the last decades (1984-2017) to cope with the decreasing annual rainfall. The water requirement is highest during February and March and the lack of rainfall in these months fails to satisfy the total irrigation demand. However, with the introduction of storage systems, urban water could supply the required amount throughout the year. The results from this chapter provided a solid quantitative assessment of the matching potential of urban water to sustain agricultural activities.

In **Chapter 3,** the spatio-temporal variability in macro-chemical surface water quality was analyzed and the subsequent usability in agriculture was mapped. Statistical analysis to correlate the water quality with urban land uses and mapping using ArcGIS were carried out to further elaborate on the laboratory analysis of the collected water samples from different locations. The negative impact of direct discharge of urban wastewater and solid waste on water quality is reflected by elevated values of the related parameters such as solids (TSS), organic matter (BOD_5, COD) and low DO concentrations. The adjacent salt-carrying tributary rivers impact the water quality which is evident in elevated saltwater influenced parameters such as TDS, Na^+ and Cl^-. Results showed that the current surface water quality does not meet FAO guideline thresholds for related parameters and a significant seasonal variation in chemical-physical water quality parameters restricts the agricultural use. The influence of surrounding land use was evident in the study area, which can be used to improve surface water quality and future planning strategies. The method of integrating water quality information at a spatial scale provided valuable insights on the variability of water quality and usefulness, restrictions and treatment requirements for further use in agriculture.

In **Chapter 4,** the microbial and heavy metal contamination in the surface water was assessed through laboratory analysis and subsequent risk was assessed. A screening level Quantitative Microbial Risk Assessment (QMRA) was performed for assessing the health risk of farmers considering E. coli concentrations in water samples. Results show that the mean concentrations of microbial indicators exceeded the thresholds of the WHO and local guidelines for safe irrigation. However, no such significant thresholds were observed for heavy metals (other organic micropollutants possibly present in the water were not addressed in this study). The microbial health risk assessment suggested that the existing surface water quality poses a health risk for farmers as they are in direct contact with the microbially polluted surface water and do not use any protective equipment. However, farmers do not prioritize their health due to their longstanding practices and lack of better-quality irrigation sources. A multi-barrier approach containing reduction of pathogen concentrations through proper treatment and reduction of accidental ingestion through protective equipment and awareness among farmers was discussed as a way to lower the risk within the safety limit. The results further reiterated the need for the necessary treatment of wastewater for ensuring safe use.

In **Chapter 5,** the governance aspects of urban water reuse were investigated employing several participatory methods such as questionnaire survey, Key Informant Interview and Focus Group Discussion. Results indicated a high level of awareness among urban citizens (80%) about the negative impacts of wastewater discharge. There is a positive attitude towards urban water reuse as an alternative to combat irrigation water scarcity due to climate change. Citizens are willing to pay for the treatment which could cover half of the operation and maintenance costs of the treatment plant. The willingness of citizens is influenced by their socio-economic conditions, such as educational background or family income. Several governmental agencies are parallelly involved in urban water-related issues; however, there is no clear strategy to work together on an interdisciplinary issue like urban water reuse. Adjustments in existing rules and regulations are necessary for the organization to collaborate and work together cohesively.

Finally, in **Chapter 6,** the findings of this thesis were synthesized and four socio-technological scenarios for treating and reusing urban water in agriculture were illustrated. The potential and drawbacks of urban water reuse were discussed to highlight the need for proper treatment infrastructures. An extensive literature review was carried out to list the crucial factors that need to be considered for selecting suitable treatment technologies and defining a proper technical collection and treatment strategy including storage and redistribution to agriculture. Consideration of local context and the aim of treatment is decisive for selecting appropriate technology. After identifying the most critical driving forces in the Bengal delta, scenario planning was used to portray four scenarios: red scenario, grey scenario, golden scenario and green scenario. The red scenario promoted the centralized treatment approach and the grey scenario identified a community-based low-cost treatment system as a solution to meet the water demand in agriculture. The golden scenario advocated for advanced treatment, whereas the green scenario emphasized natural treatment systems. The chapter also identifies several limitations of current research and provided suggestions for future research.

Considering the future uncertainties around the provision of freshwater supply, planned urban water reuse presents a viable alternative to meet the growing water demand in agriculture. Improvement of existing water quality with adequate treatment and infrastructures for collection, storage, and supply would ensure safe urban water reuse. Supportive governance arrangement and stakeholder participation in the decision-making process could ensure the implementation of urban water reuse projects for sustaining agricultural activities in the Bengal delta.

Samenvatting

Water is essentieel voor al het leven op onze planeet, en de toenemende ongelijkheid in de verdeling van zoetwater zet de beschikbaarheid hiervan onder druk. Daarnaast vergroten klimaatverandering en verstedelijking de waterschaarste. Rivierdelta's zijn vanwege de nabijheid bij zee extra kwetsbaar voor de toenemende waterschaarste. De Bengaalse delta is de grootste delta ter wereld en er lijkt een overvloed aan water aanwezig in de omgeving. Toch is er schaarste in water van goede kwaliteit, omdat het land te weinig economische middelen heeft om de benodigde water infrastructuur aan te leggen. De stijgende zeespiegel, indringing van zoutwater en het lozen van onbehandeld of onvoldoende gezuiverd afvalwater bedreigen de kwaliteit van de watervoorraden en zet de beschikbaarheid en kwaliteit van drink- en irrigatiewater onder druk. Stedelijk water (*Urban Water*), in dit proefschrift gedefinieerd als een combinatie van licht verontreinigd (grijs-) water uit huishoudens en bedrijven, en regenwater dat oppervlakkig afstroomt, wordt over het algemeen verzameld in dezelfde infrastructuur van kanalen en sloten. Dit water is over het algemeen beperkt vervuild door instroom van rioolwater (zwartwater), wat in septic tanks wordt opgevangen. Stedelijk water kan in de landbouw gebruikt worden als alternatieve bron voor irrigatiewater en heeft maar een relatief kleine opwaardering in kwaliteit nodig. Hergebruik van stedelijk water is mogelijk een kosteneffectieve oplossing voor een duurzame, sociaaleconomische en ecologisch verantwoorde oplossing voor voorziening van water aan de landbouw in de delta. Echter, onderzoek naar adequate planning en de sociaaleconomische-, gezondheids- en technologische aspecten van het verzamelen, behandelen en distribueren van dat stedelijk water is noodzakelijk om de kennis te leveren die nodig is voor de implementatie van stedelijk water in hergebruikprojecten.

Gezien de groeiende vraag voor kwalitatief goed irrigatiewater in de delta van Bangladesh worden in dit proefschrift de mogelijkheden van en de barrières in het hergebruiken van stedelijk water in de landbouw onderzocht. Gegeven de complexiteit van dit onderwerp is een focus gekozen en zijn doelstellingen geformuleerd voor de sociaal-technologische aspecten van stedelijk water hergebruik. De doelstellingen zijn als volgt geformuleerd: (i) afstemming van de vraag naar irrigatie water in de directe omgeving van de stad op de potentiële aanbod van stedelijk water uit de stad, (ii) vaststelling van de variabiliteit in macro-chemische kwaliteit van het oppervlaktewater waar het stedelijk water naartoe afstroomt, in zowel ruimte als tijd en de invloed daarvan op de herbruikbaarheid van dat water in de landbouw, (iii) bepaling van de verontreiniging door pathogene micro-

organismen en zware metalen in stedelijke waterbronnen die voor irrigatiewater worden gebruikt door de boeren in de omgeving van de stad, en een beoordeling van de gezondheidsrisico's, (iv) inventarisering van de bestaande wettelijke regelingen en perceptie van belanghebbenden ten aanzien van stedelijke water hergebruik, (v) ontwikkeling van sociaal-technologische transitiescenario's en manieren om het veilig behandelen en beheren van stedelijk water en hergebruik in de landbouw te faciliteren.

Khulna, de belangrijkste kuststad in Bangladesh, is als casestudy genomen, en is een van de meest kwetsbare steden in de delta vanwege verzilting en overstroming als gevolg van klimaatverandering. Het stedelijk gebied en de agrarische landerijen in de directe omgeving vormen de gebiedsafbakening van dit onderzoek. De volgende onderzoeksvragen vormen de leidraad voor het onderzoek welke in verschillende hoofdstukken worden behandeld:

1. In hoeverre kan stedelijk water bijdragen aan de irrigatievraag van de peri-urbane landbouw tijdens het droge seizoen?
2. Heeft de bestaande oppervlaktewaterkwaliteit invloed op het hergebruikpotentieel in de landbouw?
3. Wat zijn de gezondheidsrisico's voor boeren bij indirecte irrigatie van stedelijk water?
4. Vormen het bestaande beleid en de perceptie van belanghebbenden hulpmiddelen of barrières bij de implementatie van stedelijk water hergebruik?

Hoofdstuk 1 begint met een globaal overzicht van de beschikbaarheid van water en beperkt zich tot de negatieve impact van klimaatverandering en snelle verstedelijking op de toenemende waterschaarste in verschillende regio's. Met behulp van literatuur onderzoek wordt de geschiedenis en belangrijke trends en ontwikkelingen op het gebied van hergebruik van stedelijk water wereldwijd geïllustreerd. Beschikbaarheid van water voor sanitie, drinkwatervoorziening- en irrigatie in de landbouw komen aan de orde, en geven de groeiende uitdagingen en behoeften in de Bengaalse delta aan. Ten slotte definieert het hoofdstuk de reikwijdte van het onderzoek door de stand van zaken op het gebied van hergebruik van stedelijk water te illustreren en de bestaande kennislacunes en onderzoekvragen in het onderzoeksgebied te identificeren.

Er worden verschillende kwantitatieve en kwalitatieve onderzoeksmethoden gebruikt om gegevens te verzamelen van het studiegebied. De focus van die gegevensverzameling ligt op verschillende aspecten in de opeenvolgende hoofdstukken: op het verkrijgen van voldoende irrigatiewater uit verschillende stedelijke waterbronnen (hoofdstuk 2), op saliniteit en andere macro-chemische parameters die afvalwater karakteriseren (hoofdstuk 3), op micro-chemische (vooral zware metalen) en microbiologische (vooral coliforme en enterococcus bacteriële) verontreinigingen (hoofdstuk 4) en de acceptatie van belanghebbenden ten aanzien van hergebruik van stedelijk water (hoofdstuk 5).

In **Hoofdstuk 2** is het potentieel voor hergebruik van stedelijk water in de peri-urbane landbouw kwantitatief geïnventariseerd en beoordeeld. Boro-rijst is het meest gebruikte gewas in de regio. De behoefte aan irrigatiewater voor de teelt daarvan tijdens het droge seizoen is bepaald met behulp van het FAO AquaCrop-model. Vervolgens is de hoeveelheid stadswater, bestaande uit (gescheiden opgevangen) grijswater en afgedicht oppervlaktewater, berekend. Dit is gedaan op basis van drinkwaterverbruik en de jaarlijkse neerslag in 2018 voor verschillende typen oppervlak in het studiegebied. Vervolgens werd de gemiddelde irrigatievraag in 2018 geëvalueerd aan de hand van verschillende scenario's voor het verzamelen en beschikbaar maken van stedelijke water voor irrigatie. Uit de analyse blijkt dat het stedelijk water een positieve bijdrage kan leveren aan de vraag naar irrigatiewater van de landbouw in de omgeving van de stad. Daarbij is gevonden dat de netto-irrigatiebehoefte van Boro-rijst de afgelopen decennia (1984-2017) is afgenomen, terwijl ook de jaarlijkse regenval afnam. De vraag naar irrigatiewater is het hoogste in de maanden februari en maart, door zeer beperkte regenval in deze periode is er in die maanden onvoldoende water om in de vraag te voorzien. Met de introductie van bergingssystemen zou stedelijk water echter het hele jaar door de benodigde hoeveelheid irrigatiewater kunnen leveren. De resultaten van dit hoofdstuk geven een solide kwantitatieve onderbouwing die aantoont dat het potentieel aan gegenereerde hoeveelheden stedelijk waterpassend is om de landbouwactiviteiten in de Khulna regio van de Bengaalse delta te ondersteunen.

In **Hoofdstuk 3** is de variatie in kwaliteit van het oppervlaktewater in ruimte en tijd geanalyseerd, en daaropvolgend is de bruikbaarheid voor irrigatie in de landbouw in kaart gebracht. Statistische analyses zijn gebruikt om de waterkwaliteit te correleren met het stedelijk landgebruik en daarnaast zijn de variaties in waterkwaliteit gevisualiseerd met behulp van ArcGIS. De negatieve impact van directe lozing van stedelijk afvalwater en vast afval op de waterkwaliteit wordt gekenmerkt door verhoogde waarden van parameters zoals de concentraties van vaste stoffen (TSS), organische afbreekbare stoffen (BOD5, COD) en verlaagde waarden van de concentratie van zuurstof. De aangrenzende zilte zijrivieren hebben ook invloed op de waterkwaliteit, dit blijkt uit de hoge zoutwaarden (verhoogde Na^+ en Cl^- concentraties). De macro-chemische kwaliteit van het oppervlakte water in de regio Khulna wordt dus bepaalt door lozingen van stedelijk afvalwater, vast afval stortingen, en zoutintrusie via de grotere rivieren die uitmonden in zee. De resultaten tonen aan dat de huidige oppervlaktewaterkwaliteit niet voldoet aan de FAO-richtlijndrempels voor irrigatie voor de genoemde parameters. Een significante seizoengebonden variatie in deze fysisch-chemische waterkwaliteitsparameters beperkt het gebruik van oppervlaktewater voor agrarisch gebruik. Het is duidelijk dat de waterkwaliteit medebepaald wordt door omringend landgebruik. In toekomstige planningstrategieën kan hiermee rekening worden gehouden. De methode om waterkwaliteitsinformatie op ruimtelijke schaal te integreren, levert waardevolle inzichten op over de variabiliteit van waterkwaliteit en bruikbaarheid, beperkingen en zuiveringseisen van stedelijk water voor verder gebruik in de landbouw.

Hoofdstuk 4 evalueert de microkwaliteit van het oppervlakte water in de regio Khulna. Deze is gebaseerd op metingen van concentraties van microbiële en zware metalen verontreiniging in het oppervlaktewater door middel van een brede bemonstering in het veld, laboratoriumanalyses van de genomen monsters, en een daaropvolgende risicobeoordeling. Daarvoor is een Quantitative Microbial Risk Assessment (QMRA) methodiek toegepast, gebaseerd op de E. coli-concentratie in watermonsters, om zo de gezondheidsrisico's voor boeren te vast te stellen en te beoordelen. De resultaten tonen aan dat de gemiddelde concentraties van deze microbiële indicatoren de drempels van de WHO en lokale richtlijnen voor veilige irrigatie overschrijden. Voor zware metalen werden geen overschrijdingen van gezondheidsdrempels gevonden. . Andere organische microverontreinigingen die mogelijk in het water aanwezig zijn, werden in dit onderzoek niet behandeld. De QMRA-resultaten suggereren dat de bestaande kwaliteit van het oppervlaktewater een gezondheidsrisico vormt voor landarbeiders werkzaam op de Boro rijstvelden, aangezien zij in direct contact staan met het microbieel vervuilde oppervlaktewater en geen beschermende kleding dragen of andere beschermende voorzieningen gebruiken. In de praktijk blijkt dat de boeren echter geen prioriteit geven aan zulke bescherming en dus aan hun gezondheid vanwege hun jarenlange ervaring, gewoontes en gebrek aan schone irrigatiebronnen. In dit hoofdstuk wordt een aanpak besproken om de concentratie van ziekteverwekkers te verminderen en de gezondheidsrisico's verder te verlagen beneden geaccepteerde limieten door gebruik te maken van beschermende middelen en het creëren van bewustwording bij de boeren. De resultaten van dit hoofdstuk bevestigen verder de noodzaak voor behandeling van stedelijk afvalwater om veilig gebruik voor irrigatie in de peri-urbane landbouw te garanderen.

Hoofdstuk 5 onderzoekt de bestuurlijke aspecten van hergebruik van stedelijk water met behulp van verschillende participatiemethoden, zoals vragenlijstonderzoek, *Key Informant Interview* en *Focus Group Discussion*. De resultaten wijzen op een hoge mate van bewustzijn onder de stadsbewoners (80%) over de negatieve effecten van directe lozing van afvalwater. Daarnaast is er een positieve houding ten aanzien van hergebruik van stedelijk water als alternatief voor de bestrijding van de schaarste aan irrigatiewater als gevolg van klimaatverandering. Burgers zijn bereid een gedeelte van de exploitatie- en onderhoudskosten voor zuiveringsinstallaties en de opvang en distributie infrastructuur te betalen. De bereidheid van burgers wordt beïnvloed door hun sociaaleconomische omstandigheden, zoals opleidingsachtergrond of gezinsinkomen. Verschillende overheidsinstanties zijn parallel betrokken bij stedelijke water gerelateerde vraagstukken; er is echter geen duidelijke strategie om de noodzakelijke samenwerking binnen de overheden aan te gaan, om zo stedelijk water-hergebruik mogelijk te maken. Aanpassingen in bestaande wet- en regelgeving zijn nodig en ook de organisatie en bestuurscultuur dient omgebogen te worden naar organisaties die goed samen werken.

Ten slotte vat **Hoofdstuk 6** de bevindingen van dit proefschrift samen. De mogelijkheden en nadelen van hergebruik van stedelijk water worden besproken, waarbij de noodzaak voor inrichting van goede infrastructuren voor opvang zuivering e distributie wordt benadrukt. Er is een uitgebreid literatuuronderzoek uitgevoerd om de cruciale factoren op te sommen waarmee rekening moet worden gehouden voor het selecteren van geschikte technologieën voor behandeling van water en het definiëren van een juiste inzamelings- en behandelingsstrategie, inclusief opslag en herverdeling naar de landbouwgebieden. Het is duidelijk dat aandacht voor de lokale context en het doel van de behandeling bepalend zijn voor de keuze van de juiste technologie. Om de keuze te faciliteren zijn vier verschillende scenario's voor hergebruikhergebruik van stedelijk water in de landbouw opgesteld. De vier scenario's zijn ingedeeld als goud, groen, rood en grijs. Het gouden scenario pleit voor een geavanceerde behandeling van het stedelijk water, terwijl het groene scenario de nadruk legde op meer natuurlijke behandelingssystemen. Het rode scenario promoot de gecentraliseerde behandelingsaanpak en het grijze scenario identificeert een op de gemeenschap gebaseerd goedkoop behandelingssysteem als een oplossing om aan de watervraag in de landbouw te voldoen. Het hoofdstuk identificeert ook een aantal beperkingen van het in het huidige onderzoek en geeft suggesties voor toekomstig onderzoek.

Gezien de toekomstige onzekerheden rondom de zoetwatervoorziening vormt gepland hergebruik van stedelijk water een haalbare alternatieve oplossing om aan de groeiende vraag naar water in de landbouwsector te voldoen. Verbetering van de bestaande waterkwaliteit met adequate behandeling en ondersteunende infrastructuur voor opvang, opslag en levering moet gerealiseerd worden om veilig hergebruik van stedelijk water te waarborgen. Ondersteunende innovaties in bestuursregelingen en participatie van belanghebbenden in het besluitvormingsproces kunnen een succesvolle implementatie van projecten voor stedelijk waterhergebruik bevorderen. Met al deze maatregelen kunnen landbouwactiviteiten in het Bengaalse deel van de Ganges–Brahmaputradelta mogelijk blijven.

সারমর্ম

পৃথিবীতে প্রাণ টিকিয়ে রাখতে পানি অপরিহার্য এবং মিঠাপানি সম্পদের অসম বন্টন পানির সহজলভ্যতাকে প্রভাবিত করছে। অধিকন্তু, জলবায়ু পরিবর্তন ও দ্রুত নগরায়ন পানির সহজলভ্যতাকে বাধাগ্রস্থ করে, পানির বৈশ্বিক সংকট সৃষ্টি করেছে। সমুদ্রের সান্নিধ্যে থাকায় বদ্বীপ অঞ্চলসমূহ দ্রুত বর্ধনশীল পানি ঘাটতির জন্য সবচেয়ে নাজুকতা প্রদর্শন করে। বঙ্গীয় বদ্বীপ পৃথিবীর সবচেয়ে বৃহৎ বদ্বীপ এবং প্রকৃতিতে পানির প্রাচুর্য থাকা সত্ত্বেও প্রয়োজনীয় অবকাঠামোর অভাবে অর্থনৈতিক পানির ঘাটতিতে ভুগছে। সমুদ্রপৃষ্ঠের উচ্চতা বৃদ্ধি, লবণাক্ততার অনুপ্রবেশ, অপরিশোধিত অথবা কমশোধিত বর্জ্যপানি অবমুক্ত হলে ভূপৃষ্ঠের উপরিভাগের পানির মান ক্ষতিগ্রস্থ হয় এবং পানীয় ও সেচের পানির সহজলভ্যতা ও গুণগতমানকে হুমকির মুখে ঠেলে দেয়। নগরীর পানি বলতে এই অভিসন্দর্ভে গ্রে-ওয়াটার (রান্নাঘর, গোসলখানা থেকে নিঃসৃত বর্জ্যপানি) ও সার্ফেস রানঅফ (বৃষ্টি ভুমিতে পতিত হওয়ার ফলে সৃষ্ট জলরাশি) কে বোঝানো হয়েছে; যা একই অবকাঠামোতে সংগৃহীত হয় এবং উভয়ই উল্লেখযোগ্যভাবে ব্ল্যাক-ওয়াটার (শৌচাগার থেকে নিঃসৃত বর্জ্যপানি) থেকে কম দূষিত। কৃষিক্ষেত্রে নগরীর পানির ব্যবহার সেচের জন্য একটা বিকল্প উৎস কিন্তু নিরাপদ প্রয়োগের জন্য এর গুণগতমান বৃদ্ধির দরকার হয়। নগরীর পানির পুনর্ব্যবহার পানি সম্পদের সমাজ-পরিবেশগত স্থায়িত্ব বৃদ্ধির মাধ্যমে একটা মূল্য-সাশ্রয়ী সমাধান দেয়। তবে নগরীর পানির পূনর্ব্যবহার প্রকল্পসমূহের সাফল্যজনক বাস্তবায়নের জন্য আর্থ-সামাজিক, স্বাস্থ্য ও প্রাযুক্তিক (সংগ্রহ, পরিশোধন, পুনঃবিতরণ) দিকসমূহের পর্যাপ্ত পরিকল্পনা ও গভীর উপলব্ধি প্রয়োজনীয়।

বঙ্গীয় বদ্বীপে মানসম্মত সেচের পানির ক্রমবর্ধমান চাহিদাকে বিবেচনায় নিয়ে, এই গবেষণা নগরীর পানি কৃষিতে নিরাপদভাবে পুনর্ব্যবহারের সম্ভাবনা ও প্রতিবদ্ধতাসমূহের দিকে নজর দিয়েছে। এই বিষয়ের জটিলতা বিবেচনা করে এই গবেষণার উদ্দেশ্যসমূহকে সমাজ-প্রাযুক্তিক প্রেক্ষিতসমূহকে আমলে নিয়ে নিম্নোক্ত সুনির্দিষ্ট উদ্দেশ্যসমূহ সাজানো হয়েছে: এক) শহরতলির (Peri-Urban) কৃষির সেচ চাহিদার বিপরীতে নগরীর পানি সরবরাহ সম্ভাবনার সমকক্ষতা যাচাই; দুই) ভূপৃষ্ঠের পানির গুণগতমানের স্থানিক-সময়গত পরিবর্তনশীলতা বদ্বীপ অঞ্চলের কৃষিতে এর ব্যবহারকে কতটা প্রভাবিত করতে পারে তা অনুধাবন; তিন) ভুপৃষ্ঠের পানির অনুজীব ও ভারি ধাতব দূষণ বিশ্লেষণ এবং শহরতলির কৃষকরা সেচের জন্য ভূপৃষ্ঠের দূষিত পানির (সাথে বর্জ্য পানির) ব্যবহারের জন্য কি ধরণের স্বাস্থ্য ঝুঁকিতে রয়েছে -তা নিরূপন করা; চার) বিদ্যমান প্রাতিষ্ঠানিক আয়োজন ও কৃষিতে পরিকল্পিত পানি পুনর্ব্যবহার বিষয়ে অংশীজনের উপলব্ধি অন্বেষণ করা; এবং পাঁচ) কৃষিতে নিরাপদ নগরীর পানি পুনর্ব্যবহারের সুবিধার্থে নগরীর পানি ব্যবস্থাপনা ও পরিশোধনের জন্য সমাজ-প্রাযুক্তিক দৃশ্যকল্পসমূহ নির্মান করা।

কেসস্টাডির জন্য জলবায়ু পরিবর্তনজনিত কারণে খুব নাজুক বাংলাদেশের উপকূলীয় নগর খুলনাকে বেছে নেয়া হয়েছে। মূল নগরী ও শহরতলিকে গবেষণার সীমানা হিসেবে নির্ধারণ করা হয়। নিম্নোক্ত গবেষণা প্রশ্নসমূহ গবেষণার সামগ্রিক লক্ষ্য অর্জনে পথনির্দেশ করে, যা বিভিন্ন অধ্যায়ে বিন্যস্ত করা হয়েছে।

১. শুষ্ক মৌসুমে নগরীর পানি শহরতলির কৃষিকাজের সেচ চাহিদা মেটানোর জন্য কতটা অবদান রাখতে পারে?
২. ভূপৃষ্ঠের পানির গুণগতমান কি কৃষিতে পুনর্ব্যবহারের সম্ভাবনাকে ক্ষতিগ্রস্থ করে?
৩. অপ্রত্যক্ষ বর্জ্য পানি সেচের সাথে কৃষকদের কি কি স্বাস্থ্য ঝুঁকি রয়েছে?
৪. বিদ্যমান প্রাতিষ্ঠানিক আয়োজন ও অংশীজনের উপলব্ধিকে কি পরিকল্পিত নগরীর পানি পুনর্ব্যবহারের সুবিধার্থে কাজ করবে?

প্রথম অধ্যায়ে, পানির বৈশ্বিক প্রাপ্যতা সংক্রান্ত ধারণা দেয়া হয় এবং পৃথিবীর বিভিন্ন অঞ্চলে ক্রমবর্ধমান পানি ঘাটতির কারণ হিসেবে জলবায়ু পরিবর্তন ও দ্রুত নগরায়নের নেতিবাচক প্রভাবকে সুনির্দিষ্টভাবে চিহ্নিত করা হয়। বিশ্বব্যাপী নগরীর পানির পুনর্ব্যবহারের ইতিহাস, প্রধান প্রবনতা ও অর্জনসমূহ চিত্রিত করার জন্য বিদ্যমান গবেষণাসমূহ পর্যালোচনা করা হয়েছে। বঙ্গীয় বদ্বীপে ক্রমবর্ধমান চ্যালেঞ্জ ও প্রয়োজনীয়তা নির্দেশ করার জন্য পয়ঃনিষ্কাশন ও পানীয় জলের সরবরাহ এবং কৃষিকাজের জন্য সেচের পানি নিয়ে আলোচনা করা হয়েছে। সবশেষে, এই অধ্যায়ে নগরীর জলের পুনর্ব্যবহার সংক্রান্ত জ্ঞানের পরিস্থিতি এবং বিদ্যমান জ্ঞানের ব্যবধান ও এ বিষয়ে গবেষণার প্রয়োজনীয়তাকে আমলে নিয়ে গবেষণার ক্ষেত্রকে সংজ্ঞায়িত করেছে।

বিভিন্ন রকম গুণগত ও পরিমানগত গবেষণা পদ্ধতি ব্যবহার করে খুলনা নগরী ও এর চারদিকের ভূপৃষ্ঠের জলাশয় থেকে তথ্য/নমুনা সংগ্রহ করা হয়। মাঠ থেকে তথ্য সংগ্রহের প্রধান মনোযোগ ছিলো: বিভিন্ন পানিসম্পদ থেকে পানির পরিমান নির্ধারন ও সেচের জন্য প্রয়োজনীয় পানির পরিমাপকে বিবেচনায় নেওয়া (দ্বিতীয় অধ্যায়), বৃহৎ রাসায়নিক লবনাক্ততা ও বর্জ্য পানির সাথে সম্পর্কিত প্যারামিটার (তৃতীয় অধ্যায়), ক্ষুদ্র রাসায়নিক (বিশেষ করে ভারি ধাতু ও অনুজীব, যেমন কলিফর্ম) দূষণকারী (চতুর্থ অধ্যায়), এবং পুনর্ব্যবহার সংক্রান্ত অংশীজনের উপলব্ধি (পঞ্চম অধ্যায়)।

দ্বিতীয় অধ্যায়ে, শহরতলির কৃষিকাজে নগরীর পানি পুনর্ব্যবহারের সম্ভাবনা পরিমানগতভাবে মূল্যায়ন করা হয়েছিলো। প্রথমত, খাদ্য ও কৃষি সংস্থা (FAO) পানি শস্য মডেল (AquaCrop)অনুসরন করে, শুষ্ক মৌসুমে প্রধান ফসল হিসেবে বোরো ধান চাষের জন্য সেচের পানির প্রয়োজনীয়তা মাপা হয়েছিলো। তারপর পানীয় জলের ব্যবহার ও গবেষণা এলাকায় বিভিন্ন ভুপৃষ্ঠে ২০১৮ সালের বার্ষিক বৃষ্টিপাতের উপর নির্ভর করে মোট নগরীর পানির (ভিন্নভাবে সংগৃহীত চিন্তা করে) উৎপাদনের হিসাব করা হয়েছে। এরপর ২০১৮ সালে নগরীর বিভিন্ন পানি উৎপাদন পরিস্থিতির বিপরীতে শহরতলীর কৃষিতে (বোরো ধান) গড় সেচ চাহিদা মূল্যায়ণ করা হয়েছিলো। বিশ্লেষণে দেখা যায়, নগরীর পানি শহরতলিতে কৃষিকাজের সেচের পানির চাহিদা মেটানোর ক্ষেত্রে ইতিবাচক ভুমিকা রাখতে পারে এবং মডেলের তথ্য অনুসারে বিগত কয়েক দশক ধরে (১৯৮৪- ২০১৭) বোরো ধানের সেচ-চাহিদা বার্ষিক বৃষ্টিপাত হ্রাসের সাথে কমে গেছে। ফেব্রুয়ারি ও মার্চ মাসের বোরোধান জন্মানোর সময়ে পানির প্রয়োজনীয়তা সর্বাধিক এবং এই সময়ে বৃষ্টির ঘাটতি সেচের চাহিদা পুরোপুরিভাবে মেটাতে ব্যর্থ হয়। তবে, নগরীর পানি সংরক্ষণের ব্যবস্থা চালুর হলে তা দিয়ে সারাবছরের চাহিদা মেটানো সম্ভব। এই অধ্যায় থেকে প্রাপ্ত ফলাফল বঙ্গীয় বদ্বীপে কৃষিকাজ চালু রাখতে নগরীর পানির উপযুক্ত সম্ভাবনার একটি দৃঢ় পরিমাণগত নিরীক্ষা হাজির করে।

তৃতীয় অধ্যায়ে, ভুপৃষ্ঠের উপরিভাগের পানির রাসায়নিক- ভৌত গুণমানের স্থানিক- সময়গত পরিবর্তনশীলতা বিশ্লেষণ করা হয় এবং পরবর্তী সময়ে কৃষিতে ব্যবহারযোগ্যতার ম্যাপিং করা হয়। পরিসংখ্যানিক বিশ্লেষনের মাধ্যমে নগরীর ভুমিব্যবহারের সাথে পানির গুণগতমানকে সম্পর্কিত করে দেখা হয় এবং জি.আই.এস ব্যবহার করে ম্যাপিং এর মাধ্যমে বিভিন্ন স্থান থেকে সংগৃহীত পানির নমুনাসমূহ আরও বিশদ বিশ্লেষণ করা হয়। পানির গুণগতমানের উপর নগরীর বর্জ্যপানি ও কঠিন বর্জ্য সরাসরি অবমুক্ত করার নেতিবাচক প্রভাব প্যারামিটারসমূহের উচ্চমান দ্বারা প্রতিফলিত হয়, যেমন: কঠিন বস্তু (টি.এস.এস), জৈব পদার্থ (বিওডি$_5$, সিওডি) এবং নিম্নমাত্রার ডিও ঘনত্ব। সংলগ্ন লবণাক্ততা বহনকারী শাখা নদীসমুহও পানির গুণগতমানকে প্রভাবিত করে যা উচ্চমাত্রার লবণপানি প্রভাবিত প্যারামিটারসমূহের মাধ্যমে বোঝা যায়, যেমন টিডিএস, সোডিয়াম $^+$ ও ক্লোরিন $^-$। ফলাফলে দেখা যায়, বিদ্যমান ভুপৃষ্ঠের পানির গুণগতমান সম্পর্কিত প্যারামিটারসমূহের জন্য খাদ্য ও কৃষি সংস্থা (FAO) নির্ধারিত গ্রহনযোগ্যমাত্রা পূরণ করে না। পানির রাসায়নিক-ভৌত গুণগতমানের প্যারামিটারসমূহ ভুপৃষ্ঠের পানির কৃষিকাজে ব্যবহারকে সীমাবদ্ধতা নির্দেশ করে। আশেপাশের ভুমিব্যবহারের প্রভাবও গবেষণা এলাকায় সুস্পষ্ট ছিল, যা পানির গুণগতমান এবং ভবিষ্যতের পরিকল্পনার কৌশলসমূহ উন্নত করার কাজে ব্যবহার করা যেতে পারে। স্থানীয় পর্যায়ে পানির গুণগতমানের তথ্যকে স্থানিকভাবে সমন্বয় করার পদ্ধতিটি পানির গুণগতমান ও উপযোগিতার পার্থক্য, কৃষিতে পুনঃ ব্যবহার সীমাবদ্ধতা এবং পরিশোধন সম্পর্কে মূল্যবান অন্তর্দৃষ্টি প্রদান করে।

চতুর্থ অধ্যায়ে, ভূপৃষ্ঠস্থ পানিতে অণুজীব ও ভারী ধাতব দূষণের মাত্রা পরীক্ষাগার বিশ্লেষণ এবং পরবর্তী ঝুঁকি মূল্যায়নের কাজ করা হয়েছে। পানির নমুনায় E. coli এর উপস্থিতি বিবেচনা করে কৃষকদের স্বাস্থ্য ঝুঁকি মূল্যায়নের জন্য একটি স্ক্রিনিং লেভেল পরিমাণগত অণুজীব ঝুঁকি সমীক্ষা (QMRA) করা হয়েছিল। ফলাফল থেকে জানা যায় যে, অণুজীব সূচকসমূহের গড় উপস্থিতি বিশ্ব স্বাস্থ্য সংস্থা (WHO) ও নিরাপদ সেচের জন্য স্থানীয় নির্দেশিকাসমূহের গ্রহনযোগ্য মাত্রা অতিক্রম করেছে। তবে ভারী ধাতুসমূহের জন্য এ জাতীয় কোনও তাৎপর্য মাত্রা লক্ষ্য করা যায় নি (সম্ভবত পানিতে অন্যান্য জৈব ক্ষুদ্রাণু দূষণকারী উপস্থিত কিন্তু এই গবেষণায় তা ধর্তব্যে আনা হয়নি)। অণুজীব স্বাস্থ্য ঝুঁকি সমীক্ষা থেকে দেখা যায় যে, বিদ্যমান ভুপৃষ্ঠের পানির অণুজীবগত মান কৃষকদের জন্য স্বাস্থ্য ঝুঁকি তৈরি করে কারণ তারা অণুজীব-দূষিত ভুপৃষ্ঠের পানির সরাসরি সংস্পর্শে আসে এবং কোন সুরক্ষামূলক সরঞ্জাম ব্যবহার করে না। তবে দীর্ঘদিনের চর্চা ও উন্নতমানের সেচ উৎসের অভাবে কৃষকরা তাদের স্বাস্থ্যকে অগ্রাধিকার দেন না। একাধিক বাধা সম্বলিত পদ্ধতি যেমন প্রয়োজনীয় পরিশোধনের মাধ্যমে অণুজীবের পরিমাণ কমানো, প্রতিরক্ষামূলক সরঞ্জামের মাধ্যমে দুর্ঘটনাজনিত সেচপানি গলধঃকরন হ্রাস এবং কৃষকদের মধ্যে সচেতনতা বৃদ্ধিকে স্বাস্থ্য ঝুঁকি কমানোর পদ্ধতি হিসেবে আলোচনা করা হয়েছে। এই অধ্যায়ের ফলাফলসমূহ কৃষিকাজে নিরাপদ ব্যবহারের জন্য বর্জ্যপানির পরিশোধনের প্রয়োজনীয়তাকে পুনরায় গুরুত্বপূর্ন করে তুলেছে।

পঞ্চম অধ্যায়ে, বেশ কয়েকটি অংশগ্রহণমূলক পদ্ধতি যেমন প্রশ্নজরিপ, সুনির্দিষ্ট তথ্যদাতার সাক্ষাৎকার ও কেন্দ্রদলীয় আলোচনা (FGD) ব্যবহার করে নগরীর পানির পুনর্ব্যবহারের সুশাসনের দিকসমূহ গবেষণা করা হয়। ফলাফল থেকে জানা যায়, অধিকাংশ নাগরিকদের মধ্যে (৮০%) বর্জ্য পানির সরাসরি অবমুক্তকরণের নেতিবাচক প্রভাব সম্পর্কে উচ্চ মাত্রার সচেতনতা রয়েছে। অধিকন্তু, জলবায়ু পরিবর্তনের কারণে সেচের পানির ঘাটতি মোকাবেলার বিকল্প হিসাবে নগরীর পানির পুনর্ব্যবহারের প্রতি ইতিবাচক মনোভাব লক্ষ্য করা গেছে। নাগরিকরা পরিশোধনের জন্য অর্থ প্রদান করতে ইচ্ছুক যা পরিশোধনাগারের পরিচালনা ও রক্ষণাবেক্ষন খরচের অর্ধেক তুলতে পারে। নাগরিকদের সদিচ্ছা তাদের আর্থ-সামাজিক অবস্থা যেমন শিক্ষার পটভূমি বা পারিবারিক আয় দ্বারা প্রভাবিত হয়। বেশ কয়েকটি সরকারী সংস্থা সমান্তরালভাবে নগরীর পানির সাথে সম্পর্কিত বিষয়সমূহ নিয়ে কাজ করে, তবে নগরীর পানির পুনর্ব্যবহারের মতো আন্তঃবিদ্যায়ন্তিক বিষয় সংক্রান্ত বিষয়ে একসাথে কাজ করার সুস্পষ্ট কৌশল নেই। সংস্থারসমূহের মধ্যে সহযোগিতা ও একসাথে কাজ করার জন্য বিদ্যমান বিধিমালায় সমন্বয় সাধন একান্ত প্রয়োজন।

পরিশেষে, ষষ্ঠ অধ্যায়ে, এই অভিসন্ধর্ভের অনুসন্ধানসমূহকে সংশ্লেষিত করা হয় এবং কৃষিতে নগরীর পানির পরিশোধন ও পুনর্ব্যবহারের জন্য চারটি পৃথক সমাজ-প্রাযুক্তিক দৃশ্যকল্প তুলে ধরা হয়েছে। নগরীর পানির পুনর্ব্যবহারের সম্ভাব্যতা ও সীমাবদ্ধতাসমূহ বিবেচনায় নিয়ে যথাযথ পরিশোধন অবকাঠামোসমূহের আবশ্যকতা আলোচনা করা হয়েছে। উপযুক্ত পরিশোধন প্রযুক্তি ও সেচ কাজে পুনরায় বিতরণের জন্য সংরক্ষণসুবিধাসহ প্রয়োজনীয় প্রযুক্তি নির্বাচনের জন্য যে গুরুত্বপূর্ণ বিষয়সমূহ বিবেচনা করা প্রয়োজন তার তালিকা তৈরির জন্য বিদ্যমান তথ্যের একটি বিস্তৃত পর্যালোচনা করা হয়। এটি স্পষ্ট যে, স্থানীয় প্রেক্ষাপট বিবেচনায় নিয়ে পরিশোধনের জন্য যথাযথ প্রযুক্তি বাছাইয়ের কোন বিকল্প নেই। বঙ্গীয় বদ্বীপে সর্বাধিক গুরুত্বপূর্ণ চালিকা শক্তি চিহ্নিত করার পরে, দৃশ্য পরিকল্পনা ব্যবহার করে চারটি দৃশ্যকল্প হাজির করা হয়: লাল দৃশ্যকল্প, ধূসর দৃশ্যকল্প, সুবর্ণ দৃশ্যকল্প ও সবুজ দৃশ্যকল্প। লাল দৃশ্যকল্প কেন্দ্রীভূত পরিশোধন পদ্ধতিকে প্রাধান্য দেয় ও ধূসর দৃশ্যে এলাকাভিত্তিক স্বল্প খরচের পরিশোধন ব্যবস্থা কৃষির পানির চাহিদা মেটাতে একটা সম্ভাব্য সমাধান হিসাবে চিহ্নিত হয়েছে। সুবর্ণ দৃশ্যকল্প উন্নত পরিশোধনের জন্য জোর দেয়, সেখানে সবুজ দৃশ্যকল্প প্রাকৃতিক পরিশোধন ব্যবস্থার উপর গুরুত্ব আরোপ করে। এই অধ্যায়ে বর্তমান গবেষণার বেশ কিছু সীমাবদ্ধতাকে নির্দেশ করে ভবিষ্যতের গবেষণার জন্য পরামর্শ প্রদান করে।

মিঠাপানি সরবরাহ সম্পর্কে ভবিষ্যতের অনিশ্চয়তা বিবেচনা করে, পরিকল্পিতভাবে নগরীর পানির পুনর্ব্যবহার কৃষিক্ষেত্রে ক্রমবর্ধমান পানির চাহিদা মেটাতে একটি কার্যকর বিকল্প সমাধান হিসেবে উপস্থাপন করে। নগরীর পানির নিরাপদ পুনর্ব্যবহার নিশ্চিত করতে পর্যাপ্ত পরিশোধন, সংগ্রহ, সংরক্ষণ ও সরবরাহের জন্য সহায়ক অবকাঠামোসহ বিদ্যমান পানির গুণগতমান বৃদ্ধি করতে হবে। সহায়ক সুশাসন আয়োজন ও সিদ্ধান্ত গ্রহণ প্রক্রিয়ায় অংশীদারদের অংশগ্রহণ বঙ্গীয় বদ্বীপে কৃষিকাজ টিকিয়ে রাখার জন্য নগরীর পানির পুনর্ব্যবহার প্রকল্পসমূহের সফল বাস্তবায়ন নিশ্চিত করতে পারে।

List of key terms and abbreviations

ADB	Asian Development Bank
AOSED	An Organization for Socio-Economic Development
BADC	Bangladesh Agricultural Development Corporation
BBS	Bangladesh Bureau of Statistics
BELA	Bangladesh Lawyers Association
BMD	Bangladesh Meteorological Department
BWDB	Bangladesh Water Development Board
DAE	Department of Agricultural Extension
DC	District Commissioner
DOE	Department of Environment
DPHE	Department of Public Health Engineering
ETP	Effluent Treatment Plant
FAO	Food and Agriculture Organization
FGD	Focus Group Discussion
GoB	Government of Bangladesh
IMF	International Monetary Fund
IWMI	International Water Management Institute
IWRM	Integrated Water Resource Management
KCC	Khulna City Corporation
KDA	Khulna Development Authority
KII	Key Informant's Interview
KWASA	Khulna Water Supply and Sewerage Authority
LGED	Local Government Engineering Department
NWRC	National Water Research Council
O&M	Operation and Maintenance
PMO	Prime Minister's Office
USEPA	United States Environmental Protection Agency
WB	World Bank
WHO	World Health Organization
WTP	Willingness to pay
WWTP	Wastewater Treatment Plant

Chapter 1

Introduction

1.1 General Background

1.1.1 Water Availability and Scarcity, Climate Change and Urbanization

Water Availability and Scarcity

Water is one of the essential resources on this planet and only 3% of the total global water resource is freshwater (Du Plessis, 2017; Shiklomanov, 1998). Nevertheless, 69% of that freshwater is trapped in icecaps and glaciers in the polar region and only 1% of all water on Earth is usable by humans (Du Plessis, 2017; Lui et al., 2011). This leaves 2120 km^3 of freshwater available for human consumption and use (Cassardo and Jones, 2011). In general, water availability is 58% higher in developed countries (11392 m^3/capita.year) compared to developing countries (7693 m^3/capita.year) (Jiménez and Asano, 2008). This is because water availability varies across regions as water resources are distributed unevenly across the world geographically and economically (Cassardo and Jones, 2011; Kibona et al., 2009; Pimentel et al., 2010). An important parameter used to characterize water stress is renewable freshwater availability which is defined as the availability of potentially usable water per person (Du Plessis, 2017; Jiménez and Asano, 2008). Based on this, a region can be identified as water-stressed when this water availability is below 1700 m^3/capita.year and with water availability below 100 m^3/capita.year the region is classified as below the minimum survival level (Table 1.1) (Bixio et al., 2006; Eslamian, 2016; Jiménez and Asano, 2008; Lazarova et al., 2001).

Water availability is most critical in the Middle Eastern, North African and some Mediterranean countries as these nations have already exploited the conventional water resources (Dubreuil et al., 2013; Lazarova et al., 2001; McNally et al., 2019; Procházka et al., 2018). The situation is changing in Europe and North America due to long-lasting, frequent droughts and quality deterioration (Bixio et al., 2006; Lazarova et al., 2001). The changes in climate and socio-economic conditions will impact the "water towers" of the mountains in supplying natural and anthropogenic water demands impacting 1.9 billion people globally (Immerzeel et al., 2020). Water availability can be affected by geographical setting (physical scarcity) or lack of adequate infrastructure (economic scarcity), both resulting in water scarcity (UN-Water, 2021). Different regions face various forms of physical and economical water scarcity, the latter occurring even water is abundant in nature (Figure 1.1). Around 1.2 billion people of Arid regions face physical water scarcity as there is not enough water available to meet the demand and around 1.6 billion people in Sub-Saharan Africa and South Asia encounter economic water scarcity due to lack of financial and human capacity to meet the demand (IWMI, 2007).

Table 1.1: Threshold values to characterize water stress in terms of availability (Adapted from Jiménez and Asanno, 2008)

Characteristics	Threshold (m^3/cap.yr)	Situation	Example Countries
No water stress	>1700	No water stress due to water availability	Bangladesh, Canada, Cyprus, Malta
Water Stress	1000-1700	Begin to experience the effect of stress	Denmark, Poland, South Africa, India
Chronic Water Stress	500-1000	Often experiences long and short-term water problem	Egypt, Morocco, Cyprus, Burkina Faso
Absolute Water Stress	100-500	Completes over available water sources seawater	Jordan, Malta, Israel, Oman, Singapore
Minimum survival level	<100	Compromised water supply among sectors	Kuwait, Qatar, Saudi Arabia, Maldives

In recent times, water scarcity is considered one of the most significant threats to society and a constraint for sustainable development (Eslamian, 2016; Jiménez and Asano, 2008). Studies show that 40% of the total global population is currently affected by water scarcity (FAO, 2016a; Jahan et al., 2015; Mekonnen and Hoekstra, 2016; WWAP, 2012). The future projection suggests that based on existing consumption practices and policies, by the year 2025, the percentage of the water scare population may rise to 60% (Cosgrove and Rijsberman, 2000; Qadir et al., 2007). The growing water demand due to population growth, rapid urbanization, rising economic activities, overexploitation of land covers

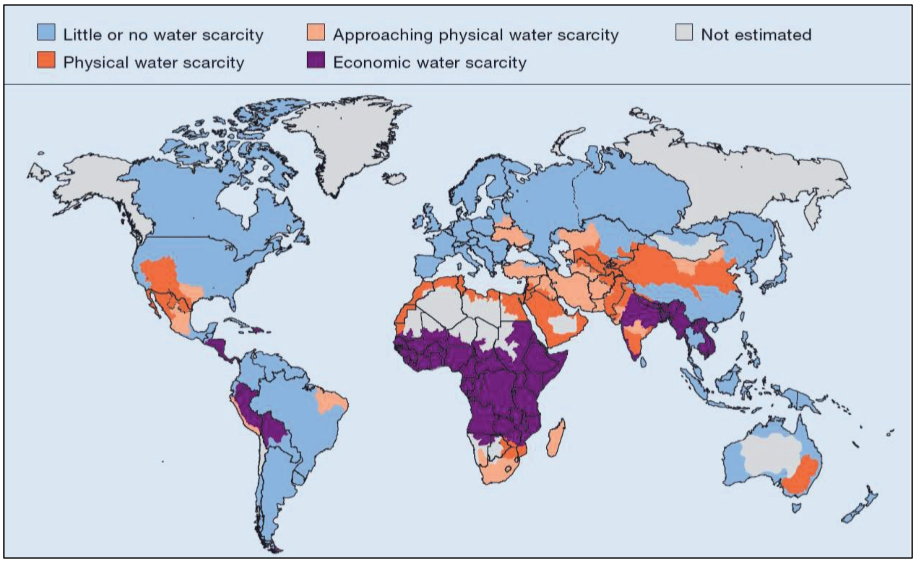

Figure 1.1: Map showing the areas of physical and economic water scarcity (Source: IWMI, 2007)

and most importantly, climate change will accelerate the water scarcity in the coming decades (Eslamian, 2016; Gallopín, 2012; Kummu et al., 2016; Rodell et al., 2018).

Climate Change

Global warming is one of the key environmental risks persistently threatening the hydrological cycle (Vairavamoorthy et al., 2008). Within the 21st century, the competition for freshwater sources is expected due to variable climatic patterns (Flörke et al., 2018; Koutroulis et al., 2019). Changing climatic patterns with extreme events such as high temperature, variable rainfall and overall less predictable weather conditions can lead to drought and further limit water availability (Flörke et al., 2018; Kummu et al., 2016). By 2050, 0.5 to 3.1 billion people, mainly in South Asia and East Asia, are expected to be exposed to severe water scarcity due to climate change (Gosling and Arnell, 2016). The climatic impact on snow and ice reserves of Asian mountains will affect the water availability and threaten the food security of 60 million people living around the Brahmaputra and Indus basin (Immerzeel et al., 2010).

Urbanization and Agricultural water use

In addition to climate change, rapid urbanization, population growth, increased industrial and economic activities are deteriorating the water quality and threatening the availability of fresh water sources (Eslamian, 2016; Frederick and Major, 1997; Sophocleous, 2004). In 2007, the urban population exceeded the total number of the rural population and by 2050, two-thirds of the world population would be living in the urban areas (Flörke et al., 2018; United Nations, 2014). Providing a reliable and safe water supply to urban habitats is a crucial contribution to society's overall economic and welfare advancement (Raj, 2016). Safeguarding drinking water provision for consumption and food production for the growing population will challenge achieving the SDGs (SDG2: zero hunger, SDG 6: clean water and sanitation, SDG 11: urban sustainability).

The agricultural sector accounts for 70% of the global water withdrawal, out of which 90% occurs in the developing countries (Cai and Rosegrant, 2002; IWMI, 2007; Wisser et al., 2008). Estimation about the availability and withdrawals is vital for forecasting food production, human and ecosystem health, energy generation and social conflict (Rodell et al., 2018). Groundwater has slow recharge rates and needs to be managed carefully to prevent depletion (Pimentel et al., 2010). Alternative measures such as infrastructure to transport water to scarce areas, desalination, water-efficient technologies (i.e. drip irrigation) have been adopted to cope with the water demand in the agricultural sector (Lazarova et al., 2001). However, desalination is not deemed to be a viable solution as it is energy intensive and expensive (Pimentel et al., 2010). In comparison, water reuse has often been seen as a cost-effective solution due to valorising the social and environmental value of water (Eslamian, 2016; Jiménez and Asano, 2008; Lazarova et al., 2001).

1.1.2 Definition of key terms

Peri-urban area

Defining peri-urban area is not easy as it goes beyond geographic location and represents a "third space" between urban and rural areas within an interconnected continuum (Camagni, 1994; Cattivelli, 2021; Hoggart, 2016; Iaquinta and Drescher, 2000; Qviström, 2013; Rauws and De Roo, 2011). Peri-urban can be defined as the area in the "proximity to the city" which undermines the clear understanding of urban-rural spectrum as it is interactive, dynamic and transformative (Iaquinta and Drescher, 2000). The area is often referred to as rural fringe but should also coexist in social, environmental, physical, institutional and economic terms (Allen et al., 2006; Narain and Nischal, 2007). The peri-urban area does not follow the traditional planning procedures and contains a wide variety of land uses (Cattivelli, 2021; Hogrewe et al., 1993). However, this area is not a place of disorder rather a place for innovation with growing infrastructure and extensive green areas (Foot, 2000; Rauws and De Roo, 2011).

Urban Water or Wastewater

Wastewater generally combines domestic wastewater, stormwater, effluents from industrial or commercial establishments and institutions such as hospitals and care homes (Drechsel et al., 2010). Domestic wastewater can be divided into blackwater, which is generated in the toilet (feces and urine) and greywater, which contains wastewater from bathing, washing, laundry and kitchen water (Gross et al., 2015; Metcalf & Eddy, 2013). In this thesis, urban water (containing runoff) and (domestic) wastewater have been used interchangeably.

Reclaimed (waste)water

Reclaimed (waste)water is defined as treated wastewater that can be used legally under controlled conditions for beneficial purposes such as irrigation (Drechsel et al., 2010; Jiménez and Asano, 2008).

Direct and Indirect Wastewater Irrigation

Direct wastewater irrigation denotes that the treated or untreated wastewater is used for agricultural production with little or no prior dilution (Drechsel et al., 2015; Jeong et al., 2016; Jiménez and Asano, 2008). When the wastewater is discharged into a stream and is diluted before it is further used for agriculture, it is termed indirect wastewater irrigation (Drechsel et al., 2015; Jiménez and Asano, 2008; Rutkowski et al., 2007).

Circular Urban Metabolism

Circular urban metabolism has been emerged as a concept based on circular economy and urban metabolism (Agudelo-Vera et al., 2012a; Lucertini and Musco, 2020). A circular economy alleviates the environmental pressure by replacing the end-of-life concept of resources, whereas, in urban metabolism, cities are regarded as living organisms that require resources to survive and discard wastes (Leusbrock et al., 2015; Lucertini and Musco, 2020). Circular urban metabolism integrates and promotes collaboration across disciplines which enhances sustainability through proper management of complexities of cities (Céspedes Restrepo and Morales-Pinzón, 2018; Lucertini and Musco, 2020; Van den Berghe and Vos, 2019).

Urban and Peri-urban Agriculture

Urban agriculture has various definitions but, in simple terms, it can be defined as any farming activities for crop production and livestock goods within cities (intra-urban) or on the fringe (peri-urban) (Ambrose-Oji, 2009; Zezza and Tasciotti, 2010). Globally, around 25-30% of the urban dwellers participate in urban farming, especially in emerging economies which contributes to food security, employment, income diversification and potentially environmental sustainability (Foeken, 2005; Orsini et al., 2013). There is a debate of not differentiating urban agriculture with peri-urban agriculture however, study indicates that peri-urban agriculture is distinct from urban agriculture and plays a crucial role in food security (Opitz et al., 2016). Peri-urban agriculture takes place in the transition zones of urban and rural areas and has a significant contribution to employment generation, thus reducing poverty (Bryld, 2003; Graefe et al., 2008; Opitz et al., 2016).

Scenario Planning

Scenario planning is a tool widely used for stimulating strategic thinking to address future uncertainties (Amer et al., 2013; Lindgren and Bandhold, 2003; Peterson et al., 2003; UNEP, 2016). Traditional planning was based on beliefs and often failed to address various local contexts, whereas scenario planning systematically considers various possible futures, including many crucial uncertainties (Peterson et al., 2003). Scenario planning is instrumental in decision making as it helps the organizations be more flexible and innovative towards possible outcomes (Amer et al., 2013). Herbert Kahn first developed scenario planning while working at RAND corporation and had difficulty creating accurate forecasts (Kahn and Wiener, 1967; Peterson et al., 2003). Since then, scenario planning has been frequently used in decision making at national and international contexts such as Shell Scenario for Oil, Millennium Ecosystem Assessment, Global Environmental Assessments (Lehr et al., 2017; Lindgren and Bandhold, 2003; Peterson et al., 2003). In the last 40 years, scenario planning has been promoted as a key technique for strategy forming and still has many challenges to be resolved by effective execution (Lehr et al., 2017).

Socio-technological Solutions

The term "socio-technological solutions" has been derived based on socio-technical systems design, an approach to formulate strategies considering human, social, technical and organizational factors (Baxter and Sommerville, 2011; Geels, 2004). Systems that are designed adapting to the local condition, favorable institutional and regulatory framework accompanied by infrastructures are more stable (Geels and Kemp, 2007). Especially, with emerging science and technological solutions it is important to provide necessary governance modes to co-evolve with the changes in society (Borrás and Edler, 2020; Kuhlmann et al., 2019).

1.1.3 Water Reuse in Agriculture: History and trends

Water reuse in agriculture or other activities is not a new concept as the practice dates to pre-historic times (ca. 3200–1000 BC). The utilization of wastewater as irrigation water and fertilizer on agricultural lands is evident in the Bronze civilizations such as Minoans and Indus valley (Angelakis et al., 2020, 2018, 2005; Asano and Levine, 1996). Minoans developed sewerage systems to dispose of wastewater to the river or the agricultural land; also, in the *Indus valley,* sewers transported the collected wastewaters through local, covered drains to dispose of in the agricultural lands (Angelakis et al., 2018). Later in the historical times (ca. 1000 BC–330 AD), the use of wastewater in agriculture was evident in ancient Greek cities (Angelakis et al., 2018; De Feo et al., 2010). The drains of Agora in Athens delivered wastewater and rainwater to a collection basin and then further conveyed through brick-lined conduits to the adjacent agricultural fields (Angelakis et al., 2018; Antoniou, 2010; Yannopoulos et al., 2015). The use of semidry night soil (human faeces and urine) as fertilizer in the fields were reported in ancient China and other Asian countries until recently (Khouri et al., 1994; Oinam et al., 2008).

During medieval times (ca. 330–1400 AD), new ways to reuse water in agriculture were tested and used in Central and South America (Angelakis et al., 2018). Chinampas, a Meso-American floating garden, was built over wetlands, shallow lakes, or flood plains using sediments, manure, compost and was very productive and ecologically sustainable (Angelakis et al., 2018; Smith, 1996; Villalonga Gordaliza, 2007). During medieval times Europe was preoccupied with wars and people died due to water-borne diseases, which forced to realize the necessity of proper sanitation practices (Angelakis et al., 2020). During early and mid-modern industrial revolution times (ca. 1400–1900 AD) engineered applications based on sewage farms (land-based effluent disposal and reuse system) evolved around Europe, whereas faeces and urine separation was practiced in many parts of the Orient (Angelakis et al., 2018). Urine separation is an old technique widely used in China to reuse human excreta's nutrients as a fertilizer whereas, in Yemen, the warm climate evaporated the urine quickly and left the nutrients for further use (Antoniou et al., 2016; Johansson et al., 2000).

The advancement of modern wastewater treatment plants (WWTP) with large septic tanks and trickling filters was developed in the mid-nineteenth century in Europe which had significant growth in the twentieth century (Angelakis et al., 2018). The adoption of mechanised WWTP by major urban centres of the world took place in the contemporary times (1900AD – present) as these systems were compact and therefore required smaller areas (Jiménez and Asano, 2008; Metcalf & Eddy, 2013). However, with the installation of mechanized WWTP, reclaiming nutrients and organic matter to fertilize was diminished which regained popularity again in the late twentieth and early twenty-first century due to climate change, resource scarcity, pollution growth and high water demand for various applications (Angelakis et al., 2018; Kehrein et al., 2020).

Implementation of water reuse standards can prevent water-borne diseases and ensure the optimum utilization of available water resources. In the early twentieth century, the increasing number of water-borne disease outbreaks raised public health concerns related to water reuse in agriculture, leading to establishing guidelines (Figure 1.2) for the safe use of reclaimed water (Angelakis et al., 2018; Paranychianakis et al., 2015).

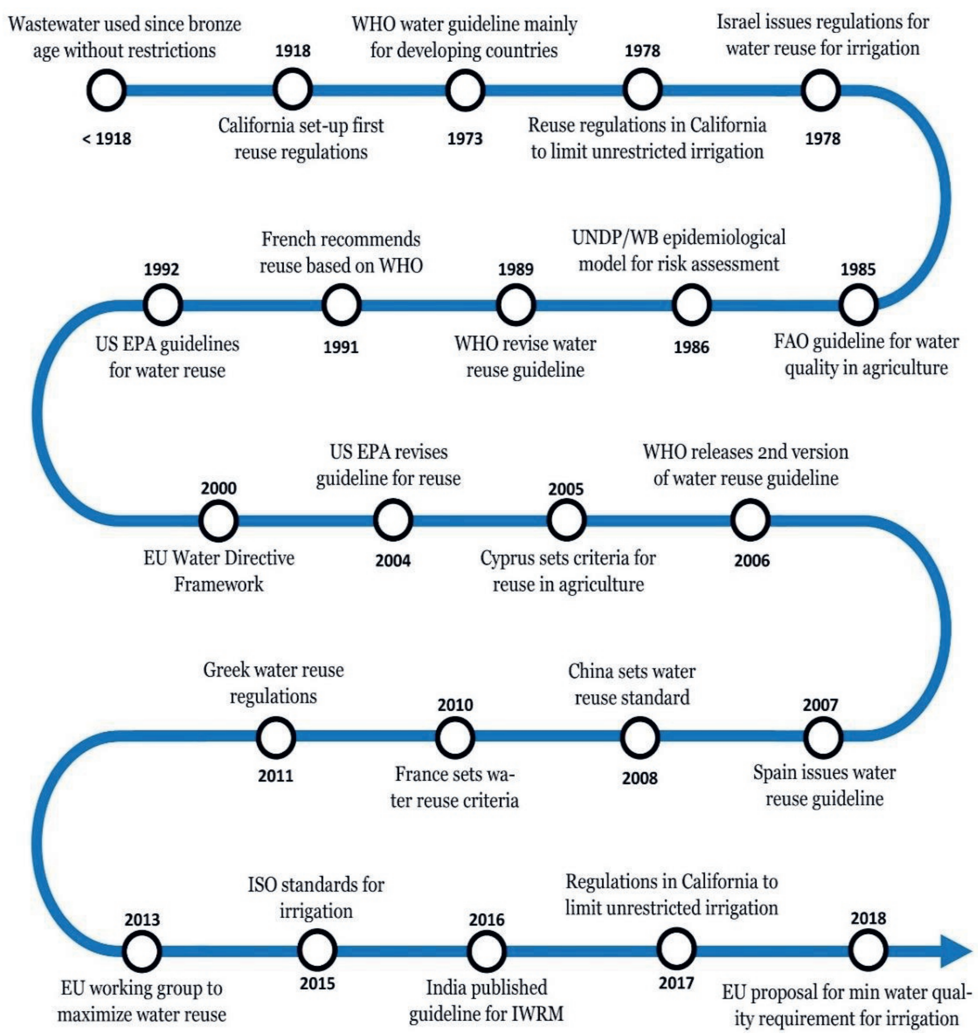

Figure 1.2: Historical timeline of selected milestones on water related regulations (Adapted from Angelakis et al. 2018)

California State Board of Public Health proposed the first legislation in the United States of America, where the regulation for water reuse for irrigation of crops was set (Angelakis et al., 2018). However, until the 1970's, surface waters were heavily polluted due to the direct discharge of wastewater, stimulating the creation of the Clean Water Act in 1972 (Cotruvo, 2016).

In 1973, World Health Organization (WHO) developed the water reuse guideline to ensure the safe reuse and reduction of health-related risks, mainly focusing on developing countries as these nations lacked proper guidelines and the guideline was revised in 1989. In 1985, Food and Agriculture Organization (FAO) formulated water quality guidelines for restricted and unrestricted irrigation and around the same time, United States Environmental Protection Agency (US EPA) published guidelines for water reuse in 1992 (Angelakis et al., 2018; Ayers and Westcot, 1985). In early 2000, the European Union (EU) proposed Water Framework Directive 2000/60/EC (WFD) to address the growing challenges related to irrigation water scarcity and increase pollution level in surface water bodies and, within a short period of time, gained wider acceptance by member countries (Voulvoulis et al., 2017). In the beginning, guidelines were strictly adopted by the developed countries as these countries had the necessary capacity to enforce it. Due to the growing public health and environmental concern in 2008, China set water reuse standards and India revised their integrated water management guideline focusing on reuse in 2016 (GoI, 2016; Yi et al., 2011).

1.1.4 Latest trends and developments: Linear vs. Circular resource management

Currently, around 55% of the world's population (more than 4 billion) live in cities and it is predicted that by 2050 the percentage will rise to 68% (UN-Habitat, 2016). Cities are the major contributor to the global GDP (Kookana et al., 2020). Most cities worldwide consume resources originating from peri-urban or rural areas and emit waste in linear resource management which is inefficient and contains valuable remains in the waste streams (Agudelo-Vera et al., 2012a; Girardet, 1996a; Kennedy et al., 2007; Lucertini and Musco, 2020; McPhearson et al., 2016; Wielemaker et al., 2018). With further population growth, resource consumption will also increase dramatically (Huang et al., 2010). The supply of Earth's resources has limitations, and exploitation will result in fierce competition over resources (Prior et al., 2012). In this context, circular urban metabolism presents an opportunity to make cities more sustainable, evolving from the current linear metabolism (Girardet, 1996b; Van den Berghe and Vos, 2019).

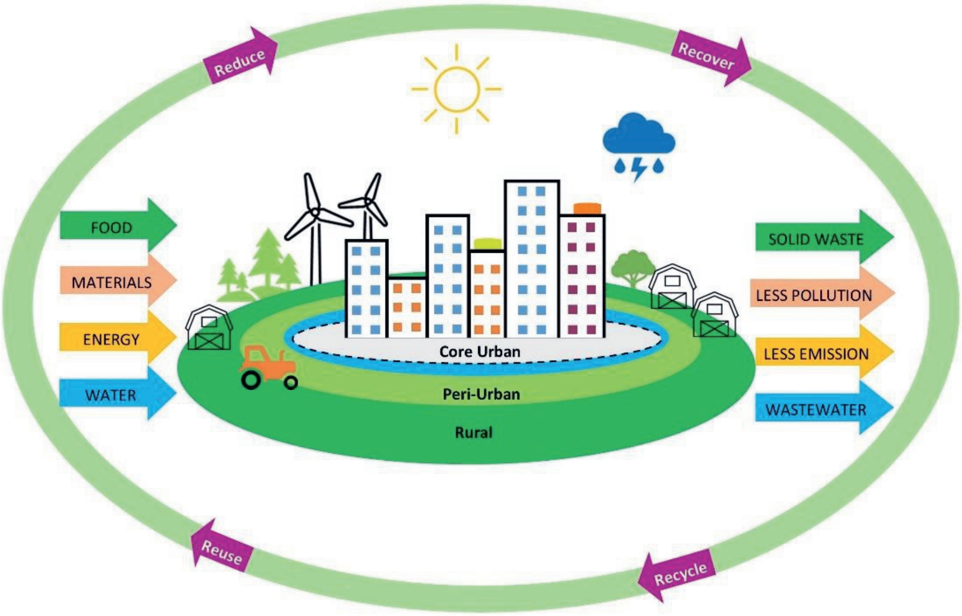

Figure 1.3: Desired circular urban water metabolism (Adapted from Lucertini and Musco, 2020)

Circular urban metabolism enhances the sustainability of cities by lowering the resource consumption rate supported by recycling and reuse, which has less impact on the production areas and enhances the resilience of urban areas (Agudelo-Vera et al., 2012b; Lucertini and Musco, 2020; Wielemaker et al., 2018). Even after the introduction of the wastewater treatment systems in the early twentieth century, around 52% of the global wastewater has still been released into the environment without any treatment and approximately 11% of all irrigated cropland is supplied with untreated or partially treated wastewater (Jones et al., 2021; Kookana et al., 2020). Around 3 out of 4 cities in the developing world (especially in the emerging economies) irrigate their agricultural land with wastewater either planned or unplanned (Drechsel et al., 2015). Urban Harvest Approach (UHA) is a systematic methodology that improves cities' resource management by adopting demand minimization, output minimization and multi-sourcing (Agudelo-Vera et al., 2012a, 2012b). Cities can become more resilient by shifting resource consumption towards available and renewables sources and recovering water, nutrients for reuse in agriculture and recycling waste products in a circular system (Figure 1.3).

1.2 Water Resource Management in the Bengal Delta

1.2.1 Drinking water supply and Sanitation in the Bengal Delta

Ample food resources from the sea, fertile soils and convenience of transportation fueled the formation of civilizations around coastlines and river deltas (Bianchi, 2016; Edmonds et al., 2017; Stanley and Warne, 1997). More than 300 million people live in these delta areas and most of them are in the developing or least developed countries (Edmonds et al., 2017; Ericson et al., 2006). The Bengal Delta is the largest delta in the world and drains sediments from the Ganges, Brahmaputra and Meghna (Akter et al., 2016; Gupta, 2008). Bangladesh covers the major share of the Bengal delta and is home to around 170 million people which accounts for 2% of the world's population (Akter et al., 2016; Steckler et al., 2010). After two violent partitions, Bangladesh became independent in 1971 but inherited political instability and therefore limited economic growth and investments in sanitation and water provision. Continuous efforts and development initiatives advanced the economic performance of the country, which was evident in the 80's (Khan, 2013). The United Nations declared "International Drinking Water Supply and Sanitation Decade" during 1981-1990 to promote and improve the poor water supply and sanitation facilities in the developing countries (Hadi, 2000; Larsimont, 1995).

Historically Bangladesh had an agrarian economy but from the 1960's industrialization took a faster pace, which helped to gain economic growth and from the 1980's on, provision of safe drinking water and access to sanitation was prioritized in the national and local community budgets (Hadi, 2000; Khan, 2013). The country now successfully eradicated open defecation as more than 99% of the population has access to toilet facilities (either personal or community) that was only 2% in the 1980's (Hadi, 2000; UNICEF, 2019; Zaqout et al., 2020). Currently, over 92.7% of the population uses pit latrine: this presents a new challenge due the unsafe removal and transportation practices of faecal sludges from the septic tanks (Zaqout et al., 2020).

Similar to the success in sanitation coverage, Bangladesh made significant progress in connecting over 97% of the population to drinking water sources, yet only 35% of them having access to clean drinking water (UNICEF, 2018). Access to safe drinking water is limited due to climate change-induced salinity intrusion, quality degradation, lack of proper infrastructure and over-extraction of groundwater resources. Additionally, excessive levels of arsenic in groundwater is limiting access to water for domestic activities (Ayers et al., 2017; Burgess et al., 2010). Water is one of the most vibrant resources of Bangladesh with around 700 rivers (Bhuiyan and Dutta, 2012; Mirza, 1998). The country also shares 57 cross-boundary rivers with neighboring India and Myanmar (Chowdhury, 2010). Climate change induced natural disasters (flood, cyclones, draught) and resources degradations (higher salinity level in soil and water) limits the access to safe drinking water in many parts of the delta (Karim and Mimura, 2008; Khan et al., 2016).

1.2.2 Water for Agriculture in the Bengal Delta

The Bengal delta has an ecologically rich and highly productive agricultural landscape (Kumar et al., 2020). The agriculture sector contributes significantly (around 20%) to Bangladesh's total GDP employing nearly half of all labour force (BBS, 2017; Chowdhury, 2010; Islam and Nursey-Bray, 2017; Kumar et al., 2020). Agriculture is dominated by rice production and has three different cropping seasons pre-monsoon, monsoon and dry season (Chowdhury, 2010). Boro rice is a major crop cultivated during the dry season (January to April) in many parts of Bangladesh and requires irrigation based on groundwater supplemented by surface water (Acharjee et al., 2017a). Bangladesh has 7684 m^3/capita.year renewable freshwater availability and still ranks 6th globally in groundwater extraction (FAO, 2016a; WWAP, 2012) of which 88% of the total extracted water is used for irrigation, followed by urban water supply (10%) and industries (FAO, 2016b; Hanasaki et al., 2018; Shamsudduha et al., 2020). Excessive groundwater extraction for irrigation, declining groundwater recharge are leading to a drop in groundwater levels around the country (Acharjee et al., 2017a; Dey et al., 2017).

The two million hectares of arable land along the coastal areas of Bangladesh has been suffering from poor quality irrigation water due to salinity intrusion and quality degradation (Rahman et al., 2011; Shammi et al., 2016). The escalation in salinity and deficiency in freshwater flow to the coastal rivers may be attributed due to the construction of Farakka barrage upstream to the Padma (the Ganges) along with the consequences of rapid changes in the climatic pattern (Gain et al., 2014; Rahman et al., 2011; Shahid et al., 2006). An increase in salinity level in river water has increased groundwater extraction, creating opportunities for saltwater to enter freshwater aquifers (Shahid et al., 2006). Farmers in coastal Bangladesh are highly dependent on agricultural activities and the limited access to irrigation sources would threaten their livelihood (Gain et al., 2012; Huq et al., 2015; Karim et al., 2012; Kumar et al., 2020). Loss of agricultural production has forced farmers to switch with shrimp farming since experimented in coastal Bangladesh in the 1970's (Ahmed et al., 2010; Rahman et al., 2011). Extensive shrimp farming also contributes to increased soil salinity, further threatening agricultural production (Rahman et al., 2011). Studies indicate that by 2050, an increase in soil salinity may reduce the high-yielding rice production by 15.6 percent, which is a definite threat to the economic development of the region (Dasgupta et al., 2014b, 2014a).

1.2.3 Research Context: Khulna; a coastal city in the lower Bengal Delta

Khulna, a coastal city of Bangladesh, located in the lower Bengal Delta is vulnerable to climate change impacts due to its close proximity to Bay of Bengal (Auerbach et al., 2015; Datta et al., 2020; Khan et al., 2016; Shahid et al., 2016). The city is located on the bank of river Bhairab, Mayur and Rupsha (Figure 1.4). Khulna City Corporation (KCC) is the municipal authority given the formal status of municipal town during the British period in 1884 and is responsible for providing municipal services among urban dwellers (KCC, 2016). Currently, KCC has a jurisdictional area of 45.65 sq. km. spread over 31 wards[1] (Figure 1.4) and has a plan to extend this area up to 60 sq. km. (KCC, 2016). According to the last official census in 2011, the core city area accommodated over 660 thousand people with 73.6% literacy rate (BBS, 2011). Being an administrative and economic hub of the region, the city also provides necessary services to millions of people from the surrounding areas on a regular basis. The city has 1134 slums covering around 8% of the total city area (Alam and Mondal, 2019). The majority of the people living in the slums of Khulna are climate migrants who were forced to leave their original homes in the rural areas due to climate change impacts, effectively contributing to the 20% increase in city population (Rahaman et al., 2018).

Based on the Koppen-Geiger climate classification map, Bangladesh (also Khulna) has an equatorial wet and dry climate with six seasons (Kottek et al., 2006; Mourshed, 2011). Two-third of the total annual rainfall occurs during the monsoon (July to October). The residential land use dominates the urban area whereas the agricultural areas of peri-urban area is transforming rapidly to meet the growing demand. The city's economic growth stagnated in the early 2000's due to the closure of several jute mills in the areas.

[1] *Ward is the lowest level of administrative unit within a municipality. Several neighborhoods form a single ward.*

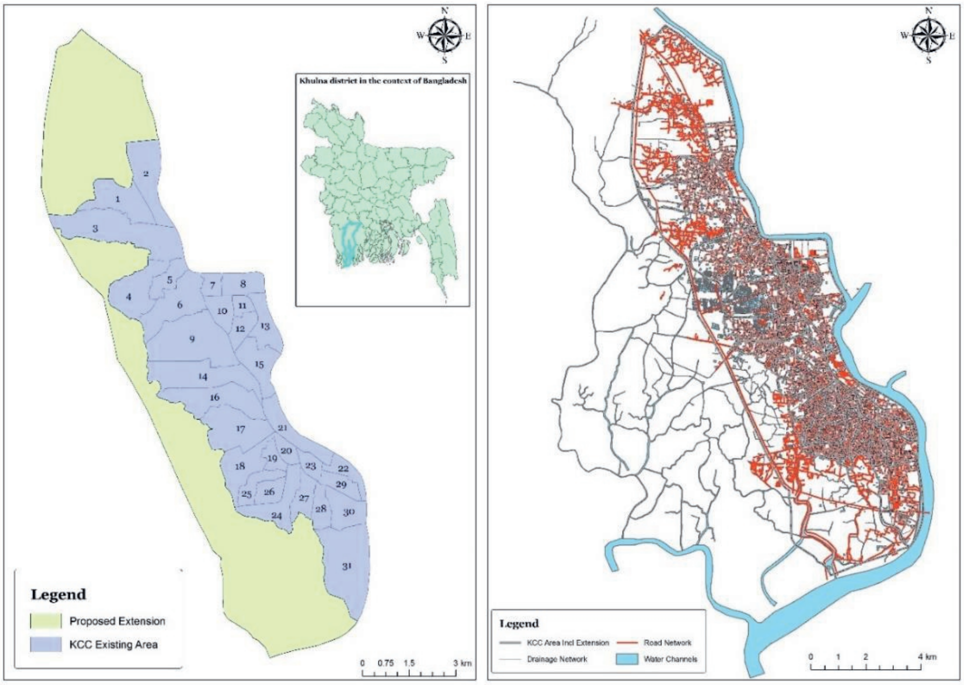

Figure 1.4: Existing 31 wards and proposed extension of KCC area (left), drainage, road and water channels around KCC (right) Data Source: KCC, 2011

Construction of a bridge over the Padma River began in 2014 to have a faster road connection with the country's capital and the southern part. Mongla port, the 2nd largest seaport in the country has been renovated to enhance economic productivity in the adjacent Export-Processing Zones (EPZ). These recent developments have boosted the region's economic activity and population growth, which is projected to grow even more in the coming days. Khulna Water Supply and Sewerage Authority (KWASA) was established in 2008 as an autonomous institution separating from Khulna City Corporation (KCC) to supply potable water and sewerage solutions to the urban dwellers (KCC, 2016). Before establishing KWASA, KCC and DPHE (Department of Public Health Engineering) were responsible for ensuring access to potable water. Currently, KWASA operates 85 production tube wells and a drinking water purification plant to collect and supply piped water among urban dwellers (KWASA, 2016). KWASA supplies piped water to only 23% of the population and over 70% of the residential users meet their daily water demand by extracting groundwater though private water pumps (ADB, 2011; Datta et al., 2020; Datta and Ghosh, 2015).

Water extracted from the aquifers is consumed within the household as drinking water and used for domestic activities (bathing, washing) and is discharged as grey water into the nearby drainage network. Blackwater originating from flushing the toilet is mostly collected in septic tanks. Around 90% of the city population has access to toilets with septic tanks and pits and emptying and transport service is carried out by formal and informal services (Kabir and Salahuddin, 2014; Singh et al., 2021). Even though the majority of the toilets comprises containment units, faecal sludge emptying is not frequent and often sludge overflows and gets diluted with drainage and surface water sources (Kabir and Salahuddin, 2014). Surface runoff is collected in the same drainage network that carries the greywater (Figure 1.5) and in recent times, the city has been struggling with water logging issues during late monsoon (Sarkar et al., 2020). The city has around 1200km of drainage network and 22 natural canals that run through the city and carries untreated greywater to the Mayur river located west of the city (Roy et al., 2018). Industrial areas are mostly located on the bank of Rupsha and Bhairab river and industries are by-law required to treat effluent using ETP before discharging into the natural streams.

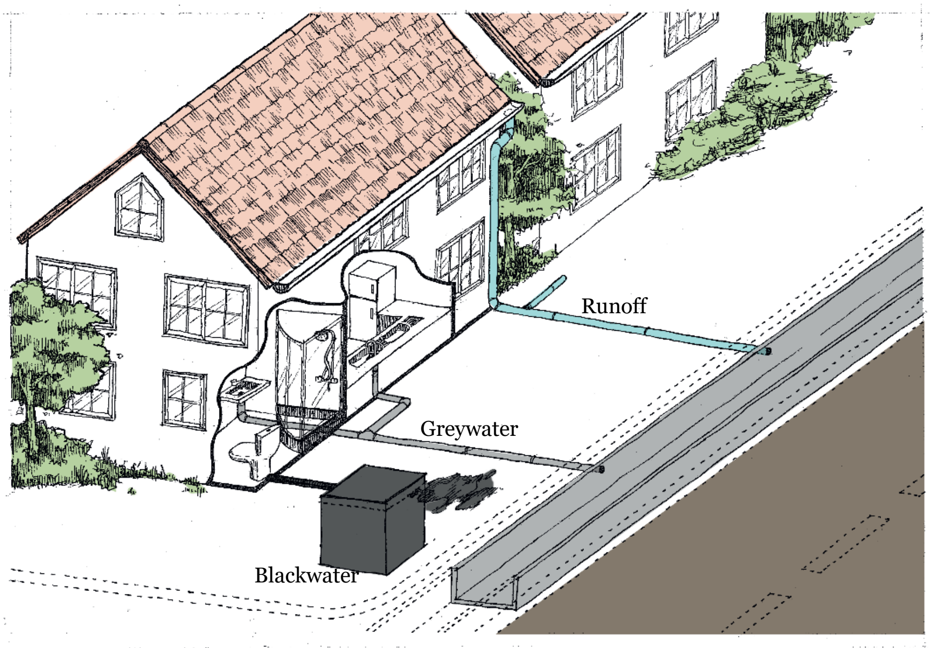

Figure 1.5: Artistic illustration of origins of different urban water streams in the study area

1.3 Problem Statement

1.3.1 Lack of quality surface water for peri-urban agriculture

Agriculture is the dominant land use in the peri-urban areas of Bangladesh. South Asia's peri-urban areas always played an essential role in shaping urban areas by providing land and water resources to the urban residents (Narain et al., 2013; Prakash and Singh, 2013). Similarly, peri-urban areas of Khulna city support the city's growth by providing necessary services, i.e. food production and thus rely on groundwater and surface water for irrigation (Gomes et al., 2018b; Gomes and Hermans, 2018). Studies show that due to a higher level of salinity in soil and water, the southern region of Bangladesh is struggling to provide the necessary irrigation as compared to the other parts of the country (Bell et al., 2015; FAO, 2016a; Mirza, 1998). Climate change-induced natural disasters (floods, cyclones, draughts) and resource degradations (higher salinity level in soil and water) transformed the coastal region of Bangladesh into one of the most vulnerable regions in the world, leading to conflict and competition over available water resources (Gomes et al., 2018b; Karim and Mimura, 2008; Kumar et al., 2011).

Mayur river originated in the upstream Beel Pabla (a large wetland system) is about 11 km long and plays a crucial role in providing irrigation water to the peri-urban farmers during the dry period (Kumar et al., 2011; Roy et al., 2018). The sluice gate downstream connecting with Rupsha river regulates the water flow and prevents tidal floodwater from entering the Mayur river. However, physical interventions such as sluice gates and embankments at the upstream have hampered natural flow of Mayur river (Roy et al., 2018). Dumping of untreated wastewater and the wastes from different anthropogenic and commercial activities (slaughterhouse, markets, health clinics) into the Mayur river has led to the deterioration of water quality leading to the damage of the river ecosystem (Akber et al., 2015; Rahman et al., 2014; Roy et al., 2018). Elevated levels of a broad range of pollutants, including a high level of salinity and pathogens and a low level of oxygen, state the current poor condition of Mayur river (Prakash and Singh, 2013; Rahman et al., 2014). Due to the lack of alternative sources, the farmers are forced to use this hygienically and chemically unsafe water for agricultural activities. This uncertainty over the good quality irrigation water would threaten peri-urban agriculture resulting in loss of employment for thousands of farmers and their family members. Wastewater dumped in the Mayur river is generated from potable drinking water; thus valuable freshwater resources in the form of urban water being lost without reutilising its potential.

1.3.2 State of the art, knowledge gaps and research needs in the context of Bengal Delta

Climate change impacts agricultural water requirements, especially during dry seasons, primarily due to limited freshwater availability (Islam et al., 2019). Studies on the crop water requirement under climate change in Bangladesh indicated that the overall water requirement has declined in the recent past due to variability in water availability which also increased the crop water stress(Acharjee et al., 2017a, 2017b; Ahammed et al., 2020; Hossain et al., 2019; Islam et al., 2018; Islam et al., 2019; Shahid, 2011). Also, the aggravated extraction of groundwater to meet the irrigation demand has lowered the groundwater level in the country (Acharjee et al., 2017a; Chowdhury, 2010; Shahid, 2011). Several studies investigated the possible implications of wastewater use in agriculture (Mojid et al., 2016, 2010); however, a comprehensive study on quantifying the supply of wastewater for meeting the irrigation demand in the Bengal delta during the dry season is yet to be realized.

Farmers rely on surface water for irrigation and thus, knowledge of the geochemical composition of surface water is crucial for water security in the coastal areas of Bangladesh (Datta et al., 2020). Several studies were conducted to understand the hydro-chemistry of ground and surface water sources and concluded that natural causes such as salt intrusion, arsenic contamination are influencing the water quality of the lower Bengal delta (Akter et al., 2016; Ayers et al., 2017; Burgess et al., 2010; Datta, 2015; Datta et al., 2020; Datta and Ghosh, 2015; Rahman et al., 2014b; Roy et al., 2018). The impact of anthropogenic activities such as wastewater discharge has also been studied indicating the negative role in the presence of exceeding the level of pollutants and pathogens in surface and groundwater sources of the region (Abedin and Rakib, 2013; Alam and Hossain, 2009; Datta et al., 2020; Datta and Ghosh, 2015; Islam et al., 2017; Islam et al., 2018; Momtaz et al., 2012; Rahaman et al., 2009; Rahman et al., 2014b, 2013; Reza et al., 2010; Roy et al., 2017, 2018; Sarwar et al., 2010). Most of these studies relied on statistical analysis (i.e descriptive statistics, Gibb's plot, Piper diagram) and lacked further extrapolation and explanation of the water quality variations.

High-level concentration of heavy metals (Cd, Cu, Zn, Cr, Pb, Ni) was reported in both leafy and non-leafy vegetables irrigated with wastewater in most areas of Bangladesh (Khan et al., 2008; Singh et al., 2010; Sridhara Chary et al., 2008). Studies on the application of wastewater for agricultural production showed that wastewater usage reduces the fertilizer requirement but elevates pH, salinity, number of total coliforms and faecal coliform on the top layer (0 - 40 cm) of the soil (Mojid et al., 2016; Mojid and Wyseure, 2014, 2013; Sales-Ortells et al., 2015). Lack of adequate wastewater infrastructure affects farmers' health due to their direct contact with wastewater and contaminated soil (Ferrer et al., 2012; WHO, 2006). Studies indicated that farmers of the coastal region had skin-related infections due to wastewater irrigation and severe health impact due to river bathing (Islam and Islam, 2020; Mojid et al., 2010). However, there are no insights on the gastro-intestine-related health risks of peri-urban farmers in the Bengal delta due to contact with wastewater.

Governance related to water management is a complex regulatory process in the Bengal Delta (Gain and Schwab, 2012). Studies on the governance of water management around the coastal areas of Bangladesh mainly focused on the groundwater, river and floodwater management and found a lack of coordination among different actors in the policy forming and implementation (Bernier et al., 2016; Bhattacharjee et al., 2019; Chan et al., 2016; Dewan et al., 2015; Gain et al., 2017; Gain and Schwab, 2012; Gomes et al., 2018a; Islam et al., 2020; Mondal et al., 2010; Mutahara et al., 2019; Yasmin et al., 2018). Availability of surface water flows supported by good governance would result in a 15% increase in rice production in coastal Bangladesh (Bernier et al., 2016; Mondal et al., 2010). Good governance is vital for water resource management and Bangladesh showed the potential to adopt a new governance model in water management (Gain et al., 2017; Yasmin et al., 2018). Thus, explicit knowledge of the governance issues related to urban water reuse in agriculture in the Bengal delta is necessary which is absent at this moment. Additionally, the participation of stakeholders in the decision-making processes in water projects is expected to increase efficiency and equity (Sultana, 2009). Evidence shows that negative public perception was a significant barrier in implementing wastewater related projects and such perception is changing gradually around the world (Chen et al., 2015; Fielding et al., 2019; Friedler et al., 2006; Massoud et al., 2018; Smith et al., 2018). Implementation of any policy and programs on water reuse should consider public perception and suggestions at every stage (Gross et al., 2015). Therefore, there is a need to investigate the stakeholders' perception towards urban water reuse for future project implementation.

The consequences of climate change and competition over freshwater accessibility will compel the coastal farmers of Bangladesh to find adequate irrigation water in the coming years. A large volume of wastewater originating from potable water; is currently disposed into the natural streams without utilising its true potential. The use of unhygienic and chemically unsafe water for irrigation in the field poses a serious health threat for humans and the environment. Thus, an integrated approach for planned water reuse is deemed necessary for promoting the sustainable growth of this region. Ensuring alternative irrigation water supply for improved food production and protection of river ecosystem will contribute to achieving the Sustainable Development Goals (SDG2: zero hunger, SDG 6: clean water and sanitation, SDG 11: urban sustainability) in the Bengal delta.

1.4 Research Objectives, Research Questions and Research Approach

Urban water reuse is a complex topic and requires an integrated approach as successful implementation is often confronted with the technological, market, institutional and cultural barriers (de Jesus and Mendonça, 2018; Kirchherr et al., 2017). Thus, this research aimed to explore the prospects and challenges for implementing planned reuse in agriculture and following objectives were formulated covering socio-technical aspects related to urban water:

(i) To match the peri-urban irrigation demand with potential urban water supply

(ii) To understand the spatio-temporal variability of surface water quality influencing its use in agriculture in the delta

(iii) To analyze the microbial and heavy metal contamination of surface water and assess the health risks for peri-urban farmers practicing irrigation with polluted surface water with wastewater

(iv) To explore the existing institutional arrangement and stakeholders' perception towards planned water reuse in agriculture and finally

(v) To develop socio-technological scenarios for the management and treatment of urban water facilitating safe reuse in agriculture.

The following research questions were formulated to attain the objectives of the research:

RQ1. To what extent can urban water contribute to peri-urban agriculture's irrigation demand during the dry season?

- This research question quantifies the irrigation demand and potential urban water supply to understand the potential of alternative water sources.

RQ2. Does the existing surface water quality affect the reuse potential in agriculture?

- This research question evaluates the chemical-physical contamination of surface water sources and the influence of land uses on the water quality.

RQ3. What are the health risks of farmers related to indirect wastewater irrigation?

- This research question evaluates the microbial and heavy metal contamination of urban water sources and assess the associated health risk among farmers. Also, the need for technical and non-technical solutions to reduce the health risk is addressed.

RQ4. Is the existing state of governance arrangement and stakeholders' perception conducive to the facilitation of the urban water reuse plan?

- This research question investigates the scope of water reuse within the existing regulatory framework by analysing stakeholder perception and related policy analysis.

1.5 Thesis Outline

The thesis is arranged in a publication-based format where several chapters are already published or under-review in different high-impact, peer-reviewed scientific journals. This thesis has six chapters arranged chronologically (Figure 1.6).

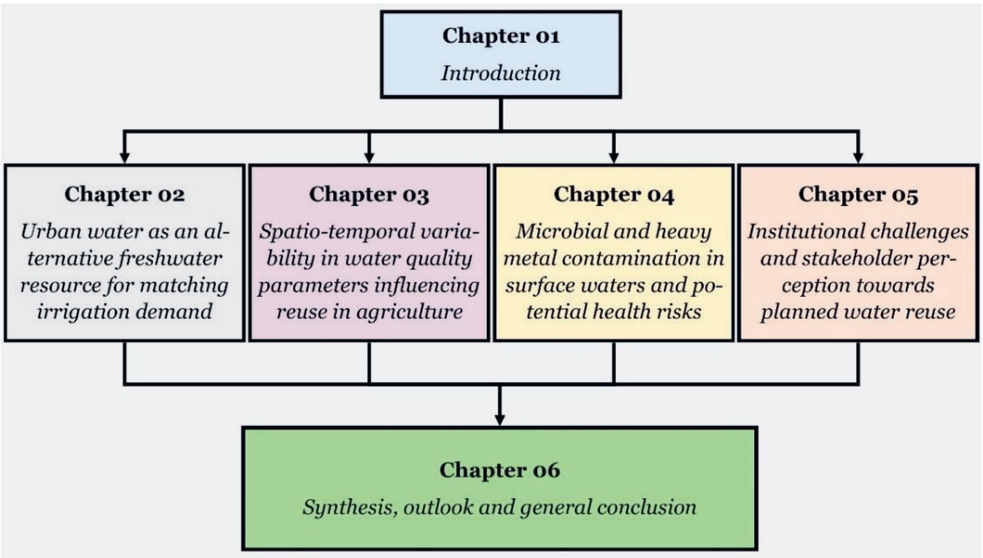

Figure 1.6: Organization of chapters in the thesis

In ***Chapter 1*** of this thesis, the general background on the contemporary issues related to urban water management in a global and a local context was discussed. The scope of the research was defined by illustrating state of the art on urban water reuse and identifying the existing knowledge gap and research needs.

In ***Chapter 2,*** the irrigation requirement of Boro rice during the dry season was assessed using FAO AquaCrop. Simultaneously, urban wastewater generation was calculated and supply potential against irrigation requirement was simulated under different scenarios. Spatial analysis with ArcGIS was performed to identify the residential wastewater generation hotspots, which could be used to develop an infrastructural plan to facilitate proper collection and transport.

In ***Chapter 3,*** the seasonal and spatial variation of surface water quality concerning agricultural usability was explored. Water samples were collected from different locations of the study area and were analysed for relevant chemical-physical parameters important for agricultural use. Results from the laboratory analysis were then integrated into the spatial analysis in ArcGIS to map the spatial variability of surface water quality. Also, water quality relations with land uses adjacent to the sampling stations were evaluated using statistical analysis. The water quality was also used to evaluate the spatial usability for agricultural purposes.

In ***Chapter 4,*** peri-urban farmer's health risks concerning microbial irrigation water quality were assessed. Water samples were collected from different irrigation sources of the study area and were analyzed in the laboratory to understand the microbial and heavy-metal contamination in the sources. Statistical analysis was performed to describe the microbial contamination while risk assessment tool QMRA was used to simulate the health risk of farmers. A survey was conducted among the farmers to understand their risk perception and issues they face while irrigation with surface water.

In ***Chapter 5,*** the evaluation of existing rules of regulations enabling water reuse in agriculture were explored. Perception and motivation towards water reuse among major stakeholders were also evaluated. Several data collection tools such as questionnaire survey, interview, focus group discussion was used to understand the awareness, motivation and perception of different stakeholder groups on urban water management-related issues. To have a clear understanding of the scope of institutions under the existing legal framework, related policies, acts, rules and regulations were analyzed.

These analyses were used to identify the limitations and ways to overcome the limitations to implement successful urban water reuse projects in the study area.

Based on the insights from Chapter 2-5 and the necessary literature review, ***Chapter 6*** portrays different socio-technological scenarios to enable urban water reuse in peri-urban agriculture. Also, the limitation of current research and future research needs are described in the chapter.

Chapter 2

Urban water as an alternative freshwater resource for matching irrigation demand

Abstract:

Rapid changes in climate patterns, population growth, urbanization and rising economic activities have increased the pressure on the delta's freshwater availability. Bangladesh's coastal planes suffer from a shortage of good quality irrigation water, which is crucial for peri-urban agriculture and discharges a high volume of untreated wastewater originating from quality potable water into the surface water. This calls for a transition towards efficiently managing and (re)using available urban water resources for irrigation, which is addressed in this chapter. A quantitative match between the irrigation demand and freshwater supply potential has been assessed considering different urban water generation scenarios. The FAO AquaCrop model has been used to calculate the irrigation water demand for Boro rice during the dry period. Results indicate 7.4 million m^3 of irrigation water is needed, whereas over 8.2 million m^3 of urban water is being generated during the dry season. Simultaneously, mismatches between irrigation demand and alternative water supply mainly occurred in February and March, which could be resolved with water storage capacities. However, to make urban water reuse a reality, the water management policy needs to change to facilitate the construction of required infrastructures for collection, treatment and storage. The proposed method helps to realize urban water's hidden potential to sustain agricultural activities in the delta areas.

Keywords: Urban water reuse; water resource management; peri-urban agriculture; delta

A slightly modified version of this chapter has been submitted for publication as:
Haldar, K., Kujawa-Roeleveld, K., Acharjee, T. K., Datta, D. K., Rijnaarts, H. (2021). Urban water as an alternative freshwater resource for matching irrigation demand in the Bengal delta (under review).

2.1 Introduction

The demand for freshwater around the world has increased significantly during the last century and climate change, population growth, rapid urbanization, rising economic activities have escalated the pressure on freshwater security, especially in the urbanized deltas of the world (Davies and Simonovic, 2011; Greve et al., 2018; Heinke et al., 2019; Kumar et al., 2011; Mojid et al., 2010; Richter, 2014; Sadegh et al., 2020; Tukimat et al., 2017; Wilcox et al., 2016; WWAP, 2012). Changes in the climate have resulted in varying precipitation patterns and the frequency and intensity of both floods and droughts in the delta areas and this trend is expected to continue. Sea-level rise enhances soil and water salinization, limiting access to freshwater affecting food production (Stucker and Lopez-Gunn, 2014). Agricultural water use accounts for more than 80% of the global and 88% for Bangladeshi groundwater withdrawals (FAO, 2016; Richter, 2014; Sadegh et al., 2020), while food production is increasing to meet rising demand. More than 300 million people live in delta areas (Edmonds et al., 2017) with limited access to freshwater for agricultural production, which increasingly poses a threat to their existence. Reusing water in food production can lower groundwater pressure and increase irrigation water availability in the delta region.

Khulna, an urban agglomerate in the lower Bengal delta, is foreseen to expand to 2-3 million people in the coming decade despite some recent stagnation in population growth. Seasonal rice varieties and vegetables are the major crops cultivated in the city's urban and peri-urban agricultural areas and play a key role in supporting the region's food production. Rice, an aquatic plant, requires large quantities of freshwater (Hossain et al., 2019) and in recent years, farmers struggle to find good quality irrigation water, especially during the dry season (November to March). The decline in rainfall in the dry season, increased saltwater intrusion, unplanned urbanization and direct untreated wastewater discharge are to blame for this struggle. The urban wastewater discharged into rivers without proper treatment while being on its way to the sea pollutes surface and groundwater. Urban water represents a valuable resource stream because of its nutrients, freshwater character and most importantly, a stable flow (Haldar et al., 2020; Mojid et al., 2010) and can be an alternative irrigation water source.

Urban water reuse is a worldwide used measure and treated wastewater has already been practiced in water-scarce areas of Egypt, Iraq, Saudi Arabia, UAE, Israel and USA (WWAP, 2012). Simultaneously, unplanned water reuse has already been practiced for a long time, especially in developing countries (Ensink et al., 2002; Fawell et al., 2016; Kookana et al., 2020; Mojid et al., 2010). The presence of contaminants as pathogenic micro-organisms, micropollutants and heavy metals when applying untreated wastewater can have undesired adverse consequences on human health, food quality and the environment and should be minimized. Therefore, planned water reuse mitigating such adverse effects is essential, i.e., the water use is preceded with appropriate treatment delivering water meeting the appropriate reuse standards. However, collection, treatment and distribution infrastructure pose a challenge for developing countries which could be resolved by implementing decentralized, low-cost (partly nature-based) technologies (Asano and Levine, 1996; Drechsel et al., 2015). Implementing planned urban water reuse enhances water circularity and is vital for ensuring sustained food supply in water-scarce regions (Nazemi and Madani, 2018).

Agro-engineering techniques like alternative irrigation management, drip irrigation, shifting planting dates, efficient use of rainwater and change in crop selection have also been suggested to tackle the irrigation water scarcity (Bouman, 2007; Hoekstra, 2019; Qadir et al., 2010; Rivera et al., 2018). However, these alone cannot sufficiently resolve the freshwater provision issue in delta areas. The literature hypothesized that urban water can supplement irrigation water in many delta areas; however, reports on concrete and quantitative assessments are scarce (Chu et al., 2004; Haldar et al., 2020; Ronco et al., 2017; Trinh et al., 2013). Thus, this study aims to provide such a quantitative assessment for Khulna city, a vital urban agglomerate in the lower Bengal delta. The assessment followed three steps: i) determination of irrigation water demand for Boro rice during dry seasons, ii) estimation of greywater and surface runoff as potential freshwater supply sources, taking spatial distributions and dynamics into consideration and iii) finally, a quantitative match between the demand and supply.

2.2 Methodology

2.2.1 Conceptual Framework: Matching Demand and Supply

"Urban Harvest" is a concept based on urban metabolism principles and has been coined to assess resource harvesting opportunities within the city (Agudelo-Vera et al., 2012; Rovers, 2007). Currently, most cities and especially those in developing countries, have linear non-sustainable urban metabolism. However, the urban water cycle should be circular in climate-vulnerable delta areas to reach optimal use of available water resources, thus lowering the stress on freshwater supply (Figure 2.1).

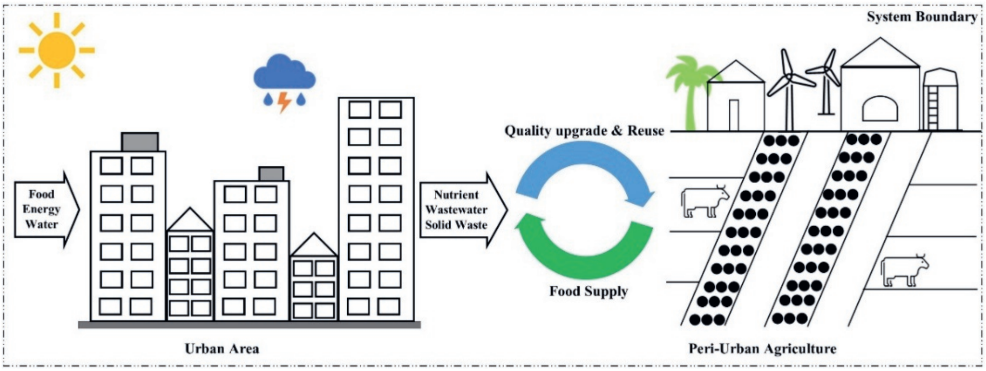

Figure 2.1: Desired circular urban metabolism linking urban water and peri-urban agriculture

A circular urban metabolism transition will enhance cities' resilience (Agudelo-Vera et al., 2012; Wielemaker et al., 2018). However, the primary challenge in circular transition is to quantitatively match the peri-urban irrigation demand with the potential supply from urban activities, which is the aim of this chapter. A 3-step approach has been adopted: first, an inventory of the irrigation demand for Boro rice, a major crop of the region, was made; second, the availability of alternative urban water sources was calculated and finally, it was assessed if and how the demand can be matched. Greywater originating from groundwater and surface runoff are currently collected through the same drainage network that carries greywater. As greywater and sealed surface runoff are easily collectible and significantly less polluted than blackwater, a combination of greywater and surface runoff is considered as available alternative sources reusable for irrigation.

Though less polluted, urban water will be needed treatment before reusing it as irrigation water, but such treatment technologies are not considered in detail in this study. Wastewater from other sectors (especially industrial) is regarded as an unsuitable source for irrigation due to quality variations and separate management processes. Finally, the comparison between irrigation water demand and possible water supply options has been evaluated at different temporal scales (months, cropping season) through three scenarios:

1) greywater generated in the households,
2) sealed surface runoff and
3) urban water combining greywater and surface runoff.

2.2.2 Operationalization of the framework

Calculation of irrigation water requirement of Boro rice

Boro rice is one of the major dry season crops cultivated in the peri-urban areas of Khulna city. AquaCrop was used to calculate the irrigation demand, yield and water productivity of Boro rice during the dry season using the transplant date of January 1. AquaCrop is a model developed by the Food and Agriculture Organization (FAO) of the United Nations and simulates the yield response of crops as a function of water availability (FAO, 2020; Raes et al., 2018; Steduto et al., 2012). Depending on the variety, generally, Boro rice plants pass through different growth stages from seeding to harvest in 3-6 months (IRRI, 2015). The transplantation of Boro rice in the region usually occurs from December–January and the crop is harvested during April–May. Water requirements for nursery and field preparation were not considered in this study. Daily climate data for the Khulna region, including rainfall, temperature, humidity, sunshine hours and wind speed for the period of 1984 to 2017, were collected from the Bangladesh Meteorological Department (BMD) and crop data, irrigation management, field management and soil data were simulated based on the field visits and literature. Evapotranspiration (ET), net irrigation requirement, biomass production, dry yield and ET water productivity of Boro rice from 1984 to 2017 were calculated following standard irrigation and field management practice. Reference crop evapotranspiration (ET_o) was estimated utilizing the daily climate data, including minimum and maximum temperature, sunshine hour, wind speed and relative humidity using FAO Penman-Monteith equation (Smith et al., 1998).

Annual mean atmospheric CO_2 concentration in the study area was simulated using the pre-loaded file in AquaCrop. The irrigation management file contained the selection of the allowable root zone depletion expressed as a percentage of the readily available water (RAW). RAW indicates the allowable root zone depletion was set at 0% since crop growth can be hindered if root zone water level drops (Raes et al., 2018). Field visit and literature indicated that the peri-urban rice fields have a varied soil bund height, but for the simulation, soil bund was set at 0.25 meters and excellent weed management was used due to regular work by farmers (Critchley, 1991; Maniruzzaman et al., 2015). The peri-urban area of Khulna has silty clay soil with a 2.5-meter groundwater depth below the surface (Islam et al., 2017; Shamsudduha, 2011) and this is used for simulation. Additional Crop input parameters related to phenology, planting, management and stress for AquaCrop simulation have been obtained based on literature (Raes et al., 2018; Steduto et al., 2012) and added in the supplementary materials *(Table i)*.

Estimation of recoverable urban water

Khulna city is the administrative hub for its surrounding coastal cities and the core urban area has drainage networks to collect wastewater and surface runoff. The whole urban area is divided into 31 wards and has over 1200 km of the drainage network (KCC, 2016). Two types of urban water are considered useful for irrigation: greywater and surface runoff. Total urban water generation was estimated as the sum of generated domestic greywater and surface runoff as follows:

$$\text{Urban Water Generation} = GW_D + Q_{rain} \qquad (2.1)$$

where, GW_D (m^3/month) is the domestic greywater generation and Q_{rain} (m^3/month) is the sealed surface runoff.

Domestic wastewater (greywater) generation

Groundwater, being the source of potable water used within the household for domestic activities (drinking, bathing, washing, cooking) is discharged and collected in the drains as greywater. Water used for drinking and flushing the toilets resulted in black water mostly collected into a separate septic tank and considered unfit as the water source for irrigation. Septic tanks are being occasionally emptied and further processed by the local municipal authority (Khulna City Corporation) or informal services, thus preventing overflow and polluting surface water.

Domestic greywater generated (GW_D) in the urban areas in 2018 was calculated as:

$$GW_D = DW \times WW_C \times P_n \times t \qquad (2.2)$$

where, DW (m^3/cap/day) is the per capita water consumption, WW_C is the wastewater generation coefficient (the portion of potable water converted into greywater), P_n is the projected population at the year 2018 and t is the temporal scale (30 or 365 days).

The population of Khulna City was projected using the following formula:

$$P_n = P_o\,(1+r)^n \qquad (2.3)$$

where, P_n is the population at the year 2018, P_o is the population at the base year of 2011 (as the census only takes place every ten years and last census took place in 2011), n is the time (the chosen year is 2018, hence n = 7 years) and r is the population growth rate (percentage change in population per year). The population growth rate (r) was -1.5% based on the growth of the total population of Khulna city between 2001 and 2011.

Khulna city had a declining population trend in the last decade and climate change, salinity intrusion and lack of economic activities were reported as major reasons for this decline (UNFPA, 2016). Despite the recent decline, an increase in population is expected due to increased industrial and infrastructural investments in the region over the coming decades (ADB, 2020). Detailed population projection for 2018 has been added in the supplementary materials *(Table ii)* and per capita potable water consumption was 100 liters per day (KWASA, 2016). All potable water consumed in the household does not reach the sewer and thus, a wastewater generation coefficient between 0.6 - 0.9 has been recommended (Metcalf & Eddy, 2013). For this study, a wastewater generation coefficient (WW_C) of 0.8 was used based on similar studies in other metropolitan cities of Bangladesh and India (CWASA, 2017; DWASA, 2016; Tchobanoglous and Schroeder, 1985; Van Rooijen et al., 2005).

Estimation of sealed surface runoff

Land use determines the amount of runoff and infiltration of stormwater. Only sealed surface runoff (residential and built-up area, commercial area, industrial area and road network) was considered convenient. The following equation was used to calculate the sealed surface runoff:

$$Q_{rain} = c \times I \times A \qquad (2.4)$$

where, Q_{rain} (m^3/month) is the total runoff, I (m/month) is the rainfall intensity, A (m^2) is the available drained surface and c is the runoff coefficient. The runoff coefficient is dependent on the land use types (Goel, 2011; Tsutsumi et al., 2004) and for the conservative calculation lower limit of the coefficient was used per land-use category (Table 2.1).

Table 2.1: Surface runoff coefficient of different land-use (Goel, 2011; Tsutsumi et al., 2004)

Land use	**Surface Runoff Coefficient**
Residential/Roof/Built-up area	1
Road/Circulation Network/Pavement	0.7 of 0.7-0.9
Commercial/Industrial	0.7 of 0.7-0.9
Park with vegetation	0.1 of 0.1-0.3
Paddy field/ Water	0.7 of 0.7-0.8
Flat Agriculture	0.1 of 0.1-0.5
Unused bare land/Vacant land	0.2 of 0.2-0.4

According to the rainfall data collected from BMD (supplementary material: *Table iv*), the total annual rainfall in Khulna for 2018 was 1151 mm, with the highest in June (272 mm) and lowest in January (1 mm). The urban area of Khulna is around 45 km^2 and the city administrator is planning to acquire adjacent 40 sq. km. of the peri-urban area (Haldar et al., 2020; KCC, 2016). The urban area, the land-use is dominated by the built-up area (59%), wherein the peri-urban area is dominated by agricultural lands (48%). Urban agriculture is present (13%) in the core urban area, but more agricultural land is being transformed into built-up areas due to urbanization. The increase of built-up area and road network will further increase sealed surface runoff's contribution in the future. The total peri-urban agricultural area is about 1935 ha, where mostly Boro rice is cultivated along with some seasonal fruits and vegetables.

2.2.3 Identifying greywater generation hotspots-coldspots

Hotspot analysis identifies spatial cluster features with either high or low values of a given variable (Sánchez-Martín et al., 2019). Significant z-score (supplementary materials*: Table iii*) results in more intense clustering of high values known as hot spots and lower significant negative z-scores with smaller z-score results in clustering of low values known as cold spots (ESRI, 2020). In this study, we were able to identify greywater generation hotspots-coldspots that can be useful in designing the necessary centralized or dis-centralized infrastructures. As a first step of the analysis, the geographic boundary of the city and ward was delineated. GIS database was collected from the local planning agency and building information (area of the structure, height) was included in the database. Then demographic information (population density) and water-related data (per capita water consumption, greywater generation coefficient) were integrated into the GIS database to calculate the greywater generation rate per residential structure. Then hotspot analysis (Getis-Ord Gi*) was performed in ArcGIS and hotspots-coldspots of greywater generation were identified.

2.3 Results and Discussion

2.3.1 Assessment of changes in irrigation demand of Boro rice

The irrigation water requirement of Boro rice is affected by climate change-induced parameters, such as evapotranspiration, effective precipitation and changes in plant phenology (Shahid, 2011). The Boro rice's water requirement has also been changing over the last decades. Total evapotranspiration has declined (from 547 mm in 1984 to 358 mm in 2017) during the Boro growing season between 1980 and 2020 (Table 2.2).

Table 2.2: Simulation results of evapotranspiration, CO_2 concentration, net irrigation requirement, biomass production, dry yield, ET productivity and water productivity

Parameter	***Mean***	***SD***	***Min.***	***Max.***	***Changes in 34 yr.***
Evapotranspiration (mm)	459	42	358	564	-19%
CO_2 concentration (ppm)	372	18	345	406	15%
Irrigation requirement (mm)	387	49	286	518	-20%
Biomass (ton/ha)	15	0.8	14	18	9%
Dry yield (ton/ha)	7	0.4	6.7	9	8%
ET productivity (kg/m^3)	1.6	0.2	1.3	2.6	27%
Water productivity (kg/m^3)	1.7	0.3	1.2	2.6	26%

A gradual and linear increase (345 ppm in 1984 to 406 ppm in 2017) in atmospheric CO_2 concentration was observed, relatable with the country's sharp increase in industrial activities. An elevated CO_2 concentration can cause a decrease in reference evapotranspiration (Baker et al., 1990; Baker and Allen, 1993). However, the reference evapotranspiration decline can also be caused by increased relative humidity, decreased wind speed and sunshine hours (Acharjee et al., 2017a; Hossain et al., 2019; Mojid et al., 2010). Despite having a decreased available rainfall in the growing period, the result indicates a declining trend of net irrigation requirement of Boro rice in Khulna (Figure 2.2). This result is uniform with a similar outcome for Boro rice in the Northwest part of Bangladesh (Acharjee et al., 2017b). However, the simulation indicates no decrease in crop yield (Figure 2.2). Instead, the biomass production and dry yield showed an increase (0.04 and 0.02 ton/ha/year, respectively). The increase of biomass and dry yield is positively correlated with increased atmospheric CO_2 concentrations, especially for rice (Krishnan et al., 2007; Li et al., 2017; Lv et al., 2020). Both ET productivity and water productivity showed a considerable increase in the last 30 years (27 and 26%, respectively) because of the decline in evapotranspiration and net irrigation requirement.

2.3.2 Assessment of monthly net irrigation requirement of Boro rice

Analysis of the net irrigation requirement at a temporal scale (per month) indicates that the monthly irrigation requirement is lowest in January during the initial stage of crop development and highest during March (Figure 2.3).

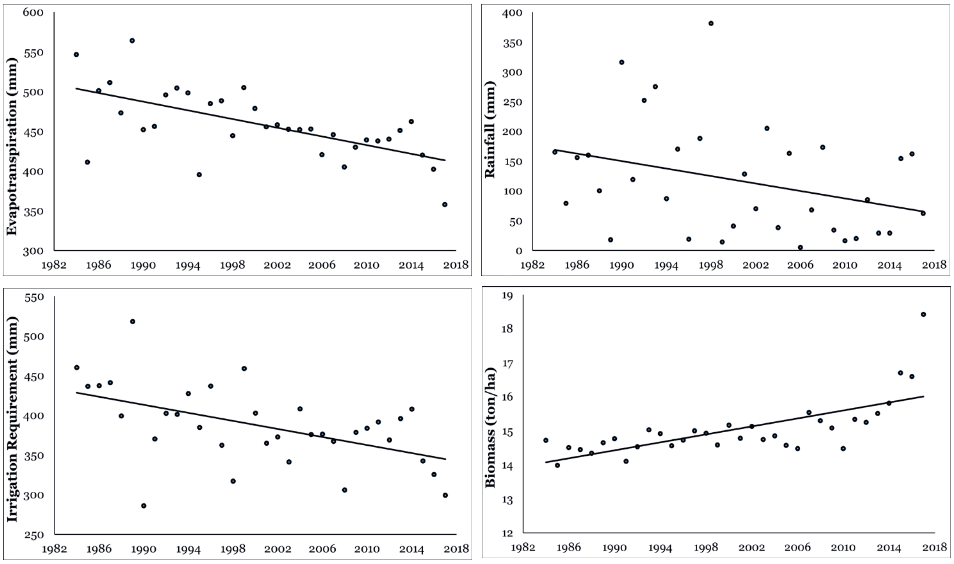

Figure 2.2: Trends of simulated results of evapotranspiration, rainfall, net irrigation requirement and biomass of Boro rice between 1984-2017

The initial stage of crop development is characterized by relatively low crop (21.8 mm) transpiration (Brouwer and Heibloem, 1989). Based on the simulation results, the average net irrigation requirement for Boro rice in January was 59±9 mm, in February 100±15 mm, in March 142±25 mm and 85±21 mm in April. Fully grown crops require additional water and therefore, transpiration is highest in March, corresponding with the highest net irrigation requirement. Crop senescence occurs in April (based on transplant in January), resulting in a lower crop coefficient and, thus, lower transpiration (Raes et

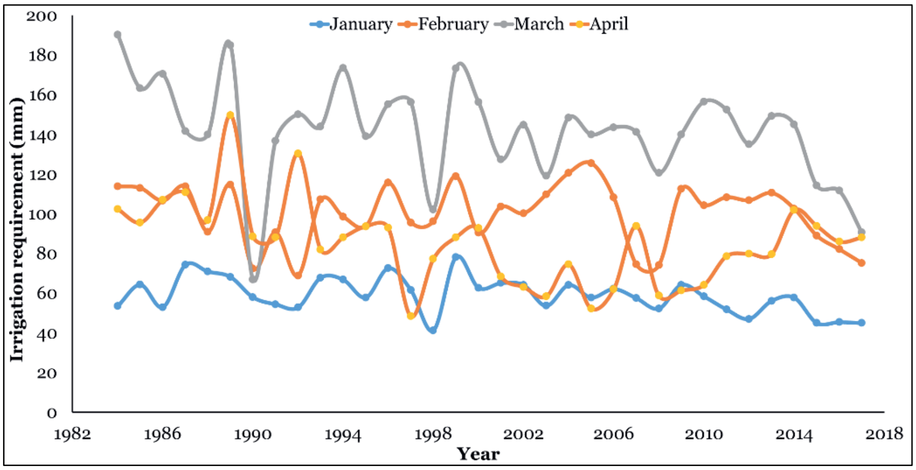

Figure 2.3: Changes in the net irrigation water requirement between 1984-2017 of Boro rice

al., 2018). Analyzing the simulation data, the average net irrigation water requirement for Boro rice in the dry season is 3867±710 m^3/ha with a minimum of 2860 m^3/ha in 1990 and a maximum of 5180 m^3/ha in 1989. Based on average irrigation requirement, the total irrigation water demand in peri-urban agriculture for Boro rice is about 7.4x10^6 m^3 for the dry season. The demand is highest in March (2.7x10^6 m^3) and lowest in January (1.4x10^6 m^3), accounting for 37% and 15%, respectively, of the total seasonal demand. In February and April, the irrigation demand is around 1.9x10^6 m^3 and 1.7x10^6 m^3, respectively.

2.3.3 Urban water generation

Greywater generation

Groundwater consumed at a household and discharged as greywater in an average volume of around 4.8x$10^4$$m^3$/day and around 1.7x$10^7$$m^3$/year. Greywater generation varies among wards depending on the population as the wastewater generation coefficient and water consumption rate were both constant. Ward number 24 has the highest population and thus generates the highest volume of greywater, contributing around 5.7% of the total greywater generation and ward number 8 and 13 generates the lowest (1.4% each). On average, the annual greywater generation rate for the total urban area is around (0.5±0.3) m^3/m^2, whereas the rate is around (0.8±0.3) m^3/m^2 for the residential area. Ward-wise calculation of greywater generation is added in the supplementary materials *(Table vii)*.

Greywater generation hotspots

Hotspot analysis indicates that densely populated residential areas have a higher number of greywater generation hotspots than the other parts of the city. Ward numbers 10, 11, 12, 19, 20, 23, 24, 27 and 30 are predominantly recognized as residential areas in the city's land-use map and have a higher number of hotspots (Figure 2.5). Multi-story residential buildings are typical in these wards, influencing the increased population density. Statistical analysis shows that average building occupancy, residential surface floor area, the height of the building and population density is significantly positively correlated with the greywater generation intensity (Table 2.3). In contrast, per capita residential area and per capita residential floor area negatively correlates with greywater generation. Highly dense residential areas produce a higher volume of greywater; thus, the infrastructure for collection and transport should be planned accordingly.

Sealed surface runoff

Khulna has an equatorial wet and dry climate (Kottek et al., 2006; Mourshed, 2011), which has a hot summer with heavy rainfall and drier winter with lesser rainfall. Annual rainfall data from the last two decades indicate that the average annual rainfall in the Khulna region was around (1894±380) mm, with the highest in 2002 (2594 mm) and lowest in 2018 (1151 mm). Based on the annual rainfall of 2018, the total annual surface runoff for the urban area was calculated as $4.1 x 10^7 m^3$, where the sealed surface (built-up area, road network, commercial area, industrial area) runoff was about $3.8 x 10^7 m^3$, annually. The built-up area has the highest runoff ($3.1 x 10^7$ m^3) and the commercial area has the lowest ($9.3 x 10^5$ m^3).

Table 2.3: Correlation among spatial characteristics and (hot)spots for greywater generation (m^3)

Spatial Characteristics	***Correlation at different CI***		
	99%	*95%*	*90%*
Area (sqm)	-0.267	-0.347	-0.355
Residential area (sqm)	-0.193	-0.208	-0.280
Percentage of residential area	0.245	0.449*	0.384*
Population (2018)	0.393*	0.394*	0.297
Total Residential Buildings (number)	-0.043	-0.032	-0.076
Avg. building occupancy (person/structure)	0.374*	0.567**	0.649**
Total Residentials Floors (number)	0.119	0.163	0.096
Total Residential Surface Area (m^2)	0.183	0.245	0.173
Total Residential Floor Surface Area (m^2)	0.394*	0.478**	0.380*
Average Building Height (Floors)	0.521**	0.689**	0.673**
Per capita avg. Residential Surface (m^2)	-0.430*	-0.543**	-0.585**
Per Capita Average Floor Space Area (m^2)	-0.371*	-0.506**	-0.567**
Population Density (per km^2)	0.518**	0.634**	0.617**

*** Correlation is significant at the 0.01 level (2-tailed)*

** Correlation is significant at the 0.05 level (2-tailed)*

Runoff increases during May–July and drops during the winter months of December–February) (Figure 2.4). Sometimes, heavy rainfall even causes waterlogging around the city area. In June, the surface runoff is highest (8.9×10^6 m^3) and in January, it is the lowest (3.3×10^4 m^3). Having the highest amount of sealed surface area, ward number 31 has the highest sealed surface runoff (3.1×10^6 m^3), whereas ward number 11 has the lowest (3.4×10^5 m^3).

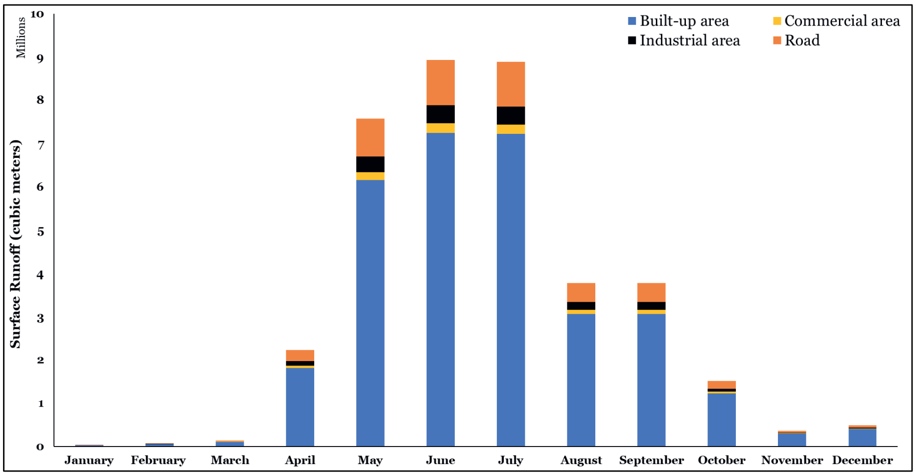

Figure 2.4: Month-wise sealed surface runoff in Khulna city in 2018

The average sealed surface runoff rate is (1.1±0.1) m^3/m^2, whereas the total urban area surface runoff rate is (1±0.1) m^3/m^2. Ward-wise calculation of sealed surface runoff is added in the supplementary materials *(Table viii)*.

Total urban water generation

The urban area annually generates around 5.5×10^7 m^3 of urban water, combining annual greywater and sealed surface runoff. In 2018, the annual per capita urban water generation rate was (75±30) m^3 and per square meter of urban area generated (1.4±0.4) m^3 of urban water. Ward number 31 generates the highest amount (4×10^6 m^3) of urban water, whereas ward number 11 generates the lowest (6.7×10^5 m^3). Ward number 19 has the highest generation rate (2 m^3/m^2) as the areas have the highest population density (3344 person/km^2) and the highest sealed surface (97%) in the study area. On the contrary, ward number 4 has a lower population density (700 person/km^2) and only 46% of the area is a sealed surface resulting in a lower urban water generation rate (0.7m^3/m^2). Ward-wise calculation of greywater generation and spatial information related to hotspot analysis is added in the supplementary materials *(Table ix and x)*.

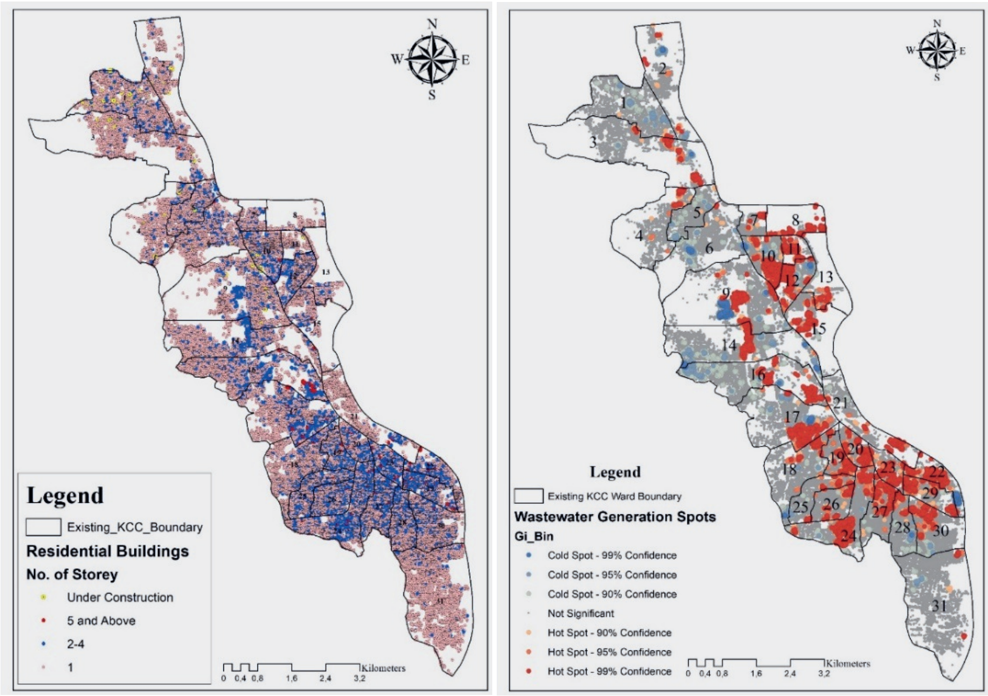

Figure 2.5: Map showing the residential building heights (left) and greywater generation hotspots (right)

2.3.4 Matching irrigation demand with urban water

Scenario 1: Matching demand with greywater

Analysis indicates that minimum and average irrigation demand in January can be satisfied with the greywater generated in the urban area (Figure 2.6). Greywater generated in the remaining months of the dry season (February, March and April) is only enough to meet the minimum irrigation demand, i.e., the crop water requirement for the other demand levels (average and maximum) cannot be met by the greywater produced in those months. If water storage is implemented, greywater generated from January to April can satisfy 100%, 76% and 50% of the minimum, average and maximum irrigation demand, respectively. Greywater is generated all year round and a reliable source to satisfy the irrigation demand at all levels if stored and supplied to the farms when needed after appropriate management.

Scenario 2: Matching demand with sealed surface runoff

Being dry season, minimal rainfall results in lower surface runoff and in January, February and March, only 3-5% of the average irrigation demand could be matched from

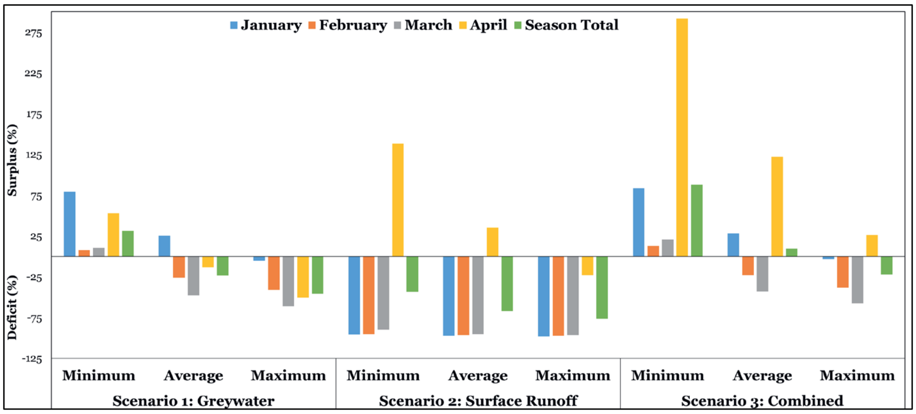

Figure 2.6: Surplus and deficit of demand and supply under different scenarios for the Boro rice crop season (minimum, average and maximum indicate the level of irrigation demand)

rainwater harvesting (Figure 2.6). However, in April, the excessive rainfall contributes to the surplus of the monthly minimum and average irrigation demand. Excessive rainfall in April cannot contribute to the irrigation demand in the previous months and the general conclusion is that surface runoff occurring in the dry season is not a reliable source to meet the irrigation demand. However, annual surface runoff can completely satisfy the irrigation demand if collection and storage can be ensured to supply for the next year. The highest amount of surface runoff occurs between May-July (Figure 2.4) as monsoon season hits the region; hence collection, treatment and storage should already be arranged to preserve the water for irrigation in the dry season.

Scenario 3: Matching demand with combined sources

Combining greywater and sealed surface runoff has a great potential to meet the irrigation demand, especially with the minimal demand (Figure 2.6). For the average demand in January, urban water can supply 128% of the average irrigation demand, which increases substantially (222%) in April. The irrigation demand in February and March cannot be matched entirely due to lower precipitation in this period. However, total urban water generated during the cropping season can be matched entirely with the minimum and average demand if collected, treated and stored to use; for the maximum demand, a deficit of 33% still remains. A further possibility of storing urban water for the whole year can potentially supply the required irrigation demand during the entire season.

Based on the above analysis, none of the scenarios alone can provide 100% match for irrigation water demand every month of the crop season. Only when additional supply from water stored in former months is included a full coverage can be achieved. Scenario three has the best potential to meet the irrigation demand during the whole cropping season, requiring some but minimal storage capacity. The same drainage network is currently used to collect greywater and surface runoff, which perfectly aligns with the scenario. Scenario two only can supply the required irrigation water in April and the rest of the cropping season, the supply is meager.

2.4 Challenges and opportunities towards matching demand and supply

Urban water generated in Khulna city is a potential alternative water resource for peri-urban agriculture and this chapter showed that temporal variation can be overcome and that with the inclusion of some storage facilities. However, the reuse of urban water is not without barriers in implementation. The first physical challenge is the spatial distribution of available water resources, limiting access to meet the local demand (Basharat et al., 2014; Karandish et al., 2021). Urban water is generated all over the city and the demand is also spread around the peri-urban area. This spatial distance between urban water generation areas and irrigation water demand areas can be solved by implementing connective infrastructure, which is often a challenge. Previous research indicated a spatio-temporal variation in surface water quality that could restrict urban water from reused for irrigation during the dry season (Haldar et al., 2020). However, that can be overcome if the urban water can be collected, treated and stored for a few months to keep good water quality available for the cropping season.

One solution could be retrofitting the Mayur river to be used as a natural system for treating and storing urban water as currently, the water flow in the Mayur river is controlled using a sluice gate and receives most of the city's untreated wastewater. However, technologies and infrastructure for collection, treatment and redistribution need to be flexible, adaptive and robust under changing climatic conditions to ensure sustainability (Spiller et al., 2015). The majority of the developing countries lack adequate urban water-related infrastructure and worldwide, around 80% of the wastewater is poorly treated (Kookana et al., 2020); Khulna is not different from this. The city does not yet have any wastewater treatment plant (except for on-site septic tanks for black water), while treatment is essential to safely provide urban water at adequate quality to serve as irrigation water for food production. Research indicated that the current irrigation water sources mixed up with greywater are not suitable for agricultural activities and pose a risk to the environment, soil, crop and, above all, the study area's farmers (Haldar et al., 2021, 2020; Mojid et al., 2016). Using current surface water will also lead to health-related problems for farmers, market vendors, consumers. Therefore, it is essential to upgrade the existing water quality before supplying it to agricultural farms. Surface runoff requires less quality up-grading; however, stormwater quality and quantity can directly be related to impervious areas in an urban catchment (Mackintosh et al., 2015; Schmitt et al., 2015; Tran et al., 2019).

Measures like separate sewers for runoff collection and greywater collection have been widely criticized as intensive planning and additional economic investments, which might not be an attractive option for countries like Bangladesh. The next challenge is the social acceptability of reuse practices and many reuse projects failed due to societal prejudices of negative attitude towards reuse practices (Garcia-Cuerva et al., 2016; Po et al., 2003; Smith et al., 2018). A change in society is needed towards not perceiving urban water as dirty and gross anymore to overcome this barrier in the reuse of urban water for irrigation and other purposes. In addition to proper and secure treatment, one solution to be considered is to restructure existing river arm segments as storage basins for treated greywater storage facilities i.e. gets a natural water image for the public and farmers, similar to showcases of Singapore. Also, stakeholder inclusion in treatment and natural storage can change such negative perceptions, which will be essential in successfully implementing urban water collection and reuse in upscaled projects. Another critical challenge related to reuse is to lack of necessary rules and regulations to support such action. There is no direct policy or institutional guideline in Bangladesh (and many other global south and global north countries) to facilitate urban water reuse. A policy can help to delineate administrative boundaries, roles of different stakeholders, infrastructural development and societal development essential for implementing reuse projects.

2.5 Conclusion

Climate change, saltwater intrusion and rapid urbanization threaten freshwater availability in many urbanized deltas, including Bangladesh's coastal region. Peri-urban agriculture contributes to the food production for the urban as well as for surrounding areas. Over the years, agriculture has been confronted with a lack of good quality and required quantity irrigation water, especially during the dry seasons and this chapter shows that urban water has the potential to contribute substantially to the peri-urban irrigation demand. However, this supply varies in different months and can only match the demand entirely if proper treatment, collection and storage can be ensured. Hotspot analysis indicated that the residential areas have a varied greywater generation and careful planning is crucial for designing infrastructural measures. Further research on the feasibility of urban water storages and redistribution networks is also necessary. This study proved that urban water could match the peri-urban irrigation demand quantitatively, which is crucial for water-scarce delta areas. Challenges like quality improvement, changing societal perception, adequate collection-treatment-distribution infrastructures and governance structure for water reuse require further investigation.

Chapter 3

Spatio-temporal variability in water quality parameters influencing reuse in agriculture

Abstract

Agriculture in delta areas of emerging economies is highly reliant on the provision of water with adequate quality. This quality is often under pressure by season-related saltwater intrusion and poor domestic or industrial wastewater management. Methods to separate these two negative impacts on water quality for the delta areas are lacking but essential for proper management and supply of irrigation water. Therefore, the main aim of this chapter is to propose a method that maps salt and wastewater impacts on seasonal water quality and relate that to different land uses. Khulna, a delta city of Bangladesh was taken as a representative case study. Surface water samples have been collected from different city locations in winter, summer and monsoon seasons and were analyzed for a variety of chemical-physical water quality parameters. Spatio-temporal variation maps were generated using Inverse Distance Weighted (IDW) interpolation method and weighted overlay method was employed to map the current irrigation water use suitability based on FAO guidelines for the interpretations of water quality for irrigation. The influence of land-use on water quality was assessed by correlation analysis followed by bi-variate linear regression analysis. Analysis indicated significant ($p < 0.05$) seasonal-dependent variation in water quality parameters, especially for saltwater influenced and generic water quality parameters. Also, the land-use percentage within 500 m radii to the sampling stations had a significant positive correlation with several parameters indicating saltwater and urban wastewater influences. Weighted overlay analysis revealed that during summer, approximately 1/3rd of the total studied area has a severe restriction for irrigation water use. The method presented here is shown to be effective in presenting variabilities on the effects of salinization and wastewater discharge on water quality in urbanized deltas and can be used as a knowledge base for formulating and implementing future urban infrastructure planning to improve water quality.

Keywords: Spatial and temporal, Water quality, Land-use, Water reuse, Agriculture

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3.1 Introduction

Water is one of the most vibrant resources on this planet and only 2.5% of the total global water resource is fresh (Shiklomanov, 1998). Climate change, rapid urbanization is affecting water quality and threatening the availability of freshwater sources causing water scarcity in many regions of the world (Eslamian, 2016; Frederick and Major, 1997; Sophocleous, 2004). At present, water scarcity is considered to be one of the most significant threats to society and also a constraint for ensuring sustainable development (Eslamian, 2016; Jiménez and Asano, 2008). Delta areas around the world are more vulnerable to water scarcity due to their proximity to the sea. Sea level rise induces saltwater intrusion, a serious threat for agricultural production feeding growing populations in delta regions. Besides, intensified anthropogenic activities in the delta areas have led to the increasing discharge of solid waste and wastewater into the environment without prior treatment leading to the deterioration of surface water and groundwater quality.

Wastewater originates mainly from drinking water and represents, therefore, a potential freshwater resource; it is often only considered as a source of pollution to be treated and discharged and not reused as a valuable resource. Urban water reuse is an inevitable solution to address irrigation water scarcity, especially in the delta regions due to its availability, freshwater character and its richness with nutrients essential for agricultural production. Research indicated that water reuse could help cities and surrounding areas in the closing water cycle and decrease the water demand to improve their water self-sufficiency (Agudelo-Vera et al., 2012; Leusbrock et al., 2015). Upgraded wastewater can be cascaded to nearby agriculture in the delta areas to provide with freshwater and nutrients and help to mitigate salinization.

Water quality is an essential indicator to determine the reuse potential. Water quality varies with geographic location, season, weather, human activities, site-specific conditions and the presence of pollution sources. Point source pollution like domestic or industrial wastewater loads can easily be identified and therefore managed, whereas non-point source pollution like urban or agricultural runoff increases the complexity in finding and implementing quality improvement measures (Ongley et al., 2010; Shi et al., 2017; Tran et al., 2019, 2015; Wang et al., 2016). Land use and environmental land use conflicts represented by the use of land disrespecting soil capability is a source of water pollution that plays a pivotal role in determining water quality (Giri and Qiu, 2016;

Junior et al., 2014; Pacheco and Fernandes, 2016). Numerous previous studies concluded that there is a significant correlation between land use and water quality (Bu et al., 2014; Ding et al., 2016; Giri et al., 2018; Mainali and Chang, 2018; Rozario et al., 2016; Saeidi et al., 2018; Tran et al., 2015; Tu, 2011; Wang and Zhang, 2018; Wijesiri et al., 2018; Yua et al., 2016). In general, the higher percentage of anthropogenic land use associated with a higher level of activities contribute to a higher concentration of pollutants in water systems in comparison with natural areas like a forest, urban vegetation that sustain good water quality (Álvarez et al., 2017; Pacheco et al., 2015; Santos et al., 2015; Tu, 2011). However, this relationship is interpreted inconsistently in literature due to the varieties in the physical environment, changing economic activities and entanglement of the natural and anthropogenic area's in contact with water bodies making a comprehensive assessment difficult.

In the delta areas, this relationship has not yet been addressed in a consistent quantitative way. In this study, we address this knowledge gap for the delta areas by developing a spatio-temporal method in which a multitude of water quality parameters is mapped spatialy and then evaluated concerning the suitability for reuse in irrigated agriculture. The research objectives of this chapter are, (i) to provide a method to assess the spatial variations of water quality for macro quality parameters relevant for agriculture in different seasons; (ii) to quantify the influence of land use on water quality and identify the influence radii and finally; (iii) to determine the spatio-temporal potential area for reuse of urban water in agriculture.

The method is tested in Khulna, the delta city of Bangladesh, which is one of the most vulnerable regions in the world because of climate change-induced natural disasters (flood, cyclones, draught) and resources degradations (higher salinity level in soil and water) (Karim and Mimura, 2008). Without proper mitigation measures, farmers living in the region will increasingly struggle to find adequate irrigation water, due to climate change-induced salinity increase in solid and water and competition over available freshwater sources. Planned urban water reuse along with other sustainable methods like rainwater harvesting, multi-sourcing could provide a significant share of the required irrigation water and help farmers in combating irrigation water scarcity.

3.2 Materials and Methods

3.2.1 Study area selected for testing the method

The south-west coastal region of Bangladesh is one of the most vulnerable areas to climate change and Khulna city is the central administrative capital of this region. Khulna is also the third-largest city in the country and one of the primary recipient of migrants from surrounding areas (Kartiki, 2011). The city has two big rivers, Rupsha and Bhairab on the east side and Mayur river flows on the west side (Figure 3.1) and are the major recipient of the discharged wastewater. Large volumes of urban wastewater are disposed-off in these rivers without utilizing its real potential. The city has 22 natural canals running throughout the city and more than 1200 km man-made drains, which play a crucial role in water circulation as well as wastewater transportation (KCC, 2011; Roy et al., 2018). The city accommodates more than 0.6 million people (BBS, 2011) within its existing 45km^2 jurisdictional area. Due to population pressure and increased economic significance, the city authority is planning to acquire an adjacent 40 km^2 area on the west side to extend the city area. Residential land use (23%) followed by waterbody (10%) dominates the land use in the city and the adjacent area is dominated by agricultural land use (27%) (KCC, 2011). The topographic map of the study area shows that the general slope of the land is from north to south alongside the bank of Rupsha and Bhairab river and the lateral slope is downward from the river bank meaning the eastern part of the city is higher than the western side (Figure 3.1).

The peri-urban areas of South Asia always play an important role by providing land and water resources to the urban residents (Prakash and Singh, 2013). However, defining a peri-urban area in the context of rapidly urbanizing delta areas is quite challenging. In general, the peri-urban area can be termed as the area in the "proximity to the city" which undermines the clear understanding of urban-rural spectrum as interactive, dynamic and transformative (Iaquinta and Drescher, 2000). The area is also referred to as rural fringe but should also coexist in the social, environmental, physical, institution and economic terms (Allen et al., 2006; Narain and Nischal, 2007). The peri-urban agricultural products are mostly consumed by the urban population. Existing infrastructural development trend and need of the city indicates that those agricultural areas are soon to be transformed into urban built-up areas. However, for this study, the proposed adjacent areas of the city (more than 40km^2) will be termed as peri-urban area whereas the city's existing administrative area (more than 45km^2) will be called as the main urban area.

3.2.2 Sampling: Collection and Laboratory Analysis

The wastewater generated by different anthropogenic activities in Khulna city is discharged into open water sources. Wastewater generated in the residential areas is collected in open drains and canals, which then finally released into the rivers without treatment. In some cases, mills-industries also discharge the effluent directly into the rivers even though by law effluents should receive required treatment before discharge. Farmers extract irrigation water from these polluted rivers resulting in indirect wastewater use in agriculture (Qadir et al., 2010). The city also has a number of enclosed waterbodies (also known as ponds) that are being used for small-scale agriculture (home gardening) as well for daily activities (bathing, washing, etc.). A total of 25 water quality monitoring stations (Figure 3.1) including rivers, canals, drains and enclosed waterbody were selected for sample collection. Monitoring stations were chosen considering the land-use pattern, accessibility (for example a large area in the northern part of the city has restricted entry so no sample could be taken there), distance to the laboratory and the ability to cover the distance within a day.

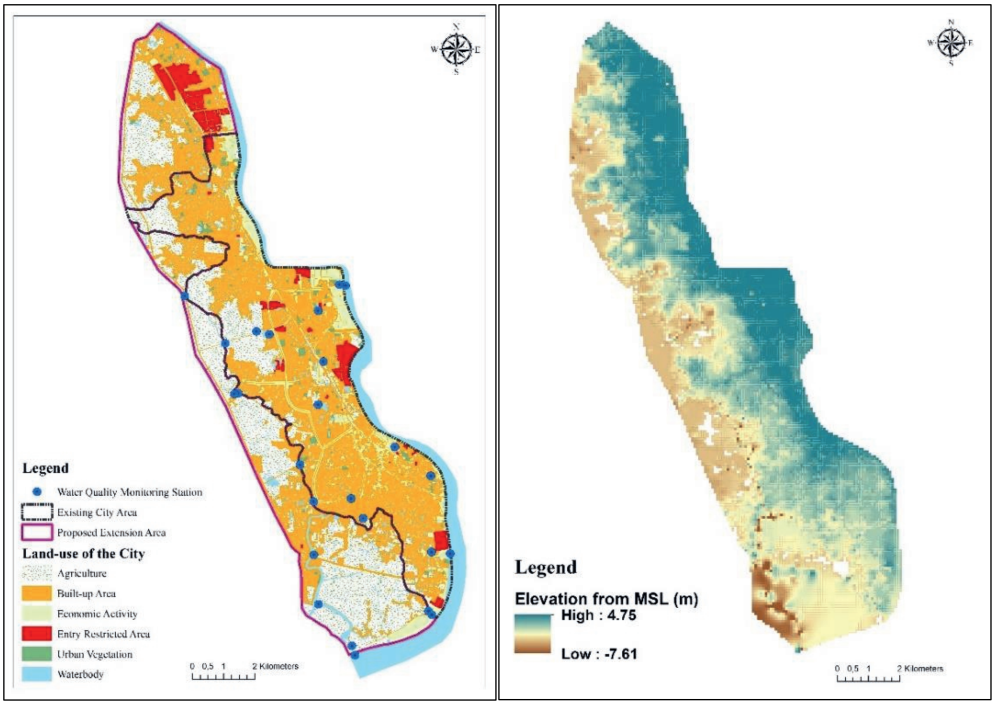

Figure 3.1: Water quality monitoring stations embedded on the land-use map (left) and topography of the study area (right)

Based on the Koppen-Geiger climate classification map, Khulna city falls within the tropical climate zone which has an equatorial wet and dry climate (Kottek et al., 2006; Mourshed, 2011). By analyzing the climatic data, the climate of Khulna city can be divided into hot summer from March to June with high temperature (between 32°C to 36°C) with occasional rainfall, hot and humid monsoon from July to October with heavy rainfall (more than 67% of the total annual rainfall) with moderate temperature (around 32°C) and finally the cooler (between 13°C to 19°C) drier winter from November to March *(supplementary materials: Table iv, v, vi)* Table . The sample collection and analysis for the winter period was performed in January-February, for the summer period in April-May and for the monsoon period in September-October, 2018.

Water quality can be assessed based on chemical-physical, biological and radiological and micro-chemical characteristics and this study focuses on only the macro chemical-physical parameters. Samples were collected at 40-50 cm depths in 2-liter PET bottles from the sampling stations. The bottles were labeled correctly and sealed before transporting to the laboratory. All analysis was performed based on the standard methods developed for the examination of a chemical-physical parameter of water (APHA/AWWA/WEF, 2012; Ramesh and Anbu, 1996). Basic physical measures like pH, electrical conductivity (EC), temperature, total dissolved solids (TDS), dissolved oxygen (DO), turbidity were determined by portable water quality multi-probe meters. Nitrate (NO_3^-) was measured using ultraviolet spectrophotometric screening method, whereas sulfate (SO_4^{2-}) was measured using the turbidimetric method and phosphate (PO_4^{3-}) was measured using the ascorbic acid method. Ammonia-Nitrogen (NH_3-N) was measured using a spectrophotometer while sodium (Na^+) and potassium (K^+) were measured using a flame photometer. Calcium (Ca^{2+}), chloride (Cl^-), bicarbonate (HCO_3^-) and magnesium (Mg^{2+}) were determined through the titration method. Total suspended solids (TSS) was measured using oven-dried method. These parameters were further divided into three groups (Table 3.1) for further use in the study as i) generic parameters ii) saltwater influenced indicator parameters and iii) urban wastewater-impacted indicator parameters.

Table 3.1: Grouping of chemical-physical water quality parameters

Group	Parameters
Generic	pH, Temperature, Turbidity, HCO_3^-
Salt water influenced	TDS, EC, Na^+, Cl^-, Mg^{2+}, Ca^{2+}, K^+, SO_4^{2-}
Urban wastewater-impacted	TSS, DO, BOD_5, COD, NO_3^-, PO_4^{3-}, NH_3

Salinity is considered as one of the most critical factors for determining water quality for agricultural use as the soil can create an unfavorable environment and provoke toxicity due to salinity (Bauder et al., 2014; Jeong et al., 2016). In addition to that, the yield can be reduced due to sodium imbalance, also known as Sodium Absorption Ratio (SAR). SAR is used to assess the potential infiltration problem caused by excessive sodium in irrigation water. SAR can be derived using the following formula based on (Ayers and Westcot, 1985; Bauder et al., 2014):

$$\text{SAR} = \frac{Na^{+}meq/L}{\sqrt{\frac{(Ca^{++}meq/L)+(Mg^{++}meq/L)}{2}}} \qquad (3.1)$$

where meq/L = mg/L divided by atomic weight of ion divided by ionic charge

3.2.3 Land-use within a different radius of sampling stations

Geo-database of the city was collected from the municipal service and land-use planning authority (Khulna City Corporation and Khulna Development Authority). The database has vast information about the administrative boundary, rivers and canals, roads and drainage network, buildings etc. Land-use patterns in the study area were then further categorized into five major categories: built-up area (includes residential buildings, road network, educational institutions etc.), agriculture (mostly in the peri-urban area), waterbody (includes rivers, canals, ponds), economic activity (includes commercial areas, industrial areas) and urban vegetation (includes recreational areas, vacant areas). The northern part of the city has several restricted areas which are also demarked in the maps based on the information from the database. To understand the extent of influence of land-use on water quality for the study area three different buffer radius (200m, 500m and 1000m) from the sampling sites were considered and land-use percentage within these buffer radiuses were analyzed using ArcGIS 10.5. Land use areas within different buffer radius are attached in supplementary material *(Table xiii)*.

3.2.4 Statistical Analysis

The percentage of five different land-use types and water quality at the sampling station were used for the analysis of the spatial relationship. Pearson correlation analysis was performed to understand the influence among different water quality parameter in different seasons. The correlation coefficient (r) near +1 or −1 means a good relationship between two variables and value around zero implies no relationship between them. For this study, correlation coefficient ($r \geq 0.7$) is considered as strong, while r between 0.4 to

0.7 is considered as moderately strong and finally, r value below 0.4 is considered as weak correlation (Gidey, 2018; Giridharan et al., 2008; Kumar et al., 2006). Shapiro-Wilko test, visual interpretation through histogram and Q-Q plot were used to identify the normality of the data. Analysis indicated that the value of COD, HCO_3^-, PO_4^{3-} and Ca^{2+} were normally distributed and thus, Pearson's correlation was used to identify the relationship between land-use and these variables. Rest of the water quality variables were not normally distributed and thus natural log transfer was carried out to normalize the data. The percentage of land-use within the buffer is dominated by the built-up area and urban vegetation is the lowest. Spearman rank correlation analysis is used to perform simple linear bivariate regression and scatter plot was created to explain the changes in water quality with the changes in the land-use pattern. IBM SPSS Statistics 23 and Microsoft Excel 2016 was used to perform the necessary statistical analysis.

3.2.5 Concept of Inverse Distance Weighted (IDW) Interpolation

The Inverse Distance Weighted (IDW) interpolation method was developed based on the first law of geography coined by W. Tobler in 1970. The law states, "everything is related to everything else, but near things are more related than distant things" (Tobler, 1970). Inverse distance weighted (IDW) interpolation determines the cell value of an unsampled point using a linearly weighted combination of a set of sample points (ESRI, 2016). IDW method assumes that the variable being mapped decreases in influence with distance from its sampled location (Johnston et al., 2003). IDW is a deterministic method as it requires less calculation to meet specific statistical assumptions compared to another stochastic method like kriging (Chen and Liu, 2012). IDW has the ability to handle the extreme values (outliers) in the datasets compared to other spatial analysts and easier to explain the results and comprehensively used in literature to determine values in unknown areas (Chen and Liu, 2012; Dhanasekarapandian et al., 2016; Gidey, 2018; Madhloom et al., 2017). The value of the unknown point is the weighted sum of the values of N known points. In this study, the IDW method has been used to interpolate spatial data, which will estimate the unknown water quality data based on the known water quality data.

The following equations describe the formulas employed for the IDW:

$$\hat{Q}_w = \sum_{i=1}^{N} w_i Q_i \qquad (3.2)$$

$$w_i = \frac{{d_i}^{-\alpha}}{\sum_{i=1}^{N} {d_i}^{-\alpha}} \qquad (3.3)$$

where, $\hat{Q}_w$ is the unknown water quality, Q_i is the known water quality data of the sampled stations, N is the total number of sampling stations, w_i is the weighting of each sampling station, d_i is the distance from each sampling station to unknown points and α is the power parameter which allows controlling the significance of known points on the interpolated values based on their distance. It is a positive, real number and its default value is 2. Interpolated maps were generated and legend was created using equal interval of the concentration in each parameter. Due to higher variation in concentration it was not possible to create similar color ranged legend, but more close-by color ranged legend was assigned. In addition, an increased number of sampling points especially in the non-sampled areas with different interpolation method would further improve the mapping accuracy.

3.2.6 Concept of Weighted Overlay

Over the years, interest among researchers has grown towards the integration of GIS and multi-criteria decision analysis due to their synergic capabilities (Malczewski, 2007). An integrated map can be produced by applying a common measurement scale for diverse and dissimilar inputs (Riad et al., 2011). The weighted overlay is used to create suitability models by solving multi-criteria problems. The formula employed to produce the maps can be interpreted as:

$$Q_w = \sum_{i=1}^{n} W_i X_i \qquad (3.4)$$

where, Q_w = degree of restriction for each pixel in the map, W_i = the weight of i and X_i = criteria score of the class of factor i.

The analysis follows a three-step procedure (Junior et al., 2015; Malczewski, 1999) i) selection of the water quality parameters and reclassification of the pixel-based (raster) maps ii) allocation of weight to each water quality parameter and iii) combining weighted parameters and generating final maps. FAO water quality guideline has a degree of restriction for irrigation for pH, bicarbonate, TDS, SAR, Chloride and Nitrate (Ayers and Westcot, 1985). So, interpolated maps of pH, bicarbonate, TDS, SAR, Chloride and Nitrate were reclassified using ArcGIS 10.3 based on the guideline and measurement scale from 1 to 3 where 1 means no degree of restriction for irrigation, 2 meaning the moderate degree of restriction for irrigation and 3 meaning the severe degree of restriction for irrigation (Table 3.2).

Table 3.2: Water quality reclassification scale based on FAO Water Quality Guideline (Ayers and Westcot, 1985)

Parameter[1]	**The degree of restrictions on use**		
	None	**Moderate**	**Severe**
	Reclassification measurement scale		
	1	**2**	**3**
EC_W or	<0.7	0.7-3.0	>3.0
TDS	≤450	450-2000	≥2000
Na^+	≤3	3-9	≥9
Cl^-	≤140	140-350	≥350
NO_3^-	≤5	5 - 30	≥30
HCO_3^-	≤90	90-500	≥500
pH	Normal range 6.5 – 8.4		

Then equal weight was (16%) assigned for all the water quality parameters by ArcGIS and SAR weighted 20% automatically as the last assigned parameter in the analysis. Finally, weighted overlay analysis was performed to obtain the final degree of restriction maps for a different season. The total weights of each pixel of the final merged layer were derived based on the following formula:

$$Q_w = (W_{pH} . X_{pH} + W_{Bi\text{-}carbonate} . X_{Bi\text{-}carbonate} + W_{TDS} . X_{TDS} + W_{SAR} . X_{SAR} + W_{Chloride} . X_{Chloride} + W_{Nitrate} . X_{Nitrate}) \qquad (5)$$

where W = the weight of each parameter and X = criteria score of each parameter

3.3 Results and Discussion

3.3.1 Spatio-temporal Variation in Water Quality

A statistical summary of surface water quality parameters of three different seasons (winter, summer and monsoon) are presented in the following table (Table 3.3). Results indicate that there are different levels of variation in quality as influenced by seasons. A very strong and significant variation was demonstrated by statistical analysis (ANOVA, $p<0.05$) for pH, TDS, Turbidity, water temperature, HCO_3^-, EC, NO^{3-}, NH_3-N, SO_4^{2-}, Na^+, Ca^{2+}, Mg^{2+}, K^+ and smaller insignificant changes occurred for TSS, DO, BOD_5 and PO_4^{3-} . TSS, DO, BOD_5 and PO_4^{3-} are indicatory for impact by urban wastewater and throughout the year such an impact appears to occur. A significant variation occurs in the parameters that fall under the “generic” and “saltwater influenced” categories.

[1] *All the values presented in the table are in mg/L except for Sodium (which is indicated as SAR)*

Table 3.3: Water quality in different season in the study area

Group	Parameter[2]	Winter (*n*=25)		Summer (*n*=25)		Monsoon (*n*=25)		Overall (*n*=75)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Generic	**pH**	6.8	0.2	7.3	0.4	7.2	0.3	7.1	0.4
	Temp.	23.5	1.1	31.8	1.5	30.2	1.0	28.5	3.8
	Turb.	6.8	5.2	196.9	384.6	133.8	41.5	112.5	30.2
	HCO_3^-	430.2	168.7	380.8	150.5	259.2	150.1	356.7	170.6
Salt water influenced	**TDS**	987.0	529.0	2884.9	2803.6	500.2	331.1	1457.4	1936
	EC	2.0	1.1	5.8	5.6	1.0	0.7	2.9	3.9
	Na^+	290.6	150	1277.0	1446.8	157.8	113.0	575.1	971.1
	Cl^-	485.7	327.5	1685.1	1931.7	163.0	162.1	777.9	1299.3
	Mg^{2+}	40.2	21.3	113.0	118.9	22.6	20.0	58.6	80.1
	Ca^{2+}	62.8	33.8	277.1	237.7	86.8	30.1	142.3	168.2
	K^+	17.9	6.3	42.0	33.9	10.5	6.9	23.5	24.2
	SO_4^{2-}	26.7	44.6	286.1	267.9	77.3	103.7	130.0	200.5
Wastewater impacted	TSS	245.1	365.7	471.8	598.0	544.3	406.6	420.4	479.0
	DO	3.0	2.0	2.8	2.0	3.4	2.2	3.1	2.1
	BOD_5	30.0	30.1	38.1	23.8	44.5	43.1	37.5	33.4
	COD	85.5	40.2	186.9	96.7	87.0	31.4	119.8	78.5
	NO_3^-	5.8	2.9	43.7	31.1	36.1	52.0	28.5	38.3
	PO_4^{3-}	3.1	3.1	5.2	3.0	3.2	3.8	3.8	3.4
	NH_3	0.8	1.1	3.8	4.3	0.5	0.6	1.7	2.9

[2] *Values presented in the table are in mg/L except for pH, Turbidity (NTU), Water Temperature (°C) and EC (dS/m) and bold parameter indicates the significant ($p<0.05$) temporal variation*

During summer TDS/EC increases three times compared to the winter and almost six times compared to the monsoon season. This is presumably under the influence of salinity variations in surrounding rivers and seasonal weather conditions are varying between dry and heavy precipitation. Pearson correlation indicated the correlation among parameters within a specific season, showing that the parameters indicating saltwater influence, had a strong and significant correlation with each other. In contrast, generic and urban wastewater impact parameters had moderate to no correlation. The correlation matrix during the winter season indicates that TDS and EC were strongly positively correlated with Na^+, Cl^-, Mg^{2+}, K^+ and SO_4^{2-} (Table 3.4). Additionally, Na^+ was strongly positively correlated with Cl^-, SO_4^{2-}, Mg^{2+} and K^+. This correlation can be explained due to the lack of rainfall and a stronger effect of salts on water quality (Roy et al., 2018; Shammi et al., 2017). In contrast, DO was strongly negatively correlated with BOD_5 and PO_4^{3-} indicating wastewater impacts.

Analysis indicates that correlation among saltwater influenced parameters is stronger during summer (Table 3.5) than in winter and monsoon seasons. TDS and EC are strongly positively correlated with Cl^-, SO_4^{2-}, Na^+, Ca^{2+}, Mg^{2+} and K^+. Also, a strong positive correlation was found for Cl^- with SO_4^{2-}, Na^+, Ca^{2+}, Mg^{2+}, K^+ and SO_4^{2-} with Na^+, Ca^{2+}, Mg^{2+} and K^+. Lack of rainfall, excessive heat enhancing evaporation and saltwater inlets from rivers are likely reasons for the correlation among “saltwater influence” related water quality parameters. During monsoon, correlation among the water quality parameters changes compared to the previous seasons. The correlation between water quality parameters during the monsoon season indicates that TDS and EC have a strong positive correlation with HCO_3^-, NO_3^-, Cl^-, Na^+ and Ca^{2+} (Table 3.6). In addition to that, BOD_5 with HCO_3^- and Ca^{2+}, HCO_3^- with NO_3^- and PO_4^{3-}, NO_3^- with PO_4^{3-} and Cl^- with Na^+ are strongly positively correlated. This strong parameter association appears to be a result of excessive rainfall that washes away a lot of soil and dust particles from the land and by re-suspending deposits of sewage drains, which both influence the water quality. To summarize, all the seasons influence water quality parameters, but in the summer – the most critical regarding urban water potential for use in irrigation, saltwater impacts and wastewater influences are both apparent.

Standard deviation indicates that most of the parameters have higher variability in the dataset except for the generic parameters and wastewater-impacted parameters (DO, BOD5, COD and $PO4^{3-}$). Spatial variation of bicarbonate and TDS indicates that TDS in the southern part of the city increases during summer most likely due to the increase in salinity in the river Rupsha and Bhairab (Figure 3.2). During monsoon, surface water gets diluted with the excessive rainfall and contributes to lowering the TDS. The concentration of TDS remains within a similar range in different seasons around the central part of the city due to the prevailing presence of ponds in that part. HCO3- remains similar all over the year and the middle part of the city, which is residential and commercial has the highest concentration. During the summer concentration values of Na^+, Cl^-, Mg^{2+} ions increase in the southern part of the city and decreases during monsoon due to the dilution with excessive rainfall (Figure 3.3).

Topographically, the southern part is lower than the eastern part, which leads to washout from east to west after a rainfall event. It is evident from the maps that during summer concentration of Ca^{2+}, K^+ and SO_4^{2-} increases compared to the concentration during winter and monsoon (Figure 3.4). Higher concentrations for Ca^{2+}, K^+ and SO_4^{2-} are present in the southern part of the city whereas values remain the same in the northern part over the seasons. However, sulfate concentration values seem higher in the south-eastern part of the city during monsoon, which can be explained due to the occurrence of soil and sewage drain runoff events during excessive rainfall.

A lower concentration of NH_3-N and higher concentration of TSS are present in the water throughout the season (Figure 3.5). Surface runoff and sediment brought during high tide can be the major contributors to a higher level of TSS in the summer, whereas surface runoff can also contribute to this during the monsoon. NO_3^- and NH_3-N also vary in the study area, especially in the south-eastern part.

Table 3.4: Correlation coefficient[3] matrix of water quality during winter

	pH	**Temp.**	**Turb.**	**HCO_3^-**	**TDS**	**EC**	**Na^+**	**Cl^-**	**Mg^{2+}**	**Ca^{2+}**	**K^+**	**SO_4^{2-}**	**TSS**	**DO**	**BOD_5**	**COD**	**NO_3^-**	**PO_4^{3-}**	**NH_3**
pH	1.000																		
Temp.	0.109	1.000																	
Turb.	-0.131	-0.061	1.000																
HCO_3^-	-0.162	0.021	0.255	1.000															
TDS	-0.386	-0.123	-0.015	-0.085	1.000														
EC	-0.385	-0.124	-0.016	-0.086	1.000	1.000													
Na^+	-0.441	-0.151	-0.012	-0.145	**0.968**	**0.968**	1.000												
Cl^-	-0.377	-0.158	-0.103	-0.273	**0.853**	**0.852**	**0.890**	1.000											
Mg^{2+}	-0.418	-0.038	-0.021	-0.134	**0.844**	**0.842**	**0.879**	**0.830**	1.000										
Ca^{2+}	-0.119	0.195	0.139	0.523	0.255	0.254	0.104	0.143	0.134	1.000									
K^+	-0.411	-0.226	0.344	0.086	**0.731**	**0.730**	**0.780**	0.617	0.591	0.040	1.000								
SO_4^{2-}	-0.250	-0.112	-0.346	-0.535	**0.734**	**0.735**	**0.747**	0.692	0.615	-0.200	0.442	1.000							
TSS	-0.212	-0.254	0.080	-0.242	0.419	0.420	0.489	0.695	0.487	-0.132	0.406	0.286	1.000						
DO	0.143	0.278	-0.150	-0.770	0.109	0.109	0.208	0.268	0.224	-0.406	0.044	0.354	0.176	1.000					
BOD_5	0.106	-0.134	0.180	0.696	-0.159	-0.159	-0.251	-0.329	-0.151	0.371	-0.161	-0.477	-0.169	**-0.757**	1.000				
COD	0.421	-0.311	0.348	0.123	-0.303	-0.300	-0.346	-0.259	-0.351	0.048	-0.289	-0.280	0.090	-0.306	0.257	1.000			
NO_3^-	-0.549	-0.097	0.233	-0.022	0.431	0.428	0.466	0.391	0.423	0.062	0.651	0.368	0.025	0.000	-0.289	-0.393	1.000		
PO_4^{3-}	-0.009	-0.183	0.479	**0.780**	-0.140	-0.140	-0.177	-0.326	-0.253	0.231	0.227	-0.470	-0.123	**-0.723**	0.637	0.397	0.086	1.000	
NH_3	-0.355	-0.331	0.313	0.441	0.134	0.132	0.119	0.018	0.131	0.013	0.277	-0.093	0.062	-0.330	0.206	0.193	0.352	0.533	1.000

[3] *The bold number indicates the strong correlation ($r \geq 0.7$) at the 0.05 level*

Table 3.5: Correlation coefficient[4] matrix of water quality during summer

	pH	**Temp.**	**Turb.**	**HCO_3^-**	**TDS**	**EC**	**Na^+**	**Cl^-**	**Mg^{2+}**	**Ca^{2+}**	**K^+**	**SO_4^{2-}**	**TSS**	**DO**	**BOD_5**	**COD**	**NO_3^-**	**PO_4^{3-}**	**NH_3**
pH	1.000																		
Temp.	**0.721**	1.000																	
Turbidity	-0.202	-0.313	1.000																
HCO_3^-	-0.142	0.128	-0.444	1.000															
TDS	-0.127	-0.191	0.323	-0.490	1.000														
EC	-0.127	-0.192	0.323	-0.490	1.000	1.000													
Na^+	-0.105	-0.227	0.254	-0.502	**0.828**	**0.828**	1.000												
Cl^-	-0.143	-0.193	0.278	-0.474	**0.973**	**0.974**	**0.783**	1.000											
Mg^{2+}	-0.118	-0.183	0.325	-0.498	**0.995**	**0.995**	**0.830**	**0.970**	1.000										
Ca^{2+}	-0.161	-0.218	0.306	-0.436	**0.991**	**0.991**	**0.804**	**0.969**	**0.993**	1.000									
K^+	-0.094	-0.115	0.414	-0.517	**0.978**	**0.978**	**0.829**	**0.944**	**0.974**	**0.959**	1.000								
SO_4^{2-}	-0.112	-0.129	0.422	-0.607	**0.949**	**0.949**	**0.763**	**0.911**	**0.956**	**0.936**	**0.948**	1.000							
TSS	-0.245	-0.167	0.694	-0.320	0.370	0.369	0.269	0.330	0.362	0.360	0.427	0.436	1.000						
DO	0.652	0.419	0.147	-0.441	0.002	0.001	0.147	-0.035	0.042	-0.038	0.038	0.099	-0.048	1.000					
BOD_5	-0.633	-0.403	-0.045	0.545	-0.066	-0.065	-0.297	-0.060	-0.100	-0.032	-0.117	-0.157	0.050	**-0.767**	1.000				
COD	-0.009	-0.061	0.330	-0.172	0.573	0.574	0.456	0.506	0.575	0.573	0.618	0.530	0.322	-0.052	0.027	1.000			
NO_3^-	-0.256	-0.141	-0.330	0.287	-0.395	-0.396	-0.145	-0.401	-0.385	-0.374	-0.408	-0.450	-0.082	-0.234	0.124	-0.447	1.000		
PO_4^{3-}	-0.399	-0.193	-0.426	**0.702**	-0.438	-0.439	-0.226	-0.435	-0.454	-0.407	-0.451	-0.547	-0.240	-0.561	0.456	-0.289	0.502	1.000	
NH_3	-0.138	-0.170	-0.242	-0.024	0.302	0.299	0.375	0.264	0.257	0.255	0.250	0.227	-0.231	-0.181	0.046	-0.112	-0.022	0.189	1.000

[4] *The bold number indicates the strong correlation ($r \geq 0.7$) at the 0.05 level*

Table 3.6: Correlation coefficient[5] matrix of water quality during monsoon

	pH	**Temp.**	**Turb.**	**HCO_3^-**	**TDS**	**EC**	**Na^+**	**Cl^-**	**Mg^{2+}**	**Ca^{2+}**	**K^+**	**SO_4^{2-}**	**TSS**	**DO**	**BOD_5**	**COD**	**NO_3^-**	**PO_4^{3-}**	**NH_3**
pH	1.000																		
Temp.	0.168	1.000																	
Turbidity	0.061	-0.311	1.000																
HCO_3^-	-0.085	-0.130	-0.524	1.000															
TDS	0.004	-0.063	-0.618	**0.860**	1.000														
EC	-0.028	-0.088	-0.606	**0.853**	**0.997**	1.000													
Na^+	0.126	0.026	-0.365	0.666	**0.864**	**0.868**	1.000												
Cl^-	0.024	-0.021	-0.451	0.605	**0.845**	**0.853**	**0.815**	1.000											
Mg^{2+}	0.073	-0.149	-0.200	0.508	0.641	0.651	0.573	0.492	1.000										
Ca^{2+}	-0.269	-0.234	-0.448	0.612	**0.749**	**0.769**	0.695	0.655	0.375	1.000									
K^+	-0.400	0.292	-0.449	0.627	0.511	0.498	0.338	0.343	0.199	0.327	1.000								
SO_4^{2-}	0.011	0.303	0.496	-0.326	-0.273	-0.266	0.068	-0.151	-0.184	-0.175	0.073	1.000							
TSS	0.141	-0.124	0.318	-0.277	-0.317	-0.303	-0.204	-0.234	-0.079	-0.286	-0.258	0.446	1.000						
DO	0.620	0.347	0.206	-0.577	-0.531	-0.563	-0.426	-0.428	-0.208	**-0.714**	-0.557	0.086	0.286	1.000					
BOD_5	-0.385	-0.241	-0.396	0.698	0.622	0.633	0.505	0.520	0.151	**0.813**	0.520	-0.134	-0.287	-0.830	1.000				
COD	-0.141	-0.435	0.028	0.506	0.359	0.352	0.357	0.220	-0.014	0.421	0.218	-0.100	-0.386	-0.579	0.588	1.000			
NO_3^-	-0.142	-0.219	-0.357	**0.907**	**0.713**	0.717	0.574	0.471	0.581	0.503	0.551	-0.235	-0.154	-0.528	0.600	0.434	1.000		
PO_4^{3-}	-0.331	-0.089	-0.335	**0.860**	0.622	0.628	0.451	0.469	0.352	0.403	**0.768**	-0.094	-0.146	-0.631	0.656	0.442	**0.893**	1.000	
NH_3	-0.132	-0.148	-0.179	0.023	0.162	0.172	0.068	0.014	0.220	0.083	-0.023	-0.290	-0.237	-0.156	-0.124	-0.027	0.025	-0.093	1.000

[5] *The bold number indicates the strong correlation ($r \geq 0.7$) at the 0.05 level*

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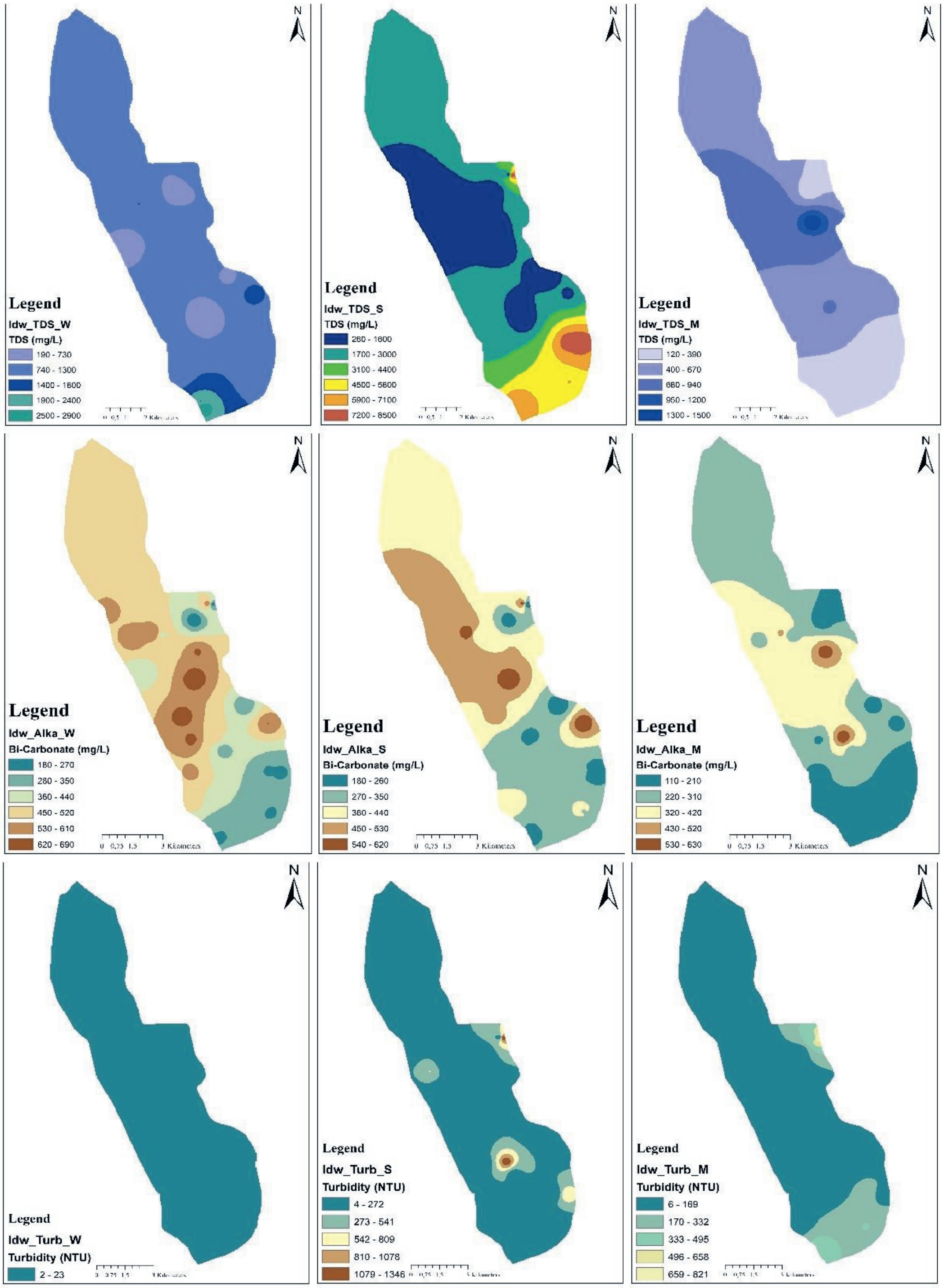

Figure 3.2: Spatial variability of TDS, Bicarbonate and Turbidity in winter (left), summer (middle) and monsoon (right))

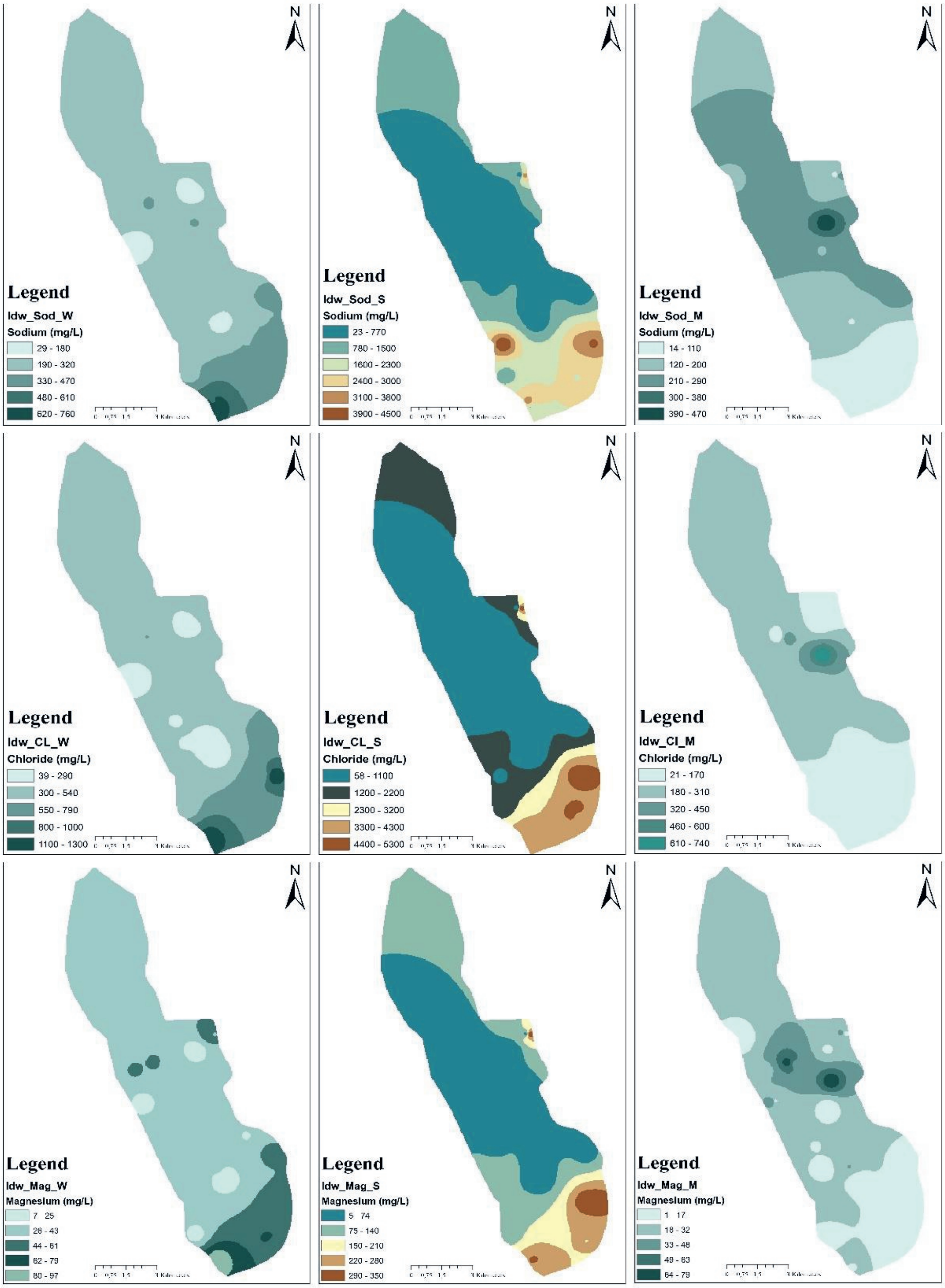

Figure 3.3: Spatial variation of Sodium, Chloride and Magnesium in the study area in winter (left), summer (middle) and monsoon(right))

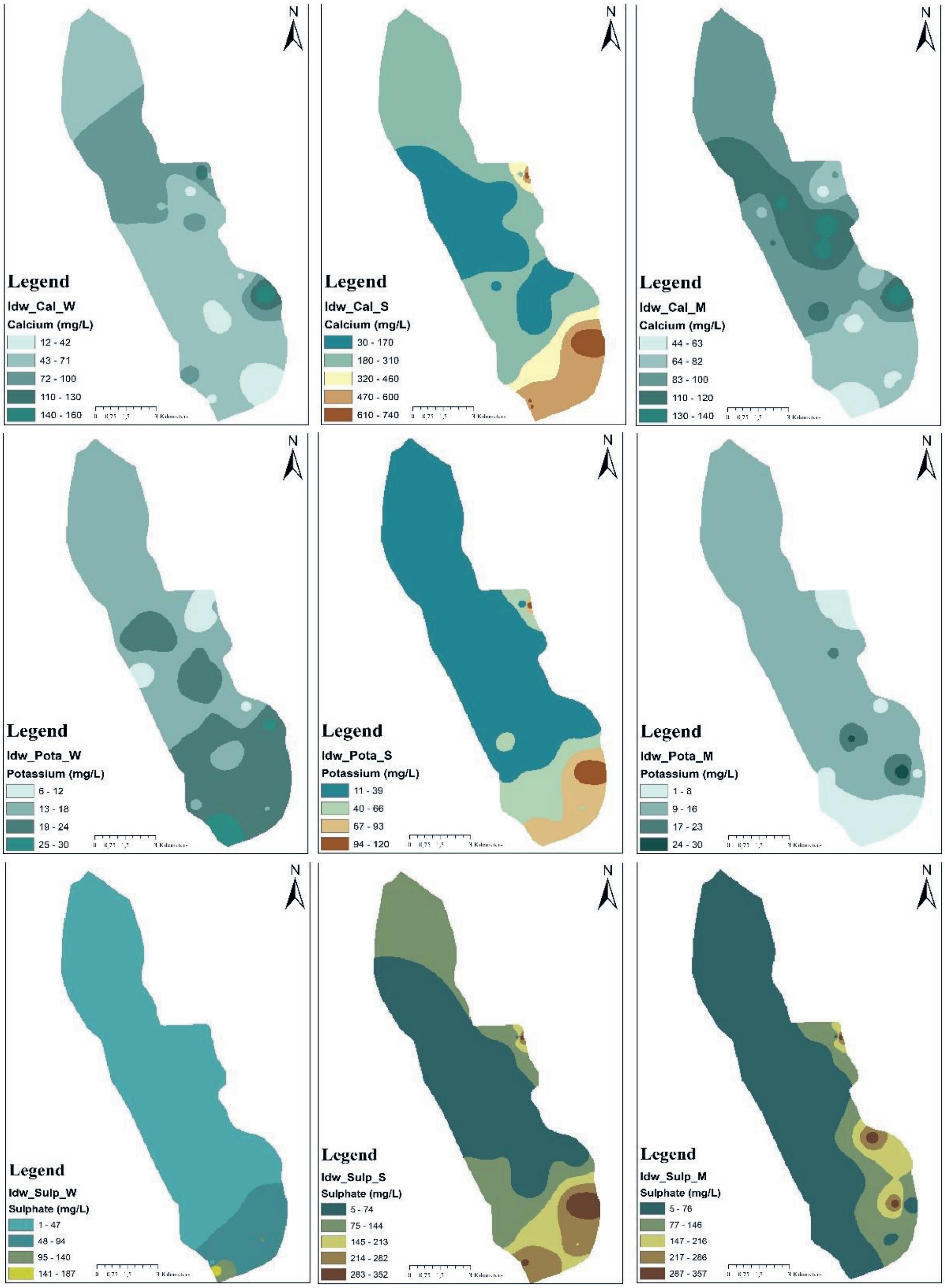

Figure 3.4: Spatial variation of Calcium, Potassium and Sulphate in winter (left), summer (middle) and monsoon (right)

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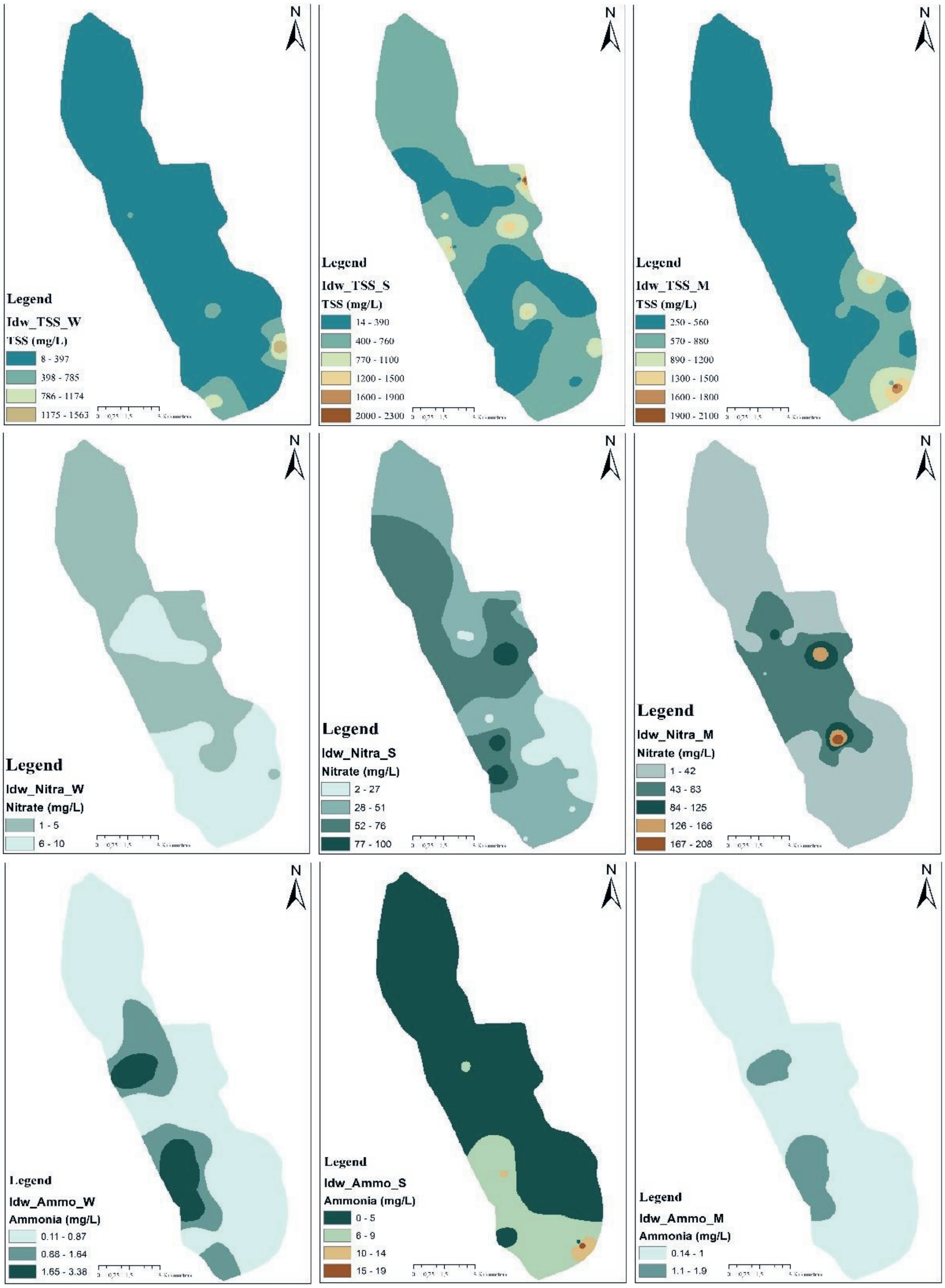

Figure 3.5: Spatial variability of TSS, Nitrate and Ammonia in winter (left), summer (middle) and monsoon (right)

3.3.2 Influence of land-use on overall water quality

Water quality at a sampling site is likely to be influenced by anthropogenic activities in its upstream area rather than within the limit of an administrative region (Tu, 2011). Effects of land-use on surface water pollution suggested that within 200m radius the relationship between land-use and fluorescence component (microscopic algae, colored dissolved organic matter, etc.) is most significant (Wang and Zhang, 2018). However, this is not uniform for every area and in this study, three different buffer radii (200m, 500m and 1000m) have been tested to identify the optimum buffer radius for relating land-use to water quality.

Correlation analysis indicates that the correlation between the percentage of land-use and water quality parameter is strongest at 500m buffer radius *(supplementary materials: Table xiv)*. The results indicate that the percentages of the waterbody (%WB), built-up area (%BA) and economic activity (%EA) within a 500m radius from the monitoring stations have a significant correlation with several water quality parameters (Table 3.7). For %WB, this relationship is positive with TDS/EC, Na^+, Cl^-, Mg^{2+}, Ca^{2+}, K^+, $SO4^{3-}$ and negative with HCO_3^-, BOD_5, NO_3^- and PO_4^{3-}. An increase in the waterbody area within the 500m buffer radius leads to increased concentrations for the parameters indicating saltwater influence (such as the elevation for TDS/EC) in the dry season, i.e., by the intrusion of saltwater from the river towards the inland water bodies (Ratnayake et al., 2018).

For the %BA this correlation is positive with water temperature and NO_3^- whereas negative with TDS, Na^+, Cl^-, Mg^{2+}, Ca^{2+} and TSS, i.e., showing a high dilution potential to mitigate irrigation water salinity to be present in the urban wastewater. A smaller percentage of urban green areas, climate change and urbanization induced impervious concrete surface can influence water body temperature (Palmer and Nelson, 2007). Anthropogenic activities are known to accelerate the rate and level of eutrophication by nutrient emissions as exemplified by elevated concentrations in N and P in waterbodies (Chislock et al., 2013; Eslamian, 2016; Hossain and Rahman, 2012), were also observed at higher percentages of urban land use. Increased %WB reduces the urban discharge areas per volume of the waterbody and thus the higher dilution/lower input lowers the NO_3^- and PO_4^{3-} concentrations.

Table 3.7: Correlation matrix between percentage of land-use and water quality variables

Parameter	Waterbody	Built-up Area	Economic Activity	Agriculture	Urban Vegetation
pH	-0.153	0.029	0.116	0.012	0.115
Temp	-0.187	**0.487***	0.382	-0.348	0.389
Turbidity	0.329	-0.272	0.110	-0.150	-0.195
HCO_3^-	**-0.568****	0.254	-0.395	0.330	0.074
TDS/EC	**0.651****	**-0.564****	0.144	0.052	0.037
Na^+	**0.600****	**-0.445***	0.162	0.079	0.078
Cl^-	**0.655****	**-0.526****	0.238	-0.001	0.113
Mg^{2+}	**0.602****	**-0.558****	0.265	-0.034	0.130
Ca^{2+}	**0.662****	**-0.520****	**0.528****	-0.208	0.048
K^+	**0.452***	-0.394	0.090	0.019	-0.099
SO_4^{3-}	**0.602****	-0.335	0.355	-0.342	0.288
TSS	0.361	**-0.466***	0.233	-0.174	0.099
DO	0.382	-0.212	0.146	-0.132	-0.103
BOD_5	**-0.452***	0.162	-0.200	0.182	-0.113
COD	0.123	-0.289	0.075	0.184	-0.174
NO_3^-	**-0.714****	**0.409***	-0.277	0.223	-0.134
PO_4^{3-}	**-0.585****	0.365	**-0.457***	0.275	-0.069
NH_3	0.309	-0.258	-0.340	0.382	-0.176

** Correlation is significant at the 0.05 level (2-tailed).*
*** Correlation is significant at the 0.01 level (2-tailed).*

Built-up areas are reducing the area of the open soil surface, decreasing soil erosion, which has been sustained by a negative relation between the %BA and TSS. Percentage of economic activity is significantly positively correlated with Ca^{2+} and negatively correlated with PO_4^{3-}. In addition, the role of rivers and canals in quick transportation of wastewater resulted in a weaker correlation between built-up area and parameters related to wastewater.

The relationship between agricultural land and water quality parameters found in this study negates some of the findings from several previous studies. In general runoff from agricultural areas contributes to the increase of nutrients in nearby water sources. However, in the study area, most of the agricultural areas are outskirts of the city and often a negligible percentage of the area within the buffer radius, which automatically led to a weaker relationship. To better address, the impact of agricultural land on surface water quality, a larger area around the city needs to be taken into account, which was, however, not the focus of this study.

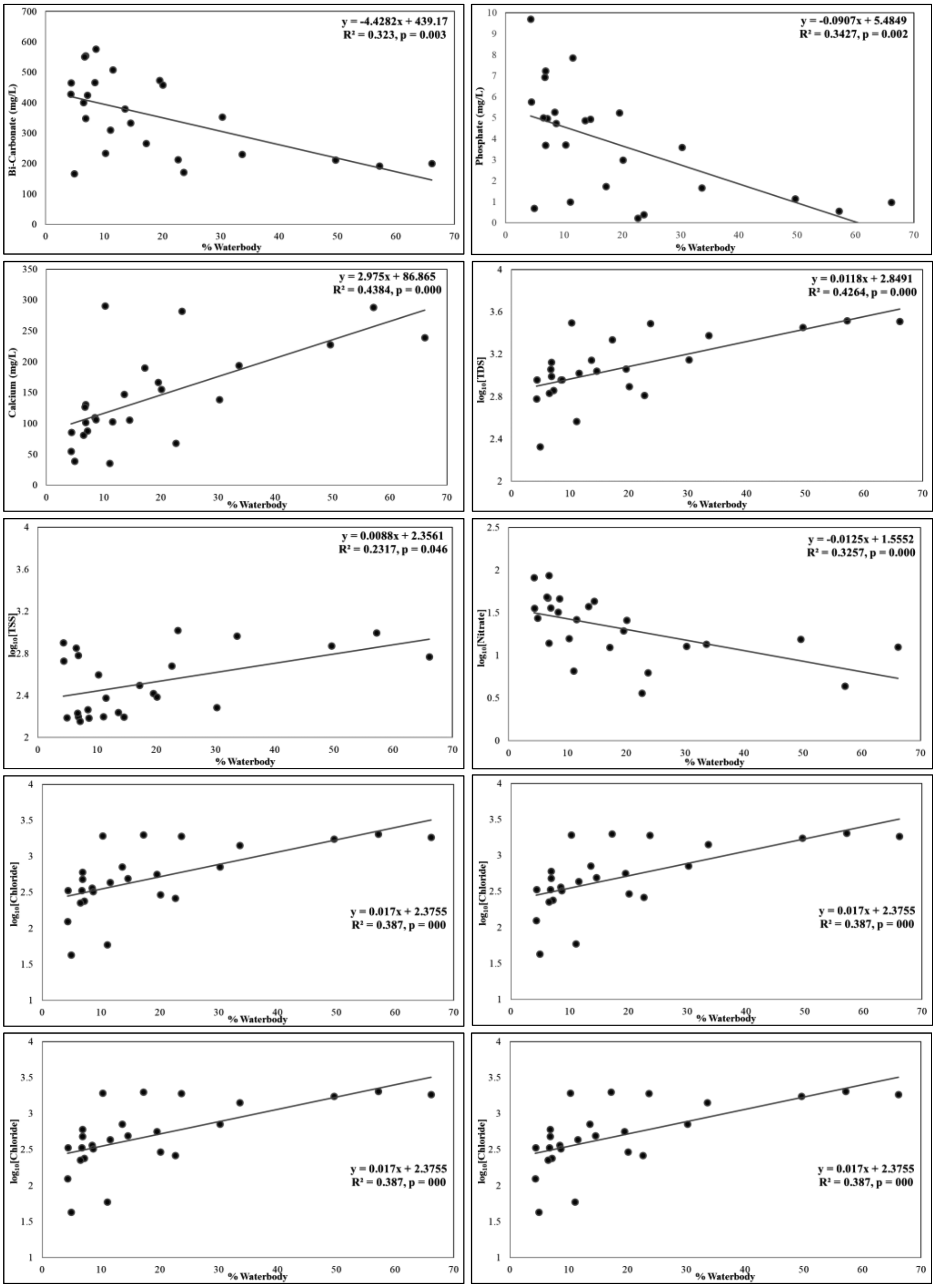

Figure 3.6: Scatter plot between percentage of waterbody within 500m buffer and correlated water quality parameters

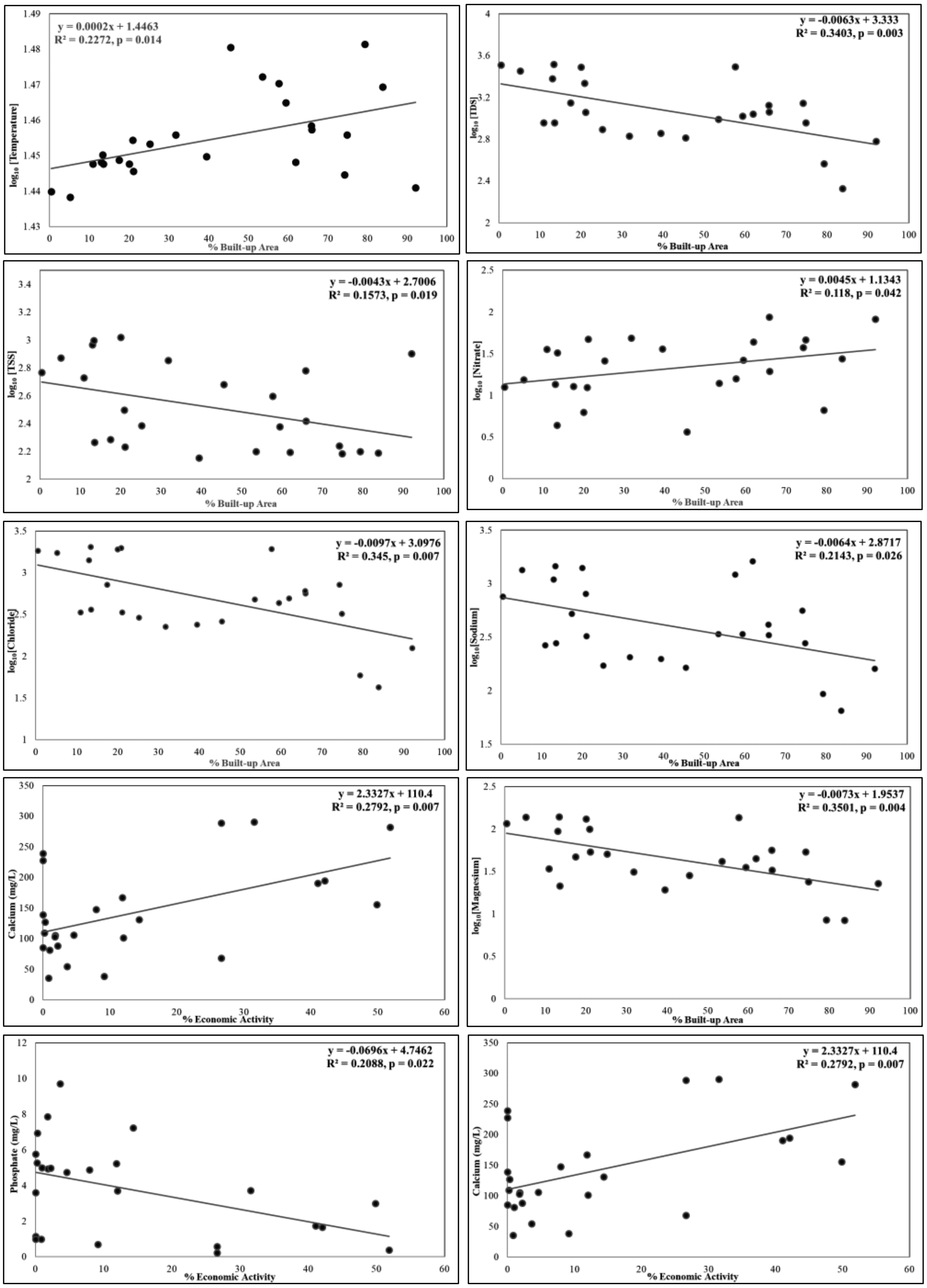

Figure 3.7: Scatter plot between percentage of built-up area and economic activity and correlated water quality

The spatial variation in water quality parameters in response to the change in the percentage of land-use can be explained through the scatter plot and simple linear bivariate regression. Figure 3.6 shows that the change in %WB explains 32%, 34%, 44%, 43%, 23%, 33%, 39%, 22%, 31% and 39% of the spatial variance of HCO_3^-, PO_4^{3-}, Ca^{2+}, TDS, TSS, NO_3^-, Cl^-, K^+, Na^{2+} and Mg^{2+} ($p=0.000$ to $p<0.05$). Figure 3.7 shows that change in %BA explains the spatial variance ($p = 0.000$ to $p<0.05$) of water temperature, TDS, Cl^-, Na^{2+}, Mg^{2+} and Ca^{2+}, with 22%, 34%, 35%, 21%, 35% and 27%, respectively and change in %EA explains 21% and 28% of the spatial variances of PO_4^{3-} and Ca^{2+} respectively ($p = 0.000$ to $p<0.05$).

3.3.3 Water quality evaluation for indirect reuse in agriculture

Irrigation water quality may differ greatly depending on the quantity and type of salt present in the water and this salt profile is a convenient indicator to evaluate the quality of the water for its suitability for irrigation (Ayers and Westcot, 1985; Bauder et al., 2014). The FAO guideline identified water quality-related problems in irrigated agriculture is associated with salinity, water infiltration rate, specific ion toxicity and miscellaneous (NO_3^-, HCO_3^-, pH) ion contributions. Evaluation of water quality based on these factors may vary depending on soil type, geographic location and type of crop but is very useful for effective interpretation (Ayers and Westcot, 1985).

Table 3.8 presents the evaluation of water quality in the study area using FAO guideline values for the degree of restriction in use with the study area: under “no restriction” no cropping or soil-related problems are expected, under “moderate restriction” careful crop selection and alternative management is required to achieve full yield and under “severe restriction” problems associated to soil performance and strong limitations to crops are expected (Ayers and Westcot, 1985). Based on the following table, it can be observed that water quality remains under moderate to severe throughout the year. Even during monsoon season, water quality remains under moderate restriction. Rainfall inducing low salinity creates excessive runoff placing some sources to be affected by high TSS, triggering potential severe reductions for the rate of infiltration during irrigation use. Even though the water use is moderately restricted during the monsoon, it is not expected to have any significant effect on irrigation. The crops that are cultivated in the coastal areas of Bangladesh during the monsoon season are entirely rainfed and do not require external irrigation (Mondol et al., 2018; Shammi et al., 2014; Shelley et al., 2016).

Table 3.8: Comparison of water quality parameter in the study area with FAO irrigation water quality guideline

Param -eter[6]	Observed value (mean±sd) in the study area (n=25 in each season)					
	Winter	**Restriction**	**Summer**	**Restriction**	**Monsoon**	**Restriction**
EC_W or	2.0±1.1	Moderate	5.8±5.6	Severe	1.0±0.7	Moderate
TDS	987±529	Moderate	2884.9±2803	Severe	500±331	Moderate
Na^+	6.83±0.5	Moderate	14.14±2.92	Severe	3.69±0.46	Moderate
Cl^-	485±327	Severe	1685.1±1931	Severe	163±162.1	Moderate
NO_3^-	5.8±2.9	Moderate	43.7±31.1	Severe	36.1±52	Severe
HCO_3^-	430±168	Moderate	380.8±150.5	Moderate	133.8±41	Moderate
pH	6.8±0.2	None	7.3±0.4	None	7.2±0.3	None

Nevertheless, looking into the spatial distribution will give ideas for determining the areas with urban water sources suitable for irrigation. Overlaying interpolated maps using the parameters prescribed by FAO shows the spatial distribution of restriction on use for irrigation. The overall degrees of restriction of water use in the three different seasons. During summer approximately 1/3rd of the area (the northern and south-western part of the city) falls under a severe degree of restriction area for using water from those areas (Figure 3.8). That water poses a severe threat to the crops in cultivation and also to the functioning of the soil due to the exchange of sodium with calcium, magnesium and other multi-valiant cations creating strongly swelling clays with strongly reduced infiltration rates (Ayers and Westcot, 1985; Bauder et al., 2014). During winter and monsoon (in the southern part of the city), water quality will improve compared to the summer season but still will not meet the adequate quality standard partly because of the influence of nearby rivers on water quality in the area. Due to the lack of available water resources, farmers are currently using urban water sources with poor quality for irrigation (indicated by the severe or moderate degree of restriction). This current practice is expected to have an adverse effect on soil health and food production in the study area. Future planning measures should focus on improving the surface water quality to enable it for reuse in agriculture.

[6] *All the values presented in the table are in mg/L except for Sodium (which is indicated as SAR)*

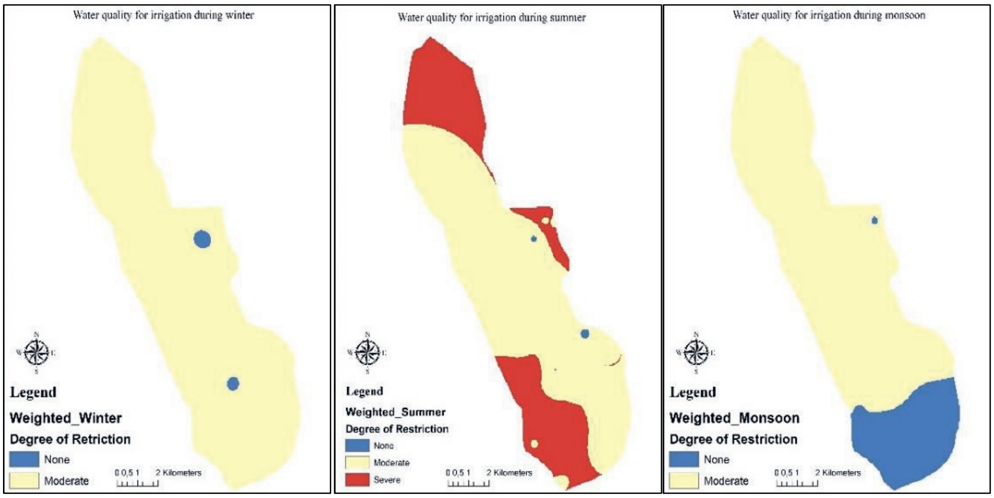

Figure 3.8: Degree of restriction of water use for irrigation in winter (left), summer (middle) and monsoon (right)

3.4 Conclusion

In urban delta areas, people are increasingly concentrating every day on extending and new agglomerations and their demand for resources, especially water and food, is correspondingly growing. Saltwater intrusion is already threatening the existing available freshwater sources for irrigation in the delta areas, in Bangladesh and worldwide. Alternative irrigation sources with adequate quality for agriculture are increasingly needed to sustain current and future food production in these climate change-affected delta areas. Urban wastewater has the potential to provide such a freshwater resource for irrigation if quality and utilization are properly managed. For this, a spatial and time inclusive information system is needed on water quality in such Delta's and this research aims to provide the basic elements for that.

In this study, we provide a method that gives insights in spatial and seasonal dependent variations in water quality, the significance of these variations and the interdependencies among water quality parameters. From this, the usefulness and restrictions of water sources for irrigation can be deduced and visualized. Also, we can differentiate by this method between the influence of saltwater carried by rivers to water resources in the adjacent areas and the effects on water quality by anthropogenic activities. The information mapped by using this procedure gives a solid basis for land use planning and water management in the service of providing high-quality irrigation water. In this way, targeted and effective management actions become possible such as planned urbanization, maintaining green spaces, restricting direct discharge and enforcing the proper treatment of urban wastewater. Also, infrastructural measures can be taken to prevent saltwater intrusion in existing water resources.

We have used chemical-physical parameters of the FAO guideline to identify the usefulness or restrictions for water resources for irrigation use. Although salinity-related water quality is of utmost importance, other aspects, especially related to urban wastewater as a resource, are also important and it would be interesting to combine more parameters to understand the suitability of water for irrigation. For instance, the concentrations of pathogenic microorganisms, micropollutants such as pharmaceuticals, pesticides, industrial chemicals and heavy metals, also need to be taken into account to provide a complete evaluation on the suitability of urban water for reuse in irrigation agriculture and this will be the focus of our future studies.

Chapter 4

Microbial and heavy metal contamination in surface water and potential health risks

Abstract:

Ensuring safe irrigation practice is vital to sustaining food production in water-scarce delta areas. Bangladesh and many other developing countries discharge untreated wastewater into their surrounding surface water bodies, which serves subsequently as the primary source of irrigation. This indirect irrigation of wastewater is believed to pose threats to the farmers, consumers and market vendors and may also affect crop and soil quality. To assess the risk, peri-urban farmers who use surrounding water bodies of Khulna city, Bangladesh, for crop irrigation were chosen as a case. The microbial and heavy metal concentrations were measured over different seasons in water samples collected from various locations. For heavy metals As, Co, Ni, Cd, Cr, Cu and Pb, concentrations were below the detection limit, whereas Al, Fe, Mn, Ti and Zn were present but below the FAO recommendation limit for safe irrigation. The mean seasonal concentrations of microbial parameters were above the thresholds of WHO guideline for crop irrigation intended for human consumption. Significant temporal variations in Faecal Coliform, E. coli and Enterococcus concentrations in the water samples were observed. The annual risk of infection for farmers was determined using the screening-level Quantitative Microbial Risk Assessment (QMRA). The results indicated that the annual probability of infection with pathogenic E. coli in different seasons ranges between 2×10^{-3} to 1×10^{-1}, above the WHO's acceptable threshold for annual risk of infection for safe water reuse in agriculture ($<10^{-4}$). During the farmers' survey, around 45% reported health-related issues while more than 26% reported suffering from water-borne diseases after getting in contact with polluted surface water which illustrates the actuality of the risks in practice. To ensure safe irrigation the health risks need to be reduced below the acceptable limits. Suggested technical measures include adequate treatment of wastewater before disposal into rivers and provision of access to protective equipment for farmers. This should be complimented with raising awareness through education programs among farmers to reduce accidental ingestion.

Keywords: Pathogenic indicators, heavy-metals, indirect irrigation, health risks, farmers

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4.1 Introduction

The growing water demands associated with the rising populations, climate change are aggravating the global water scarcity (Mekonnen and Hoekstra, 2016). The urbanizing delta's such as Bengal delta is also severely confronted with freshwater scarcity (Murshed and Kaluarachchi, 2018). Current water resource management practices in urban areas are in most situations is linear and waste valuable resources such as water and nutrients. Though some countries have close to 100% coverage of collecting and treating urban wastewaters, globally, around 63% of the total wastewater generated is collected and 48% is discharged without any treatment, which deteriorates the surface water quality in many countries (Jones et al., 2021; Kookana et al., 2020). Urban water reuse has been practiced globally, to make this water reusable for irrigation to mitigate the impact of freshwater scarcity on food production.

The use of wastewater for irrigation gained attention worldwide during the last decade of the twentieth century because of the growing demands for irrigation water supply but the concerns associated with health effects to farmers and consumers also have been raised (Jaramillo and Restrepo, 2017). For decades, farmers in Jordan and Israel have been utilizing wastewater for agricultural production due to the minimal local availability of water resources (Angelakis and Gikas, 2014; Carr et al., 2011). These examples demonstrated good irrigation practices using treated wastewater with minimal health risks. But these practices are not yet applied in many regions of the world. The use of untreated wastewater as irrigation water can negatively impact human health and the quality of the environment (including soils) and crops. Wastewater generally contains excreta-related pathogens (bacteria, viruses, protozoa and helminths) and often toxic chemicals, such as heavy metals and micropollutants (pesticides, household chemicals, pharmaceutical residues) (Drechsel et al., 2010a; Gross et al., 2015; Jiménez and Asano, 2008; Mojid and Wyseure, 2013). Especially in developing countries, untreated wastewater is discharged into the natural surface water streams that are a major source of irrigation water for crop production and as a results, farmers and consumers are regularly exposed to unknown chemical and biological pollution.

To minimize health risks due to the increasing unplanned and indirect wastewater irrigation practices, several risk assessments such as sanitary inspection, risk matrix, QMRA and risk mitigation frameworks such as Stockholm framework, sanitation safety planning, multiple-barrier approach have been drafted and used (WHO, 2006). Below these approaches are briefly discussed. Sanitary inspection is an on-site visual evaluation tool, whereas the risk matrix approach provides a semi-quantitative and qualitative evaluation of the likelihood of a hazardous event. QMRA is the formal WHO-approved quantitative risk assessment approach that integrates the scientific knowledge on infectious effects of pathogens present in the water (WHO, 2016). QMRA is a tool used for predicting the risk of infection or illness rates of humans exposed to pathogens, using ingestion probability estimations and dose-response models for a given population (Ferrer et al., 2012; Haas et al., 1999). The numerical outcomes of QMRA bring more specific insights useful for risk management than other methods such as sanitary inspection and risk matrix (WHO, 2016). Though less sensitive, QMRA is less costly and less time-consuming than epidemiological studies and therefore a preferred method often applied (Ferrer et al., 2012). However, QMRA is a standardized model applicable to a limited range of pathogens and not yet to the full range of pathogens actually present in wastewater, restricting its wider use for risk assessment (Hamilton and Haas, 2016). In risk mitigation, The Stockholm framework is used to improve the health-related guideline and standards through a coherent system (WHO, 2006). Similarly, the multiple barrier approach is such a risk mitigation framework that combines technical and non-technical strategies for risk mitigation and complements the sub-optimal wastewater treatment, which is seen as the best possible approach to reduce risks (Bos et al., 2010; Keraita et al., 2008; WHO, 2006). The approach stretches from wastewater generation to consumption of irrigated crops (farm to fork) and vital for strategizing safe water reuse practices. This is crucial, especially for many urbanized deltas in developing and emerging economies where untreated urban wastewaters are regularly dumped in rivers flowing to the sea, while the very same water is also needed for irrigation to combat with rising salinization.

Khulna: the 3rd largest city of Bangladesh, has been taken as an example to assess the health risks (to later define risk mitigation) of the irrigation practices in urbanized deltas. Presence of elevated levels of pathogen in surface water bodies due to anthropogenic activities have been reported in the coastal region of Bangladesh (Islam et al., 2018a, 2018b, 2017). Peri-urban agriculture in deltas contributes to regional food production and surface water is the primary irrigation. Peri-urban farmers around the country have reported having skin irritation, skin itchiness in the hands and legs while working with the surface water (Mojid et al., 2010). These effects are suspected to be related to untreated wastewater discharge in surface waters. Aside from skin contact, there is also a high probability that farmers and their family members contact the wastewater pollutants through ingestion or aerosols inhalation (An et al., 2007). Several studies focused on assessing health risks associated with river bathing or urban flooding; however, risk assessment related to indirect wastewater irrigation is scarce (Islam and Islam, 2020; Mark et al., 2018). Thus, there is a need to investigate the actual wastewater-related pollutant concentrations in surface waters and link these to actual risks for farmers as a base to design adequate risk mitigation measures. Faecal indicator bacteria (FIB) are widely used to understand the presence of pathogenic microorganisms in water (WHO, 2002). E. coli, faecal coliforms and faecal streptococci (with enterococci as subgroup) are commonly used as FIB (Islam et al., 2017). FIB could be used in assessing potential health risks and formulating risk mitigation strategies (Islam et al., 2017; Maimon et al., 2010; Teklehaimanot et al., 2014; Wu et al., 2011).

The first step in any set of measures to mitigate risks due to direct or indirect use of wastewater for irrigation is assessing the risks associated with pathogens, heavy metals and other (organic) chemical pollutants. In this study, the first steps of pollutant characterization were chosen based on local laboratory capacities and availabilities and therefore on selected microbial pathogens as indicators for domestic wastewater pollution and a suite of heavy metals as an indicator of industrial pollution, leaving inclusion of organic chemical pollutants for future research. Thus, in this chapter, the microbial and heavy metal contamination in surface water was evaluated and potential health risk for farmers was assessed assuming continuous exposure to pollutants in wastewater indirectly used for irrigation. Additionally, the risk perception of farmers towards the current irrigation practice was analyzed to address the required management strategies (technical and non-technical measures) to reduce the risk of infection among peri-urban farmers.

4.2 Methodology

4.2.1 Study area and sampling

Khulna City is positioned on the banks of rivers Rupsha and Bhairab, with the tributary Mayur river as the primary source for irrigation for peri-urban farmers, especially during the dry period (November – April) (Figure 4.1). To evaluate the prevailing water quality, samples were collected from 20 sampling points localized in different surface water bodies in and around the city in winter (November to February), summer (March to June) and monsoon (July to October) seasons.

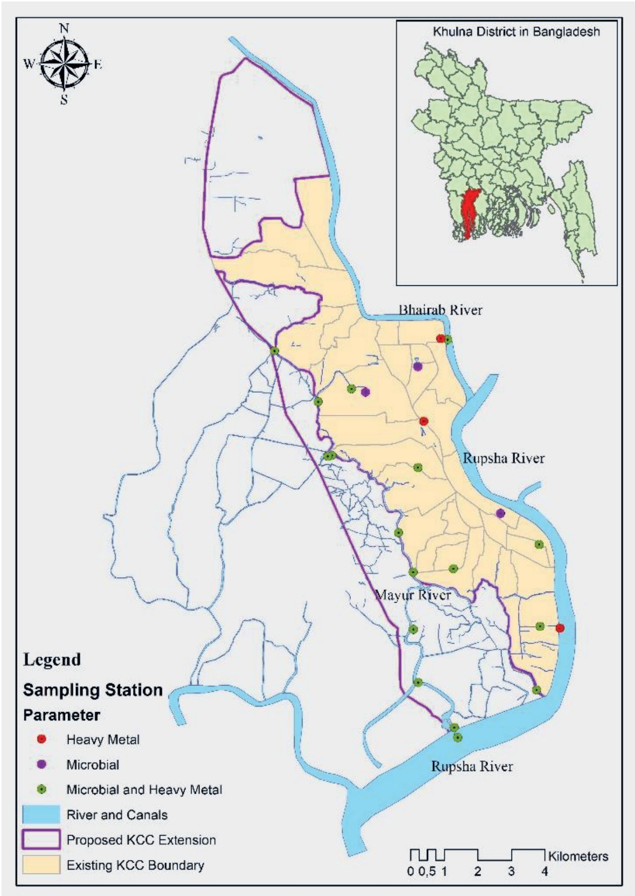

Figure 4.1: Locations for collecting water samples

Sampling points cover the various sources of irrigation, i.e., rivers, canals/drains, lakes and ponds *(supplementary materials: Table xii)*. Canals and drains receive domestic wastewater directly from households and discharge to the surrounding rivers. Small lakes and urban ponds (too small to be made visible in Figure 4.1) are used by a small part of the population for bathing, washing and fishing and generally do not connect with the rivers or canals, except in case of floods. Sampling points were also selected considering the land use pattern of the city. For example, the eastern part of the city accommodates several small and medium-sized industries and thus, samples from the east were primarily selected for heavy metal analysis. Similarly, samples for microbial analysis were collected mainly from the western part, especially from the areas where farmers were extracting irrigation water. Sample collection for winter, summer and monsoon seasons occurred respectively in January, April and August 2018 and in each season, a total of 40 samples (20 each for microbial and heavy metal analysis) were collected.

4.2.2 Laboratory analysis

Microbial assessment samples were collected in sterilized glass bottles to estimate the concentrations of Total coliform (TC), Faecal coliform (FC), E. coli and Enterococcus using the standard Membrane Filtration (MF) method number 9222 and 9230 as explained in literature (APHA/AWWA/WEF, 2012). Membrane filters (0.45µm pore size, Sartorius RC White-sterile brand) were used to filter the samples that were used to inoculate agar plates in various dilution series. The plates were prepared from different agar media and after inoculation Petri dishes were incubated (35°C for 24h for TC, 44°C for 24h for FC, 44.5°C for 24h for E. coli, 35°C for 48h for Enterococcus). After incubation, colonies formed were counted and back-calculated in colony-forming units per 100 ml (cfu/100ml). Following the analysis geometric mean was used to express the average number of microorganisms in water which was recommended in the literature (APHA/AWWA/WEF, 2012; Haas, 1996). Related necessary chemical-physical water quality information was used based on the previous study carried out in the same sampling locations of the study area (Haldar et al., 2020).

For determining heavy metal contamination, the samples were collected in standard PPT bottles and transported to the laboratory. First, the samples were filtered with filter paper (Whatman No. 41) and 1 ml HNO_3 (65%) per 100 ml was added to the samples to reduce the pH level for preservation. Then the samples were homogenized and directly measured with the ICP-OES AVIO 500 machine from PerkinElmer. The determination of aluminium (Al), arsenic (As), cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), iron (Fe), lead (Pb), manganese (Mn), nickel (Ni), titanium (Ti) and zinc (Zn) in the water samples were conducted following the standard method number 3120 (APHA/AWWA/WEF, 2012). Arithmetic mean was used to express the average concentration of heavy metal in collected water samples. MS Excel and IBM SPSS 25.0 were used to perform necessary statistical analysis (descriptive statistics, ANOVA, correlation analysis) at 95% confidence interval and produce graphical illustrations (graphs, scatter plots). ArcGIS 10.6 was used to generate maps based on the spatial information of the study area collected from the local municipal agencies.

4.2.3 Quantitative Microbial Risk Assessment (QMRA)

In the early 1990s, QMRA was first proposed for water safety management (Regli et al., 1991; WHO, 2016). Since then, QMRA has been used to estimate risk levels for different water usage such as drinking water, recreational water, wastewater irrigation (WHO, 2016). In general, QMRA predicts risk based on exposure to one type of pathogen at a given time (Drechsel et al., 2010a). Based on the general characteristics, QMRA can have three different levels: screening, advanced and in-depth level and includes four steps for water-related risk assessment: hazard identification, exposure assessment, health effects assessment and risk characterization (Abrahams et al., 2004; Haas et al., 1999; WHO, 2016). Screening provides a quick, low-cost overview on the level of risk, whereas advanced and in-depth level risk assessment offers more detailed and comprehensive information on risks but requires higher cost and time involvement (WHO, 2016).

The selection of appropriate levels and steps of QMRA depends on the overall aim of risk assessment (WHO, 2016). This study aimed to highlight the concerns associated with the current irrigation practice and thus, an initial screening-level risk assessment was performed using a deterministic model with point estimates of pathogen concentrations. Theoretically superior and accurate to the deterministic model, is a stochastic model, which accounts for the uncertainty over model elements; however, the model is complex and require previously obtained knowledge on probability distributions and the use of Monte Carlo simulation (Hamilton and Stagnitti, 2008). Using a simple deterministic model also provide insights which could be useful in identifying the potential errors for a complex stochastic models (Zwietering, 2009). As the necessary knowledge on variability and uncertainty over model inputs to quantify the risks was not available, this study oriented on determining initial screening-levels of risks, using single-point pathogen concentration estimates (WHO, 2016). This is the first step in risk assessment and can be followed (not done in this study) by a more quantitative assessment, eventually delivering risk results expressed in Disability Adjusted Life Years (DALYs). But this requires much more detailed knowledge on probabilities of infection and illness and variability herein and needs to be accompanied with uncertainty analyses based on Monte Carlo modeling techniques and was beyond the scope of this study.

Hazard Identification

As the first step in QMRA, hazard identification was performed to define the investigation's scope and purpose and formulate specific risk problems (WHO, 2016).

The local context and socio-cultural aspect of the situation were considered to select the particular pathogenic indicators and the relevant exposure pathways as done in literature (Ferrer et al., 2012). Pathogenic bacteria such as E. coli O157:H7, Salmonella Typhimurium, Shigella dysenteries and Vibrio Cholerae in water sources are associated with the major causes of diarrheal diseases and gastrointestinal infections worldwide (Momba et al., 2006; Teklehaimanot et al., 2014). In the study area, the presence of FIB, especially E. coli and Enterococcus, in the surface water is mentioned in previous studies (Islam et al., 2018b; Islam and Islam, 2020). Thus, in this study, the probability of infection is modeled assuming a fraction of the total counted E. coli being E. coli O157:H7. Also, in literature, no indications are given on the value of this ratio, hence a ratio of 1:0.08 for E. coli:E. coli O157:H7 was used based on literature (Haas et al., 1999; Machdar et al., 2013) to assume the concentration of E. coli O157:H7 as this specific variant could not be detected in the local laboratory. Absence of research infrastructure in developing countries have been identified as a major challenge for an in-depth QMRA (Dias et al., 2019; Islam and Islam, 2020). This study focuses on the peri-urban farmers surrounding Khulna city who are indirectly using urban wastewater for irrigation and levels of human and animal fecal pathogen-related bacteria, such as E. coli was selected as microbial parameters.

Exposure Assessment

In exposure assessment, the frequency and magnitude of exposure to pathogens through different pathways were estimated (WHO, 2016). Exposure quantitatively indicates the pathogen's dose that a host ingests, inhales, or gets in contact with and is often identified as a route from the pathogen source (e.g. presence in the water) to the actual exposure event (e.g. accidental ingestion) (Haas et al., 1999). This study focused on the oral route of accidental surface water ingestion by farmers while working in the field. Wastewater that enters the surface water body without any treatment typically contains remnants of human excreta. Similarly, domestic and non-domestic animals grazing in the surrounding areas also excrete into the environment and the microbial pollutants in part reach surface water bodies through surface runoff. Farmers pump surface water to their agricultural fields and move around the field with bare feet. They contact the surface water containing pathogens or accidentally ingest the polluted irrigated water (Figure 4.2).

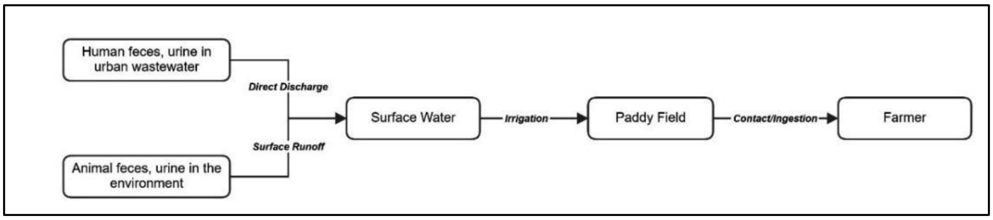

Figure 4.2: Exposure route of accidental ingestion of wastewater

The exposure dose (cfu) per event was calculated using the following formula:

$$\text{Dose} = C \times q \qquad (4.1)$$

Where, C is the concentration of pathogens in the surface water (cfu/ml) and q is the volume of accidental irrigation water ingestion by farmers (ml).
Studies suggest that farmer's accidental ingestion of irrigation water ranges from 1-5 ml/event and a median value of 3 ml/event was used and single event per day spent in the field was assumed for the simulation purpose (Moazeni et al., 2017; Symonds et al., 2014).

Health effect assessment and risk characterization

The health impact data for the identified hazards and the specific study population was assessed using a dose-response model in health impact assessment (WHO, 2016). The dose-response model is a mathematical relationship between the dose of pathogen taken up by the receptor (farmer) through various routes (direct ingestion, inhalation or contact) and the probability of response (a form of infection, illness or death) (Haas et al., 1999). In this study, ingestion was assumed to be the main route because study indicated that farmers work in the field without any protection which enhances the chance for accidental ingestion (Mojid et al., 2010). In general, two types of models are being used to assess the dose-repose relation: the exponential model and the Beta-Poisson model (WHO, 2016). The exponential model assumes that the probability of infection can be shown as a function of ingested dose and Beta-Poisson is characterized by a median infectious dose and a slope parameter (Haas et al., 1999). In this study, for pathogenic microorganisms, the Beta-Poisson model is more appropriate and thus used due to the distribution of microbes in the environment and the interaction with the target population (Ferrer et al., 2012; Haas et al., 1999).

The probability of daily infection from a specific pathogenic microorganism was calculated using the following formula:

$$P_{i(d)} = 1 - \left[1 + Dose\,\frac{2^{\frac{1}{\alpha}} - 1}{N_{50}}\right]^{-\alpha} \qquad (4.2)$$

Where, $P_{i(d)}$ is the daily probability of infection from specific pathogen i, N_{50} is the number of pathogens infecting 50% of the exposed population and α is the kinetic parameter (constant).

The annual probability of infection was calculated using the following formula:

$$P_{i(A)} = 1 - [1 - P_{i(d)}]^{n} \qquad (4.3)$$

Where, $P_{i(A)}$ is the annual probability of infection by ingesting pathogens and n is the exposed duration (days/year).

Literature indicates that farmers are exposed 50-80 days while irrigating field, however, a default value of 75 days/year was used as exposure days for simulating the annual risk of infection (WHO, 2006). For seasonal risk of infection, the exposure days were determined based on the farmer's survey and other related information such as kinetic parameter α, a dose resulting in 50% infection, were also based on literature and presented in the following table (Table 4.1).

Table 4.1: Values used for QMRA simulation

Parameter	**Unit**	**E. coli O157:H7**	**Reference**
Geometric mean concentration (C)	cfu/ml	Winter: 1.5×10^{1} Summer: 8.3×10^{1} Monsoon: 6.3×10^{1} Overall: 4.3×10^{1}	(Haas et al., 1999; Machdar et al., 2013) and this study
Kinetic parameter (α)	-	0.49	(Amha et al., 2015; Gibney et al., 2014; Haas et al., 2000, 1999)
Dose resulting 50% infection (N_{50})	-	5.96×10^{5}	
Volume of ingestion (q)	ml	1-5; Median: 3	(Moazeni et al., 2017; Symonds et al., 2014)
Exposed days (n)	days/year	50-80 (WHO default value 75)	(Moazeni et al., 2017; Symonds et al., 2014; WHO, 2006)
	days/season	22	This study

4.2.4 Farmer's survey

A structured questionnaire was developed, pre-tested and deployed to understand health-related issues of the farmers who use surface water for irrigation and in total, 38 peri-urban farmers were surveyed in 2018. Demographic information of the surveyed farmers is in the supplementary materials (*Table xv*). The questionnaire included questions on crops' health and yield, irrigation and fertilizer practices, perception towards water quality, experienced health-related problems, use of protective equipment during irrigation practices and risk perception. In addition, farmers were asked to rate their risk perception on various issues related to current irrigation practice on a scale of 1 to 5 where 1 means low-risk perception and 5 means high-risk perception. Responses were recorded in an online-offline platform (Kobo Toolbox), including their GPS locations. Farmers were selected randomly among whose farm was in the proximity of the Mayur river and had a higher chance of regularly exposing themselves to the water from indirect wastewater irrigation.

4.3 Results and Discussion

4.3.1 Microbial quality of water

Laboratory analysis provided information into concentration levels of TC, FC, E. coli and Enterococcus in the study area's surface water bodies (Figure 4.3). The count of TC exceeded the local standards (<1000 cfu/100ml) for inland surface water usable for irrigation for all sampling points around the year (GoB, 2002). The mean concentration of TC was the highest during summer (9×10^5 cfu/100ml) and lowest in the winter (6×10^5 cfu/100ml). Similarly, the mean concentration of FC (in cfu/100ml) was high during summer and monsoon (2×10^5) compared to winter (3×10^4). The mean E. coli concentration (in cfu/100ml) was also lower during winter (2×10^4) than in summer and monsoon i.e., 1×10^5 and 8×10^4, respectively (supplementary materials: Table xvi). Several previous studies indicated the elevated level of FC and E. coli during summer and monsoon in other areas of Bangladesh (Islam et al., 2011, 2017; Kostyla et al., 2015; Zabed et al., 2014). However, the concentration of enterococcus was lower during summer (4×10^3 cfu/100ml) compared to monsoon season (2×10^4 cfu/100ml). The presence of light accelerates the decay of enterococcus which may be linked with the lower concentration during summer compared to monsoon season (Bordalo et al., 2002).

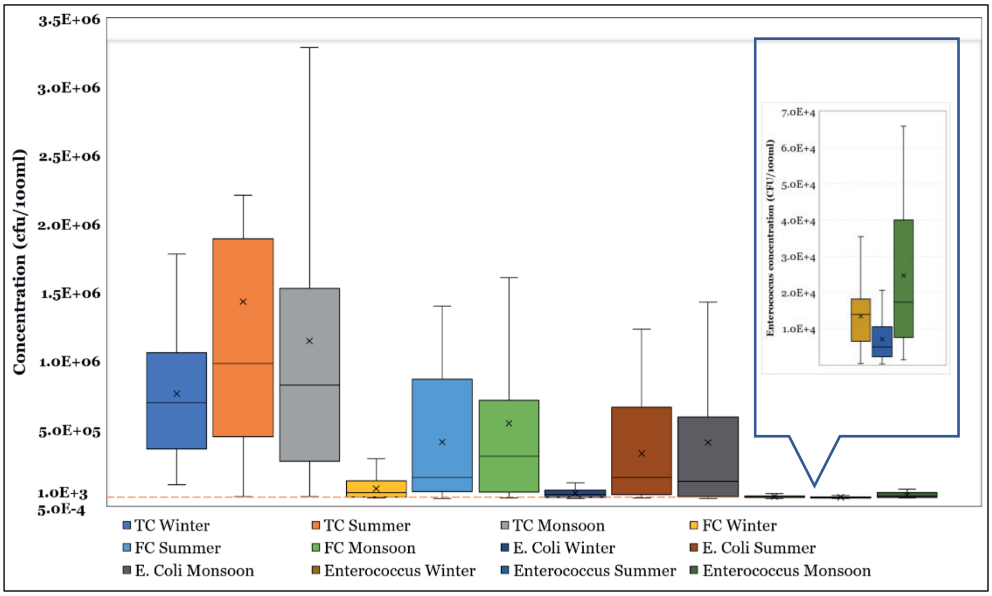

Figure 4.3: Concentrations of TC, FC, E. coli and Enterococcus in the surface water (red dotted line indicates the allowable threshold for coliforms in WHO and local standards)

Correlation analysis indicates that water temperature had a significant positive influence on FC ($P<0.01$) and E. coli ($P<0.05$) concentrations (Figure 4.4). Similarly, a positive correlation between water temperature and TC was found, but it was not statistically significant. The climatic data in last two decades indicates that the region had an average maximum atmospheric temperature between 32 °C and 36 °C from April to October and warm climate may have favored the growth of FC and E. coli in surface waters resulting in higher concentrations (Barcina et al., 1986; Dey et al., 2017; Haque et al., 2019; Islam et al., 2017; Jang et al., 2017; Vermeulen and Hofstra, 2014). Similarly, ANOVA indicates the significant seasonal variation ($P<0.05$) in FC, E. coli and Enterococcus concentrations except for TC. Heavy rainfall contributes to the higher dilution and excessive runoff during the monsoon season from nearby built-up areas where septic tanks, domestic animal sheds and wet markets are common. The variation was highest during monsoon for all microbial indicators, which is most likely related to heterogeneous contributions of pollution sources and dilution by run-off waters. The presence of grazing cattle, wet markets, runoff from septic tanks and the dumping of untreated wastewater most likely all contribute to the high and varying concentrations of FIB in the surface waters also found by other authors (Ekklesia et al., 2015; Falardeau et al., 2017; Islam et al., 2018b; Myers and Kane, 2011; Ramos et al., 2006).

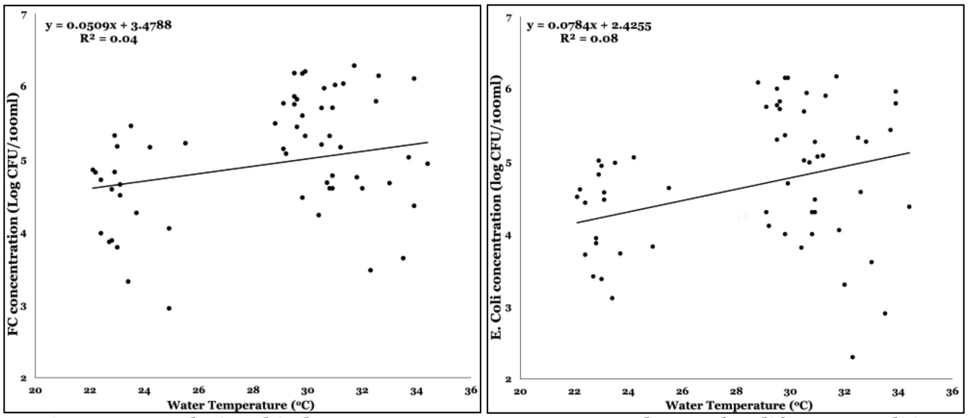

Figure 4.4: Relationship between water temperature and Faecal Coliform, E. coli in surface water

The standard deviation of pathogen concentrations indicates the very high concentration variability among sources which is further validated using statistical analysis. ANOVA shows the significant ($P<0.05$) spatial variation in TC, FC, E. coli concentrations among different sources in the study area (supplementary materials: Table xvii). The overall mean concertation of TC for canal/drains was 1×10^6 cfu/100ml, whereas for the river, the concentration was 6×10^5 cfu/100ml and the concentration was highest during summer. The canals and drains occasionally receive effluents from the septic tanks via leakage or illegal dumping, whereas wastewater or runoff gets diluted with the river water and the tidal effect contributes to the movement of water, which may have an impact on the variability of the concentration over different sources.

FC and E. coli concentrations in all the sampling stations also exceeded the WHO guideline (≤1000 cfu/100ml) for unrestricted use in agriculture, except for an urban pond owned by the local municipal authority. The pond is not open for regular activities and is occasionally treated with bleaching powder. The application of chlorinated lime or bleaching powder (calcium hypochlorite) can reduce (around 60%) the fecal contamination in water sources (Roy et al., 2016; Sirajul Islam et al., 2007). Two other urban ponds that were not under the municipal authority were used extensively by the local population for domestic activities, such as bathing and washing and had several folds higher TC and FC concentrations than the WHO threshold. Bathing in such microbially polluted waterbodies could lead to severe illness and increase infection chances, especially among children (Islam and Islam, 2020). Overall, the pathogen concentrations exceed the current national and international guidelines for using surface water for irrigation and daily activities, thus posing a health risk for the user groups.

4.3.2 Heavy and other metal concentration

Heavy metal analysis indicates that only Al, Fe, Mn, Ti and Zn were detected in the surface water and all, except Mn, had significant ($P<0.05$) seasonal variations. However, all measured concentrations were below the FAO recommended limit for agricultural use (Table 4.2). The Mn concentration in surface water was near the FAO maximum allowable limit for safe irrigation (0.2 mg/L). Prevailing sources such as untreated dumping of wastewater could lead to the presence of manganese in the surface water (Metcalf & Eddy, 2013). The coastal districts of Bangladesh have manganese (Mn) concentrations beyond the national (BDS) and international (WHO) drinking water guidelines, which could also contribute to the Mn concertation in surface water (Rahman et al., 2021). Fe's concentration increases five-fold (from 0.26 mg/L to 1.37 mg/L) during monsoon compared to winter and Al concentration increases drastically (from 0.12 mg/L in winter to 1.41 mg/L in monsoon) due to the excessive runoff during that period (Bhardwaj et al., 2017; Measures et al., 2005).

The concentration of As, Co, Ni, Cd, Cr, Cu and Pb in the collected water samples was below the detection limits, which can be explained by the declining presence of traditional heavy mills and industries (jute, garments, cable) in the area (Rahman and Kabir, 2019) and prevalence of manufacturing SME's in categories like agro-processing, bakery, light engineering, timber and furniture. Several studies from the other parts of the country where heavy industrial zones (textiles, agro-chemical, dye, paint and ceramics) are present, the concentrations of heavy metals in water, soil and the crops (vegetables) were above the national and international standards (Ahmad and Goni, 2010; Ahmed et al., 2019, 2018). Two apparent reasons could cause a bit deviating situation in the study area i) a relatively low contribution of SME and other enterprises to water pollution or removing pollutants from the surface water resources. In addition to that, during the field survey, the excessive presence of water hyacinths - a fast-growing, free-flowing weed was observed in surface water bodies. Water hyacinth can absorb and remove heavy metals from wastewater through the roots (Ingole and Bhole, 2003; Muramoto and Oki, 1983; Rezania et al., 2015; Zheng et al., 2016). For example, studies show that water hyacinth removed almost 65% of Cr and Cu from wastewater simulated in a wetland-based system (Lissy and Madhu, 2011).

Table 4.2: Heavy metal concentration in the surface water of Khulna

Parameters (mg/L)[1]	**Season (N = 20) (Mean ± Std. Dev.)**			**FAO Recommendation Limit (mg/L)**
	Winter	**Summer**	**Monsoon**	
Aluminium (Al)	0.12±0.09	0.57±1.09	1.41±1.81	5
Iron (Fe)	0.26±0.23	0.62±1.14	1.37±1.41	5
Manganese (Mn)	0.26±0.37	0.18±0.25	0.21±0.25	0.2
Titanium (Ti)	0.05±0	0.06±0.04	0.09±0.06	N/A
Zinc (Zn)	0.67±1.23	0.1±0.03	0.16±0.27	2
Arsenic (As)	*Below the detection level of 0.1 mg/L*			0.1
Cobalt (Co)				0.05
Nickel (Ni)				0.2
Cadmium (Cd)	*Below detection level of 0.01 mg/L*			0.01
Chromium (Cr)				0.1
Copper (Cu)				0.2
Lead (Pb)				5

Similarly, in artificial lake water Cu, Pb, Cd and Zn concentration decreased 24%, 26%, 50% and 57%, respectively, after 8 days of experiment with water hyacinths (Smolyakov, 2012). A similar process might have taken up a portion of heavy metals by the roots of water hyacinths from the surface water bodies resulting in below detection level heavy metal concentrations. Another reason for the lower concentrations of heavy metals in surface water could be the deposition of heavy metal minerals in the riverbank soils and sediment, giving a delayed emission to the water phase due to sorption processes. Studies indicate that the riverbank soil can absorb heavy metals in large quantities of heavy metals even when repeatedly exposed to highly polluted mineral or effluent disposals (Chang et al., 1984; Kumar Sharma et al., 2007; Li et al., 2015; Yang et al., 2018). However, at some point, adsorption saturation would occur and higher emissions levels can then be expected. As the surface water bodies and riverbanks receive wastewater and mineral disposals for decades, the deposition of heavy metals in the riverbank soils and river sediments requires further investigation.

[1] *Bold-italic parameter indicates the significant ($P<0.05$) temporal variations*

4.3.3 Risk perception of farmers

Farmer survey indicated that most farmers (95%) have been using surface water sources, especially the Mayur river and close by canals, as their primary source of irrigation for decades. Most of them (63%) understand their irrigation source regularly receives domestic wastewater from adjacent urban areas and mentioned the reliance on the existing sources due to lack of alternatives. Most farmers (84%) do not use any protective equipment during irrigation, thus enhances the chance of accidental ingestion. Lack of protective equipment could lead to a higher risk of infection for farmers and their family members (Keraita et al., 2008; Mojid et al., 2010). In addition to accidental ingestion, peri-urban farmers also face other obstacles daily. More than 45% of the farmer reported odor, skin irritation, skin blistering and water-borne diseases like diarrhea after working in the field during irrigation which was also reported in a previous study (Mojid et al., 2010). However, farmers' risk perception towards their current practice indicates that the peri-urban farmers rank health-related issues lower in the list compared to other issues (Figure 4.5).

Farmers rank excessive growth of weeds and pests, which grow due to indirect wastewater irrigation in the field, as a top risk, followed by crop health. Their own health comes third in the list, followed by soil health and the local environment. Prioritizing farming-related issues over health issues is also observed in previous studies and farmers accepted those health risks considering the lack of available irrigation sources and potential economic gains of wastewater use (Adjaye-Gbewonyo, 2008; Drechsel et al., 2010a; Weldesilassie et al., 2011). Studies also indicated that experience in working with wastewater, education level, source of information, socio-economic condition influence the health risk perception among farmers (Drechsel et al., 2010a; Keraita et al., 2008; Obuobie et al., 2006; Weldesilassie et al., 2011). Similarly, in the study area, farmers who have been farming for more than 20 years did not perceive health risk as a major concern. Damage to the pump is the lowest on the list as the pumps are easily repairable and required materials are locally available. As excessive weed growth is common in the study area, farmers use chemical fertilizer to increase the crop yield and control weed growth and pest control in the field.

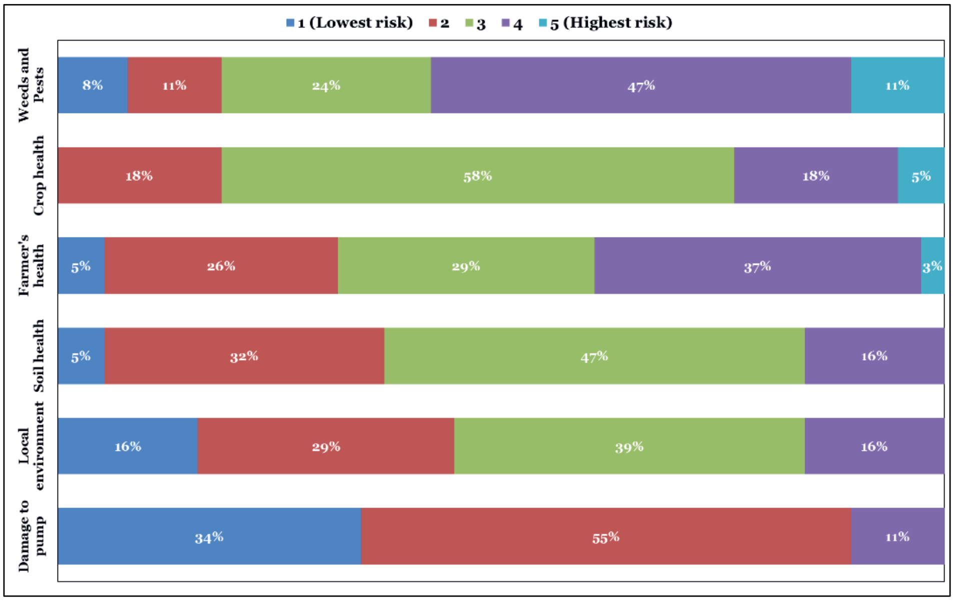

Figure 4.5: Risk perception of farmers of their current irrigation practice

A very small number of farmers (16%) use a cloth to cover their face during field activities, but that is not sufficient to protect them against the polluted surface water. The survey also revealed that lack of information about the usefulness of protective equipment and high cost of protective equipment as the primary reasons for not using necessary protections which is common globally (Drechsel et al., 2008; Lamnisos et al., 2013; Mayilla et al., 2016; Obuobie et al., 2006). Using necessary protective equipment during farming activities is a low priority for their health due to their long-standing irrigation practices without any protection when the water used to be comparatively clean (Mayilla et al., 2016). Farmers also mentioned that they face difficulty in farming activities while wearing protective equipment such as boots or gloves, making it difficult to move and work in the muddy paddy field. However, this should not be a reason for failing to protect farmer's health as this equipment could easily be used for other farming activities such as vegetable or fruit farming. Farmers also mentioned taking basic medicines from local pharmacies and home remedies when they get sick after contacting polluted surface water.

4.3.4 Microbial health risks

The relation between the pathogen concentration and farmer's health risk due to accidental ingestion was simulated through the QMRA model. The model indicates the different infection probabilities in different seasons and is based on various irrigation water sources (Table 4.3). The daily probability of infection is highest in summer (6×10^{-4}) followed by monsoon (5×10^{-4}) and winter (1×10^{-4}). The overall daily probability of infection for a single event is two orders of magnitude higher compared to the recommended limit of $<10^{-6}$ by WHO and similar to other studies from the other parts of the worlds (Amha et al., 2015; Kouamé et al., 2017; Signor and Ashbolt, 2009; WHO, 2016). The infection probability also varies over the sources used for irrigation. The overall daily probability of infection was high for canal/drain (1×10^{-3}) followed by river (2×10^{-4}) and lake/pond (2×10^{-5}) samples. This variation is understandable due to the E. coli concentrations that vary over different sources; rivers and drains have a higher concentration than lakes and ponds.

Table 4.3: Daily probability of infection due to current practice

Source	**Winter**	**Summer**	**Monsoon**	**Overall**
All Samples	1×10^{-4}	6×10^{-4}	5×10^{-4}	3×10^{-4}
River	9×10^{-5}	5×10^{-4}	4×10^{-4}	3×10^{-4}
Canal/Drain	3×10^{-4}	3×10^{-3}	3×10^{-3}	1×10^{-3}
Pond/Lake	2×10^{-5}	3×10^{-5}	1×10^{-5}	2×10^{-5}

Considering the 22 seasonal exposure days, the annual probability of infection in winter is lowest (0.003), whereas the summer (0.014) and monsoon (0.011) have the highest probability (Figure 4.6). However, the annual risk of infection is still much higher than the WHO guideline ($<10^{-4}$) for an acceptable risk limit (Amha et al., 2015; Signor and Ashbolt, 2009; WHO, 2016). Similar to values for the daily probability of infection based on sources, the annual risk of infection (considering WHO default 75 exposure days) is also high for river and canal/drain samples compared to the pond/lake samples. The overall annual risk of infection is highest (0.1) for canal/drain samples, followed by the river (0.02) and lake/pond (0.001) samples. Considering all samples, the overall annual risk of infection is 0.02 which is two orders of magnitude above the acceptable limit. The E. coli concentration was significantly different over sources, thus resulting in a higher annual risk of infection probability for canal-drain than lakes.

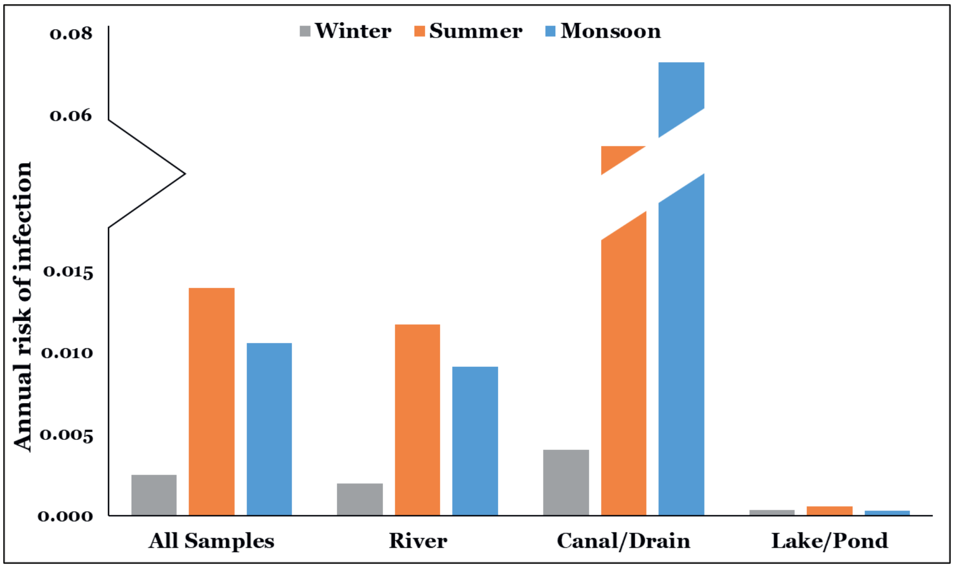

Figure 4.6: Annual risk of infection over different sources for E. coli

Farmers only rely on external irrigation during the dry period, i.e. the whole winter and parts of the summer season; thus, the calculated risks of infection for the monsoon season may not correspond to practical situation of the farming practices of the past years. However, changes in the climatic variability in the Bengal delta will result in greater unpredictability of rainfall and droughts, which might force farmer's reliance on surface water throughout the year in the future (Gain et al., 2014; Kumar et al., 2020; Rahman et al., 2011). In addition to that, assuming the counted fractions of E. coli to be all E. coli O157:H7, one of the most infectious pathogenic E Coli variants, may result in an overestimated values for probabilities for infection, as also has been indicated by others (WHO, 2016). However, additional simulations considering 1%, 5%, 10%, 15% and 20% of the original concentrations being E. coli O157:H7 also resulted in daily and annual probability of infection above the WHO acceptable limit except for most urban ponds and lakes (*supplementary materials: Table xviii*). Considering 20% of the counted E. coli concentrations to be this pathogenic variant, the overall annual risk of infection was 0.06, whereas for 1% the annual risk of infection this was 0.003, which is still above the WHO acceptable limit.

The survey among the local farmers who has been using polluted surface water as irrigation water revealed that more than 26% of the farmers suffered from water-borne diseases after working in the field. We calculated an overall infection probability between

2 – 10 % (Figure 4.6) and only for pathogenic E. coli, so the actual observed infection risk from the survey is higher than this QMRA assessed value. This is logical since other pathogens, such as the enterococcus (Figure 4.3) and Salmonella (data not shown) were also identified to be present in these waters, hence an accumulative risk of multiple pathogens can be expected. Moreover, the actual infection rate in real-world situation may differ from the theoretical QMRA based risk assessment as infectivity varies between individuals based on the immune system, age and other health factors (WHO, 2016). The input model parameters of QMRA are often derived based on studies conducted in developed countries raising the debate on the applicability of QMRA for developing countries. It is often generalized that people from developing countries have a stronger immune response system for water-related pathogens compared to their counterparts, though the opposite could also be easily reasoned. Thus, concrete further investigation is necessary to estimate the actual risk in the context of the study area. The insights from this study on the seasonal probability of risk of infection were used to highlighting the current risk to take necessary strategies to mitigate the health risks.

4.3.5 Risk management for safe reuse and future research

The analysis has indicated that the concentrations of selected pathogenic microbial indicators in the surface water is exceeding the national and international guidelines for use, leading to an increased annual risk of infection. A multiple-barrier approach containing a series of technical and non-technical measures could reduce the current risk for the farmers (Drechsel et al., 2010b; Fuhrimann et al., 2016; Janeiro et al., 2020; Keraita et al., 2008). Reducing pathogen concentration by treating wastewater before discharge as a technical strategy and reducing accidental ingestion to the minimum (1 ml/event) using protective equipment and raising awareness and education programs as non-technical strategies could contribute significantly to lowering the health risk within the acceptable limit (Figure 4.7). As the current irrigation sources receive a regular discharge from a nearby urban area, a treatment system followed by necessary disinfection would be needed to remove $\log_{10}$ 3-4 of the prevailing concentrations of E. coli lowering it to the safe limits. The authority should regularly monitor the water quality and enforce the necessary rules and regulations to prevent untreated discharge even from individuals. The outflows from the septic tanks should be managed and de-sludged to prevent the overflow of partially treated black water into the surface water bodies. The sludge can be processed further using appropriate technology suited to the local context (Drechsel et al., 2015; Fuhrimann et al., 2016; Hanjra et al., 2012; Tilley, 2014).

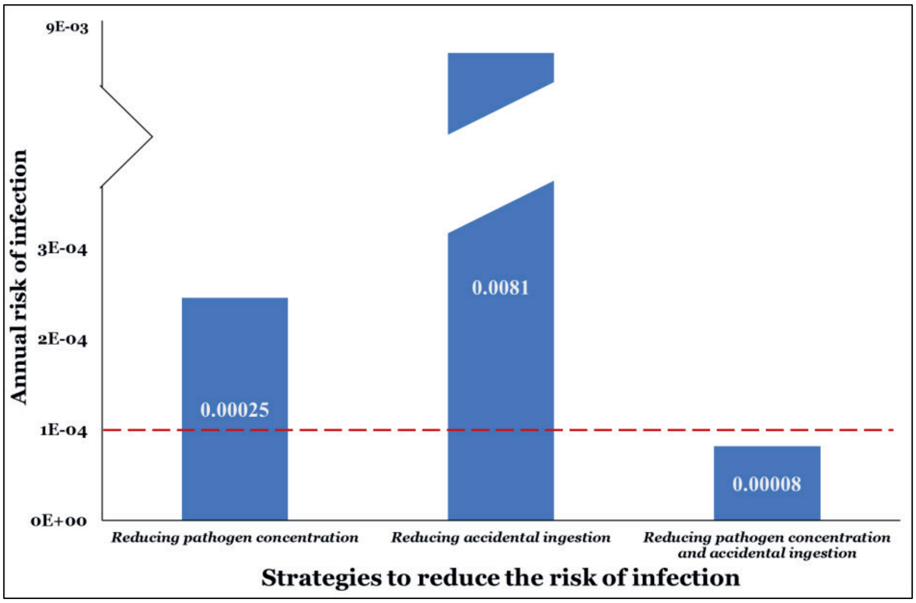

Figure 4.7: Health risk after implementing technical and non-technical strategies (red dotted line indicates the acceptable health risk limit)

Implementation of technical strategies alone usually cannot reduce the health risk below the acceptable limit unless exposure events are also reduced. Farmers should be encouraged to use protective equipment, where possible, to reduce the incidents related to accidental ingestion. Only reducing the accidental ingestion to a minimum (1 ml/event) will be insufficient to reduce the health risk if the concentration remains high in irrigation water (Figure 4.7). In addition to that, access to necessary health treatment (for severe illness), regular health awareness, an education program for farmers and their family members is crucial to reducing health risks (Utzinger et al., 2009). The local agency responsible for agricultural extension could ensure easy access to protective equipment or education programs through government subsidies or grants, especially to the economically marginalized farming groups. Combining technical and non-technical strategies would lead to reduced pathogen concentration in surface water sources and decreased chances of accidental ingestion which would bring the annual risk within the acceptable limit. Strategies should also include other stakeholder groups in the food chain i.e, market vendors, consumers as they also suffer from indirect wastewater irrigation (Barker et al., 2013; Ferrer et al., 2012). Awareness and information campaigns are necessary to prevent cross-contamination at the market level and increase safe storage and processing at the household level (Drechsel et al., 2010a; Fuhrimann et al., 2016; Tram et al., 2008).

A strong monitoring and warning system for microbial contamination can help early detection take necessary measures to protect farmers' health (Fuhrimann et al., 2015; WHO, 2006). This study has indicated a potential health risk related to current practice, but an in-depth level study would provide a more comprehensive understanding of the health risks, which would be useful in adopting required risk mitigation strategies. Future assessment considering the human enteric pathogens should include at least one bacteria, one protozoan and one virus to understand the range of behaviors in pathogen groups to formulate specific risk mitigation strategies (WHO, 2016). Additionally, study on plant uptake and deposition in the soil could provide further insights into the study area's heavy metal contamination. Currently, the surface water is deemed safe in terms of heavy metal contamination for agricultural use. However, increasing industrial activities may threaten the chemical health risk for farmers and consumers. The city is expected to have growing economic activities in the coming period (ADB, 2020), which may increase the presence of heavy metals in the surface water if not treated.

4.4 Conclusion

This study aimed to assess the risks related to indirect wastewater irrigation among peri-urban farmers based on a survey among farmers and a determination of the microbial quality of surface water resources around the Bengal delta city of Khulna. In the survey, 26% of the farmers indicated water-borne related health effects. They rank the importance of weeds' excessive growth, the nuisance of pests and crop health above their own health. This seems to be related to their longstanding experience of working with polluted surface water. Our results for Khulna city indicate that surface water used for peri-urban agriculture has no significant problem in heavy metal concentrations but a very poor microbial quality. Comparing to national and international guidelines the pathogen levels are 3 to 4 magnitudes too high and this pollution is linked to direct discharge of domestic wastewater and associated anthropogenic activities affecting surface water quality excessively. Taking E. coli concentrations in surface water and variations herein as the base of a QMRA risk assessment, noteworthy health threats to farmers (3 to 4 magnitudes too high compared to WHO limits) were identified, especially during the monsoon and summer. Various measures were considered in mitigating these risks, such as an education program for the farmers to protect their health, protective equipment for farmers during irrigation with polluted surface water, but the most effective measure is treatment of the urban water reducing pathogen levels in surface water with at least 3 – 4 orders of magnitude. Overall, the surface water quality needs to be improved by preventing the direct discharge and proper treatment of wastewater and awareness among all stakeholder groups should be raised to ensure safe irrigation practices. This research showed possible health outcomes for farmers due to E. coli infections and an in-depth level QMRA considering other microorganisms such as bacteria, viruses, protozoa would provide a comprehensive image of the risks associated with indirect wastewater irrigation. Moreover, chemical pollution such as organic micropollutants, in addition to the heavy and other metals studied here could further complete the picture of risks and treatment measures needed. Consumers and market vendors should also be considered in such a complete risk assessment and designing strategies to reduce the risk of infection and chemical pollution. Implementation of technical and non-technical measures are needed to ensure safe water reuse for farming activities which is crucial for sustaining agricultural production in this part of the Bengal delta.

Chapter 5

Institutional challenges and stakeholder perception towards planned water reuse

Abstract

The indirect, unplanned use of urban wastewater by peri-urban farmers in developing countries poses a severe risk to the environment and the farmers. Planned water reuse could contribute substantially to the irrigation water demand in peri-urban agriculture and minimize the risk. However, implementing such practice requires a thorough evaluation of concerned stakeholders' perception and the scope within the existing organizational structures. This chapter aims to assess the level of awareness, perception and willingness of different stakeholders toward current practices and the prospect of urban water reuse in Khulna City - one of the most vulnerable cities located in the southwest of Bangladesh due to the consequences of rapid climate changes in the Bengal delta. Also, institutional arrangements and their functioning were analyzed to understand the current sectoral performance. One questionnaire with 385 respondents from the urban area, 32 in-depth interviews and one focus group discussion with farmers in the peri-urban area and ten interviews with key informants from government and the non-government organization was conducted. Results indicate an overall positive attitude among major stakeholder groups towards planned water reuse for peri-urban agriculture. More than half of the citizens (53%) are willing to pay for the treatment of wastewater and majority of the farmers (66%) are willing to pay for the supply of better-quality irrigation water. However, the public sector responsible for wastewater collection and treatment requires adjustments in rules and regulations to implement planned water reuse. Interrelated factors such as lack of transparency and coordination, shifting responsibilities to other organizations, lack of required resources need to be addressed in the updated rules and regulations. Strategies to enforce current regulations and align all stakeholders are also crucial for implementing the planned collection and treatment of wastewater and its subsequent use for crop production.

Keywords: water reuse, perception, governance, stakeholder, agriculture

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5.1 Introduction

5.1.1 Background and objective of the study

The demand for good quality water in food production and industrial activities is proliferating in Bangladesh. However, the quality degradation of water resources and the threat of natural disasters (floods, cyclones) intensified by rapid climate change is limiting the availability of freshwater resources and thus threatening cities' existence in this part of the Bengal delta. A large volume of wastewater generated in the urban area is discharged every day into the nearby rivers and canals and flows to the peri-urban agricultural lands. Peri-urban farmers are left with no other alternative than to use this polluted surface water; a practice termed as indirect-unplanned wastewater use (Drechsel et al., 2015; Jiménez and Asano, 2008). This practice lacks quality irrigation sources, unavailability of adequate wastewater management infrastructure, inadequate financial resources, absence of adequate policy, lack of farmer's awareness and willingness to use untreated wastewater (Ensink et al., 2002).

Planned reuse can improve water circularity and ensure the optimum use of available resources (Agudelo-Vera et al., 2012; Wielemaker et al., 2018). However, public consent is essential for implementing planned water reuse, especially in agriculture. Evidence shows that the negative emotional response towards wastewater, also known as '*Yuck Factor*' is one of the most critical factors that triggered the failure of wastewater management plans (Gross et al., 2015; Hartley, 2006). Besides, trust and knowledge, related costs and benefits, attitudes toward the environment and socio-demographic factors, also crucially influence the social acceptance of wastewater use (Drechsel et al., 2015; Po et al., 2003). Institutional arrangements also play a crucial role in planned water reuse in agriculture. Lack of coordination among national and local agencies for wastewater management, unclear institutional arrangements and overlapping responsibilities across organizations make it difficult to have a functioning reuse scheme (Drechsel et al., 2015).

Institutional aspects and stakeholder perception of urban water reuse in Bangladesh are yet to be investigated. This chapter aims to study the perception of major stakeholder groups towards urban water reuse, through a questionnaire survey, interviews and analysis of the existing governance structure. Additionally, the economic aspects of reuse through assessing willingness to pay by farmers to receive better quality irrigation water and by citizens for treating domestic wastewater are also explored. Khulna, a coastal city, located at the southwest of Bangladesh, vulnerable to climate change impacts, has been taken as a case study.

5.1.2 Urban water management in Khulna

Khulna is the third-largest city of Bangladesh and is an administrative powerhouse of the region struggling to find an adequate drinking water supply. Due to the lack of good quality water sources in the city, recently, a drinking water purification plant has been inaugurated to collect surface water from *Modhumati River,* 58 kilometers away from the city. However, most private residential users meet their daily water demand from deep tube wells as they are not connected with a centralized system. Water extracted from aquifers is consumed within the household as drinking water and used for domestic activities (bathing, washing) and is discharged as greywater into the nearby drainage network (Figure 5.1). Blackwater originating from flushing the toilet is mostly collected in septic tanks and often, effluent gets mixed with surface water. The drainage network carries around 50,000 m^3 of untreated greywater daily to the *Mayur river* located west of the city. The industrial wastewater is treated before discharge as this is required and enforced by the authority. The *Mayur* river separates the urban area from the peri-urban area and the majority of the farmers are connected to the *Mayur* river for irrigation purposes. The peri-urban farmers extract water from the river for irrigation during the dry period (mid-November to mid-April). As river water gets polluted with untreated wastewater, the farmers are indirectly using wastewater for irrigation. Study showed that river water quality deteriorates severely during the dry period and based on FAO irrigation water quality standards, this water is not suitable for irrigation (Haldar et al., 2020). However, the farmers are forced to use this polluted surface water due to the lack of other sources.

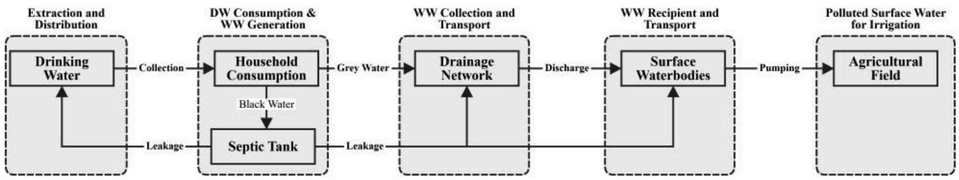


Figure 5.1: Existing water chain in the study area

5.1.3 Analytical framework

Framework for the analysis of stakeholders and institutional practices

Stakeholder analysis is a pivotal tool to identify and classify the major stakeholder groups according to their interests and influence (Mendelow, 1981). The stakeholders related to urban water management are placed in the axis and divided into four different groups according to the degree of interests and influence: 'keep satisfied', 'manage closely', 'monitor' and 'keep informed'. Stakeholders in 'keep satisfied' group has little interest but quite some influence, 'manage closely' group has the highest level of interest and influence, the 'monitor group' has lesser interest and influence on the subject and finally 'keep informed' stakeholder group has high interest but low influence (Mendelow, 1981).

To analyze the institutional practices and outcomes of dealing with wastewater, a conceptual framework composed of structural variables and a set of dynamic factors is presented (Table 5.1). The structural variables describe the roles and duties of the actors involved in wastewater production, treatment and use and their institutional resources (Hassenforder and Barone, 2019). The formal and informal actors involved in collecting, treating, monitoring and using wastewater have specific roles and duties. This relate to specific responsibilities, objectives, legal actions, institutional level, domain and geographical area; according to the water law and regulations (Wiering et al., 2015). Whether or not the actors can act according to these rules and duties depends on the capabilities and resources. Resources include access to financial means, information and time. Access to financial resources depends on the distribution of costs and benefits, imposed fees and fines.

The set of factors that influence institutional dynamics includes decision making, representation, accountability and credibility. Decision making is about who defines the objectives and the rules (there might be different factions within the public organizations) and how the stakeholders are represented in the decision-making platforms. Accountability of the state apparatus vis-a-vis the citizens is a vital mechanism to enforce rule-of-law. To circumvent accountability mechanisms organizations might shift responsibilities and blame to others (Bickerstaff and Walker, 2002). Authority, policies and rules will gain importance if those are accepted and credible (Jacobs and Matthews, 2017). Besides institutional structure and dynamics, actual outcomes of wastewater treatment are also influenced by the infrastructure available, climate and the type and levels of contamination of the wastewater.

Table 5.1: The common set of structural variables and factors used to analyze the institutional practices and outcomes (Hassenforder and Barone, 2019)

The common set of structural variables:
1. Actors that are involved (formal and informal) a. Roles and duties of the actors b. Capabilities, actionability and enforceability (How can the actors achieve outcomes, autonomy and dependence on others)
2. Resources a. Financial resources (distribution of the costs and benefits, fees, fines, willingness to pay) b. The information available (data generated and access to information of others) c. Time input available (staff time input)
The common set of factors of institutional dynamics:
3. Decision making and representation a. Definition of objectives and regulations b. Enforcement of regulations and sanctions (formal and informal authority) c. Advocacy influence
4. Accountability a. How the state apparatus is held accountable by citizens b. How risks and damage are formulated, blame and responsibility shifted to others
5. The credibility of authority, policy and rules

Water pricing and willingness-to-pay

Water pricing may be an incentive for the user group to use water more efficiently and raise funds to provide the drinking water service. However, high fees can exclude poor people from access. Similarly, citizens are generating and discharging wastewater that contaminates farmers' irrigation source. Charging for treatment could cover the costs of collection and treatment, but in Khulna treatment is not charged at the moment. The three most important concepts for water economies is the cost, value and price set by authorities (Rogers et al., 1998, 2002). Cost includes a wide range of aspects including O&M costs, capital cost, opportunity cost, cost of economies etc. whereas, value and price can be defined by the benefit and value received for the service against the amount set by the socio-political system (*supplementary materials: Figure a*). The opportunity cost and economic externalities were assumed to be zero, as there is no shortage of supply and no alternative use (Rogers et al., 1998).

Willingness to pay (WTP) is a widely-used method where citizens and farmers willingness is estimated to implement services and can be compared to the Full Economic Cost of water and wastewater treatment (Akter, 2007; Markantonis et al., 2018; Saldias et al., 2016; Zakaria et al., 2014). To avoid the respondents' strategic bias by deliberately exaggerating the amount they would be willing and could afford to pay (Carson et al., 2001; Zakaria et al., 2014), both groups were explained clearly the necessity of the treatment system and possible positive socio-environmental benefits. The average amount mentioned by the urban citizens and farmers was then used to indicate that they are willing to pay for improved services.

5.2 Methodology

5.2.1 Questionnaire survey

A questionnaire survey was conducted in 2018 among the urban citizens to understand the awareness, perception and knowledge towards water reuse and related issues. During the questionnaire survey, urban residents were asked to indicate an open amount that they are willing to pay to treat wastewater and improve to treat wastewater and improve existing drainage infrastructure. Correlation analysis of the associated socio-demographic factors (education, age, income) was calculated to validate the respondents' amount. Besides WTP, the questionnaire included necessary demographic data, domestic water use, wastewater generation and attitude towards water reuse. The questionnaire was pre-tested and the finalized version was deployed in the digital data collection platform Kobo Toolbox. The total number of respondents was 385 and their basic demographic profile is presented (along with the details of area-specific sample size and locations) in the supplementary material (*Table xix, Figure b*). In the questionnaire, respondents were asked to rate different aspects of water from a scale of one to five, where one means negative or low responses and five means excellent or positive responses.

5.2.2 In-depth farmers interview and Focus Group Discussion (FGD)

In-depth and structured interview questions were formulated to understand farmers' motivation and perception towards the existing indirect use of wastewater for irrigation. In addition to these, farmers were asked to indicate an open amount that they are willing to pay (*per 0.16 ha or locally termed as "1 bigha"*) for receiving clean irrigation water instead of using polluted surface water. A pre-test was executed in the study area and necessary adjustments were made before finalizing the questions. The target group consisted of randomly selected farmers involved in irrigation by drawing water from the river *Mayur* during the dry period. In 2019, a total of 32 interviews were carried out in the southern and western part of the Khulna city, which is dominated by peri-urban agriculture. Socio-demographic information of the interviewed farmers is added in the supplementary materials (*Table xx*). One Focus Group Discussion (FGD) was held at the end of the fieldwork with the farmers to validate and elaborate on the preliminary findings as FGD should be used as a mixed methodological approach to avoid biases in response (William, 2012). Especially, the amount mentioned as the willingness to pay for improved irrigation water by individual farmers was further justified during the FGD.

5.2.3 Key Informant Interview

Based on the stakeholder analysis (Figure 5.2), stakeholders related to wastewater management were identified and among them, a total of 10 representatives of organizations were selected for the interview. High-level officials from government offices i.e., Khulna Development Authority (KDA), Khulna City Corporation (KCC), Khulna Water Supply and Sewerage Authority (KWASA), Department of Environment (DOE), Department of Agricultural Extension (DAE), Department of Public Health Engineering (DPHE), Bangladesh Water Development Board (BWDB) and District Commissioner's (DC) office and two non-governmental organizations namely An Organization for Socio-economic Development (AOSED) and Bangladesh Environmental Lawyers Association (BELA) were identified as key informants for conducting the interview. Similar to other surveys, the interviews' main aim was to understand their organizational role, perceptions and plans towards improving the surface water quality and planned reuse.

5.3 Results and Discussion

5.3.1 Stakeholder analysis for urban water management

Several governmental and non-governmental agencies are directly or indirectly involved in implementation activities, policymaking, monitoring and enforcement related to urban water management in the study areas (Table 5.2). Concerned ministries in consultation with different regulatory bodies, for example, the steering committee, planning commission and Prime Minister's Office (PMO); prepare policies, rules and regulations related to water supply and sanitation. Local agencies like KWASA, KCC, DPHE, LGED and BWDB are responsible for implementing water management projects.

Table 5.2: Organizational involvement matrix in urban water chain in the study area

Organization	Involvement* of organizations in Urban Water Chain				
	Extraction and distribution	**Consumption and Wastewater generation**	**Wastewater collection and transport**	**Wastewater discharge and river management**	**Pumping irrigation water**
Concerned Ministries	+	+	+	+	+
District Commissioner's Office	-	-	-	+	-
Donor agency/ INGO/NGO	+	-	-	+	-
Industries	-	+	-	+	-
Khulna Water Supply and Sewerage Authority (KWASA)	++	+	-	++	-
Khulna City Corporation (KCC)	-	++	++	-	-
Bangladesh Water Development Board (BWDB)	-	-	-	+	+
Department of Agriculture Extension (DAE)	-	-	-	-	++
Khulna Development Authority (KDA)	-	+	-	+	-
Department of Environment (DOE)	-	+	-	++	-
Research/knowledge institutions	+	+	+	+	+
Farmers	-	-	-	-	++
Local Government Engineering Department (LGED)	-	-	-	+	-
Bangladesh Agricultural Development Corporation (BADC)	-	-	-	-	++
Department of Public Health Engineering (DPHE)	+	-	-	-	-
Citizens of the urban area	-	++	-	+	-

* ++: *Directly involved and responsible, +: indirectly involved and responsible, - : not responsible and lesser/no involvement*

Chapter 5

KWASA is responsible for supplying potable water in households and also responsible for the treatment of wastewater. Whereas, KCC being a municipal service agency, is responsible for providing a wide range of municipal services, including waste collection, street lighting, collection of holding taxes, trade license. KCC is mainly responsible for maintaining the drainage infrastructure which collects wastewater from residential, commercial and industrial areas. National and international donor agencies and concerned ministries provide the necessary funding to implement projects where NGOs and knowledge institutes generate knowledge, provides education and raises awareness among different stakeholders.

DAE and BADC carry out activities like meteorological forecasts, access to seeds, subsidy for pumping equipment and advice on the use of pesticides. The District Commissioner's (DC) office monitors and takes actions against river and canal encroachment with local agencies' help. DOE is responsible for monitoring the surface water quality as well as the effluents from industries. Heavy industries must establish an Effluent Treatment Plant (ETP) to treat the effluent before discharge, by following the government's discharge standards. Urban citizens are the greywater producers that affect the water quality in the rivers around Khulna city and do not pay for discharging greywater into the nearby drains.

The stakeholder analysis (Figure 5.2) shows that the ministries formulated policies at the national level and their input is essential for the change of current practices. Industries generate a considerable volume of wastewater which should be treated before discharge into surface water. However, the reality might be different than expected and the industries have a significant influence in setting standards for discharge and the enforcement of the standards. The '*Manage closely'* stakeholder group includes KCC, KWASA, DAE, BWDB and have a high level of interest and influence. As the success of planned reuse depends on these stakeholders, effort should be made to keep the stakeholder involved. Stakeholders in the '*monitor'* group (LGED, DPHE, BADC, Citizens) have a lesser interest and requires limited monitoring and evaluation. However, citizens are the producers of urban wastewater and thus should be included in further planning. The '*Keep informed'* consists of farmers, DoE, KDA and local knowledge institutions are eager to contribute; however, their influence is limited.

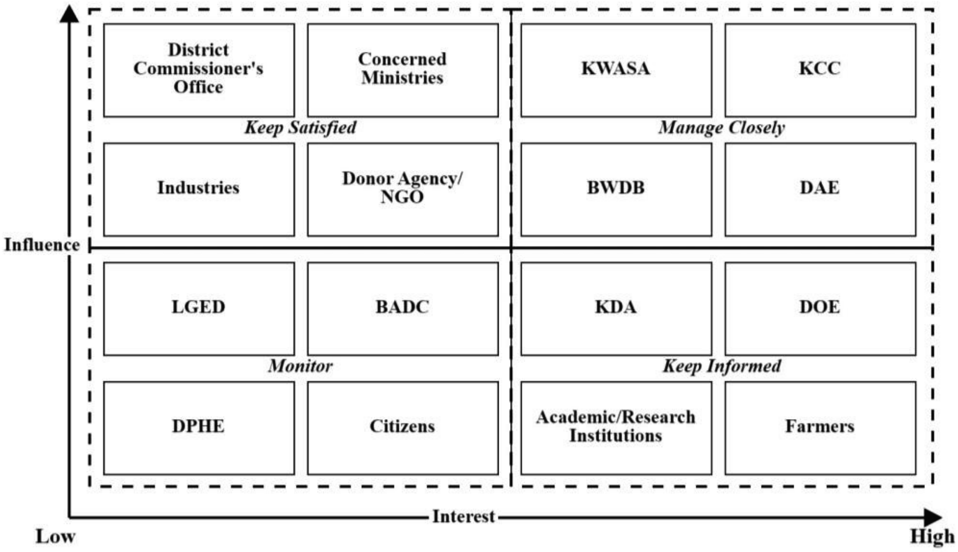


Figure 5.2: Stakeholder matrix related to urban water management

5.3.2 Institutional aspects of a planned reuse

Important actors and their roles, duties, perception towards reuse

The Khulna Water Supply and Sewerage Authority (KWASA) was created in 2008 and activities are regulated through the Water Supply and Sewerage Authority Act, 1996. The Department of Environment (DoE) monitors the river water quality and their activities are regulated by several laws e.g., the National Water Act, 1999, the National Environmental Conservation Rules, 1997, the Sound Pollution Control Rules, 2006 and the National Waterbody Management Policy, 2009. The DoE executes periodic water quality monitoring of the *Mayur* River as well as the other rivers and publishes yearly online summary reports. Key informant interviews indicate that government organizations do not always have sufficiently trained staff and lack intensive monitoring funds. The DoE generates revenue through imposing fines on polluting industries and fees for a clearance certificate on development projects.

The summary reports of the periodic water quality monitoring program of DoE are available online, yet departments do not provide relevant information to other departments. Interviews revealed that all the organizations recognize the potential of planned wastewater use in the context of climate change in coastal Bangladesh and rated the idea of planned use as 'excellent'. However, officials also pointed out the cost and changes needed in infrastructure and policy as one of the main challenges to implement such practices.

Institutional dynamics regarding wastewater disposal in Khulna

Objectives and priorities for policies and policy implementation are usually taken at the National Water Research Council (NWRC), headed by the Honorable Prime Minister. In consultation with the steering committees and planning commission, different ministries set up policies based on objectives and priorities set by NWRC (Figure 5.3). In contrast, KWASA has relatively more autonomy in defining its objectives and policies related to water supply and treatment, even though KWASA relies on government funds for implementing large projects. Installing a proper sewage system and treatment plants would require a substantial increase in the service fee, which is not deemed feasible and collecting and treating wastewater is not regarded as a priority. The low priority of wastewater collection and treatment can be analyzed in the light of citizens' limited capacity to enforce government rules. Citizens suffer most from health effects borne from polluted water in the open gutters along the streets.

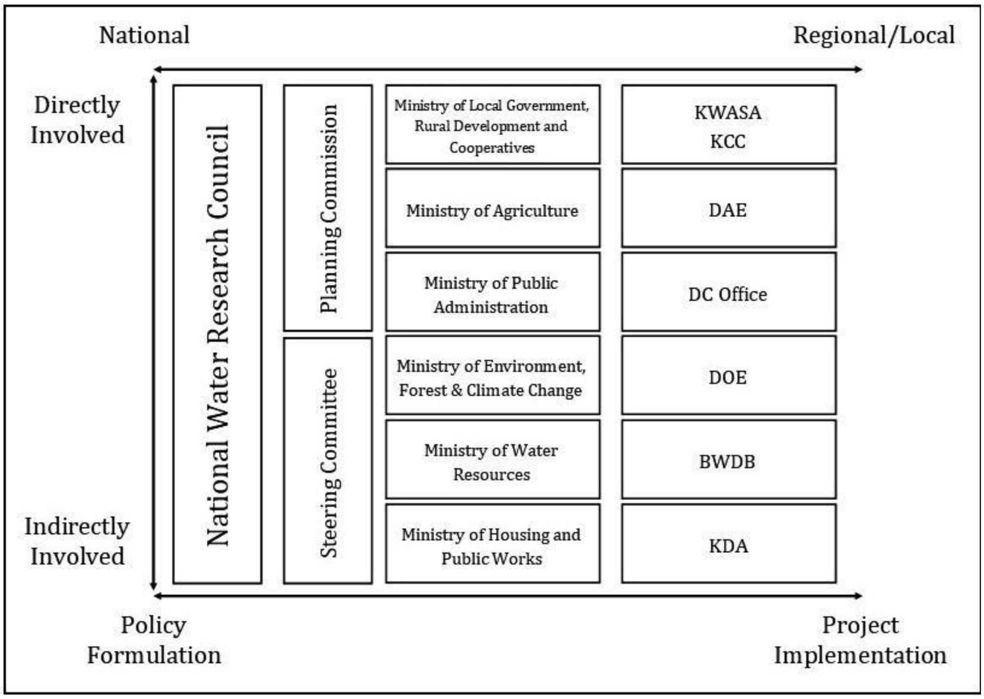


Figure 5.3: Institutional dynamics related to planned water reuse

Transparency International Bangladesh reports Patron-Client relations and office mismanagement to influence the low implementation of policies and enforcement of rules (KUET, 2015). Rules and regulations on wastewater discharge are only partially enforced and government organizations show low degrees of citizens' involvement and accountability, where this is key for effective environmental governance (Kochskämper et al., 2016). Different government organizations with functions regarding wastewater have limited cooperation (e.g. in exchange of information) and some seem to shift responsibilities to other organizations. This is because each organization has specific focus areas and not necessarily urban water issues are their primary area of interest. Similar trends of lack of coordination and prioritization among stakeholders are present in other national contexts (Hassenforder and Barone, 2019; Nhapi and Gijzen, 2004; Qadir et al., 2010; Reymond et al., 2020; Saldías et al., 2015). Such sectorization, i.e. polarization of water governance responsibilities distributed over different not adequately communicating organizations, hinders direct and effective measures to facilitate planned urban water use (Movik, 2012; Saravanan et al., 2009). Urban water issues are interrelated with other services and improved cooperation among different organizations is essential for yielding better results (Chowdhury, 2010). An intersectoral partnership among organizations where trust, continuous economic support and incentives for participation is ensured; can be a way out to overcome existing barriers in the urban water sector (Österblom and Bodin, 2012; Waddell and Brown, 1997).

5.3.3 Citizens awareness and perception towards planned reuse

Household water sources and quality perception

Access to safe, clean water for drinking and domestic activities is a challenge for people living in coastal areas. Salinity intrusion, presence of arsenic in groundwater and lack of groundwater recharge have made the situation worse in the recent past (Abedin et al., 2014; Islam et al., 2019). However, the survey in Khulna indicated that, due to a large number of government initiatives, a major portion (90%) of the citizens has access to privately-owned deep tube wells for drinking water. Other sources like water supply from KWASA and shallow tube wells are mainly used for domestic purposes. Rainwater harvesting is a popular method mostly in rural parts of the coastal area. However, in total, only 1.3% of the urban citizens used rainwater for most domestic purposes. The survey indicated that the urban residents rated drinking water (extracted from deep aquifers at around 300 m) quality at 4.31 (out of 5), where the water quality for domestic purposes (extracted from shallow aquifers around 50m) was 3.76 (*supplementary materials:*

Table xxi). Laboratory analysis also indicated that deep tube-wells' water quality was better compared to the shallow tube wells (Datta et al., 2011).

Data analysis also indicated that more than 90% of the households were connected to a drainage network, where 75% had drainage adjacent to their house and 18% had access within less than 25 meters from their house. The survey also showed that more than 64% of the respondents suggested the possibility of reducing the current water consumption and more than 88% of the respondent were willing to take necessary actions to reduce the consumption if necessary. More than 32% of the respondents indicated that they were consuming the required amount of water, thus did not see the need to reduce the current consumption. Previous studies found that water use habits and attitudes were linked with household water demand (Hoolohan and Browne, 2016; Manouseli et al., 2019). High demand in the household, because of a large family or having a newly born baby was also indicated as primary reasons for not being able to reduce the consumption.

Awareness and perception towards pollution and wastewater treatment

Public perception towards different aspects of reuse schemes has become a critically important part of the implementation (Ross et al., 2014). The respondents perceived wastewater generated from the households to be relatively less polluted than the industrial and mixed areas (Figure 5.4). Respondents thought that wastewater generated in the industrial areas is slightly less polluted than from the mixed area. The reason may be that the industries need to improve the wastewater quality before discharge into the open sewers. In contrast, there is no such treatment available in mixed areas, dominated by commercial activities. The majority (> 70%) of the respondents rated positively (4 and 5) towards treated wastewater that indicates their understanding of the necessity of treatment. More than 80% of the respondents indicated that they were aware of the negative impact of direct discharge of wastewater, indicating awareness about the impact of untreated wastewater on the natural system.

Perception towards wastewater reuse

More than 78% of the respondents rated urban water reuse concept positively (4 and 5) (Figure 5.4) and more than 75% of the respondents considered water reuse as a solution for combating the effects of climate change. Over the years perception towards planned water use has been positively changing which is evident in research from other areas of the world (Alhumoud and Madzikanda, 2010; Chen et al., 2015; Friedler et al., 2006; Garcia-Cuerva et al., 2016; Ravishankar et al., 2018).

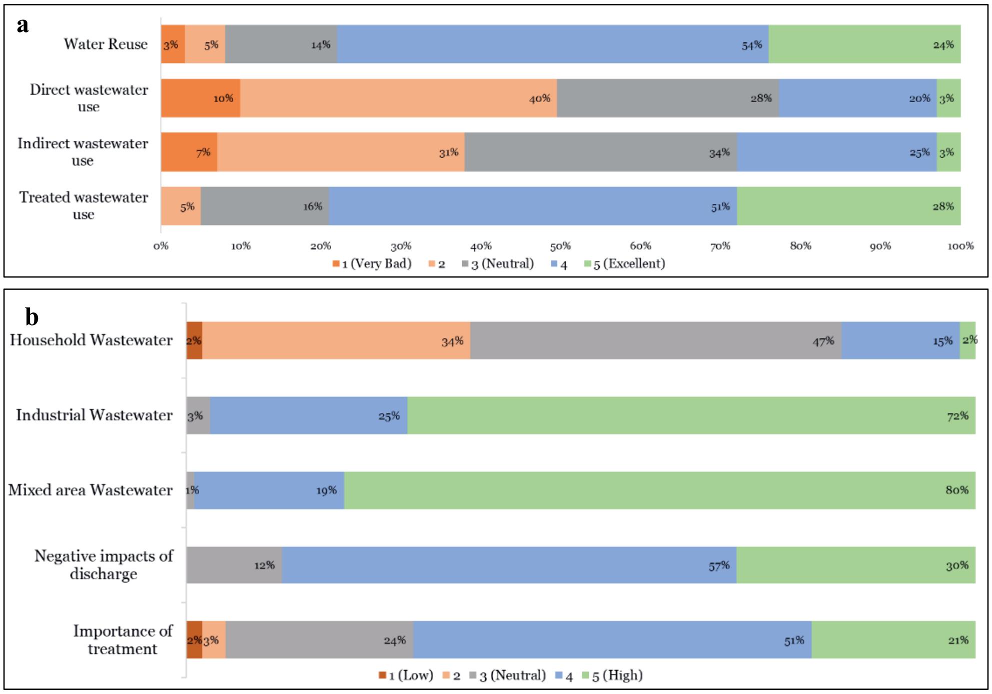


Figure 5.4: Rating of citizens on a) different aspects of reuse and b) aspects related to wastewater quality, discharge and treatment

The respondents (38%) rated negatively (1 and 2) towards the current indirect wastewater irrigation in peri-urban agriculture. 'Irrigation water is dirty, polluted', 'harmful to health' and 'damaging for crops' were mentioned by the respondents explaining their rating on current irrigation practices. The majority of the respondents (83%) also pointed out agriculture as the most recommended area for reuse of treated wastewater followed by industry and households, considering the effect of climate change in coastal Bangladesh. This indicates rather good possibilities for implementing planned water reuse in this part of the delta. Climate change and rapid urbanization have reduced access to quality irrigation water and planned water reuse could be viable to mitigate that challenge (Gross et al., 2015). The responses are provided in the supplementary materials (*Table xxiii*).

Factors affecting citizen awareness and perception

Several studies have identified the factors affecting water reuse and pointed out several socio-economic-demographic factors related to water reuse responses (Chen et al., 2015; Fielding and Roiko, 2014; Po et al., 2003; Smith et al., 2018). The socio-economic background, especially the respondent's educational status, is one of the most influential factors related to the response to different aspects of water reuse (Po et al., 2003). A similar outcome has been found in the current study along with monthly household income is the significant factor influencing the responses (

Table 5.3). Gender is a vital factor in drinking water management in Bangladesh, as women are responsible for managing water within the household (Faisal and Kabir, 2005).

Table 5.3: Socio-economic factors influencing awareness and perception

Question	**Significant Factor**[1]
How do you rate the drinking water quality?	Gender*, Household Head**
Are you willing to take necessary measures to reduce your current household water consumption?	Total Family Member*, Total Earning Members**, Monthly Income*, House structure type**
How do you rate the current practice of direct discharge of wastewater and associated negative impacts on the environment?	Education**, Family Income**, *House structure type***
How do you rate the existing drainage system?	Education*, *House structure type***
How much are you willing to pay for the improved drainage system and wastewater treatment?	Education**, Family Income**, *House structure type**
How important do you think of proper wastewater treatment?	Education**, Family Income**, *House structure type***
How do you rate the water reuse concept?	Education**, Family Income*, *House structure type***
How important is it knowing the current irrigation practices for your agricultural products?	Education**, Family Income*, *House structure type**
What are the possible water reuse sectors?	Education*
How do you rate your trust in technology in making water safe for reuse?	Education**, *House structure type***

** Correlation is significant at the 0.01 level (2-tailed)

* Correlation is significant at the 0.05 level (2-tailed)

[1] *Italic means negative correlation*

A similar result has been reflected in this study as a rating of drinking water quality was significantly related to gender. Willingness to take measures within the household to reduce the water consumption primarily depended on the number of people in the family, monthly income and the type of house they live. People living in better housing types have access to more advanced facilities, making it difficult to change their habits in reducing water consumption and have higher expectations in terms of services and trust towards technology and the institutions. The survey showed that awareness about the negative impact of wastewater discharge and service ratings of the existing drainage system was influenced by education, occupation, family income and house structure type. Residential buildings are well connected to the nearby drains, mostly covered, whereas, people living in slum/squatter do not have access to the proper drainage system or mostly earthen gutters. Willingness to pay for improved drainage systems and wastewater treatment systems was influenced by education and family income. The more income the household had, the more they were willing to spend on improving the system. Knowledge is vital for introducing new concepts and providing information through education was one of the best ways to transfer new knowledge also found in earlier research from other areas of the world (Chen et al., 2015; Fielding et al., 2019; Saldías et al., 2016).

5.3.4 Farmers motivation and perception towards planned water reuse

Existing farming and irrigation practices

Interviews with peri-urban farmers of Khulna indicated that farmers cultivate one or two crops per year dominated by different rice varieties. Farmers also produce wheat or potatoes at different times of the year and some seasonal vegetables (radish, tomato, bitter cucumber) and fruits (bananas or melons). Interviews with farmers also revealed that the type and production of crops depended on farmers' financial situation and accessibility to land. During the dry period, agricultural activities are restricted by the water availability in the adjacent rivers as river water quality and quantity decreases.

On average, a farmer leases 0.98 ha from a landowner, following a '*Borgha*' structure, meaning during the dry season, the landowner will legally claim $1/3^{rd}$ of the benefit as lease transaction and rest $2/3^{rd}$ of the benefit will be for the farmer. During the rainy season, this ratio changes to $1/4^{th}$ for the landowner and $3/4^{th}$ for the farmer. About 60% of the interviewed farmers had a supplemental job such as day labor, construction worker and rickshaw or van pulling, besides their farming practices. Structural changes in the agricultural sector contribute to this development of full-time farming to part-time farming, especially in the peri-urban areas of big cities (Salam and Bauer, 2018). All the interviewed farmers used surface irrigation as the main irrigation technique and the majority (93%) of farmers are dependent on *Mayur* river for irrigation. Farmers are also not allowed to install deep wells, thus uses a shallow pump machine to extract water from the river and use pipes to supply irrigation water for distant crop fields.

Farmers motivation and perception for current practice

Farming has not been a profitable profession in the recent past and farmers' financial capability determines their farming practices and irrigation sources. Even though the irrigation water quality is poor; 65% of the farmers were well aware of the nutrient presence in the current surface water and knew these nutrients are beneficial for rice growth. Water reuse, either planned or unplanned, has been a common practice among farmers due to the presence of nutrient and cheaply available options (Mojid et al., 2010; Owusu et al., 2012; Saldías et al., 2017). About 25% of the farmers responded by rating 1 (very bad) to irrigation water quality. They observed worms, insects, water hyacinths and household wastes as quality deteriorating factors. Farmers also identified two leading causes for the bad water quality: the salinity intrusion from nearby rivers and the direct dumping of solid waste and effluents in the river which resonates with previous studies' findings (Haldar et al., 2020; Roy et al., 2018, 2015). In the context of the current practice, farmers saw planned wastewater use -with proper treatment and quality control- as an excellent option which could ensure quality irrigation water and protect their health.

5.3.5 Willingness to pay and economic aspects of reuse

Farmers' interviews indicate that over 34% of the farmers were willing to pay US$22[2] per cropping season for the current quality of the irrigation water if authorities decide to charge for water. Overall, 66% of the farmers were willing to pay for the irrigation water (Figure 5.5). However, farmers were willing to pay $40 per cropping season for better quality irrigation water. The two most important factors behind their willingness to pay were farmers' inclination to obey the government regulations and mutual understanding with other farmers.

[2] *1 US$ = 80 BDT*

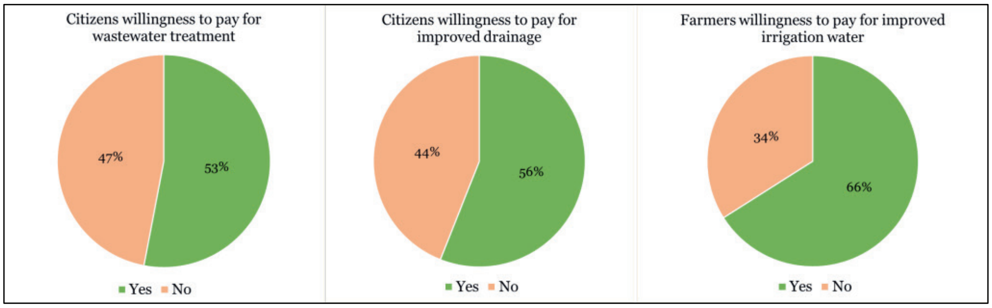


Figure 5.5: Percentage of citizens and farmers are willing to pay

Farmers also mentioned their current living conditions, land ownership, economic loss in farming in recent years and increased production cost as factors for not willing or unable to pay higher prices for better quality irrigation water. On the contrary, citizens were less enthusiastic regarding payment for wastewater treatment and improved drainage infrastructure. Analysis indicated that only 53% of the citizens were willing to pay for wastewater treatment and 56% of the citizens were willing to pay for the improvement of the existing drainage infrastructure. The survey indicated that on average citizens were willing to pay $0.7/month/household for improving the current drainage infrastructure and an additional $0.7/month/household for the treatment of wastewater.

KWASA will establish a centralized wastewater treatment system for Khulna City in three phases and the expected investment cost in immediate phase (2016-2023) is around $62 million, in the intermediate phase (2023-2029) around $54 million and in the ultimate phase (2029-2035) around $42 million (KWASA, 2016). The government of Bangladesh and donor agencies are expected to finance the project and being able to provide services for the wellbeing of the population will be considered as an economically viable return (ADB, 2015; KWASA, 2016). The treatment system is expected to have a service span of 30 years and around $4.8 million annual Operation and Maintenance (O&M) costs that could be recovered from the system's beneficiaries. The system is expected to be completed by 2035 and annually treat 50 million cubic meters of wastewater (KWASA, 2016). Based on these numbers, the system's operation and maintenance cost will be $0.10/m^3 and capital cost will be $0.11/m^3 totaling the full cost of $0.21/m^3 (Figure 5.6).

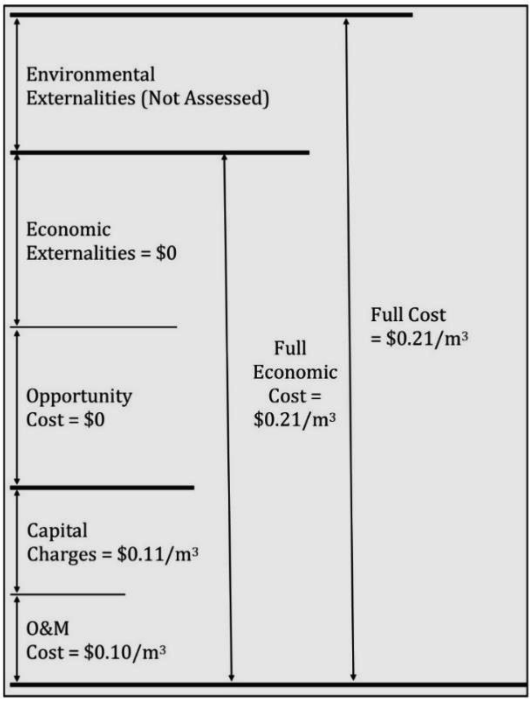


Figure 5.6: Wastewater treatment cost in study area

The capital cost will decrease over the years; however, the O&M cost is expected to increase as the system will require frequent maintenance. Citizens are willing to pay $1.4/month/household for the whole system (drainage infrastructure improvement and treatment system) and annually around $2.4 million could be collected as water tariff which is around 50% of the annual O&M cost. The population in Khulna city is expected to grow due to increased economic activity in the region (ADB, 2020) and KWASA plans to adjust the current fixed tariff annually in the coming years to cover the O&M costs (KWASA, 2016). Progressive tariff system based on citizens' socio-economic condition or based on the volume of water consumed can be an interesting approach to replacing the current fixed tariff to cover the growing O&M costs (Klassert et al., 2018). During the questionnaire survey, more than 40% of the respondents mentioned economic constraints as the primary reason for not paying more for the treatment. Respondents also pointed out that providing infrastructural services is part of the government's responsibility and does not want to pay for it. They argued that industrial and commercial areas generate a greater volume of wastewater which causes severe pollution and those sectors should be paying more for the treatment of wastewater.

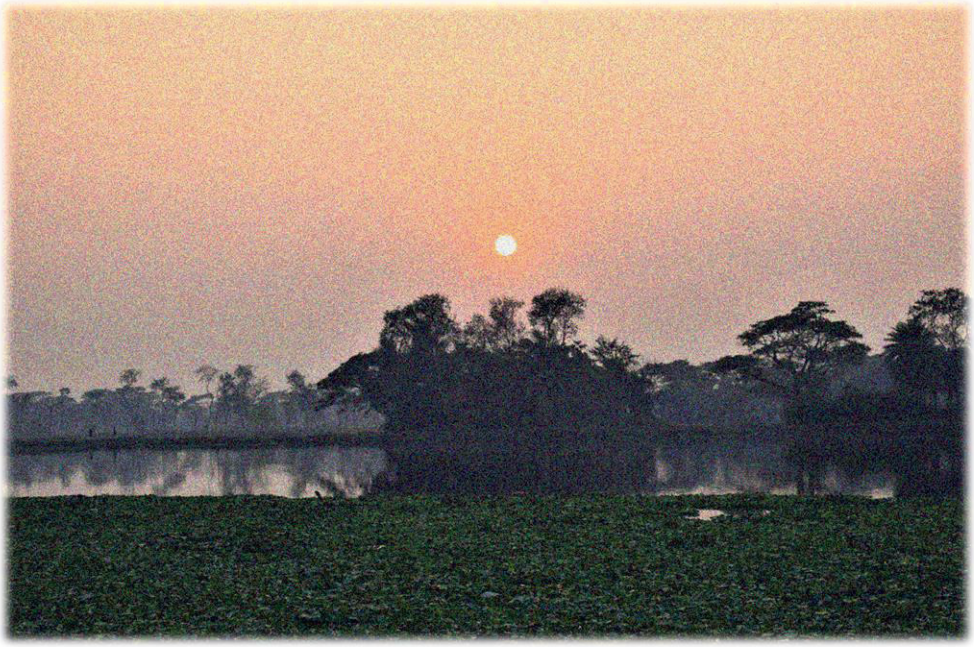
On average, a peri-urban farmer of Khulna would require around 3800 m^3 of irrigation water (Haldar et al., 2021) which would cost \$380/cropping season (if only the O&M costs of the wastewater treatment are charged). Farmers are willing to pay \$40 for clean irrigation water during the whole irrigation season, around 11% of the cost. The socio-economic consequences of charging for using natural resources like river water for agricultural activities on farmers livelihood should be further investigated before implementation. Additional financing would be necessary to cover the rest of the O&M costs and concerned authorities should investigate whether instruments like polluters pay principle could be applied to other water users.

5.4 Conclusion

The peri-urban farmers of Khulna are heavily dependent on surface water for irrigation during the dry season. Due to the current direct discharge of untreated wastewater, this water is heavily polluted. In the context of the threat of climate change, reduced water availability with adequate quality will hinder farming in this area. Planned water reuse is a preferred alternative among the major stakeholders and this can contribute to the enhanced livelihood i.e. for farmers by maintaining their ability to produce food and for citizens benefitting of the sustained food provision and improved living condition. However, adjustments in existing rules and regulations and setting up necessary discharge standards are crucial for planned water reuse in agriculture. Local government institutions need to be brought under an intersectoral partnership agreement to enhance collaboration. Additional financial and human resources should be allocated to monitor and to enforce such improved rules and regulations. Besides, participation, accountability and cooperation among all stakeholders should be ensured to create a more functional and sustained institutional arrangement. Progressive tariff system can be introduced for charging citizens for wastewater management as the study showed that the people with more income are willing to pay more for the treatment systems. This will safeguard the marginalized and poor communities living in slums and squatters of the city. Similarly, access to and clean irrigation water should be ensured so that marginalized farmer groups' socio-economic condition is not negatively affected. This research can be useful in formulating policies and strategies for effective water management in socio-demographically similar countries. Future research on water management should focus on the infrastructural aspects of collecting and treating urban wastewater and, finally, the supply of treated wastewater to the farmers for continuous food production in the region.

Chapter 6

Harnessing the potential of urban water to irrigate agriculture in the Bengal delta: Synthesis, Conclusion and Outlook



6.1 Introduction

The Bengal delta is highly impacted by climate change and the rising sea level (Ericson et al., 2006; Nicholls and Cazenave, 2010; Wong et al., 2014). Changes in climate variability would adversely impact water resources and, therefore agriculture, human health and biodiversity of the delta area (Das et al., 2020; UNFCC, 2007). The fast development of emerging economies in the urbanized delta of South Asia's areas is twinned with a rapid increase in demand for fresh, high-quality water. The intensified anthropogenic activities increasingly threaten the availability of good quality water for drinking water and food production to sustain livelihood development. With this increasing scarcity in good quality freshwater resources, the reuse of domestically used water becomes an increasingly attractive alternative. Historically, urban water reuse has been practiced worldwide, especially in water-scarce regions and areas with insufficient water management infrastructure. Reusing urban water contributes to improved utilization of available water resources as wastewater can be recycled for multiple purposes before discharging into water bodies and provides a valuable alternative where water is scarce. This measure can also contribute to achieving several Sustainable Development Goals (SDGs) (SDG2: zero hunger, SDG 6: clean water and sanitation, SDG 11: urban sustainability) of the United Nations 2030 agenda for Sustainable Development. However, a significant paradigm shift is necessary to implement proper urban water reuse plan.

During the industrial revolution (nineteenth century), the primary focus was collecting and discharging wastewater into surface water bodies, particularly in the global North. Ensuring proper treatment of wastewater that complies with mandatory discharge quality standards has been prioritized around the twentieth century due to health and environmental concerns. During the first decades of the twenty-first century, domestic and industrial water reuse has gradually become more important in wastewater management and treatment, wherein the development is still ongoing for adequate post-treatment of wastewater treatment plant effluents and quality targets to be achieved for allowing different forms of reuse. In many global south countries, including those with urbanized deltas, such as Bangladesh, development in wastewater collection and treatment are still awaiting major investments. At the same time, good quality freshwater is becoming increasingly scarce due to the aforementioned global changes. However, such threat offers at the same time an opportunity: not just simply to copy technological solutions from the global North, but to immediately invest in infrastructure and treatment that is tailored to the reuse of the water to cope with scarcity issues. In this way, global South countries can decide on the infrastructure and water treatment development in one step, leap-frogging the multiple development steps the global North has implemented in the last centuries. The reuse of collected and treated urban water to sustain peri-urban agriculture in global South urbanized delta's fits in this "grand development" picture (Figure 6.1).

To make urban water reuse possible, at least two steps are needed: i) to assess the potential of urban water to meet the demand of peri-urban agriculture, in terms of water quantities, qualities and socio-economic, planning and legal constraints; and ii) to design and define suitable water collection and treatment infrastructure to make this reuse possible. The research of this thesis has been primarily oriented on the first step, while step ii) is briefly discussed in this synthesis chapter. In this, the case of Khulna city, Bangladesh was taken as an example for such developments in the full Bengal delta, which could be implemented in other countries of the region.

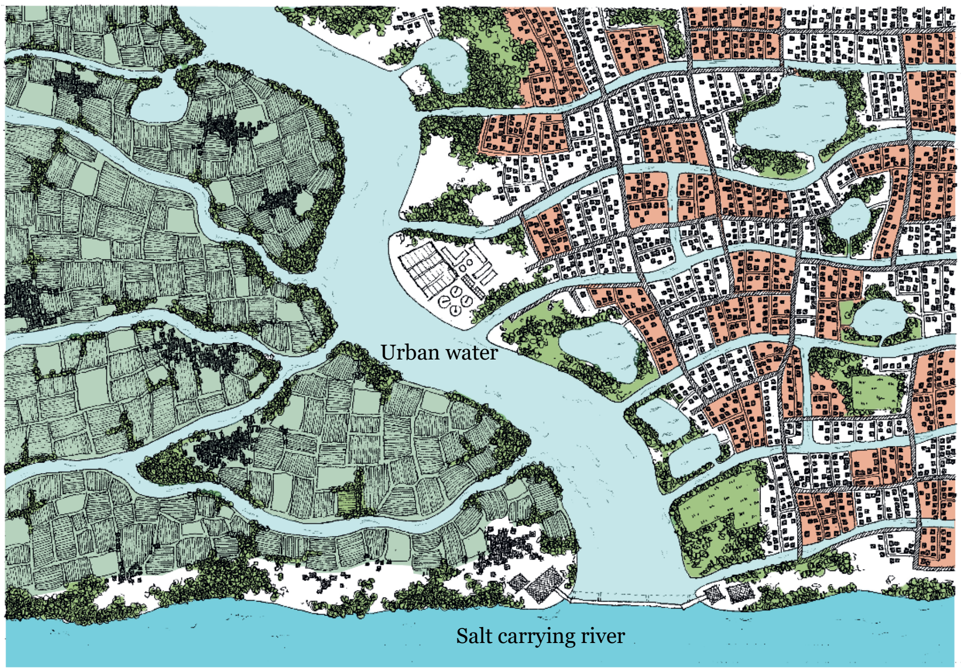


Figure 6.1: Artistic illustration of harnessing the potential of urban water to irrigate agriculture in the delta

6.2 Khulna city as a case for Bengal Delta

Khulna, a coastal city of Bangladesh, is one of the most vulnerable areas due to rapid changes in climate variability (Auerbach et al., 2015; Datta et al., 2020; Shahid et al., 2016). The city serves as a divisional administrative hub for the surrounding districts whereas the peri-urban and rural areas contribute through regional food production and employment generation. Over the years, the agriculture of peri-urban and rural areas has been confronted with increased water and soil salinity in the irrigation sources (Gomes et al., 2018; Kumar et al., 2011; Rahman et al., 2011). The unpredictability of climate variability is a risk to agricultural activities as insufficient rainfall can cause droughts and excessive rain beyond seasonal patterns can instigate urban flooding and waterlogging in some areas of the region. Moreover, the discharge of untreated wastewater pollutes the surface water, thus further limiting access to quality irrigation water. The wastewater originating from good quality potable water could play a crucial role in combatting rising salination in the region. Therefore, in the subsequent chapters, the irrigation demand against the potential urban water was quantified at first. Next, the water quality in terms of chemical-physical, microbial and heavy metal concentrations was determined and implications related to reuse were evaluated. Then the existing governance arrangement was also studied to formulate the socio-technological scenarios enabling urban water reuse in agriculture. The main findings of this thesis's contribute to a broader understanding of the unacknowledged potential, challenges, and pathways to urban water reuse for agriculture, summarized in the following table (Table 6.1). Below, the urban water potential for agriculture is further discussed in the context of the research findings of the various chapters.

In **Chapter 2**, the urban water reuse potential in peri-urban agriculture is quantitatively explored. The FAO AquaCrop model was used to assess the irrigation water requirement of Boro rice during the dry season over the last decades (from 1984 to 2017). Urban water characterized as a blend of greywater and sealed surface runoff was calculated based on drinking water consumption and annual rainfall in 2018 in the study area, respectively. Taking into account the growing population and increase in daily water consumption, the analysis concludes, urban water can meet the irrigation water demand of peri-urban agriculture of Khulna. Additionally, in assessing demand-supply balances, one should consider the influence of climate change effects on agriculture, i.e. irrigation requirement (related to amounts of precipitation during cropping season) and water productivity (related to yield).

Table 6.1: Summary of findings presented in subsequent chapters of this thesis

Ch.	Topic	Research Question	Research Method	Main Findings
2	Quantifying irrigation demand and wastewater supply potential	How does urban water contribute to satisfying peri-urban agriculture's irrigation demand?	• Irrigation water requirement for rice • Urban water generation calculation	• Irrigation water requirement has declined over the last decades • 8.2 million m^3 of urban water is generated against 7.4 million m^3 irrigation demand • Greywater and surface runoff can supply 77% and 33% of total seasonal demand
3	Spatio-temporal chemical-physical water quality variation	Does spatio-temporal variation in surface water quality affect the reuse potential in agriculture?	• Surface water quality analysis and mapping in three climatic and cropping seasons	• A significant seasonal dependent variation exists ($p<0.05$) in water quality. • During summer, 1/3rd of the area has a severe restriction for irrigation water use • Land use has a significant influence on water quality
4	Microbial and heavy metal concentrati ons and associated health risks	What are the health risks of farmers of existing indirect wastewater irrigation?	• Microbial and heavy metal analysis • Screening-level QMRA • Questionnai re survey among farmers	• The pathogen concentration exceeded the WHO guideline • Existing practices pose health risks above the acceptable limit • Technical strategy alone cannot guarantee safe reuse • No significant presence of As, Co, Ni, Cd, Cr, Cu, Pb observed
5	Governanc e of urban water reuse	Is the existing state of governance arrangement and stakeholders' perception conducive to the facilitation of the urban water reuse plan?	• Questionnai re Survey • Key Informant Interview (KII) • In-depth interview • Focus Group Discussion (FGD)	• Positive attitude among stakeholders for water reuse to combat climate change • Money collected from citizens as tariffs and fees could be used to cover a part of O&M cost of treatment systems • Existing rules & regulations do not provide enough room for implementing water reuse in agriculture

Simulation with the FAO AquaCrop model shows that the net irrigation requirement has decreased from 460 mm in 1984 to 299 mm in 2017, whereas the overall water productivity has increased around 26% in the same period due to declining water availability. The water requirement is the highest during the crop growing months of February and March. As urban water in this approach does not contain blackwater, its rather diluted character presents an attractive alternative. Under different scenarios, greywater and surface runoff can supply 77% and 33%, respectively, of the total seasonal irrigative water demand. The annual sealed surface runoff, which is expected to be less polluted compared to wastewater, if handled properly, can be a suitable alternative for irrigation as it is enough to meet the seasonal demand.

Conclusion and novelty of the outcomes: Greywater and surface runoff can meet in quantity the irrigation demand for peri-urban agriculture in Khulna city in case necessary infrastructure related to treatment, storage and distribution are implemented. Studies assumed that urban water could supplement irrigation water requirements, especially in the water-scarce areas (Chu et al., 2004; Li et al., 2020; Ronco et al., 2017; Trinh et al., 2013). This is especially important for delta areas and this chapter provides a tangible and quantitative assessment indicating the matching potential and these can be taken as a basis for formulating policies related to urban water reuse in agriculture.

In **Chapter 3,** the prevailing spatio-temporal variations in chemical-physical quality of water and its subsequent usability in agriculture were mapped. Water samples were collected in three different seasons and laboratory analysis was performed to determine these chemical-physical parameters. Results then further processed using statistical analysis and spatial mapping using ArcGIS. Results show that existing water quality does not meet FAO guideline thresholds for parameters related to agricultural use and significant ($p < 0.05$) seasonal variations in chemical-physical water quality parameters exist in the study area. The direct discharge of urban wastewater and solid waste deteriorates the water quality which is reflected by values of the related parameters (TSS, DO, BOD_5, COD, NO_3^-, PO_4^{3-}, NH_3-N). Additionally, the water quality is influenced by the adjacent salt-carrying rivers which are evident in the variation in saltwater-influenced parameters (TDS, EC, Na^+, Cl^-, Mg^{2+}, Ca^{2+}, K^+, SO_4^{2-}). Results also indicate that the percentages of land use within a 500 m radius from the monitoring stations are correlated to several water quality parameters, indicating the role of adjacent residential and commercial areas in polluting surface waters.

Conclusion and novelty of the outcomes: Existing surface water quality is highly influenced by salinization and anthropogenic activities in the adjacent areas. Numerous studies indicated that water quality is correlated with land use (Bu et al., 2014; Ding et al., 2016; Giri et al., 2018; Mainali and Chang, 2018). However, we found inconsistencies in this correlation due to varied and heterogeneous contexts in the urban environment. The method of integrating water quality information at a spatial scale provided valuable insights on the spatio-temporal variability of water quality and usefulness, restrictions and treatment requirements for use. This will be useful for future planning of delta areas and adopt necessary infrastructural strategies to prevent surface water pollution enabling good quality irrigation water in urbanized deltas.

In **Chapter 4,** the surface water's microbial and heavy metal contamination was assessed through water sample collection and subsequent laboratory analysis. A screening level Quantitative Microbial Risk Assessment (QMRA) was performed for assessing the health risk of farmers considering the E. coli concentration in water samples. Analysis showed that the mean concentrations of all microbial indicators were 3-4 orders of magnitude above the thresholds of the WHO- and local guidelines for safe irrigation. Moreover, a significant ($p<0.05$) temporal variation in Faecal Coliform, E. coli and Enterococcus concentrations existed in the water samples. No significant exceedance of such thresholds was observed for heavy metals. The risk assessment assuming E. coli O157:H7 to be part of the E. coli as a health indicator organism, suggests that existing surface water quality poses a significant health risk for farmers if they are in direct contact with polluted surface water and not using any protective equipment. However, a survey among farmers revealed that their own health comes third in risk perception behind excessive growth of weeds and insects and crop health. Suggested technical measures include adequate wastewater treatment before disposal into rivers and provision of access to protective equipment for farmers. This should be complemented with raising awareness through education programs among farmers as a non-technical measure to reduce accidental ingestion.

Conclusion and novelty of the outcomes: The existing microbial water quality of the surface water surrounding Khulna city is far beyond the safety limits of national and international guidelines and therefore presents risks to farmer's health. While poor microbial water quality due to uncontrolled wastewater discharge has been reported around the country, studies related to the consequent health risk of farmers in the delta areas are absent (Islam et al., 2018; Mojid et al., 2010). The results from this chapter identifies high levels of farmer's health risks which reiterates the significance of proper treatment of wastewater and education programs to raise awareness among farmers. Future initiatives should prioritize protecting farmer's health to ensure sustained agricultural activities in the delta areas.

In **Chapter 5,** the governance aspects related to urban water reuse were investigated using several participatory methods such as questionnaire survey, Key Informant Interviews and Focus Group Discussion. Results indicate that most of the urban citizens (80%) are aware of the negative impacts of direct discharge of wastewater and more than 53% of them are willing to pay for the treatment. The willingness of the urban dwellers is influenced by their educational background, family income and the type of house that they live in. Most farmers (66%) are willing to pay for better quality irrigation water in comparison to using the current polluted surface water. The money collected from the urban dwellers could be used to cover half of the operation and maintenance costs of the treatment plant. Several governmental agencies are parallelly involved in urban water-related issues; however, no clear strategy exists to work together.

Conclusion and novelty of the outcomes: Urban water reuse has a positive image among stakeholder groups and is economically feasible. However, adjustments in existing rules and regulations are necessary for organizations to work together cohesively on the issue. Lack of synergy among institutions is common in many parts of the world which hinders the direct and effective measures in implementing planned water reuse (Hassenforder and Barone, 2019; Nhapi and Gijzen, 2004; Reymond et al., 2020; Saldías et al., 2015). The outcome of this study could be taken as a basis for formulating necessary policy and regulatory frameworks in water-scarce delta countries globally.

6.3 Potentials and drawbacks of urban water reuse

Planned water reuse in agriculture offers both benefits and risks for the ecosystem, humans, crop health and the economy. The reuse is a suitable alternative for the regions confronted with the shortage of irrigation water either by physical or economic constraints. Water reuse presents great potential, especially in the areas with growing urban populations and depleted surface and groundwater resources caused by climate change. Reuse of water will further reduce the pressure of groundwater extraction and also extraction-related costs and energy consumption (Jaramillo and Restrepo, 2017; Toze, 2006). Most importantly, urban water can play a vital role in combatting against salinity in the delta areas, which is a limiting factor for supplying required irrigation water (Gude, 2017; Iglesias et al., 2007; Vargas-Amelin and Pindado, 2014). This is highly important for the Bengal delta as studies estimated that by 2050 the river area used for irrigation would decrease by 29.7 percent, which will also reduce agricultural production (Dasgupta et al., 2014a, 2014b). Considering the increased salinization, water reuse as an adaptation strategy to cope with water scarcity would ensure the continuous supply of required irrigation water (Gude, 2017; Iglesias et al., 2007).

The greywater and sealed surface runoff occurring in the study area would contribute significantly to meet the peri-urban irrigation demand and contribute substantially to the agricultural production in the region (*Chapter 2*). Increasing agricultural production through using alternative sources in the water-scarce regions will also contribute to food security (*SDG 2*). Direct discharge and salt intrusion highly influence the irrigation water quality restricting use in agriculture (*Chapter 3, 4*). Proper treatment of wastewater will improve the existing water quality as most of the chemical-physical, microbial and heavy metal contaminants would be reduced and an improved freshwater resource will be available for sustaining agricultural activities in the Bengal delta. In addition to that, ensuring proper treatment and reuse of urban water in agriculture prevents surface water pollution enabling financial gains for local governments (Hernández-Sancho et al., 2010; Jaramillo and Restrepo, 2017).

Planned urban water reuse also reduces the expenses related to fertilizer demand. Necessary macro and micronutrients are present in wastewater in levels which are beneficial for crop growth and prevents the emissions of these constituents, especially macro-nutrients, directly into the surface water bodies (Jaramillo and Restrepo, 2017). Governmental agencies should invest in necessary wastewater infrastructure to facilitate water reuse for food production instead of looking for alternative freshwater sources. This will result in pollution control and prevention of ecosystem destruction and, most importantly, promote both financial and environmental gains in the long run. Additionally, improvement of microbial water quality is vital for the people who work in crop production, especially the farmers, as they directly contact the polluted surface water.

Being aware of all benefits of reuse, planned water reuse still has not been widely practiced globally. The absence of necessary rules and regulations, lack of financial means for building wastewater infrastructure, potential environmental and health risks and perception of stakeholder groups hinder the implementation of planned reuse. For example, nutrients in wastewater provide fertilizer value to crop, but in excess can cause problems related to excessive vegetative growth, delayed or early maturity, or reduced crop quality (Ricart and Rico, 2019). The regular use of wastewater on the same agricultural field can also alter the soil's minerals, macro and micronutrients, pH, buffer capacity which can eventually impact the crop growth (Bañón et al., 2011; Becerra-Castro et al., 2015). Human and livestock-related pathogens, including antibiotic-resistant bacteria, can be transported into humans through regular contact with wastewater on a regular basis. The farmers who irrigate their field with wastewater, either directly or indirectly, can be infected with gastro-intestine illness due to accidental ingestion, inhalation (Drechsel et al., 2010; Gross et al., 2015; Jiménez and Asano, 2008). The use of polluted sources for irrigation can also restrict the market access of products (Wessels et al., 2019). While farmers are aware of the health risks associated with wastewater use, the lack of available alternative irrigation sources, fertilizer alternatives, the ease of use, and freely available polluted surface water motivates them to continue the current practice of unsafe reuse (*Chapter 4*).

Environmental or health-related risks can be minimized by implementing stringent guidelines. Several international organizations have formulated guidelines to ensure the safe reuse of wastewater, though the aims of developing the guidelines can become very broad (Ricart and Rico, 2019). For example, the World Health Organization (WHO) formulated guidelines focusing on health-related issues, whereas Food and Agriculture Organization (FAO) guidelines focused on the soil and crop yield. Even at a regional level, US EPA updated their guideline incorporating the recent advancement in treatment technology in support of safe reuse, whereas EU Water Directive indirectly recognizes reuse to increase water availability (Jaramillo and Restrepo, 2017; Paranychianakis et al., 2015; Ricart and Rico, 2019). However, the impact of guidelines depends on regular monitoring and strict enforcement. Each country tries to formulate its own standards based on international guidelines and similarly, Bangladesh also developed surface water quality standards, namely the Environmental Conservation Rules (ECR) in 1997. The ECR 1997 considers only basic parameters - pH, BOD, DO and Total Coliform to determine the surface water quality. Additionally, lack of trained human and financial resources are another limiting factor for not enforcing ECR against actors responsible for surface water pollution (*Chapter 5*). Regular monitoring and treatment of new emerging pollutants are missing even in the global North and also in the Bengal delta. These pollutants were not studied under this PhD but should be included in future studies considering the growing use and emissions of pharmaceuticals, personal care products and organic industrial chemicals.

Over the years the "Yuck Factor" has disrupted reuse policies worldwide (Ching, 2010; Marks et al., 2008). Though the urban water can technically be clean enough to be reused, the fact that reclaimed urban water originates from wastewater gets an instinctive rejection from many stakeholder groups (Ching, 2010; Garcia-Cuerva et al., 2016; Ricart and Rico, 2019; Smith et al., 2018). Nevertheless, the acceptance among consumer groups is also increasing as they also become more aware of climate change and its impact on water availability for agricultural activities (Dare and Mohtar, 2018; Ricart and Rico, 2019). In the study area, citizens perceived urban water reuse as a suitable and timely method to fight against the increasing salinity and lack of quality irrigation water sources (*Chapter 5*). Public trust towards reuse practices is essential as offering poor quality water would lead to long-term distrust among private/public agencies and consumers (Friedler et al., 2006; Hartley, 2006). Trust and transparency in implementation projects would be enhanced by providing necessary information through education, print and electronic media (Garcia-Cuerva et al., 2016; Ross et al., 2014).

6.4 Wastewater infrastructure and the need for proper treatment

Treatment of wastewater and its further reuse has multifaceted benefits of preventing environmental pollution, combating water scarcity, contributing to the utilization of resources (Fito and Van Hulle, 2020; Haldar et al., 2020; Yang and Abbaspour, 2007). To ensure the safe reuse of water, adequate treatment of effluents is essential. Conventional wastewater treatment systems are 85-90% efficient in BOD, N, P and TSS removal and used worldwide to produce dischargeable effluent according to prevailing quality standards (Caicedo et al., 2019; Hunter et al., 2019; Jelić et al., 2012). The traditional wastewater treatment system produces legally dischargeable effluents but often fails to deal with emerging pollutants such as pesticides, pharmaceuticals, pathogens and microplastics, which could play a role in the future (Fito and Van Hulle, 2020; Jelić et al., 2012). To tackle the emerging pollutants, wastewater treatment plants are equipping with advanced biological or chemical systems which can have a big variation (12.5-100%) in micropollutant removal (de Wilt et al., 2016; Falås et al., 2016; Luo et al., 2014; Margot et al., 2013). However, advanced treatment systems are often expensive and complex to operate and thus, developing countries rely on locally suited conventional treatment systems which removes micropollutants to a limited extent.

In many developing countries, wastewater infrastructure is relatively underdeveloped and communities mostly rely on on-site technologies such as pit latrines and septic tanks (Andersson et al., 2016; Qadir et al., 2010). A similar situation exists in the study area which is changing gradually with the set-up of local water supply and sewerage authority (KWASA). Building wastewater infrastructure requires investment from central government agencies, though often prioritizes other development activities (i.e. building roads and bridges) over wastewater infrastructure (Andersson et al., 2016; Thaher et al., 2020). Neglecting the investment in wastewater infrastructure can hinder the success of development initiatives as the absence of proper wastewater infrastructure leads to environmental pollution and affects the quality of living (Andersson et al., 2016). Nevertheless, the economic cost of technology also plays an essential role during the decision-making process (Molinos-Senante et al., 2014; Padrón-Páez et al., 2020). Finding a suitable technology at a low cost is common among the decision-makers as it ensures the proper utilization of financial resources. However, the selection of technology without considering the local factors, such as geographic condition (climate, water), available infrastructure (energy and water supply) socio-economic, political and institutional situations would hinder the successful implementation (Singhirunnusorn and Stenstrom, 2009).

6.5 Factors influencing the selection of suitable treatment technology

The centralized urban wastewater treatment system typically comprises of preliminary, primary and secondary levels of treatment and depending on the effluent quality requirement tertiary or quaternary level treatment is added, though it is not very common in practice (Figure 6.2). Preliminary treatment consists of screens to remove coarse solids and the gritters to remove sand and grit. In primary treatment consisting of sedimentation tank removes more settleable solids and parts of organic matter.

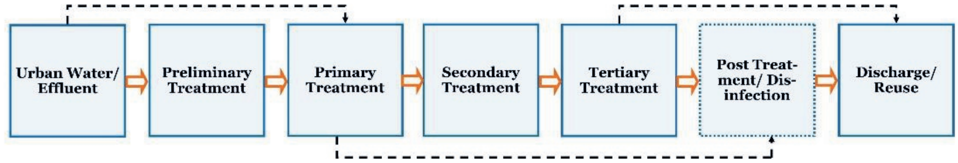


Figure 6.2: Generalized wastewater treatment stages

On-site technologies such as septic tanks do not require any preliminary treatment process and effluents are discharged after adequate disinfection (not very common) or percolated into the ground. In secondary treatment (for example, aerobic treatment), remaining organic matter is removed along with nutrients (N and P) and tertiary or quaternary treatment removes specific pollutants (e.g. pathogens) to make the effluent suitable for discharge or further use (Sperling and Lemos Chernicharo, 2005). However, tertiary treatment is often nonexistent in both developed and developing countries due to its high cost and complexity (Meena et al., 2019; Von Sperling and Augusto De Lemos Chernicharo, 2002; Zurita et al., 2012). The secondary treatment (i.e., reactor-based activated sludge system or semi-natural stabilization ponds and constructed wetlands) can remove most traditional pollutants from wastewater for further use in other sectors such as agriculture but requires large areas (Dell'Osbel et al., 2020; Hussien et al., 2020).

Adopting suitable wastewater treatment technology based on local conditions is vital to ensure the long-term sustainability of treatment systems. Previously, decision-makers of developing countries selected technologies based on the experience of developed countries, often ignoring the local contexts and this frequently resulted in failure due to high cost and operation complexity (Barnes et al., 2014; Murphy et al., 2009; Singhirunnusorn and Stenstrom, 2009; van Lier and Lettinga, 1999). As a response to such failure in technology selection, the concept of "appropriate technology" (AT) was first coined in the 60's (Murphy et al., 2009). Appropriate technology provides the best performance with the least cost and considers the local demands related to the environment, technology, institutional feasibility, and economic affordability (Singhirunnusorn and Stenstrom, 2009; Ujang and Buckley, 2002). Several factors influence the selection of appropriate treatment technology and these were reported in the literature and categorized into three broad aspects: socio-economic, environmental and technical (Figure 6.3).

Socio-Economic	Environmental	Technical
Initial Investment	Nutrient removal	Infrastructure
O&M costs	Micropollutant removal	Local climatic condition
Land (area) requirement	Resource recovery	Service area
Land price and availability	Sludge production	Reliability and Robustness
Social (public) acceptability due to cultural differences	Energy consumption	Complexity or Simplicity
Odour, noise, visual impact	GHG emission	Removal efficiency
Population growth	Reuse potential	Labour demand & availability

Figure 6.3: Factors influencing the selection of treatment technology reported in literature

Socio-economic factors play an essential role in selecting appropriate treatment technology. Among other factors, initial investment costs, operation and maintenance costs, price and availability of required land space and social acceptability plays a pivotal role in implementing wastewater treatment system (Arias et al., 2020; Dell'Osbel et al., 2020; Gherghel et al., 2020; Molinos-Senante et al., 2014; Padrón-Páez et al., 2020; Rathnaweera et al., 2020; Sun et al., 2020; Thaher et al., 2020; Woltersdorf et al., 2018). Decision-makers often look for the best treatment technology with the least financial cost involved using cost-benefit analysis tools in the decision-making process, often neglecting the voice of the general public (Molinos-Senante et al., 2014; Padrón-Páez et al., 2020; Sun et al., 2020). The negative attitude of the general public towards the treatment system due to the negative association with waste treatment and associated odor, noise and visual impacts can delay the implementation of treatment systems (Meena et al., 2019; Molinos-Senante et al., 2015; Muga and Mihelcic, 2008). Due to the growing consequences of anthropogenic activities on climate change and the growing importance of a circular economy, environmental factors such as greenhouse gas emissions, energy consumption and sludge production are becoming crucial to the decision making process (Arias et al., 2020; Dell'Osbel et al., 2020; Gherghel et al., 2020; Kamble et al., 2019; Meena et al., 2019; Su et al., 2019). As a result, newly designed treatment technologies should consume less energy or even produce energy, emit less greenhouse gases and generate less sludge (Arias et al., 2020; Lin et al., 2016; Meena et al., 2019).

The countries with already developed wastewater infrastructure are successfully removing traditional contaminants to the levels required by the standards are now transitioning towards more efficient treatment systems that facilitate resource recovery such as water, energy, gas, nutrients (N and P), cellulose (paper), Volatile Fatty Acid (acetate, propionate) for potential market supply (Kehrein et al., 2020). Micropollutant removal from the waste streams has been gaining attention as an important step in wastewater treatment systems in developed countries. These pollutants were considered to be a minor factor as the developing countries still lack the basic wastewater infrastructure (Arias et al., 2020; García-Galán et al., 2020). Water circularity reduces the negative impact on the natural environment and thus, planned water reuse potential and resource recovery have gained broader recognition in the recent past with a new series of advanced treatment technologies and systems (Dell'Osbel et al., 2020; Gherghel et al., 2020; Harris-Lovett et al., 2018; Lin et al., 2016; Singhirunnusorn and Stenstrom, 2009; Woltersdorf et al., 2018).

Simple, reliable, robust and yet less complex wastewater treatment systems would be more appropriate for developing countries to ensure long-term functioning and minimized specialized labor force, cost and energy demand (Rathnaweera et al., 2020; Singhirunnusorn and Stenstrom, 2009). Factors such as service area, labor demand and availability should also be considered before selecting a treatment technology (Arias et al., 2020; Kalbar et al., 2013; Muga and Mihelcic, 2008; Rathnaweera et al., 2020). Nature-based treatment systems such as different types of constructed wetlands or stabilization ponds tend to perform better in a warm climate than the cold climate, thus, are more suitable for tropical regions (Su et al., 2019). Climatic conditions influence the removal efficiency of the biological and natural treatment system, meaning that consideration of the local climate should be prioritized (Dell'Osbel et al., 2020; Kalbar et al., 2013; Rathnaweera et al., 2020; Thaher et al., 2020). Designing wastewater treatment systems considering technical as well as social and organizational factors would facilitate the design of socio-technological solutions well suited for the local context (Baxter and Sommerville, 2011).

6.6 Scenarios of Socio-technological solutions for the treatment of urban water and reuse

Several approaches have been practiced globally for scenario planning and four quadrants matrix is known as the minimal approach used for designing socio-technological scenarios (Amer et al., 2013; Lindgren and Bandhold, 2003). This scenario planning method is also known as the double uncertainty or 2 x 2 matrix approach (Amer et al., 2013). This is the dominant method for scenario building, considering two driving forces (uncertainties) or factors that can simulate future developments from which four scenarios are drawn (Amer et al., 2013; Lindgren and Bandhold, 2003; Pillkahn, 2008;

Schwartz, 2012). The selection of these two driving forces that complement each other in a scenario quadrant is crucial in portraying the scenarios (Lindgren and Bandhold, 2003). Population growth, rapid urbanization, economic growth, climate change, resource demand are some examples of driving forces. The selection of driving forces for this study will be based on the existing situation in the Bengal delta.

Over the years, Bangladesh has been suffering from water scarcity and severe water pollution due to a lack of adequate wastewater infrastructure (Abedin et al., 2019, 2014). During the last decades, the country had significant economic progress with annual GDP growth between 4.1% and 8.2% since 1992 (except for 2020 and presumably 2021 due to Covid-19) which helped to gain the status of a lower-middle-income country in 2015 and by 2026, Bangladesh is expected to leave from the UN's Least Developed Countries list (IMF, 2021; WB, 2021). The growing demand for water in industrial and agricultural activities has led to the increased pollution of surface and groundwater (Datta et al., 2020; Islam et al., 2011; Khan et al., 2011; Pramanik and Sarker, 2013). Thus, proper treatment of wastewater is necessary to protect the surface waters and provide much-needed irrigation water for sustaining food production in the Bengal delta. Additionally, treatment and reuse of urban water in agriculture would enable circular water management, improving environmental sustainability. For implementing such a system, four types of barriers: technological, market, institutional and cultural need to be overcome (Grafström and Aasma, 2021). *Chapter 2* of this thesis has pointed out the potential of urban water in matching irrigation demand (market) whereas *Chapter 5* sheds light on the institutional and cultural aspects of urban water reuse. *Chapter 3 and Chapter 4* have shown that the existing poor surface water quality is affected by the discharge of untreated effluents and the water quality can be improved through proper treatment. Results from Chapters 2-5 have been used to formulate socio-technological scenarios for treating urban wastewater to be used in agriculture (Figure 6.4).

Simulating scenarios for socio-technological solutions based on driving forces is useful to identify the potential technological aspects of urban water reuse. Economic growth and the demand for quality water have been used as driving forces to formulate scenarios (Figure 6.5). This is based on Bangladesh's current economic progress trajectory and the threat of climate change towards water availability in adequate quality and quantity. Assumptions are also important in scenario planning as these facilitate the environment for creating realistic futuristic scenarios (Peterson et al., 2003; Stewart et al., 2013).

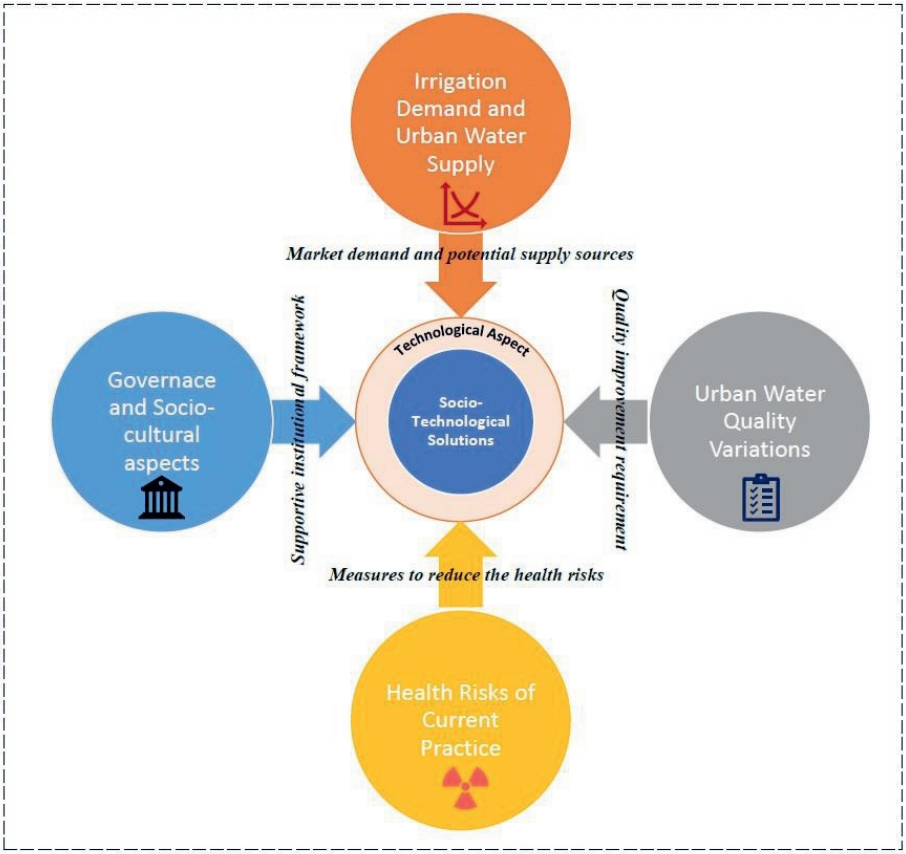


Figure 6.4: Integration of different aspects in socio-technological scenario generation

The following assumptions were considered as a pre-condition for developing scenarios:

a) There is a continuous demand and supply of urban water for agricultural activities due to natural and man-made impacts on the availability

b) The necessary conveyance infrastructure for urban water collection is present to supply the water to the agricultural area

c) Mandated regulatory and institutional frameworks support the planned urban water reuse

d) The stakeholder groups are well informed regarding the benefits of urban water reuse and there is continuous communication of information to hold the positive attitude

The high and low end of economic growth and high and low demand for good quality water are placed across the axis and four scenarios namely **Golden Scenario, Green Scenario, Red Scenario** and **Grey Scenario** are identified (Figure 6.5).

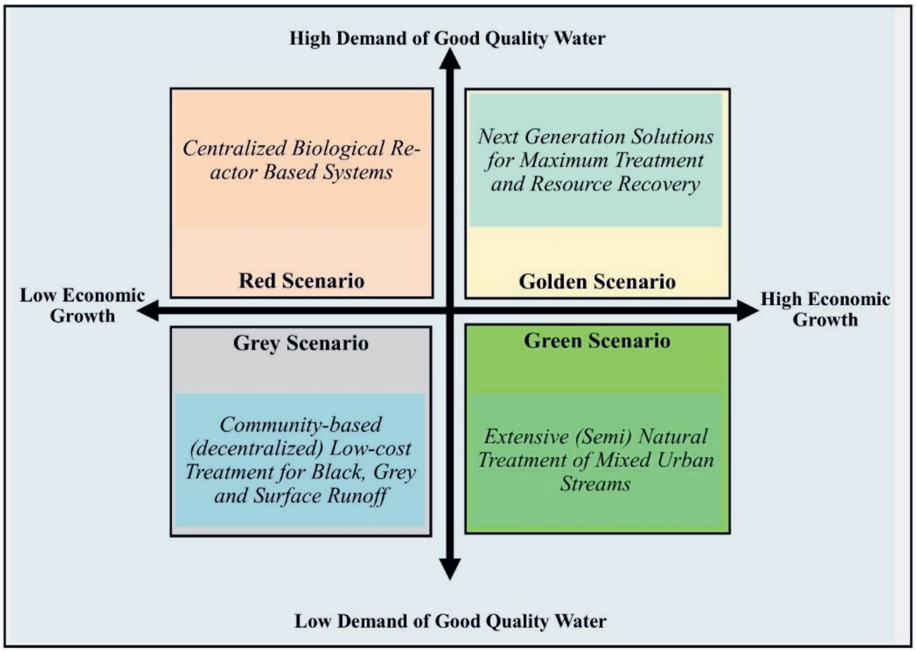


Figure 6.5: Socio-technological scenarios enabling urban water reuse

Under "**Red Scenario**", the economic growth would be rather slow and thus traditionally mechanized, biological treatment systems such as suspended growth Activated Sludge (AS) or attached growth biofilm reactor such as MBBR or Trickling filter system would be implemented with the help of external funding sources (Figure 6.6). This situation is evident from the previous planning of establishing an AS based treatment plant in the study areas with the help of the Asian Development Bank (ADB, 2011; KWASA, 2016). AS is a widely used technology and uses microorganisms to treat wastewater under aerobic conditions (Sperling and Lemos Chernicharo, 2005). The conventional AS system comprises the aeration tank and secondary sedimentation tank and excess sludge is removed to process further to be reused or disposed of. The AS system has high reliability in removing traditional macro-pollutants such as organic matter (COD/BOD), suspended solids, nutrients (N, P) and pathogens (to a certain extent) from wastewater and is not extremely complex to operate; thus suited to the local contexts (Kalbar et al., 2013; Rathnaweera et al., 2020).

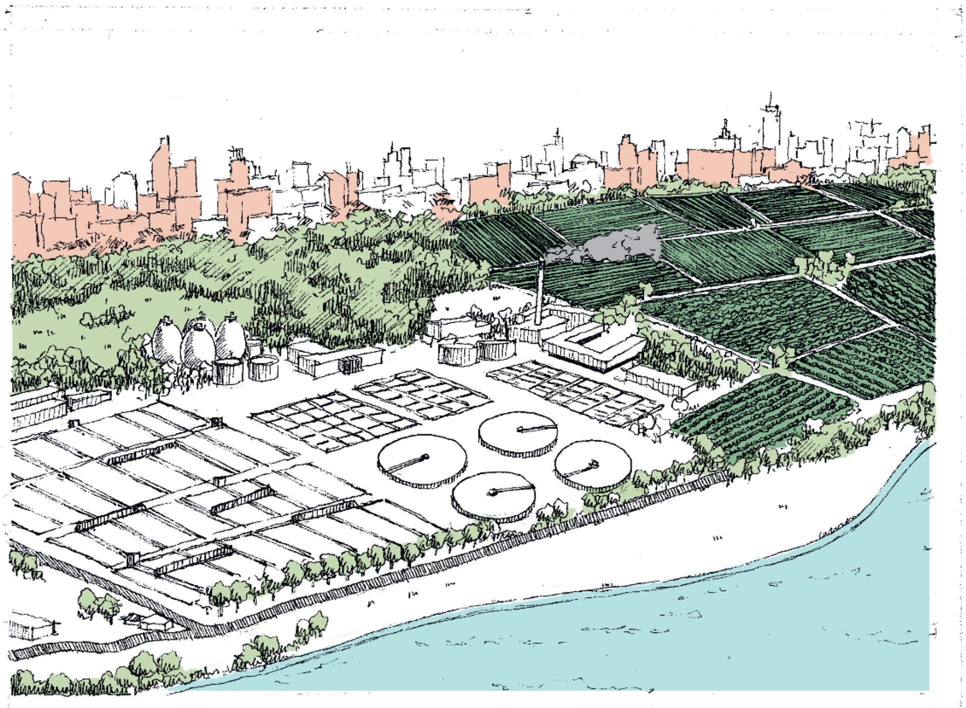


Figure 6.6: Artistic illustration of Red scenario focusing centralized solution

However, the AS system is energy-intensive and produces a high volume of sludge and some odor which could be a nuisance for the people living in the nearby areas (Kalbar et al., 2013; Kamble et al., 2019; Meena et al., 2019; Su et al., 2019). On the contrary, the MBBR uses the same principle as AS but by growing biomass in suspension but adhering to carrying material (biofilm) and a one-stage or multiple-stage system. MBBR consists of an activated sludge aeration system and can be an alternative to conventional AS systems due to the similar performance at a lower cost (Andreottola et al., 2000; Oliveira, 2014). Thus, MBBR would also be a feasible solution for the context of the study area.

Under a "**Grey Scenario**", the region's economic growth will still be low and thus, any (semi) expensive technology would not be feasible to build or operate. The focus will be on further expansion and improvement of community-based (decentralized) low-cost treatment of black, grey and surface runoff (Figure 6.7). Additionally, nature-based technologies such as constructed wetland (CW) or stabilization pond systems (PS) can also be implemented if the required space remains available and affordable. Rapid and unplanned urbanization will make it challenging to find space within the core urban area.

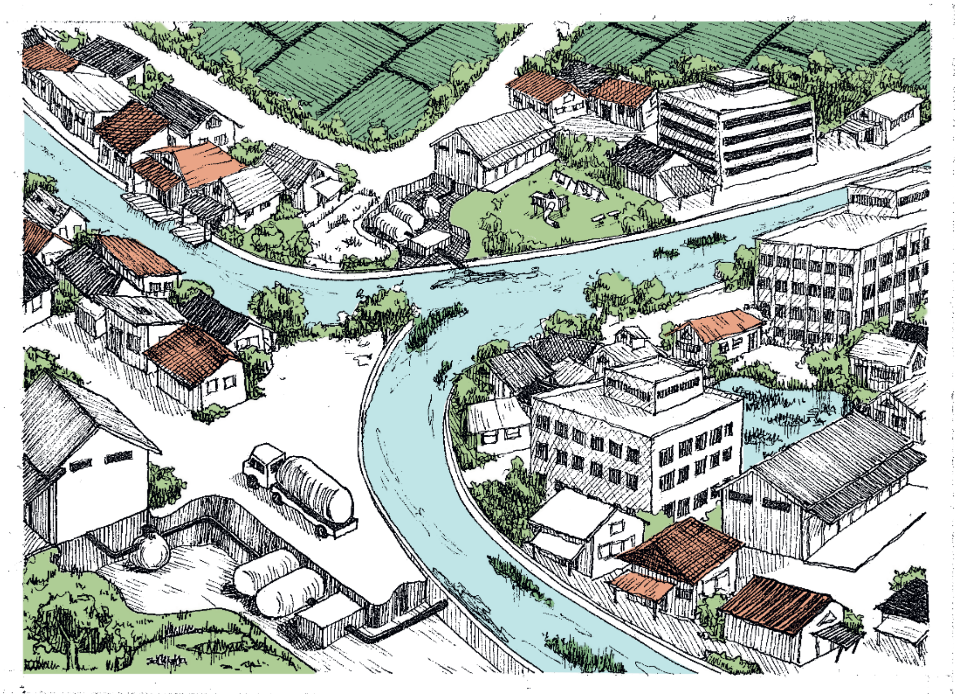


Figure 6.7: Artistic illustration of Grey scenario focusing community-based solution

The peri-urban areas could be alternative to address the shortage of space as the treated water would then be easily supplied to the adjacent agricultural areas. The city dwellers of the study area are currently using individual septic tanks (ST) for blackwater and under low economic growth, this trend could expand further. In ST the settling occurs and partial anaerobic digestion provides the efficient primary treatment. ST's are used worldwide, especially in areas whereas the basic sewer system is absent (Su et al., 2019; Tilley, 2014). The ST is a low-cost, simple technology requiring minimal labor and no sewer system and has moderate (around 50% depending on the temperature) pollutant removal efficiency (Goel and Kansal, 2020; Moussavi et al., 2010; Su et al., 2019). The use of a small-scale ST system upgraded to an anaerobic treatment system, or even bio-digester to also include feacal solids and biowaste to generate biogas has gained popularity in Bangladesh in the last decade (Kabir et al., 2013; Khan and Martin, 2016; Nasiruddin et al., 2020). A Bio-digester typically has an airtight chamber to provide anaerobic digestion to blackwater and could be a more efficient alternative to ST for serving a bigger community (Tilley, 2014). Under low economic growth, investment in wastewater infrastructure would be limited; thus, the focus on small-scale community-based technologies would still provide some form of treatment to the effluents.

The Bangladesh Delta Plan 2100 formulated futuristic strategies considering the country's economic growth potential and emphasized the treatment of wastewater and recovery of resources. Thus, under a **"Golden Scenario",** advanced wastewater treatment systems would be a justifiable solution to address the climate change impact on irrigation water availability (Figure 6.8). The region will have a high demand for good quality irrigation water due to natural or anthropogenic causes. Under this scenario, the favorable economic conditions would finance the next generation, innovative, advanced solutions focusing on extensive treatment enabling pollution control and resource recovery.

Advanced wastewater treatment technologies, for instance, intensified biological systems (e.g., Membrane Bioreactor (MBR), granular sludge technology UASB, Nereda) followed by chemical-physical oxidation techniques (e.g., ozone treatment, UV, advanced oxidation, membrane filtration) could be implemented to attain a high level of treatment efficiency (Høibye et al., 2008; Kehrein et al., 2020; Wenzel et al., 2008). For example, MBR combines biological-activated sludge process and membrane filtration removing COD, Nitrogen and Phosphorous and can also successfully remove 99.9% of the microplastics with smaller fraction size (20-100 μm) and has higher pathogen removal efficiency compared to the conventional AS system (Radjenović et al., 2008; Talvitie et al., 2017).

Similarly, Nereda, anaerobic granular biomass-based technology, has been gaining attention in the recent past and has the potential to expand due to compactness, low energy consumption, less capital and operation costs and high (>90%) organic removal efficiency (Guo et al., 2020; Khan et al., 2015; van der Roest et al., 2011). UASB technologies may be feasible to combine energy production (Biogas) with waste and wastewater treatment for sludges and high COD waters from septic tanks or industries. For tertiary or post-treatment, ozonation is an important technology for the removal of organic micropollutants, such as pharmaceuticals, pesticide residues, personal care products and pathogenic microorganisms and could be used to maximize the treatment efficiency (Carballa et al., 2007; Chen et al., 2012; Ikehata et al., 2006; Snyder et al., 2006).

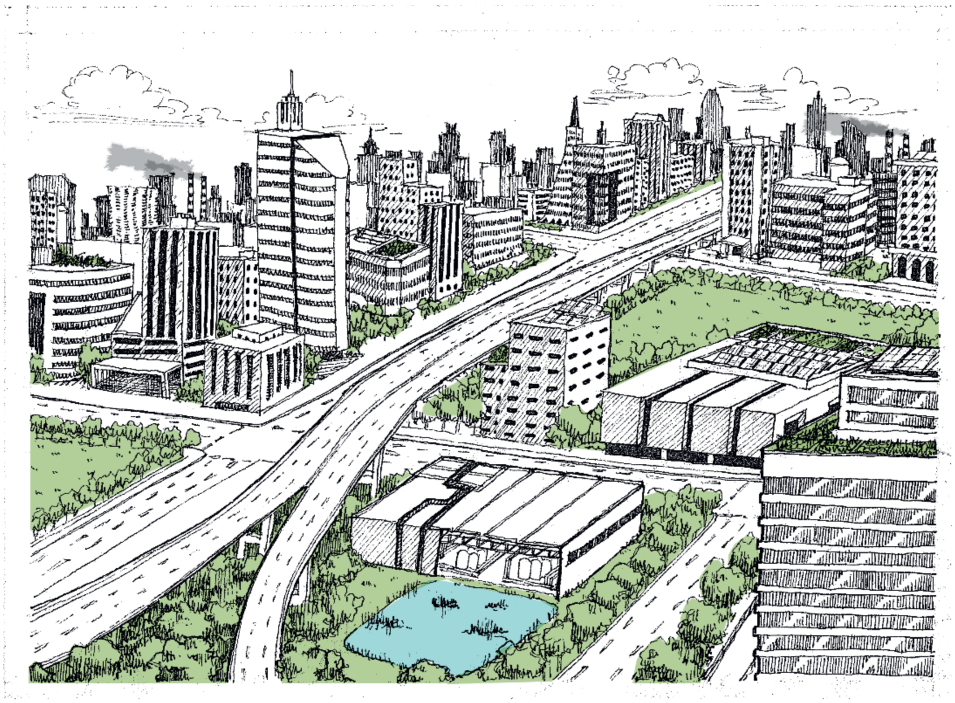


Figure 6.8: Artistic illustration of Golden scenario focusing advanced solutions

Under the "**Green Scenario**", nature-based systems such as constructed wetland (CW) or stabilization pond systems (PS) could be implemented to provide semi-extensive treatment for mixed urban streams (Figure 6.9). CW is engineered vegetated natural treatment technologies, generally suitable for small- to medium-sized communities or as a polishing step of effluents of advanced treatment systems. CWs are aquatic-based systems composed of shallow basins and can have free water surface or sub-surface flow. In CW, water slowly flows through the wetland and the particles settle on the bottom of the wetland while pollutants (COD, nutrients, micropollutants), including pathogens, are removed. The plants utilize the nutrients from the water and can – when smartly designed- also be used for commercial plant productions (Mara, 2013; Sabri et al., 2021; Sithamparanathan et al., 2021; Tilley, 2014).

The PS systems, commonly found in countries with warm climate (García-Galán et al., 2020; Molinos-Senante et al., 2012; Zurita et al., 2012) also use natural process (e.g. sedimentation, UV-radiation from sunlight, algal-bacterial symbiosis) to treat wastewater, i.e. removing COD, nutrients, micropollutants and pathogens, but this is often less efficient and stable as advanced treatments of the golden scenario.

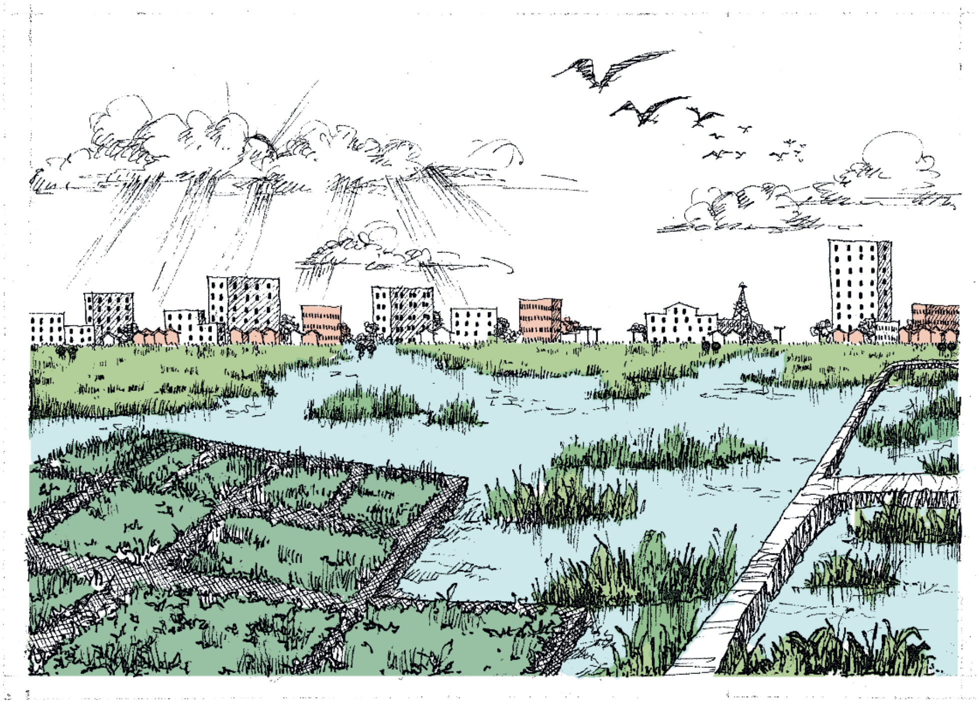


Figure 6.9: Artistic illustration of Green scenario focusing nature-based solution

The PS and CW also provide storage, crucial for matching temporal disbalances in water supply (effluents) and use (agriculture). Both of these systems have a low environmental impact, require little conveyance system and gives a positive visual impact if operated well (Dell'Osbel et al., 2020; Molinos-Senante et al., 2014; Su et al., 2019; Sun et al., 2020). These solutions have high land area requirements and would be suitable under high economic growth and lower good quality water demand (Hussien et al., 2020; Molinos-Senante et al., 2014; Sun et al., 2020).

6.7 Reflection on the socio-technological solutions for the Bengal delta

Socio-economic, environmental and technical factors play a crucial role in the decision-making process related to the selection of wastewater treatment technology (Molinos-Senante et al., 2015, 2014; Su et al., 2019). The economic factors, such as initial investment, operational and maintenance cost, seem often to be the main limiting factor for adopting advanced technology as wastewater treatment is a low priority and receives little investment (Andersson et al., 2016; Zhang et al., 2014). The recent success in economic growth of the region encourages to adopt appropriate technology that contributes to the overall pollution control and facilitate resource recovery for the local market. However, in case of economic constraints adopting to nature-based technology (if adequate space is available) such as constructed wetland or pond based system would be more appropriate as these provide the required treatment to make the wastewater reusable in agriculture and suits well with the climate (Mustafa, 2013; Zhang et al., 2014). On the contrary, the developed countries adopted more advanced system as minimizing the environmental and social impact, maximum removal efficiency, circularity potential and the robustness of the system outweigh the associated economic costs (Molinos-Senante et al., 2014). During this trade-off, reaching a higher removal efficiency (to match the quality guideline) is often regarded as more important than minimizing greenhouse gas production, sludge production and high energy demand (Molinos-Senante et al., 2014; Padrón-Páez et al., 2020). The importance of institutions and policies in the decision-making process related to wastewater treatment technology selection would also be an integral part of the successful implementation in the Bengal delta. In many developing countries existence of weaker institutions often limits the implementation of proper wastewater treatment technologies (Andersson et al., 2016; Møller et al., 2012). Thus, the technological solutions should always be supported by required rules and regulations, public support and the market demand for water reuse in the region.

6.8 Inter-sectorial partnership for successful implementation of water reuse

Sustainable urban water management requires an integrated, adaptive, resilient, coordinated and participatory approach (Brown and Farrelly, 2009). A transition from a technocratic urban management style to an adaptive and participatory style was adopted in the 70's in several climate-vulnerable delta areas (Loorbach and Rotmans, 2006; Wen et al., 2015). Governance of urban water management, including policies and regulatory framework and stakeholder involvement and collaboration, are crucial for wider adoption of urban water reuse (Frijns et al., 2016). However, complexities related to sustainable urban water management at the institutional level are often faced due to interdisciplinary, inter-organizational settings and thus, institutional changes over structural rearrangement are favored (Briassoulis, 2004; Frijns et al., 2016; Mitchell, 2005).

Similar complexity already exists in the study area as several organizations are responsible for the different components related to urban water. In addition to that, limited cooperation on the decision-making process, shifting responsibilities to other organizations, specific working areas have polarized the water governance responsibilities (*Chapter 5*). This points out the need for a transition favoring intersectoral collaboration and partnership among all sectors, including governmental agencies, knowledge institutions, industries. A partnership at city or regional level where representatives of local councils (mayors, councilors), officials of governmental and non-governmental organizations, representatives of the relevant stakeholder groups (farmers, market vendors, citizens) should be formed to formulate strategies to be implemented in the area. The partnership would bring all the involved parties under one umbrella where trust, continuous economic support and incentives for participation would be ensured to overcome the existing barriers in urban water management (Österblom and Bodin, 2012; Waddell and Brown, 1997). Involvement of root-level stakeholder groups such as farmers, market vendors will increase trust towards policymakers and institutions, improving the public acceptance of water reuse projects (Dolnicar et al., 2011; Frijns et al., 2016; Hartley, 2006).

6.9 The future of peri-urban agriculture

The agricultural activities in urban and peri-urban areas significantly reduce poverty and increase food supply in urban areas by providing around 10% of the total global food supply (Brinkley, 2012; Graefe et al., 2008; Opitz et al., 2016). Especially in developing countries, peri-urban agriculture plays an important role as a coping strategy for food security and income generation (Thornton, 2008). However, the growing pressure to accommodate the rapid urbanization, industrial activities and related infrastructural development renders peri-urban agriculture at risk (Gomes and Hermans, 2018; Vij and Narain, 2016). Peri-urban areas of the global South are continuously being transformed into urban infrastructure and thus, conflicts over the resources (land-use, water use) are increasing (Narain et al., 2013; Prakash et al., 2011). The peri-urban areas of Khulna city are also facing a similar trend and gradually, these areas would transform into urban areas to meet the growing demand for urban and industrial in the coming decades. This kind of unplanned transformation puts pressure on natural resources and threats to the ecosystem. Thus, planned urbanization is essential for reducing water pollution resulting in better water quality.

The reduction of peri-urban agricultural activities will lead to importing food from more distant areas, leading to a higher footprint for the products and reduced economic activity for the peri-urban population. The agricultural regions of the peri-urban area provide a green barrier between urban and rural settings. Conversion of peri-urban agricultural areas will bring pollution from the urban areas to the agriculture of the rural areas. This will spread issues such as urban heat island into the rural setting and affect the rural quality of life. Planned urbanization where optimum utilization of existing urban lands is ensured could prevent the current conversion of peri-urban agricultural areas. Thus, formulating and enforcing regulations in preventing water pollution even at an individual level would be necessary to safeguard the agricultural activities of Bangladesh.

6.10 Narrative of delta plans and pathways to reuse

The increased level of uncertainties regarding the future of the delta areas as a result of climate change has motivated the formulation of a renewed Delta Program in the Netherlands (Minkman and van Buuren, 2019). The program aims to become climate-proof and water-resilient by 2050 in terms of flood risk management, freshwater supply and spatial planning (Rijkswaterstaat, 2021). As the country battles with the drought and freshwater supply, especially during summer, the delta program aims to create additional water retention areas and use of alternative freshwater sources such as urban water reuse. Similarly, considering the long-term challenges posed by climate change and natural disasters, the Government of Bangladesh took the initiative to formulate a long-term Bangladesh Delta Plan 2100 (GoB, 2019).

The BDP 2100 divides the country into six geographical hotspot areas and provided a holistic water resource management plan. Urban water reuse is one of the key elements of that plan. It is foreseen, that in case of no action, further deterioration of surface water quality will occur by salt intrusion, industrialization and rapid urbanization and realizing that, a priority has been given to efficient use of urban water resources. Reuse of treated wastewater and recovery of necessary nutrients and energy has been included as a preferred strategy for balancing supply and demand for sustainable and inclusive growth of the delta areas. Also, to enhance water security and water use efficiency by promoting recycling and safe reuse of water with the appropriate technology has been recommended as a short-term and long-term measure in the country. In addition to that, facilities for small- and large-scale rainwater harvesting, improving surface water quality by reducing pollution, investment in fecal sludge management have been drafted in the BDP 2100 to ensure the sustainable urban water management of the country. Institutional reforms, including enhanced collaboration and coordination among different agencies, involving local level stakeholders, private sector and cost recovery policies related to water supply and sanitation infrastructure have been recommended to achieve the goal. In addition to the water management issues, the BDP 2100 also penned down the associated issues such as sustainable land-use and spatial planning, investment planning, governance and institutions to attain an integrated impact of the plan.

Similar strategies have also been found in the Mekong Delta Plan formulated for Vietnam. Mekong Delta Plan has recommendations like using the mangrove forest areas as a natural wastewater treatment system for the aquaculture sector. Installation of wastewater treatment systems to improve the surface water quality has been added as a priority measure in the Mekong Delta Plan. This indicates the enhanced awareness among the decision-makers regarding the necessity of proper wastewater treatment and the hidden potential of urban water reuse. Adopting strategies related to urban water reuse will improve surface water quality and reuse of urban water in different sectors in the coming days.

6.11 Limitations of current research and future research outlook

Results from this research will serve as a basis to understand the urban water reuse potential in similar climate-vulnerable delta regions of the world. Results have shown that quantitatively it is possible to meet the peri-urban irrigation demand with urban water under the condition it is properly connected, treated and stored. However, related specific issues such as matching the quantity with quality at a smaller time scale, the choice of technology in relation to the required level of treatment to remove pollutants, deposition of micro/macro nutrients on soil and the subsequent impact on crop growth and above all the financial suitability need to be investigated and validated through field demonstration and implementation projects.

6.11.1 Matching quantity and quality of water at a smaller time scale

This research provided a baseline to understand the unacknowledged potential of wastewater. Chapter 2 demonstrated that quantitatively, it is possible to meet the peri-urban irrigation demand with urban water and the research was only focused at a seasonal level (month). However, it is vital to explore the actual need with actual supply at a given moment. For that's why, the follow-up research should focus on matching demand and supply at a smaller spatio-temporal (day, week) and necessary storage requirements. The optimum location to store the treated water to supply in agriculture when required should also be investigated. Additionally, Chapter 3 showed a varied spatio-temporal water quality that is unsuitable for irrigation based on FAO guidelines. Maintaining adequate quality to meet the irrigation standard all around the year is a challenge and should be investigated further.

6.11.2 Infrastructure planning

Infrastructure facilitates the supply of urban water to match the demand and plays an important role in implementing reuse. Hotspot analysis was used to identify the areas with high greywater generation that could be considered to design the city's infrastructural plan. That plan should include networks for collecting wastewater at a minimal cost, suitable site selection for setting up the treatment plants, suitable sites for storing rainwater and related effluents. The effectiveness of the proposed technological solutions should be investigated based on a field experiment.

6.11.3 In-depth QMRA

Risk assessment is an important step in risk management. It was evident that there are health risks related to the current practice of indirect wastewater irrigation (*Chapter 4*). This conclusion was based on one microbial parameter (E. coli). To understand the actual risk, an in-depth QMRA for all stakeholder groups in the chain such (farmer, farmer's family, market vendor, consumer) should be carried out. Also, the contamination by emerging pathogens including viruses should also be investigated to develop a comprehensive risk assessment to provide necessary information to the decision-makers to adopt much-needed risk mitigation strategies.

6.11.4 Detail analysis of soil, sediment, crop

In this research attention was given to the selected chemical-physical, microbial and heavy metal parameters for understanding surface water quality. With the changes in lifestyle, new and different types of pollutants are emerging in the water bodies. Water samples should be analyzed to identify the presence of pharmaceuticals, personal care products, pesticides and any emerging microbial contaminants. In addition to that, the accumulation in soil, sediment and crop needs to be tested to understand the full spectrum of heavy metal contamination.

6.11.5 Financial modeling and innovations in governance

Urban water reuse seems an attractive solution for addressing the current seasonal water demand by peri-urban agriculture. However, implementing such reuse schemes requires a large investment in infrastructure for treatment, storage and supply. A detailed cost-benefit analysis (CBA) with possible financial implications for the local agencies, urban dwellers, farmers need to be performed before recommending any project. Additionally, the challenges and opportunities of innovations in the governance aspects to address the new and emerging issues of urban water should be studied in detail.

6.11.6 Existence of peri-urban agriculture

Due to the pressure of the expansion of the urban areas, peri-urban agriculture in developing countries is under threat. In addition to that, the industrialization of the agricultural sector has put pressure on small-scale farmers globally. Thus, the future of peri-urban agriculture hangs by a thread and needs further study. The long-term implications of the conversion of peri-urban agriculture into built-up areas would shed light on the actual contribution of peri-urban agriculture. In addition to that, the impact on the farmer and his socio-economic status due to the loss of agricultural areas could reinstate the necessity of peri-urban agriculture in a broader context. In case of existential threat to peri-urban agriculture, the role of intensified urban agriculture could be investigated to fill the void of peri-urban agriculture.

6.12 General Conclusion

Climate change, saltwater intrusion and rapid urbanization will threaten the freshwater availability for food production in the delta areas. Peri-urban agriculture of the global South substantially contributes to the food production and income generation for farmers living on the edge of the urban area. With the growing population in the urban areas, the demand for food and resources will also increase rapidly. On the other hand, per-urban areas will be disappearing and agricultural activities will be pushed to the rural areas. Urban water generated from the city's residential areas presents an opportunity to fulfill the irrigation water demand of peri-urban agriculture. Under different urban water generation scenarios, urban water can satisfy the seasonal irrigation demand if necessary, infrastructures for collection, treatment and distribution are in place. However, to make urban water reusable in agriculture, existing water quality poses a more significant challenge. Currently, urban water is dumped into the surface water bodies without any treatment and deteriorates the surface water quality. The peri-urban farmers are dependent on the surface water for irrigation during the dry period and the use of polluted surface water poses severe health risks for them as they do not use any protective equipment during irrigation. Heavy metal concentrations in surface water are still within the FAO recommendation limit but require attention considering the current economic growth of the region.

Considering the uncertainties around the future provision of freshwater supply, planned urban water reuse is a preferred alternative among the major stakeholder groups. The use of urban water in a planned manner will contribute to the enhanced livelihood for the farmers as they will be able to produce food and for citizens benefitting from the sustained food provision from the nearby areas. However, to make urban water reuse a reality, existing water quality needs to be improved with the help of proper treatment. In addition to appropriate treatment, supporting infrastructure for the appropriate collection, storage and re-distribution needs to be established. Depending on the desired water quality and economic condition of the region, different technological interventions are possible. Technological interventions also need to be supported with the proper regulatory framework, which is absent. Agencies that work in the field related to urban water also need to enhance inter-collaboration to stop the polarization of responsibilities. And most importantly, the end-users, such as urban dwellers, farmers also need to be involved in the decision-making process.

This research has indicated that urban water can be an attractive and timely alternative for sustaining food production in the water-scarce delta regions. Infrastructural measures supported by adequate institutional, environmental and economic incentives are crucial for implementing the reuse projects. Overall, a positive mindset towards urban water reuse among all stakeholder groups is necessary to attain the benefits of reuse. The future world needs to adapt to alternative resource management strategies like planned urban water reuse to sustain food production in the delta areas to maintain the quality of life.

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Supplementary Materials

Supplementary materials related to Chapter 2

Table i: Crop related values used for AquaCrop simulation

Parameter	**Unit**	**Value**
Transplantation date	-	1st January
Initial canopy cover, CC_o	%	6
Canopy size transplanted seedling	cm^2/plant	6
Maximum canopy cover, CC_x	%	95
Time to recover	DAT[1]	7
Time to the maximum canopy	DAT	69
Time to senescence	DAT	72
Time to maturity	DAT	98
Time to flowering	DAT	68
Duration of flowering	days	9
Maximum effective rooting depth	m	0.38
Time to reach the maximum effective rooting depth	DAT	45
Reference harvest index, HI_o	%	50

Table ii: Projected Urban Population of Khulna in 2018

Ward No.	**Area (sqm)**	**Population in 2001**	**Population in 2011**	**Projected Population in 2018**
1	1874508	20311	18900	17003
2	2073485	18815	13790	12406
3	3815439	23016	21821	19630
4	2027177	14299	15780	14196
5	821580	15314	14835	13346
6	2274131	20995	20734	18652
7	456868	14808	10645	9576
8	954455	18545	9308	8374
9	3590221	34614	31882	28681
10	849269	18518	27947	25141
11	388992	19398	12373	11131
12	700960	52036	21208	19079
13	1163808	19959	9287	8355

[1] Days after transplanting

14	2722414	26444	26335	23691
15	1441326	25724	16314	14676
16	2310209	35881	29213	26280
17	2343709	30352	33163	29834
18	1686973	16765	27896	25095
19	499278	26321	18558	16695
20	500492	22539	16624	14955
21	1434085	24984	20220	18190
22	664944	21633	17239	15508
23	513840	18332	13793	12408
24	1543370	42959	37889	34085
25	748312	27106	21274	19138
26	667829	18087	21011	18902
27	841211	31489	30265	27227
28	742027	22404	20148	18125
29	666403	20431	17763	15980
30	1188082	35827	33283	29942
31	3684241	32592	33844	30446
Total	45189635	**770498**	**663342**	**596748**

Table iii: Significance interval used for hotspot analysis

Z Score	P Value	Confidence Interval
<-1.65 or >+1.65	<0.10	90%
<-1.96 or >+1.96	<0.05	95%
<-2.58 or >+2.58	<0.01	99%

Table iv: Month-wise rainfall (mm) in Khulna city (Source: BMD, 2019)

Month	**‘02**	**‘03**	**‘04**	**‘05**	**‘06**	**‘07**	**‘08**	**‘09**	**‘10**	**‘11**	**‘12**	**‘13**	**‘14**	**‘15**	**‘16**	**‘17**	**‘18**
January	15	0	0	15	0	0	66	1	0	0	66	1	0	41	0	0	1
February	0	0	0	0	0	54	36	6	2	1	18	7	24	35	97	2	2
March	14	155	7	148	5	14	48	10	14	16	1	19	5	28	5	59	4
April	74	63	85	43	19	92	36	23	21	28	52	62	0	107	54	99	68
May	254	125	180	215	230	119	151	130	146	145	63	430	118	128	350	200	231
June	846	251	383	102	262	374	190	233	287	381	255	212	447	318	353	356	272
July	360	287	253	435	522	591	301	347	180	387	391	313	394	922	413	690	271
August	483	255	266	194	364	160	202	568	205	614	254	482	258	353	646	313	115
September	357	145	621	410	579	397	379	357	157	367	374	278	205	293	148	175	115
October	22	315	183	420	79	197	187	111	332	3	89	260	10	83	81	322	46
November	169	0	0	0	1	113	0	20	0	6	80	0	0	3	75	19	11
December	0	22	0	0	0	0	0	0	13	0	2	0	0	6	0	51	15
Total	**2594**	**1618**	**1978**	**1982**	**2061**	**2111**	**1596**	**1806**	**1357**	**1948**	**1645**	**2064**	**1461**	**2317**	**2222**	**2286**	**1151**

Table v:Month-wise average maximum temperature in Khulna city (Source: BMD, 2018)

Month	**‘02**	**‘03**	**‘04**	**‘05**	**‘06**	**‘07**	**‘08**	**‘09**	**‘10**	**‘11**	**‘12**	**‘13**	**‘14**	**‘15**	**‘16**	**‘17**
January	26.3	23.9	23.8	25.2	25.9	24.9	25.1	26.2	24.2	24.2	24.3	24.8	23.9	25.3	25.8	26.2
February	29.6	29.5	28.7	30	31.8	27.6	26.8	29.8	29.4	29	29.1	29.1	27.8	29.3	30.3	29.6
March	33.3	31.5	33	32.6	33.3	31.6	32.3	33.2	34.7	33	33.9	33.8	32.9	32.7	33.8	31.7
April	33.7	35.1	33.9	34.9	35	34.6	35	36.5	36.1	34.4	35.3	35.4	37.7	34.2	36.3	34.7
May	34.6	35.7	35.8	35.1	34.6	35.4	35.9	35.6	35.4	34.8	36.7	33.3	36.8	36	35.1	35.9
June	32.8	32.9	33.2	34.9	33.6	33.6	32.7	34.9	34	33.5	35.3	33.9	33.8	33.5	33.8	34
July	33.3	32.7	32.1	31.5	32.4	31.4	31.5	32.4	33.1	32.6	32.6	32.8	32.9	31.5	32.3	32
August	32.1	32.9	32	32.4	32.2	32.7	32.4	32.6	33.3	31.4	32.8	32.6	33	32.7	33	33
September	32.7	32.9	31.8	32.7	32.4	31.9	32.7	33.1	33.3	32	32.8	33.2	33.3	33.3	34	33.5
October	32.7	32.3	31.5	30.9	32.4	31.8	31.8	32.4	32.5	33.4	32.3	31.6	33.1	33.1	33.4	31.7
November	30.4	30.5	29.7	29	29.6	29.1	29.6	30.4	30.6	30.3	29.4	30.4	31	30.8	29.9	30.1
December	27.5	25.9	27.2	26.7	26.9	25.7	26.1	26.2	26.1	25.1	25.1	27	25.6	26.3	27.1	26.5

Table vi: Month-wise average minimum temperature in Khulna city (Source: BMD, 2018)

Month	**‘02**	**‘03**	**‘04**	**‘05**	**‘06**	**‘07**	**‘08**	**‘09**	**‘10**	**‘11**	**‘12**	**‘13**	**‘14**	**‘15**	**‘16**	**‘17**
January	13.7	11.1	13.2	13.5	12.8	12.2	13.8	15.2	11.9	12	14.3	11.7	12.6	13.8	13.5	26.2
February	15.3	16.7	15.7	17.3	18.8	17	15.3	16.9	16.6	16.2	15.6	15.6	15.2	16.6	19.4	29.6
March	20.7	19.6	21.9	22.1	21.1	19.6	22.4	21.1	23.4	20.5	22	21.1	20.1	19.7	22.6	31.7
April	23.9	25.5	24.9	25.2	24.9	24.4	24.5	25.6	26.9	23.5	24.3	24.1	25.1	23.9	26.6	34.7
May	25.3	26	26.2	25.9	25.7	25.9	25.3	26	25.9	25.5	26.4	25.2	26.6	26.7	25.3	35.9
June	25.4	26.2	26.2	27.3	26.9	26.3	26.2	26.9	26.6	26.5	27.7	27.1	26.4	26.8	26.5	34
July	27.1	26.5	26.4	26.3	26.4	26.3	26.3	26.5	27	26.5	26.7	26.7	26.9	25.9	26.5	32
August	26.1	26.7	26.5	26.9	26	26.8	26.6	26.3	27	26.2	26.7	26.3	26.7	26.7	26.5	33
September	25.9	26.3	26.2	26.3	26	26.1	26.2	26.4	26.4	25.9	26.5	26.4	26.1	26.2	26.4	33.5
October	24.1	25	23.7	24.7	24.9	24.1	23.8	23.6	25	25.2	23.6	24.4	24	24.3	24.8	31.7
November	19.8	19	18.6	18.9	20.1	20.5	19.6	20.1	21.1	19.4	19.1	18.2	18.4	20.1	19.4	30.1
December	15.2	15.4	15.8	14.8	15	14.4	16.4	14.2	14.3	14.7	13.7	15	14.2	16.6	15.5	26.5

Supplement

Table vii: Greywater generation in different areas of the city

Ward No.	Greywater generation (m^3)		% of the total generation	Residential Area (m^2)	Annual greywater gen. rate (m^3/m^2)
	Daily	Annual			
1	1360	496476	2.9	1357556	0.4
2	992	362244	2.1	801605	0.5
3	1570	573207	3.3	1698211	0.3
4	1136	414518	2.4	842257	0.5
5	1068	389694	2.2	624738	0.6
6	1492	544653	3.1	1216730	0.5
7	766	279629	1.6	382173	0.7
8	670	244508	1.4	384965	0.6
9	2295	837495	4.8	1488436	0.6
10	2011	734128	4.2	540743	1.4
11	890	325021	1.9	238269	1.4
12	1526	557104	3.2	518010	1.1
13	668	243956	1.4	235851	1.0
14	1895	691783	4.0	1278316	0.5
15	1174	428545	2.5	1175562	0.4
16	2102	767384	4.4	1557951	0.5
17	2387	871145	5.0	1489879	0.6
18	2008	732788	4.2	1252492	0.6
19	1336	487492	2.8	405113	1.2
20	1196	436689	2.5	389104	1.1
21	1455	531151	3.1	565633	0.9
22	1241	452844	2.6	465408	1.0
23	993	362322	2.1	404586	0.9
24	2727	995290	5.7	1187972	0.8
25	1531	558838	3.2	600719	0.9
26	1512	551929	3.2	532872	1.0
27	2178	795018	4.6	710937	1.1
28	1450	529259	3.0	618868	0.9
29	1278	466609	2.7	509951	0.9
30	2395	874297	5.0	905155	1.0
31	2436	889034	5.1	2263457	0.4
Total	**47740**	**17425047**	**100.0**	**26643518**	-

Table viii: Annual average sealed surface runoff in the urban area

Ward No.	Total Sealed Surface Runoff (m^3)	Total Sealed Surface Area (m^2)	Runoff rate (m^3/m^2)
1	1683865	1508131	1.12
2	1697493	1763310	0.96
3	2463952	2330346	1.06
4	1058161	952376	1.11
5	828036	759978	1.09
6	1614413	1482284	1.09
7	481847	434259	1.11
8	856833	898479	0.95
9	2059127	1917798	1.07
10	829699	798039	1.04
11	343591	324335	1.06
12	723391	675838	1.07
13	890205	1003804	0.89
14	1956363	1880304	1.04
15	1469031	1319485	1.11
16	2073934	1906384	1.09
17	1994760	1837291	1.09
18	1594905	1442745	1.11
19	531032	485474	1.09
20	529839	490855	1.08
21	1201669	1249045	0.96
22	669889	631977	1.06
23	546805	505277	1.08
24	1554523	1420276	1.09
25	769414	697513	1.10
26	686832	624093	1.10
27	895350	806582	1.11
28	770883	691557	1.11
29	657323	597291	1.10
30	1203363	1105639	1.09
31	3138402	2925196	1.07
Average	**1218546**	**1144063**	**1.07**

Table ix: Total urban water generation rate in the study area

Area	Annual Greywater Generation (m³)	Annual Surface Runoff (m³)	Annual Urban Water Generation (m³)	Total Surface Area (m²)	Urban Water generation rate (m³/m²)
1	496476	1683865	2180341	1874508	1.2
2	362244	1697493	2059737	2073485	1.0
3	573207	2463952	3037159	3815439	0.8
4	414518	1058161	1472679	2027177	0.7
5	389694	828036	1217730	821580	1.5
6	544653	1614413	2159066	2274131	1.0
7	279629	481847	761476	456868	1.7
8	244508	856833	1101341	954455	1.2
9	837495	2059127	2896621	3590221	0.8
10	734128	829699	1563826	849269	1.8
11	325021	343591	668612	388992	1.7
12	557104	723391	1280495	700960	1.8
13	243956	890205	1134161	1163808	1.0
14	691783	1956363	2648146	2722414	1.0
15	428545	1469031	1897576	1441326	1.3
16	767384	2073934	2841318	2310209	1.2
17	871145	1994760	2865905	2343709	1.2
18	732788	1594905	2327693	1686973	1.4
19	487492	531032	1018524	499278	2.0
20	436689	529839	966528	500492	1.9
21	531151	1201669	1732820	1434085	1.2
22	452844	669889	1122733	664944	1.7
23	362322	546805	909128	513840	1.8
24	995290	1554523	2549813	1543370	1.7
25	558838	769414	1328252	748312	1.8
26	551929	686832	1238761	667829	1.9
27	795018	895350	1690368	841211	2.0
28	529259	770883	1300142	742027	1.8
29	466609	657323	1123932	666403	1.7
30	874297	1203363	2077660	1188082	1.8
31	889034	3138402	4027435	3684241	1.1
Total	17425047	37774932	55199979	45189635	-

Table x: Greywater generations hotspots and related spatial information

Ward	Number of Hotspot at different CI			Total Residential Buildings (no.)	Total Residentials Floors (no.)	Total Residential Surface Area (m²)	Total Residential Floor Surface Area (m²)	Per Capita Average Residential Surface Area (m²/person)	Per Capita Average Floor Space Area (m²/person)	Population Density (per km²)
	99	95	90							
01	6	2	7	3237	3517	184665	226671	26381	32382	907
02	10	6	17	1736	1776	75059	80482	4415	4734	598
03	101	40	35	2650	2847	140996	175994	4028	5028	514
04	45	21	27	1641	1726	74054	84400	2743	3126	700
05	18	5	8	2184	2468	122433	161058	15304	20132	1624
06	56	18	15	3206	3652	184563	246323	12304	16422	820
07	55	8	15	1022	1141	51479	65797	3432	4386	2096
08	181	9	8	320	328	14267	15343	1783	1918	877
09	210	49	44	3998	4485	225419	306839	5123	6974	799
10	351	79	54	2396	2905	151274	226735	2801	4199	2960
11	160	32	12	485	515	19200	23446	1600	1954	2861
12	307	72	49	1801	2313	118129	187426	2411	3825	2722
13	67	52	50	815	883	43194	52966	864	1059	718
14	199	20	10	3790	4525	221942	327003	22194	32700	870
15	166	66	33	1319	1544	81986	112652	2484	3414	1018
16	114	15	10	3737	4466	212437	334398	21244	33440	1138
17	204	66	36	3601	4695	237950	409181	6610	11366	1273

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18	194	80	54	3379	3941	195657	273116	3623	5058	1488
19	193	83	56	1496	1990	104386	172678	1864	3084	3344
20	198	74	63	1193	1689	86709	155831	1376	2474	2988
21	146	22	18	1778	1908	79902	100364	4439	5576	1268
22	346	64	43	1174	1679	84231	166376	1959	3869	2332
23	172	66	55	865	1498	82265	179909	1496	3271	2415
24	382	116	67	3414	5006	266205	503730	3973	7518	2208
25	128	61	66	2271	2970	149682	240320	2268	3641	2558
26	112	44	38	2019	2696	133821	222218	3522	5848	2830
27	265	127	84	2656	3866	195749	358390	2330	4267	3237
28	74	46	32	2416	3153	164377	264458	5137	8264	2443
29	195	86	62	1341	2191	123554	268329	1993	4328	2398
30	193	83	67	3448	4164	215224	310144	3212	4629	2520
31	11	2	6	5098	5285	233493	255151	38915	42525	826

Table xi: Calculations of matching supply and demand under three scenarios

Demand Side	January	February	March	April	Total		
Min Irrigation Demand (mm)	413	688	669	484	2254	-	
Max Irrigation Demand (mm)	783	1256	1903	1498	5440		
Average Irrigation Demand (mm)	591	1003	1420	853	3867		
Irrigated Area (ha)	1935						
Min. Total Irrigation Demand (m³)	799052	1331108	1294348	936419	4360927		
Max. Total Irrigation Demand (m³)	1514909	2430046	3681829	2898256	10525040		
Average Total Irrigation Demand (m³)	1143437	1940554	2747345	1650342	7481678		
Scenario One (Greywater): Supply Side						Annual Calculations	
Total Greywater Generation (m³)	1432196	1432196	1432196	1432196	5728783	-	17186348
Percentage of Minimum Demand	179	108	111	153	131	394	-
Percentage of Maximum Demand	95	59	39	49	54	163	-
Percentage of Average Demand	125	74	52	87	77	230	-
Scenario Two (Surface Runoff): Supply Side							
Total Surface Runoff (m³)	32819	65638	131277	2231708	2461442	-	37774932
Percentage of Minimum Demand	4	5	10	238	56	866	-
Percentage of Maximum Demand	2	3	4	77	23	359	-
Percentage of Average Demand	3	3	5	135	33	505	-
Scenario Three (Greywater and Surface Runoff): Supply Side							
Total urban water Generation (m³)	1465015	1497834	1563473	3663903	8190225	-	54961279
Percentage of Minimum Demand	183	113	121	391	188	1260	-
Percentage of Maximum Demand	97	62	42	126	78	522	-
Percentage of Average Demand	128	77	57	222	109	735	-

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Supplementary materials related to Chapter 3

Table xii: Geographic information of the sampling locations used for water quality analysis

Station Number	GPS Reading	Chemical-physical sample	Microbial sample	Heavy metal sample
1	N 22.80119 E 89.53988	✓	✓	✓
2	N 22.78571 E 89.53938	✓	✓	✓
3	N 22.77202 E 89.53951	✓	✓	✓
4	N 22.75935 E 89.55114	✓	✓	✓
5	N 22.75762 E 89.55199	✓	✓	✓
6	N 22.76885 E 89.57591	✓	✓	✓
7	N 22.76814 E 85.57679	✓	X	X
8	N 22.78549 E 89.58086	✓	✓	✓
9	N 22.78522 E 89.58177	✓	X	✓
10	N 22.80811 E 89.57674	✓	✓	✓
11	N 22.81642 E 89.56596	✓	✓	X
12	N 22.84159 E 89.54411	✓	X	✓
13	N 22.86391 E 89.55067	✓	✓	✓
14	N 22.86408 E 89.54893	✓	X	✓
15	N 22.85639 E 89.54273	✓	✓	X
16	N 22.85035 E 89.52720	✓	✓	X
17	N 22.85108 E 89.52483	✓	✓	✓
18	N 22.84780 E 89.51336	✓	✓	✓
19	N 22.86197 E 89.50098	✓	✓	✓
20	N22.83388 E 89.51767	✓	✓	✓
21	N 22.83390 E 89.51667	✓	✓	✓
22	N 22.82920 E 89.54205	✓	✓	✓
23	N 22.81177 E 89.53594	✓	✓	✓
24	N 22.80182 E 89.55185	✓	✓	✓
25	N 22.79582 E 89.55561	✓	X	X

Table xiii: Land use (sq. km) within different buffer radius of the sampling stations

Sampling Stations	Radius (m)	Built-up Area	Agriculture	Waterbody	Economic Activity	Urban Vegetation	Total Area
1	200	0.071	0.000	0.018	0.021	0.016	0.126
	500	0.589	0.004	0.108	0.063	0.030	0.794
	1000	2.483	0.154	0.365	0.117	0.047	3.166
2	200	0.097	0.011	0.018	0.000	0.000	0.126
	500	0.496	0.173	0.116	0.014	0.001	0.801
	1000	1.876	0.912	0.309	0.028	0.051	3.175
3	200	0.005	0.034	0.064	0.000	0.000	0.103
	500	0.084	0.252	0.145	0.000	0.000	0.481
	1000	0.527	0.998	0.282	0.007	0.021	1.835
4	200	0.001	0.069	0.015	0.000	0.000	0.085
	500	0.029	0.249	0.274	0.000	0.000	0.551
	1000	0.146	0.722	0.790	0.003	0.000	1.660
5	200	0.000	0.013	0.094	0.000	0.000	0.107
	500	0.002	0.156	0.309	0.000	0.000	0.467
	1000	0.120	0.495	0.852	0.001	0.000	1.468
6	200	0.045	0.018	0.013	0.050	0.000	0.126
	500	0.166	0.157	0.136	0.326	0.009	0.794
	1000	0.649	0.703	1.001	0.650	0.065	3.069
7	200	0.021	0.000	0.011	0.086	0.007	0.126
	500	0.102	0.080	0.264	0.330	0.009	0.785
	1000	0.546	0.682	1.034	0.643	0.064	2.970
8	200	0.077	0.000	0.020	0.028	0.000	0.126
	500	0.454	0.003	0.081	0.248	0.001	0.787
	1000	1.608	0.187	0.789	0.515	0.047	3.145
9	200	0.002	0.000	0.085	0.038	0.001	0.126

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	500	0.105	0.000	0.449	0.209	0.022	0.785
	1000	0.926	0.333	1.133	0.622	0.130	3.145
10	200	0.101	0.000	0.005	0.017	0.003	0.126
	500	0.518	0.000	0.153	0.093	0.021	0.785
	1000	1.912	0.018	0.860	0.281	0.072	3.143
11	200	0.067	0.000	0.013	0.040	0.007	0.127
	500	0.358	0.000	0.178	0.210	0.041	0.787
	1000	1.803	0.004	0.633	0.626	0.091	3.158
12	200	0.098	0.016	0.004	0.011	0.000	0.130
	500	0.524	0.070	0.054	0.114	0.034	0.796
	1000	1.872	0.218	0.241	0.714	0.118	3.163
13	200	0.017	0.000	0.071	0.034	0.003	0.126
	500	0.157	0.008	0.186	0.407	0.028	0.786
	1000	1.351	0.119	0.523	1.010	0.149	3.152
14	200	0.038	0.000	0.014	0.058	0.015	0.126
	500	0.198	0.000	0.158	0.392	0.038	0.785
	1000	1.299	0.087	0.536	1.133	0.102	3.158
15	200	0.086	0.000	0.019	0.015	0.008	0.128
	500	0.689	0.000	0.040	0.075	0.018	0.822
	1000	2.218	0.014	0.106	0.741	0.131	3.210
16	200	0.076	0.006	0.035	0.010	0.000	0.126
	500	0.423	0.206	0.054	0.095	0.013	0.791
	1000	1.372	1.284	0.161	0.289	0.043	3.150
17	200	0.009	0.110	0.006	0.000	0.000	0.126
	500	0.166	0.566	0.053	0.002	0.000	0.787
	1000	0.952	1.821	0.122	0.223	0.032	3.150
18	200	0.011	0.104	0.011	0.000	0.000	0.126
	500	0.085	0.665	0.034	0.000	0.000	0.785

	1000	0.418	2.628	0.095	0.000	0.000	3.142
	200	0.016	0.095	0.014	0.000	0.000	0.126
19	500	0.107	0.614	0.066	0.002	0.000	0.788
	1000	0.517	2.414	0.203	0.002	0.016	3.152
	200	0.065	0.046	0.014	0.000	0.000	0.126
20	500	0.310	0.402	0.056	0.017	0.000	0.785
	1000	1.069	1.850	0.146	0.076	0.001	3.142
	200	0.053	0.062	0.010	0.001	0.000	0.126
21	500	0.249	0.478	0.051	0.008	0.000	0.785
	1000	0.921	2.011	0.146	0.062	0.001	3.142
	200	0.082	0.024	0.019	0.001	0.000	0.126
22	500	0.588	0.078	0.068	0.036	0.015	0.786
	1000	2.249	0.338	0.211	0.287	0.072	3.156
	200	0.060	0.029	0.020	0.000	0.016	0.126
23	500	0.467	0.172	0.090	0.014	0.042	0.786
	1000	1.864	0.868	0.261	0.119	0.088	3.200
	200	0.117	0.000	0.005	0.004	0.000	0.126
24	500	0.723	0.000	0.034	0.028	0.001	0.786
	1000	2.673	0.110	0.215	0.130	0.016	3.144
	200	0.099	0.000	0.026	0.001	0.000	0.126
25	500	0.623	0.069	0.087	0.007	0.000	0.785
	1000	2.304	0.502	0.284	0.047	0.005	3.142

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Table xiv: Correlation matrix with land-use at different buffer radius and water quality parameters

Spearman's rho	**Built Area**			**Agriculture Area**			**Waterbody**			**Economic Activity**			**Urban Vegetation**		
	200m	**500m**	**1000m**	**200m**	**500m**	**1000m**	**200m**	**500m**	**1000m**	**200m**	**500m**	**1000m**	**200m**	**500m**	**1000m**
pH	0.018	0.056	0.042	0.044	0.017	0.016	0.185	-0.118	-0.251	0.065	0.116	0.258	-0.061	0.119	0.238
Water Temp.	.532**	.472*	.413*	-0.318	-0.314	-0.235	0.071	-0.164	-0.054	0.345	0.382	.424*	0.192	0.391	.412*
TDS	-.518**	-.562**	-.447*	-0.026	0.023	0.006	0.329	.633**	.650**	0.110	0.144	0.031	0.020	0.037	0.073
EC	-.518**	-.562**	-.447*	-0.026	0.023	0.006	0.329	.633**	.650**	0.110	0.144	0.031	0.020	0.037	0.073
DO	-0.145	-0.226	-0.169	-0.289	-0.142	-0.115	.492*	0.384	0.281	0.210	0.146	0.119	-0.107	-0.103	0.033
BOD	0.118	0.161	0.073	0.350	0.185	0.213	-.454*	-.455*	-0.367	-0.229	-0.20	-0.173	-0.175	-0.113	-0.194
Turbidity	-0.329	-,398*	-0.298	-0.219	-0.192	-0.144	0.264	0.340	,414*	0.152	0.110	0.048	-0.195	-0.194	-0.103
TSS	-0.348	-.432*	-0.356	-0.190	-0.206	-0.205	-0.124	0.385	.500*	0.334	0.233	0.157	0.153	0.096	0.055
NO_3^-	0.361	.429*	0.299	0.390	0.271	0.236	-.565**	-.716**	-.636**	-0.368	-0.277	-0.181	-0.166	-0.135	-0.188
NH_3	-0.255	-0.261	-0.189	0.207	0.367	0.361	0.171	0.276	0.228	-0.352	-0.340	-.468*	-0.073	-0.181	-0.332
Cl^-	-.449*	-.524**	-.415*	-0.075	-0.015	-0.019	0.336	.642**	.696**	0.199	0.238	0.088	0.030	0.115	0.144
K^+	-0.365	-0.390	-0.269	-0.112	-0.006	0.009	0.385	.432*	.527**	0.054	0.090	-0.058	-0.154	-0.100	-0.088
Na^+	-0.375	-.439*	-0.323	-0.016	0.089	0.093	0.351	.589**	.594**	0.055	0.162	0.006	-0.015	0.078	0.120
Mg^{2+}	-.527**	-.542**	-.428*	-0.068	-0.050	-0.069	0.237	.602**	.638**	0.238	0.265	0.195	0.077	0.130	0.131
SO_4^{3-}	-0.254	-0.322	-0.207	-.403*	-0.370	-0.385	0.288	.612**	.713**	0.374	0.355	0.215	0.290	0.288	0.216
Pearson's Correlation	**Built Area**			**Agriculture Area**			**Waterbody**			**Economic Activity**			**Urban Vegetation**		
	200m	**500m**	**1000m**	**200m**	**500m**	**1000m**	**200m**	**500m**	**1000m**	**200m**	**500m**	**1000m**	**200m**	**500m**	**1000m**
COD	-0.367	-0.287	-0.210	0.232	0.198	0.182	.455*	0.174	0.019	-0.135	0.073	0.114	-0.316	-0.177	0.140
HCO_3^-	0.256	0.244	0.225	.430*	0.391	0.360	-.513**	-.584**	-.569**	-.401*	-0.396	-0.273	0.036	0.074	-0.184
PO_4^{3-}	0.363	0.356	0.302	0.345	0.332	0.322	-.505*	-.618**	-.554**	-.456*	-.458*	-0.391	-0.005	-0.069	-0.267
Ca^{2+}	-.510**	-.518**	-.428*	-0.186	-0.265	-0.284	.543**	.698**	.759**	.412*	.527**	0.335	-0.076	0.044	0.260

**. Correlation is significant at the 0.05 level (2-tailed).*
***. Correlation is significant at the 0.01 level (2-tailed).*

Supplementary materials related to Chapter 4

Table xv: Demographic attributes of the interviewed peri-urban farmers (n=38)

Attributes		**Percentage**
Gender of the farmer	Male	97.4
	Female	2.6
Educational qualification of the farmer	Illiterate	15.8
	Basic education	68.4
	Finished College	10.5
	University Degree	5.3
Family Size	Less than 4	15.8
	4-6	42.2
	More than 6	42
Farming experience	Less than 10 years	10.5
	Between 10-20 years	31.6
	More than 20 years	57.9
Age of the farmer	Less than 25 years	2.6
	Between 25-40 years	39.5
	Between 40-60 years	39.7
	More than 60 years	18.2

Source: Field survey, 2018

Farmer's Survey Questionnaire

(A modified version of the questionnaire was deployed in Kobo toolbox for data collection)

Consent from respondent: all the information gathered through this survey will only be used for research and academic purpose only. The respondent has agreed to provide information related to this survey and aware about the use of the data gathered. All the information will be handled securely.

Questionnaire Number: Date:
Time:

Area name: Location:

Agriculture Type: ☐ Urban ☐ Peri-urban ☐ Rural

1. Basic Information of the farmer

Name: Age:
Gender:

Education: Family Size:

Farming experience (years): Involvement of other family members in farming:

Ownership status of the land and amount : ☐ Owned ________________ ☐ Leased__________________

Is farming the only source of household income?: ☐ Yes ☐ No

If no, then other occupation involvement:

Total household monthly income (BDT):

Sources of drinking water in the household: ☐ Deep tubewell ☐ Shallow tubewell ☐ Rainwater ☐ Surface water ☐ Others

How do you rate the quality of drinking water?

○ 1 (Very Bad) ○ 2 ○ 3 ○ 4

Sources of domestic water in the household: ☐ Deep tubewell ☐ Shallow tubewell ☐ Rainwater ☐ Surface water ☐ Others

How do you rate the quality of domestic water?

○ 1 (Very Bad) ○ 2 ○ 3 ○ 4

2. Information on crops, irrigation and fertilizer

Cropping cycle:	☐ Kharif I	☐ Kharif II	☐ Rabi
Land used:			
Total production:			
Irrigation method and days:			
Irrigation duration/day:			
Type of fertilizer used:			
Total amount applied:			

Main purpose of production: ☐ Own consumption ☐ Joint production ☐ To sell in the market

Name of the market products sold: Annual profit (BDT):

Any changes in profit in the previous years

3. Irrigation sources and related issues

Sources of irrigation water: Distance to the irrigation source (m):

How do you rate the irrigation water quality?:

1 (Very Bad) 2 3 4

How do you rate the availability of irrigation water?:

1 (Very Bad) 2 3 4

Need to pay for irrigation water: ☐ Yes ☐ No.

If yes, how much (BDT)?: ___________________

Over the years, has it become difficult to find irrigation? ☐ Yes ☐ No.

If yes, why:_________________________

4. (Wastewater) Irrigation and related health issues

Are you aware that river/canal water is polluted due to direct discharge of urban wastewater? ☐ Yes ☐ No

Does any of your irrigation source is connected to river/canal that transports wastewater? ☐ Yes ☐ No

Awareness about directly/indirectly using wastewater for irrigation: ☐ Yes ☐ No

Reasons behind using current sources: ____

Duration of using current irrigation sources (years):

Number of days spent in the field in a cropping season for field related activities:

Noticing changes in yield due to irrigation: ☐ Yes ☐ No

Face any problems during irrigation: ☐ Yes ☐ No.

If yes, then elaborate: ___________________________

Rank following risks from lowest (1) to highest (5):

○ Getting ill ○ Damage to pump ○ Soil health ○ Weeds and insects
○Environment ○ Yield

Do you use any protective equipment during field activities?: ☐ Yes ☐ No

Elaborate on using or not using protective equipment: ____

Elaborate on the importance of using protective equipment:

5. Water reuse and improved services

What do you think about planned water reuse? ____

Are you satisfied with the services from governmental agencies related to irrigation:
☐ Yes ☐ No

Is no, then which areas need to be improved?: ___________________________

Would you pay for an improved service? ☐ Yes ☐ No.

If no, then why: ________________________

Table xvi: Geometric mean (cfu/100ml) of TC, FC, E. coli and Enterococcus

Parameter	River	Canal/Drain	Lake	Overall	Season
TC	6E+05	8E+05	2E+05	6E+05	Winter
	9E+05	2E+06	1E+05	9E+05	Summer
	4E+05	2E+06	1E+05	6E+05	Monsoon
	6E+05	1E+06	1E+05	7E+05	Overall
FC	3E+04	8E+04	3E+03	3E+04	Winter
	2E+05	5E+05	3E+04	2E+05	Summer
	2E+05	1E+06	2E+04	2E+05	Monsoon
	9E+04	3E+05	1E+04	1E+05	Overall
E Coli	1E+04	4E+04	3E+03	2E+04	Winter
	9E+04	5E+05	4E+03	1E+05	Summer
	7E+04	4E+05	2E+03	8E+04	Monsoon
	4E+04	2E+05	3E+03	5E+04	Overall
Enterococcus	2E+04	1E+04	2E+03	1E+04	Winter
	8E+03	3E+03	3E+03	4E+03	Summer
	2E+04	2E+04	6E+03	2E+04	Monsoon
	1E+04	8E+03	3E+03	9E+03	Overall

Table xvii: Analysis of variance (ANOVA)

Parameter	Between seasons		Between sources	
	F	Significance	F	Significance
TC	1.711	0.190	11.631	0.000
FC	5.906	0.005	8.998	0.000
E. Coli	5.382	0.007	10.961	0.000
Enterococcus	8.846	0.000	2.274	0.112

Table xviii: Daily and annual probability of infection assuming different fractions of E. coli

Concentration fraction	Sources	Daily Probability				Annual Probability			
		Winter	Summer	Monsoon	Overall	Winter	Summer	Monsoon	Overall
20%	All Samples	2.8E-04	1.6E-03	1.2E-03	8.2E-04	6.2E-03	3.4E-02	2.6E-02	5.9E-02
	River	2.2E-04	1.3E-03	1.0E-03	6.8E-04	4.9E-03	2.9E-02	2.3E-02	5.0E-02
	Canal/Drain	6.9E-04	8.0E-03	6.7E-03	3.3E-03	1.5E-02	1.6E-01	1.4E-01	2.2E-01
	Pond/Lake	4.1E-05	6.6E-05	3.5E-05	4.5E-05	9.0E-04	1.4E-03	7.7E-04	3.4E-03
15%	All Samples	2.1E-04	1.2E-03	9.0E-04	6.1E-04	4.7E-03	2.6E-02	2.0E-02	4.5E-02
	River	1.7E-04	1.0E-03	7.8E-04	5.1E-04	3.7E-03	2.2E-02	1.7E-02	3.7E-02
	Canal/Drain	5.2E-04	6.0E-03	5.0E-03	2.5E-03	1.1E-02	1.2E-01	1.1E-01	1.7E-01
	Pond/Lake	3.1E-05	4.9E-05	2.6E-05	3.4E-05	6.7E-04	1.1E-03	5.8E-04	2.6E-03
10%	All Samples	1.4E-04	8.0E-04	6.0E-04	4.1E-04	3.1E-03	1.7E-02	1.3E-02	3.0E-02
	River	1.1E-04	6.7E-04	5.2E-04	3.4E-04	2.5E-03	1.5E-02	1.1E-02	2.5E-02
	Canal/Drain	3.4E-04	4.0E-03	3.4E-03	1.7E-03	7.5E-03	8.5E-02	7.2E-02	1.2E-01
	Pond/Lake	2.0E-05	3.3E-05	1.8E-05	2.3E-05	4.5E-04	7.2E-04	3.9E-04	1.7E-03
5%	All Samples	7.1E-05	4.0E-04	3.0E-04	2.0E-04	1.6E-03	8.7E-03	6.6E-03	1.5E-02
	River	5.6E-05	3.3E-04	2.6E-04	1.7E-04	1.2E-03	7.3E-03	5.7E-03	1.3E-02
	Canal/Drain	1.7E-04	2.0E-03	1.7E-03	8.4E-04	3.8E-03	4.4E-02	3.7E-02	6.1E-02
	Pond/Lake	1.0E-05	1.6E-05	8.8E-06	1.1E-05	2.2E-04	3.6E-04	1.9E-04	8.5E-04
1%	All Samples	1.4E-05	8.0E-05	6.0E-05	4.1E-05	3.1E-04	1.8E-03	1.3E-03	3.1E-03
	River	1.1E-05	6.7E-05	5.2E-05	3.4E-05	2.5E-04	1.5E-03	1.1E-03	2.5E-03
	Canal/Drain	3.4E-05	4.0E-04	3.4E-04	1.7E-04	7.6E-04	8.9E-03	7.4E-03	1.3E-02
	Pond/Lake	2.0E-06	3.3E-06	1.8E-06	2.3E-06	4.5E-05	7.2E-05	3.9E-05	1.7E-04

<u>Supplementary materials related to Chapter 5</u>

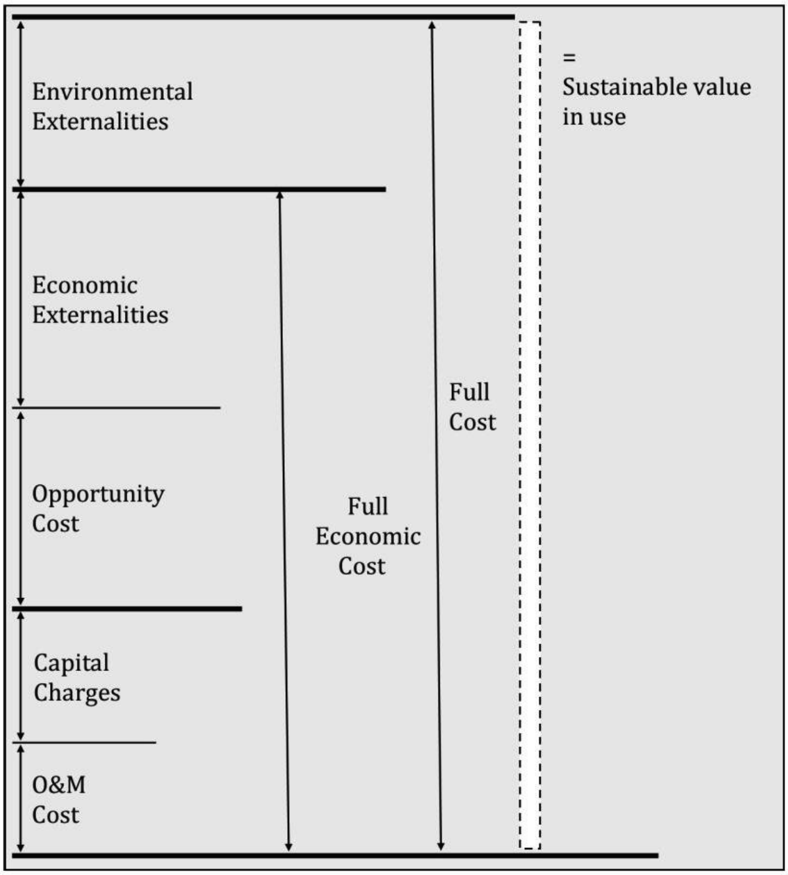

Figure a: Principles of cost of water based on Rogers et al.2002

Calculation of Sample size

Formula for calculating sample size:

$$s = [\{X^2NP(1-P)\} \div \{d^2(N-1)\} + \{X^2P(1-P)\}]$$

Where. s = Sample size

X = z score under desired (95%) confidence level = 1.96

N = The population size = 596748

P = The population portion = 0.5

d = confidence interval = 0.05

So. based on the calculation the population size is = 385. This sample size was then distributed among wards based on the population percentage in each ward.

Following table shows the ward-wise sample size calculated as:

Supplement

Table xix: Ward-wise sample size distribution

Ward Number	Population Percentage	Sample Size
1	2.86	11
2	2.14	8
3	3.23	12
4	2.39	9
5	2.43	9
6	2.94	11
7	1.65	6
8	1.44	6
9	4.74	18
10	4.27	16
11	2.09	8
12	3.29	13
13	1.53	6
14	3.71	14
15	2.43	9
16	4.34	17
17	4.90	19
18	3.86	15
19	2.77	11
20	2.35	9
21	2.69	10
22	2.53	10
23	2.05	8
24	6.15	25
25	3.23	12
26	3.27	13
27	4.69	18
28	3.16	12
29	2.69	10
30	5.07	20
31	5.09	20
Total	100	385

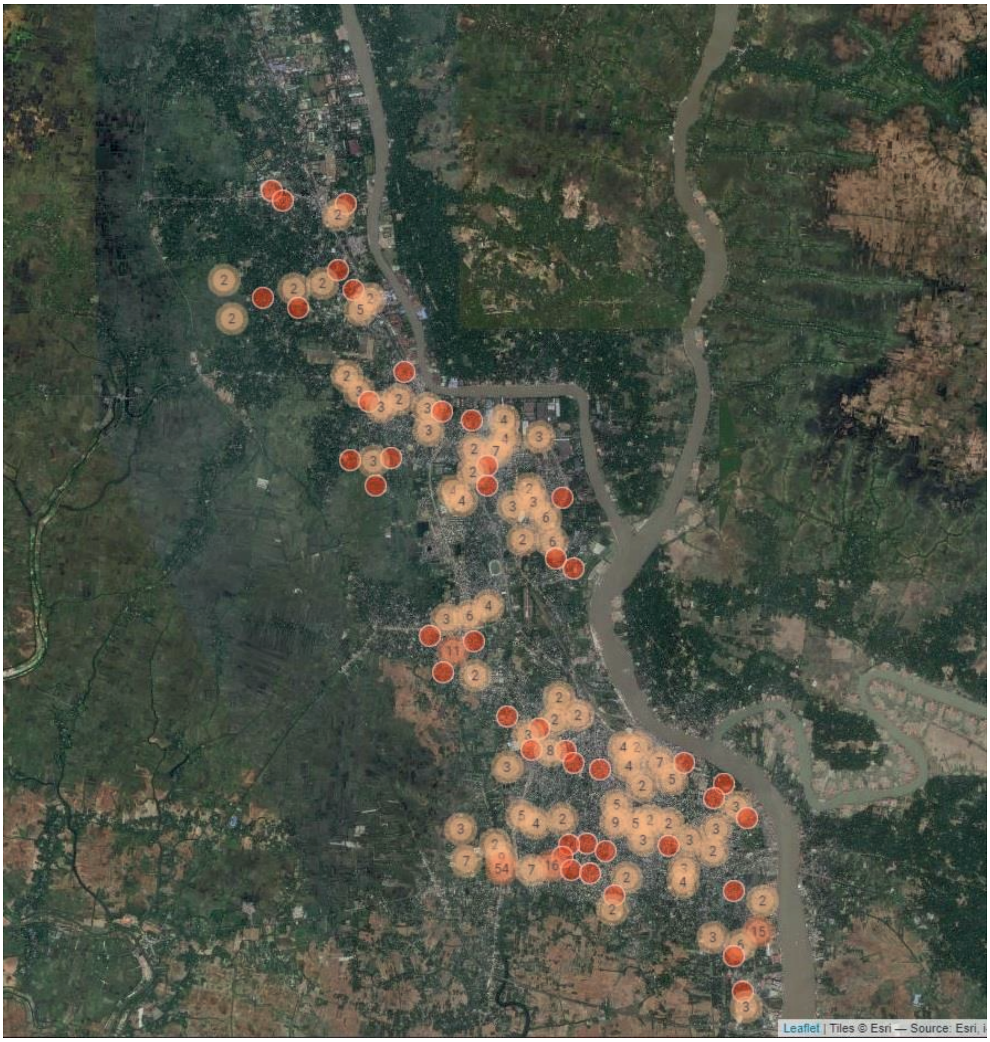

Figure b: Geographic locations of the questionnaire survey (Source: Kobo Toolbox)

Supplement

Urban Household Questionnaire

(A modified version of the questionnaire was deployed in Kobo toolbox for data collection)

Consent from respondent: all the information gathered through this survey will only be used for research and academic purpose only. The respondent has agreed to provide information related to this survey and aware about the use of the data gathered. All the information will be handled securely.

Questionnaire Number:	Date:
Time:	
Area Type:	Ward Number:

1. Basic Information	
Name:	Age:
Gender:	
Education:	Family Size:
Household head?: ☐ Yes ☐ No	Occupation:
Monthly income:	
Structure type: Ownership: ☐ Owned ☐ Rented ☐ Govt. ☐ Others	
Number of floors in the building:	Primary use of the building:

2. Water use in the household

Sources of drinking water in the household: ☐ Deep tubewell ☐ Shallow tubewell ☐ Rainwater ☐ Surface water ☐ Others

How do you rate the quality of drinking/domes water?

◯ 1 (Very Bad) ◯ 2 ◯ 3 ◯ 4

Water storage system and capacity in the household/building:

Distance to drinking/domestic water sources (m):

Do you pay for drinking/domestic water?: ☐ Yes ☐ No. If yes, how much:_____

Do you have access to toilet facilities: ☐ Yes ☐ No. If yes, what type:_________

Do you think it is possible to reduce water consumption in your house? ☐ Yes ☐ No. If no, why:____________

Are you willing to reduce water consumption in your house? ☐ Yes ☐ No. If no, why:___________________

3. Wastewater generation and treatment
Access to the drainage? ☐ Yes ☐ No. Distance and width (m):________________
Are you aware about the wastewater generation from household? ☐ Yes ☐ No.
Do you know what is the final destination of wastewater? ☐ Yes ☐ No.
Rank in order of pollution: ○ Household wastewater ○ Industrial wastewater ○ Commercial wastewater
Are you aware about the negative impact of wastewater? ☐ Yes ☐ No.
Do you have water supply connection from KWASA? ☐ Yes ☐ No.
If yes, how do you rate their service: ___________________________
Rate the service of current drainage network provided by KCC:
Are you willing to pay for improved drainage service and wastewater treatment? ☐ Yes ☐ No.
If yes, how much: ______________________; If no, why: ________________

4. Attitude towards water reuse
Have you noticed any changes in climate in recent years? ☐ Yes ☐ No
Have you heard the term "reuse"? ☐ Yes ☐ No
If yes, how do you rate it? ____________________
Which sectors in our country should reuse water?: _______________________
Can wastewater be used as an alternative irrigation source?: ______________.
How do you rate the idea?: _____
Do you know that indirect wastewater irrigation is already taking place?
☐ Yes ☐ No
Do you think it should be stopped? ☐ Yes ☐ No Why? ______________
Do you know the irrigation source of the products you consume at household?
☐ Yes ☐ No
How important it is to know about the irrigation source?: __________________
What is your trust level towards governmental agencies ensuring safe reuse practice? ______________________
What is your trust level towards technologies ensuring safe reuse practice? ______________________

Supplement

Farmer's In-depth Interview Questions

(A modified version of the questions was used during the field data collection)

Consent from respondent: all the information gathered through this survey will only be used for research and academic purpose only. The respondent has agreed to provide information related to this survey and aware about the use of the data gathered. All the information will be handled securely.

Farmer's Name: Age:
Gender:

Education: Family Size:

Farming experience (years):

Involvement of other family members in farming:

Part 1: Irrigation practice

1. How frequent do you irrigate in the dry season?
    a. How much do you irrigate?
2. What infrastructure do you need to irrigate?
    a. What are the costs of irrigation?
3. Who is irrigating most of the time?
    a. Why?

Part 2: Perceptions and motivations of irrigation source

4. What is your main source of irrigation water?
    a. How far is the source from your land?
    b. Do you mix different sources?
    c. Why and how do you mix them?
5. How do you rate the water quality of the irrigation water from 1-10?
    a. Why?
6. How do you determine the quality of the water?
    a. Color/smell/composition
7. What is your most important motivation for using current irrigation water source?
    a. No choice/crop growth/high revenues/free access/close access/no rules
    b. Second most important?
8. How has the source of irrigation water changed over time?
    a. What did you use 20 years ago?
    b. How was water quality 20 years ago?
    c. Have you considered using other crops or irrigation methods due to bad water quality?

9. Did you or one of your family members got sick after using wastewater?
   a. What kind of sickness?
   b. How long?
   c. Costs?
10. What kind of safety measures do you take to ensure safe use of irrigation water?
   a. Protection gloves/mouth cap

Part 3: Rules and regulations

11. Are you aware of any rules and regulations regarding the use of restriction of your current source of irrigation water?
   a. Which institution should be responsible?
   b. How are you informed?
   c. Understanding of rules and regulations?
12. If the rules and regulations were in place, what does the farmer think about it?
   a. What is good about the rules and regulations?
   b. Do the rules and regulations limit your production?
   c. Help to reduce risk?

Part 4: Willingness to pay

13. What are you willing to pay for the irrigation water per cropping season (give range)?
14. What if the total cost of the supply is higher than your amount (give range)?

In case the water the water is treated and is now delivered clean,

15. What are you willing to pay for the better-quality irrigation water (give range)?
16. What if the total cost of the supply is higher than your amount (give range)?

Part 5: Future ambitions

17. What are your future ambitions?
   a. Farm level
   b. Water source
18. Do you know about climate change and the effects this might have on your daily business?
   a. Farm level
   b. Water source

Open discussion or any additional comments:

Table xx: Demographic attributes of the surveyed citizens (n=385)

Attributes		Percentage
Gender of the respondent	Male	62.6
	Female	37.4
Education of the respondent	Illiterate	6.5
	Basic Education (Primary School)	41.3
	Finished college (12th grade)	30.6
	University Degree	20.3
	Others	1.3
Total Monthly Family Income (BDT)	<5000	3.6
	5001-10000	11.4
	10001-15000	23.6
	15001-20000	17.9
	20001-25000	10.1
	25001-30000	10.1
	30001-35000	4.9
	>35000	18.2
Housing Ownership	Owner	59.2
	Rented from the private market	40
	Govt. Housing	0.8
Residence Location	Residential Area	85.5
	Commercial Area	2.1
	Industrial Area	2.6
	Mixed Area	9.9
Housing structure	Multi storied buildings (Pucca)	56.4
	Galvanized iron/earthen houses, slum and squatters	43.6

Source: Field Survey, 2018

Table xxi: Ratings of drinking water and related infrastructure

Topic	Mean±SD
Drinking water quality consumed at the household	4.31±0.6
Water quality used for domestic purposes	3.76±0.75
Water quality supplied by KWASA	3.45±0.88
Drainage infrastructure managed by KCC	2.62±0.99

Source: Field survey, 2018

Table xxii: Socio-demographic factors influencing the responses related to reuse

Correlation	Gender	HH head	Education	Total family member	Total monthly income	House structure
Drinking water quality	0.121*	0.131**	0.059	-0.007	-0.005	-0.048
Willingness to take measure to reduce consumption	-0.003	-0.041	-0.088	0.105*	0.114*	0.147**
Awareness on direct discharge and negative impact	-0.007	-0.038	0.171**	-0.038	0.143*	-0.247**
Service ratings for existing drainage	0.020	-0.042	0.108*	-0.090	0.047	-0.212**
Willingness to pay for improved drainage	0.046	-0.028	0.209**	0.067	0.511**	-0.107
Willingness to pay for wastewater treatment	0.044	0.001	0.173*	0.069	0.366**	-0.158*
Importance of wastewater treatment	0.063	-0.021	0.291**	-0.068	0.148**	-0.272**
Awareness about water reuse concept	0.077	-0.104*	0.329**	-0.041	0.109*	-0.229**
Importance of awareness for current irrigation source	0.022	0.038	0.139**	0.001	0.111*	-0.116*
Preferred water reuse in Industry	-0.028	-0.093	0.126*	0.012	0.091	-0.124*
Preferred water reuse in Household	0.057	0.032	0.226**	0.014	0.056	-0.151**
Trust in technology for safe treatment	0.079	-0.003	0.178**	-0.033	0.071	-0.229**

** Correlation is significant at the 0.01 level (2-tailed)

* Correlation is significant at the 0.05 level (2-tailed)

Table xxiii: Ratings of urban citizens on different aspects of pollution, treatment and reuse (1 meaning low ratings while 5 meaning high)

Different aspects of pollution and reuse	**1 (Poor)**	**2**	**3 (Neutral)**	**4**	**5 (Excellent)**
Treated wastewater use	0%	5%	16%	51%	28%
Indirect wastewater use	7%	31%	34%	25%	3%
Direct wastewater use	10%	40%	28%	20%	3%
Water Reuse	3%	5%	14%	54%	24%
Importance of treatment	2%	3%	24%	51%	21%
Negative impacts of discharge	0%	0%	12%	57%	30%
Mixed area Wastewater	0%	0%	1%	19%	80%
Industrial Wastewater	0%	0%	3%	25%	72%
Household Wastewater	2%	34%	47%	15%	2%

Acknowledgement, About the Author and SENSE Diploma

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In the last four years, I met numerous people during fieldwork or in the office, and the support, enthusiasm, and guidance I received in those years really inspired me. It wouldn't be possible to complete my PhD without the support from these people around me. I want to say "Thank You" from the bottom of my heart to everyone who motivated me professionally and personally to reach this stage of my life. I also want to say "Sorry" if I forgot to mention some names here, simply because of my weaker memory.

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About the author

Kamonashish Haldar was born in Bangladesh in 1987. Upon completing bachelor's in Urban and Rural Planning from Khulna University, Bangladesh, in 2009 he worked for several years with consultancy companies and local government agencies. His initial work focused on the formulation of land use plans for cities of Bangladesh. He moved to the Netherlands in 2013 to acquire his MSc in Urban Environmental Management at Wageningen University. His MSc thesis focused on the influence of urban forms on energy neutrality. After his graduation in 2015, he worked as an academic staff at Wageningen University and Erasmus University. He secured funding from the Dutch organization for internationalization in education to start his PhD in 2017. During his PhD he collaborated with numerous initiatives within and outside the university. In 2019, he was selected to participate in QMRAIII program at Ohio State University, United States of America. He also served as a board member in WIMEK PhD Council and Wageningen PhD Council and contributed to numerous ongoing initiatives to improve the quality of PhD trajectory. Upon finishing his PhD, Kamonashish will continue his professional career as a Post-doctoral researcher at EWUU (An alliance of TU/e, WUR, UU and UMC).

Besides working, Kamonashish enjoys cooking and spending time with his family. He is committed to making a positive contribution to ensure the sustainable development of societies worldwide.

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- Environmental research in context (2017)
- Research in context activity: 'Reflection on UrbIA Project' (2020)

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- Topic to proposal, WASS graduate school (2017)
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- Scientific publishing, Wageningen Graduate Schools (2017)
- Teaching for PhD students, Wageningen Graduate Schools (2017)
- Scientific Writing, Wageningen Graduate Schools (2018)
- Supervising BSc/MSc Students, Wageningen Graduate Schools (2018)
- Writing Grant Proposals, Wageningen Graduate Schools (2017)
- Basic Statistics, PE&RC and WIMEK graduate schools (2018)

External training at a foreign research institute

- Scenario Analysis, Wageningen University, The Netherlands (2018)
- ANSWER, KWR Water Research Institute, The Netherlands (2018)
- QMRA III, Ohio State University, United States of America (2019)

Management and Didactic Skills Training

- Board member of WIMEK PhD council (2017-2019)
- Supervising one BSc and three MSc student with thesis (2017-2021)
- Teaching assistant in the MSc courses 'Basic Technologies for Urban Environmental Management' (2017-2021) and 'Energy, Water and Nutrient Cycles in the Built Environment' (2017-2021)

Oral Presentations

- *Spatial and temporal variation in surface water quality and its implication for safe agricultural use*. Water Science for Impact, 16-18 October 2018, Wageningen, The Netherlands
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