Assessment of Groundwater Aquifer Impact from Artificial Lagoons and the Reuse of Wastewater in Qatar



Hayat Al-Jabiry

Supervisors: Elizabeth H. Bailey and Scott D.Young

This dissertation is submitted for the degree of Doctor of Philosophy.

School of Biosciences

University of Nottingham

March 2022

Abstract

Qatar is a desert where precipitation is uncommon and occurs mostly in winter. Qatar depends on desalination for drinking water and groundwater and recycled water for irrigation. There is over-extraction of groundwater causing seawater intrusion. Re-use of treated wastewater (TWW) is extremely limited with only 14% of TWW being used for irrigation. This has led to the country disposing of unwanted water from various sources in artificial lagoons situated across the country where it evaporates and infiltrates the groundwater raising concerns over the possibility of environmental pollution. This is a unique situation that is limited to extremely arid countries. Research on the artificial lagoons is limited, with a noticeable knowledge gap in understanding the lagoon influence on Qatari aquifers. Accordingly, the hypothesis underpinning this research is that the quality and quantity of water in lagoons is currently having an impact on the groundwater reservoirs in Qatar. To validate this hypothesis a social survey, a hydrogeochemical survey and a microbial survey have been undertaken to establish the current situation and provide policy makers with recommendations for future lagoon management.

A social survey was conducted through the distribution of online questionnaires to the public and conducting semi-structured interviews with policymakers responsible for water management in Qatar. The public had variable knowledge about the lagoons and expressed a willingness to learn more about them. Public and policymakers in Qatar agreed that there were both good and harmful consequences of the lagoons on groundwater and the environment. Policymakers' views differed, dividing into groups perceiving the lagoons as having the potential to degrade groundwater quality and those suggesting that infiltration of lagoon water would improve groundwater sources. Public opinion is important in lagoon management, thus policymakers agreed to raise awareness and incorporate public views with respect to water management in Qatar. Both public and policymakers encouraged the reuse of TWW and lagoon water and Qatar might leverage this approval to promote and extend its TWW reuse programs.

A hydrogeochemical survey was conducted by sampling lagoons (n = 14) and wells (n = 54) in both the summer and winter of 2018 - 2019 (designated ‘summer’ & ‘winter’). Water, soil and plants samples from sites irrigated with well water were analysed for multiple elements by ICP-MS. Major anions were determined by ion chromatography and organic and inorganic carbon was also measured. Lagoons violated the Qatari TWW reuse standards in terms of pH, TDS, TN, SO_4^{2-}, Mn, and Zn. Groundwater samples violated WHO and Qatar drinking and irrigation standards in terms of pH, TDS, TOC, B, Ca, Cl^-, Mg, Na, SO_4^{2-}, As, Fe, Se, Sr, Tl, and U. Spatial and temporal variation in lagoons and groundwater salinization and water/rock process were visualised to illustrate the influence of

lagoon water infiltration on adjacent aquifers. Soils (collected from close to lagoons and on farms) had Ni concentrations that violated EU and FAO/Who standards. Plant samples violated EU and FAO/WHO fodder standards in terms of Cr, Cu, Mn, Mo, Ni, Pb, Se and Zn. The multivariate statistical analysis revealed similar trends in the chemical variables of soils and plants from both farms and lagoons. Contamination from water and the environment tend to be higher in plants than in soil.

A microbial survey was conducted using MALDI-TOF-MS to identify species of isolated bacteria strains (MacConkey and EMB selective media) collected from lagoons (n = 9) and wells (n = 13). Both groundwaters and lagoons were found to contain levels of coliform bacteria that exceeded national and international standards. Coliform bacteria in groundwater wells were observed to be associated with nearby lagoons, implying microbial infiltration. While the majority of the literature uses *E.coli* as a faecal indicator for wastewater contamination of groundwater, this research determined that *P.aeruginosa* is a more appropriate indicator in the Qatar lagoon context.

In conclusion, this study examined three distinct scientific domains pertaining to the lagoon situation in Qatar: social, chemical, and microbial, with the goal that policymakers and managers in Qatar may benefit from the findings. Additionally, this research will serve as a baseline for future research and policy development for future lagoon management decisions in Qatar.

Declaration

I declare that the thesis is the result of my own work which has been entirely undertaken during my period of registration for this degree at The University of Nottingham. I have complied with the word limit for my degree

The following presentations and short paper have resulted from this work:

- Oral presentation and one first-place 1st international conference on sustainable Energy-Water-Environment nexus in desert climates (ICSEWEN-19), December 2-5, 2019 in Doha, Qatar
- Oral presentation at International Conference on Sustainable Water Resources Management (ICSWRM 2019), December 12-13, 2019 in Rome, Italy
- A short paper was published. Aljabiry, H., Bailey, L. and Young, S. (2021) 'Assessment of Groundwater Aquifer Impact from Artificial Lagoons and the Re-use of Wastewater in Qatar', in Essam Heggy, Veronica Bermudez, M. V. (ed.) Sustainable Energy-Water-Environment Nexus in Deserts. Springer International Publishing, pp. 1–490.

Acknowledgement

First I would like to thank Allah for giving me the needed patience and strength to go through this PhD during such a difficult time. Secondly, I would like to thank the state of Qatar and Qatar University to sponsor my education, starting with my Bachelor's degree, ending with this PhD.

Moreover, I would express my utmost gratitude to my supervisors Elizabeth H. Bailey and Scott D.Young, for not only supporting me through my PhD journey, but also to be always available for me to troubleshoot all the hardships that I had to face to get permission, convincing ministries about my research, and handle the cultural difficulties of being a woman doing a field-based study in Qatar. Also, I thank Saul Vazquez for his help with the labs, and for being always ready to run my samples in all the instruments in the Gateway building.

Furthermore, I would like to thank the DBES faculties that opened their labs for me and provided me with much-needed guidance. First, Dr Nabil for being a very challenging mentor that always pushed me to do my best, and being my previous supervisor during my Bachelor's degree got to me in the wastewater field. Also, I want to thank his amazing team that shared their only lab hood and their equipment to finish the microbiological samples in Qatar. Second, Dr Hamda and Dr Ipek for being my role models since I was a freshman, where I got to be passionate about Qatar's environmental sustainability

In addition, I would have never been able to do the fieldwork without my supportive father and amazing brother Abdullah, thank you for driving me after the sunrise and before the sunset all around Qatar with plenty of food and amazing chats, as well as convincing the farmers to allow us to take samples for more than 160 times summer and winter, for me you are co-authors in this PhD. I also could not have done this PhD without my caring mother.

I would like to thank my wonderful friends that I meet during my studies: Afra, Martha, Maryam A, Maryam M, Momoina, Muna, Noora, Shamsah, Lylia, Karla, Alex, Mathew, Mairead, and Beckie, each one of them gave me a piece of the mosaic that represents who I am now. Also, I would like to thank my therapist Noora Kareem that tought me the tools to finally overcome my crippling anxiety and depression. Finally, I want to thank my soulmate Hana, you are one of my greatest blessings in this life, and living away from you in the UK made our relationship stronger and made me appreciate you more in my life. I cannot wait for us to grow old and crazy together.

Table of Contents

ABSTRACT ..... **I**
DECLARATION ..... **III**
ACKNOWLEDGEMENT ..... **IV**
TABLE OF CONTENTS ..... **V**
LIST OF FIGURES ..... **IX**
LIST OF TABLES ..... **XV**
LIST OF ACRONYMS, ABBREVIATION AND UNITS OF MEASUREMENT ..... **XIX**
CHAPTER.1. INTRODUCTION AND BACKGROUND TO THE RESEARCH **1**
1.1 INTRODUCTION **1**
1.2 STUDY AREA BACKGROUND **2**
1.2.1 INTRODUCTION 2
1.2.2 GEOGRAPHICAL LOCATION AND CLIMATE OF THE COUNTRY 3
1.2.3 GEOLOGY AND GROUNDWATER 3
1.2.4 DEMOGRAPHIC AND SOCIO-CULTURAL STRUCTURE 6
1.2.5 LAND AND WATER USE 6
1.2.6 QATAR URBAN WATER CYCLE DESCRIPTION 9
1.2.7 QATAR WATER RESOURCES PROBLEMS 12
1.3 LITERATURE REVIEW **14**
1.3.1 DEFINITION OF A LAGOON 14
1.3.2 LAGOON WATER SOURCES, QUALITY AND STANDARDS 14
1.3.3 LAGOON CONSTRUCTION 16
1.3.4 LAGOON WATER QUALITY STANDARDS 17
1.3.5 EFFECTS OF LAGOONS ON GROUNDWATER 19
1.3.6 LAGOONS' ADVANTAGES AND DISADVANTAGES TO THE ENVIRONMENT 21
1.3.7 LAGOON CASE STUDIES 23
1.4 RESEARCH BACKGROUND **25**
1.4.1 LACK OF WATER REUSE 25
1.4.2 RESEARCH GAP 25
1.4.3 AIM, OBJECTIVES AND RESEARCH QUESTIONS 26
1.4.4 APPROACH AND THESIS LAYOUT 27
CHAPTER.2. RESEARCH DESIGN AND METHODOLOGY **28**
2.1 INTRODUCTION **28**
2.2 RESEARCH DESIGN **28**
2.3 RESEARCH METHODS **29**
2.4 SAMPLING SITES SELECTION AND SAMPLE COLLECTION PROCESSES **29**
2.4.1 LAGOONS 29
2.4.2 WELLS 31
2.4.3 SAMPLE LOCATIONS 32
2.4.4 SAMPLE COLLECTION 33
2.4.5 LABS USED FOR SAMPLE ANALYSIS 34
2.5 HYDROGEOCHEMICAL DATA ANALYSIS **35**
2.5.1 WATER ANALYSIS 35

2.5.2 Soil and Plants analysis 37
2.5.3 Hydrogeochemical data analysis 37
2.6 MULTIVARIATE STATISTICAL ANALYSIS 38
2.6.1 Principal component analysis (PCA) 39
2.6.2 The hierarchical cluster analysis (HCA) 41
2.6.3 Correlation matrix 41
2.6.4 Generalized linear models (GLM) 42
2.7 GIS ANALYSIS USING INVERSE DISTANCE WEIGHT (IDW) ANALYSIS 42
CHAPTER.3. A PERCEPTUAL STUDY OF LAGOONS AND GROUNDWATER IN QATAR 44
3.1 INTRODUCTION 44
3.2 METHODOLOGY 47
3.2.1 Research paradigm and design 48
3.2.2 Ethical approval 48
3.2.3 Public perception survey 48
3.2.4 Policy makers interviews 52
3.3 RESULTS AND DISCUSSION 55
3.3.1 Public perception of lagoons: current situation and management 55
3.3.1.1 Demographic data 55
3.3.1.2 Public knowledge of the lagoon situation in Qatar 57
3.3.1.3 Public attitude toward lagoon health and safety risks. 62
3.3.1.4 Public Attitude toward lagoons benefits 65
3.3.1.5 Public desire to be involved in the management decisions around lagoons 67
3.3.1.6 Public attitude toward TWW reuse 69
3.3.2 Policymakers perception of lagoons current situation and management 71
3.3.2.1 Policymakers background information 72
3.3.2.2 Policymakers general knowledge about lagoons in Qatar 72
3.3.2.3 Policymakers perception of lagoon impact on the environment 75
3.3.2.4 Policymakers perceptions of public opinion and involvement with lagoon management 76
3.3.2.5 Policymakers opinions about TWW reuse 77
3.3.2.6 Policymakers recommendations regarding lagoon and general water management 77
3.3.3 Linking public and policy makers' perceptions 78
3.4 CONCLUSIONS 79
CHAPTER.4. HYDROGEOCHEMICAL SURVEY OF LAGOONS AND SURROUNDING WELLS 81
4.1 INTRODUCTION 81
4.2 METHODOLOGY 83
4.2.1 Modelling and visualising water type, precipitation and mineral saturation 83
4.2.2 Water quality indices 84
4.2.3 Soil Quality Index 90
4.2.4 Plant Bioconcentration factor relative to the soil. 92
4.3 RESULTS AND DISCUSSION 93
4.3.1 Qatar artificial Lagoons 93
4.3.1.1 Lagoon water multivariate statistical analysis. 93
4.3.1.2 Lagoon water quality compared to international and national standards. 98
4.3.1.3 Lagoon water processes and rock-water interactions. 100
4.3.2 Qatar Groundwater Aquifers 106

4.3.2.1 Groundwater multivariate statistical analysis 107
4.3.2.2 Groundwater quality compared to international and national standards 112
4.3.2.3 Groundwater processes and rock-water interactions 114
4.3.3 CORRELATION BETWEEN LAGOON WATER AND GROUNDWATER COMPOSITION 121
4.3.4 EVALUATING LAGOON AND GROUNDWATER BASED ON THEIR DESIGNATED USAGE 126
4.3.4.1 Lagoon water quality classifications 126
4.3.4.2 Groundwater Quality Classifications 127
4.3.5 GENERAL SOIL QUALITY 133
4.3.5.1 Soil multivariate statistical water analysis 133
4.3.5.2 Farm and lagoon soil quality analysis 136
4.3.5.3 Saline-sodic soil analysis 139
4.3.5.4 Soil quality index 140
4.3.6 GENERAL PLANT QUALITY 142
4.3.6.1 Plant multivariate statistical water analysis 142
4.3.6.2 Farms and Lagoon plant quality analysis 145
4.3.7 WATER, SOIL AND PLANT RELATIONSHIPS 148
4.4 CONCLUSIONS 149
CHAPTER.5 BACTERIAL SURVEY OF LAGOONS AND SURROUNDING WELLS 152
5.1 INTRODUCTION 152
5.2 METHODOLOGY 154
5.2.1 SAMPLE COLLECTION 154
5.2.2 MEDIA AND MATERIALS PREPARATIONS 155
5.2.3 SAMPLE PLATING 156
5.2.4 COLONY FORMING UNITS (CFU): DILUTION AND CONCENTRATION 156
5.2.5 PURIFICATION AND STORAGE 157
5.2.6 MALDI-TOF-MS 157
5.2.7 COLIFORM BACTERIA IDENTIFICATION 159
5.2.8 BACTERIAL FLORA HEATMAPS 159
5.3 RESULTS AND DISCUSSION 160
5.3.1 BACTERIAL IDENTIFICATION AND DISTRIBUTION IN BOTH LAGOONS AND GROUNDWATER 160
5.3.2 BACTERIAL RELATIVE ABUNDANCE 161
5.3.3 LAGOONS AND GROUNDWATER BACTERIAL SPECIES MULTIVARIATE STATISTICAL ANALYSIS 167
5.3.4 BACTERIAL AND CHEMICAL PROFILING IN THE LAGOON WATER 171
5.3.5 BACTERIAL AND CHEMICAL PROFILING IN THE GROUNDWATER 175
5.3.6 BACTERIAL AND CHEMICAL PROFILING IN BOTH LAGOONS AND GROUNDWATER 177
5.3.7 COLIFORM BACTERIA IDENTIFICATION AND DISTRIBUTION IN BOTH LAGOONS AND GROUNDWATER 187
3.3.7.1 Coliform bacteria compared to national and international standards. 188
3.3.7.2 Multivariate statistical analysis of coliform bacteria in lagoons and groundwater 188
3.3.7.3 Coliform bacteria relation to chemical variables in lagoons and groundwater 192
5.3.8 BACTERIAL RELATIONSHIP BETWEEN THE LAGOONS AND THE SURROUNDING GROUNDWATER 193
5.4 CONCLUSIONS 198
CHAPTER.6. CONCLUSION, RECOMMENDATIONS AND APPENDIX 200
6.1 INTRODUCTION 200
6.2 A PERCEPTUAL STUDY OF LAGOONS AND GROUNDWATER IN QATAR 200
6.2.1 SUMMARY 200

6.2.2 Study Limitations 200
6.2.3 Recommendation for the perceptual study of lagoons and groundwater in Qatar 200
6.2.4 Future work 201
6.3 HYDROGEOCHEMICAL SURVEY OF LAGOONS AND SURROUNDING WELLS 202
6.3.1 Summary 202
6.3.2 Study Limitations 202
6.3.3 Recommendation 202
6.3.4 Future work for the HydroGeoChemical survey of lagoons and surrounding wells 203
6.4 BACTERIAL SURVEY OF LAGOONS AND SURROUNDING WELLS 203
6.4.1 Summary 203
6.4.2 Study Limitations 203
6.4.3 Recommendation 203
6.4.4 Future work for the bacterial survey of lagoons and surrounding wells 204
6.5 OVERALL CONCLUSION 204
APPENDIX A. PUBLIC PERCEPTION ON LAGOONS SURVEY 205
APPENDIX B. POLICY MAKERS INTERVIEW QUESTIONS 208
APPENDIX C. HYDROCHEMICAL MEDIAN, RANGE, INTERQUARTILE RANGE 210
APPENDIX D. COLONY FORMING UNIT (CFU) RESULTS 211
APPENDIX E. MICROBIAL PROTEIN PROFILE RESULTS AND SCORES 212
APPENDIX F. MICROBIAL PROTEIN PROFILE PCA PRINCIPAL COMPONENTS 213
REFERENCE 214

List of Figures

Figure 1.1. Cross-section showing karstification processes producing three types of sinkholes (1.dissolution, 2.buried depression and 3.collapse), (adapted from (Al-Yousef, 2003; Duggan et al., 2014; Rivers et al., 2019). 3
Figure 1.2. Schematic summarizing the geological structure of Paleogene rocks formation history of Qatar (adapted from Al-Yousef, 2003). 4
Figure 1.3. Qatar's four main hydrological basins. Produced from data taken from Qatar MME ArcGIS documents (PSA, 2019). 5
Figure 1.4. Infrastructure projects in Qatar 2010 – 2019. Produced from data published by the Qatar planning and statistical authority (PSA, 2019). 7
Figure 1.5. Comparison of water in million m^3 (Bar) and agricultural production in tonnes (broken line) as a function of population growth (solid line). Water and agriculture productions are represented on the left Y-axis, and population on the right Y-axis. Produced from data published by the Qatar planning and statistical authority (PSA, 2019). 7
Figure 1.6. Water volumes from desalination production, groundwater abstraction and water losses (million m^3 $year^{-1}$) in Qatar between 2012-2019. Figure produced from data published by the Qatar planning and statistical authority (PSA, 2019). 8
Figure 1.7. Wastewater statistics between 2012-2019 for Qatar, show the amount of wastewater disposed of in untreated lagoons, treatment plants, and surface water pumped to the sea (million m^3 $year^{-1}$). Produced from data published by the Qatar planning and statistical authority (PSA, 2019). 8
Figure 1.8. Treated waste water (TWW) final discharge statistics (million m^3 $year^{-1}$) for Qatar between 2012-2019. Figure produced from data published by the Qatar planning and statistical authority (PSA, 2019). 9
Figure 1.9. An example of WW treatment plant processes flow diagram for Qatar where the resulting water quality is rated as 'high-grade' (adapted from (SUEZ, 2021)). 10
Figure 1.10. Desalination water supply and demand, actual and projected, 2009-2030 (Adapted from QNV, 2009). 13
Figure 1.11. Rising water table around the Abu-Nakhla lagoon creating surface water pools next to residential areas (AbuNada, 2021). 13
Figure 1.12. Diagram illustrating typical water treatment plants, with three options for tertiary treatment, before discharging water into the natural environment with constructed and non-constructed wetlands as a water polishing step (Adapted from (Sloey et al., 2021). 15
Figure 1.13. Cross-section through a typical constructed wetland, with inlet for the water source, outlet to discharge the water into the natural environment and protective lining (Adapted from (Parde et al., 2021)). 16
Figure 1.14. A cross-section through a typical unconstructed wetland, with inlet for the water source, outlet to discharge the water into the natural environment and without protective lining (Adapted from (Hunter et al., 2009)). 17
Figure 1.15 Diagram shows a conceptual model of (i) nitrate reduction to dinitrogen and (ii) phosphorus sorption from water moving from wetland to groundwater (Adapted from Ackerman et al., 2015) 20
Figure 2.1. A research design flowchart showing the main types of data collection and their sequence within the research project. 29
Figure 2.2. Map showing the sampled lagoon locations and names in Qatar. 30
Figure 2.3. Wells distribution in the different areas around Qatar and their proximity to the closest lagoon. 31

Figure 2.4. Map of Qatar with sampling locations for the hydrogeochemistry survey section. Red symbols show the location of all the lagoons; blue symbols indicate wells that were sampled. 32
Figure 3.1 Flow chart showing the social study chapter research design flowchart illustrating the main types of data collection 47
Figure 3.2. Survey participant age distribution percentage. 56
Figure 3.3. Survey participant education distribution. 56
Figure 3.4. Survey participant nationality distribution. 57
Figure 3.5. The survey question “Heard about lagoons before?’’ responses divided into different educational groups. 59
Figure 3.6. The survey question “Heard about lagoons before?’’ responses divided into different age groups. 59
Figure 3.7. The survey question “When did you first hear about Lagoons?” responses divided by the different educational groups. 60
Figure 3.8. The survey question “When did you first hear about Lagoons?” responses divided by the different age groups. 60
Figure 3.9. The survey question “How many lagoons are there in Qatar?” responses divided by the different educational groups. 60
Figure 3.10. The survey question “Are you aware of any lagoons in your city?” responses divided by the different educational groups. 61
Figure 3.11. The survey question “Lagoon water source” responses divided by the different educational groups. 61
Figure 3.12. The survey question “Ministries responsible for lagoons management’’ responses divided by the different educational groups. 62
Figure 3.13. Survey Likert scale responses for the survey question “all lagoons are the same?’’. 62
Figure 3.14. Survey Likert scale responses for the survey questions related topublic attitude toward lagoons health and safety risks. 63
Figure 3.15. The survey question “Lagoons attract dangerous animals’’ responses divided by the different nationality groups. 64
Figure 3.16. The survey question “Lagoons are a drowning hazard’’ responses divided by the different nationality groups. 64
Figure 3.17. The survey question related to public attitude toward lagoon health and safety risks divided by the different nationality groups. 65
Figure 3.18. The survey question related to public attitude toward lagoons' health and safety risks divided by the different education groups. 65
Figure 3.19. Survey Likert scale responses for survey questions related to public attitude toward lagoons’ benefits. 66
Figure 3.20. Survey Likert scale responses for the survey questions related to “Public desire to be involved in the management decisions around lagoons’’. 67
Figure 3.21. The survey question “Lagoon water source” responses divided by the different education groups. 68
Figure 3.22. The survey question related “Public should know about lagoons near them” responses divided by the different education groups. 68
Figure 3.23. Survey Likert scale responses for the survey questions related to public attitude toward TWW reuse. 69
Figure 3.24. The survey question “More efficient treated wastewater reuse is needed’’ responses divided by the different educational groups. 70

Figure 3.25. The survey question “Public attitude toward treated wastewater reuse’’ responses divided by the public’s previous knowledge of lagoons’ existence. 71
Figure 3.26. Abu Nakhla lagoon, satellite image taken in the year 2014 (left) and 2022 (right) 73
Figure 3.27. Al-Karanna lagoon, satellite image taken on 14th August 2021. 73
Figure 3.28. Interviews responses on the lagoon water source, showing the water source and number of times it was mentioned. 74
Figure 4.1. Lagoon water PCA 3D plot for 32 physical and chemical variables (summer: left, winter: right). Varibles clustered in the same group showen by three circules labled A,B and C. PCA was used with the Varimax rotation method and Kaiser Normalization. 96
Figure 4.2. Lagoon Dendrogram, produced from HCA, using ward linkage, with Euclidean distance measurement with Z score standardization transformation. Varibles clustered in the same group showen by the squares labled A,B and C. (Summer: left, winter: right) 97
Figure 4.3. Piper diagram showing different water types of lagoons based on the major cations (Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}) and major anions (HCO^{-3}, Cl^{-} and SO_4^{2-}) in meq L^{-1} (Left: summer, right: winter)); the ion exchange processes are shown in the red arrows, with typical seawater or freshwater processes illustrated 101
Figure 4.4. Gibbs plot showing lagoon water summer and winter evaporation, precipitation and rock weathering processes based on $Na^{+}/Na^{+}+Ca^{2+}$ relation and $Cl^{-}/Cl^{-}+HCO_3^{-}$ relation with TDS in mg L^{-1}. 102
Figure 4.5. A Chadha diagram illustrating the lagoon water-rock process difference between summer and winter, with each section on the diagram labelled from 1 to 8 showing different processes 103
Figure 4.6. Lagoon water Aragonite and Calcite Saturation indices for summer (left) and winter (right). 105
Figure 4.7. Lagoon water anhydrite and gypsum saturation indices for summer (left) and winter (right). 105
Figure 4.8. Lagoon water summer and winter dissolution processes are shown by gypsum log(IAP) vs Ca^{2+} ion activity with a gypsum saturation point of 4.6 ($log_{10}IAP - log_{10}Ks$). 105
Figure 4.9. Groundwater PCA 3D plot for 32 physical and chemical variables (summer: left, winter: right). Varibles clustered in the same group showen by three circules labled A,B and C. PCA was used with the Varimax rotation method and Kaiser Normalization. 109
Figure 4.10 Groundwater Dendrogram, produced from HCA, using ward linkage, with Euclidean distance measurement with Z score standardization transformation. Varibles clustered in the same group showen by three squares labled A,B and C. (Summer: left, winter: right) 110
Figure 4.11. Piper diagram showing different groundwater types based on the major cations (Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}) and major anions (HCO_3^{-}, Cl^{-} and SO_4^{2-}) in meq L^{-1} (Left: summer, Right: winter); the ion exchange processes are shown in the red arrows, with typical seawater or freshwater processes illustrated 115
Figure 4.12. Groundwater chloride isoconcentration maps in mg L^{-1} produced with the IDW geostatistical tool. 116
Figure 4.13. Gibbs plot showing groundwater summer and winter evaporation, precipitation and rock weathering processes based on the relationship of TDS (mg L^{-1}) with $Na^{+}/Na^{+}+Ca^{2+}$ and $Cl^{-}/Cl^{-}+HCO_3^{-}$ 117
Figure 4.14. Chadha diagram illustrating water-rock process difference between summer and winter, with each section on the diagram labelled from 1 to 8 showing different processes. 118
Figure 4.15. Groundwater wells divided based on the Chadha water type (1 – 8 types), summer on the left and winter on the right. 119
Figure 4.16. Groundwater aragonite and calcite saturation indices for summer (left) and winter (right). 120

Figure 4.17. Groundwater anhydrite and gypsum saturation indices for summer (left) and winter (right). 120
Figure 4.18. Groundwater summer and winter dissolution processes are shown by gypsum log_{10}(IAP) vs Ca^{2+} ion activity with gypsum saturation point (log_{10}Ks) of 4.6. 120
Figure 4.19. Groundwater Iron isoconcentration maps (µg L^{-1}) produced with the IDW geostatistical tool. 123
Figure 4.20. Groundwater Arsenic isoconcentration maps (µg L^{-1}) produced with the IDW geostatistical tool. 124
Figure 4.21 Groundwater Iodine isoconcentration maps in µg L^{-1} produced with IDW geostatistical tool 125
Figure 4.22. Groundwater nitrate isoconcentration maps in mg L^{-1} produced with the IDW geostatistical tool. 126
Figure 4.23. USSL diagram for classification of irrigation waters by four classes (low, medium, high and very high) based on SAR and EC (left summer, right winter). 129
Figure 4.24. Farms and lagoons PCA 3D plot for the soils variables (farms: left, lagoons: right). Varibles clustered in the same group showen by three circules labled A,B and C. PCA was used with the Varimax rotation method and Kaiser Normalization. 135
Figure 4.25. Farm and lagoon soil Dendrogram, produced by HCA using Ward linkage, with Euclidean distance and Z score transformation; Varibles clustered in the same group showen by two squares labled A and B. (Farms: left, Lagoons: right). 135
Figure 4.26. Diagram showing the relationship between soil electrical conductivity and SAR; delineated zones illustrate the soil classification of normal, saline, saline-sodic, and sodic soils 140
Figure 4.27. Farm and lagoon PCA 3D plot for the plants variables (farms: left, lagoons: right). Varibles clustered in the same group showen by three circules labled A,B and C. PCA was used with the Varimax rotation method and Kaiser Normalization. 144
Figure 4.28. Farm and lagoon plants Dendrogram, produced by HCA using Ward linkage, with Euclidean distance and Z score standardization transformation. Varibles clustered in the same group showen by three squares labled A,B and C. (Farms: left, Lagoon: right) 144
Figure 5.1. Summary of bacterial data collection methodology for: (1) Quantitative data of Colony Forming Units (CFU); (2) Qualitative method of bacterial speciation using MALDI-TOF-MS. 154
Figure 5.2. Map of Qatar with sampling locations for the microbial survey section. Red symbols show the location of all the lagoons; blue symbols indicate wells that were sampled. 155
Figure 5.3. Heatmap depicting the relative abundance of bacterial populations (CFU ml^{-1}) in lagoon water at the species level. 165
Figure 5.4. Heatmap depicting the relative abundance of bacterial populations (CFU ml^{-1}) in groundwater at the species level. 166
Figure 5.5. Lagoon bacterial profiles PCA 3D plot for the bacterial strains (red dots) and the water chemistry (blue dots); Varibles clustered in the same group showen by two circules labled A and B. PCA was used with Varimax Rotation Method and Kaiser Normalization. 169
Figure 5.6. Groundwater proteins profiles PCA 3D plot for the bacterial strains (red dots), the water chemical variables (blue dots) and the groundwater distance to the closest lagoon in km (yellow star); Varibles clustered in the same group showen by two circules labled A and B. PCA was used with Varimax rotation method and Kaiser Normalization 170
Figure 5.7. Qatar map with the distribution of bacterial species found only in lagoon water. 172
Figure 5.8. Qatar map with the distribution of bacterial species found only in groundwater. 175

Figure 5.9. Qatar bacteria distribution map, E. coli on the left, A. caviae on the right (CFU ml^{-1}) lagoon (red) and groundwater (green)..... 178
Figure 5.10. Qatar bacteria distribution map; A. hydrophila on the left, A. veronii on the right (CFU ml^{-1}) lagoon (red) and groundwater (green). 179
Figure 5.11. Qatar bacteria distribution map, K. pneumoniae on the left, S. marcescens on the right (CFU ml^{-1}) for lagoon (red) and groundwater (green). 180
Figure 5.12. Qatar bacteria distribution map, E. cloacae on the left, E. asburiae on the right (CFU ml^{-1}) for lagoon (red) and groundwater (green). 181
Figure 5.13. Qatar bacteria distribution map, E. kobei on the left, P. aeruginosa on the right (CFU ml^{-1}) lagoon (red) and groundwater (green)..... 182
Figure 5.14. Qatar bacteria distribution map, P. alcaliphila on the left, P. composti on the right (CFU ml^{-1}) for lagoon (red) and groundwater (green) 184
Figure 5.15. Qatar bacteria distribution map, P. oleovorans on the left, P. putida on the right (CFU ml^{-1}) lagoon (red) and groundwater (green)..... 185
Figure 5.16. Qatar bacteria distribution map with S. maltophilia (CFU ml^{-1}) lagoon (red) and groundwater (green)..... 186
Figure 5.17. Lagoon water PCA 3D plot showing the correlation between CB and chemical variables, CB shown with a red triangle clustering in the group shown in red circule; Using PCA with Varimax rotation method and Kaiser Normalization 190
Figure 5.18. Lagoon water Dendrogram showing the correlation between CB and chemical variables, produced from HCA, using ward linkage, with Euclidean distance measurement with Z score standardization transformation. Varibles clustered in the same group showen by three squares labled A, B and C. 190
Figure 5.19. Groundwater PCA 3D plot showing the correlation between CB and chemical variables with groundwater distance to the nearest lagoon on km (DL). Coliform Bacteria shown with a red triangle, DL shown with a yellow star clustering in the same group shown in green circule; using PCA with Varimax rotation method and Kaiser Normalization. 191
Figure 5.20. Groundwater Dendrogram showing the correlation between CB and chemical variables with groundwater distance to the nearest lagoon (km), produced from HCA, using Ward linkage, with Euclidean distance measurement with Z-score standardization transformation. Varibles clustered in the same group showen by three squares labled A, B and C..... 192
Figure 5.21. Qatar map with CB (CFU ml^{-1}) distribution for lagoon and groundwater..... 193
Figure 5.22. Coliform bacteria correlated bacteria PCA plot, showing bacterial strains in lagoons (L) and groundwater (F). MALDI-TOF-MS produced unique protein profiles acting as a fingerprint for each identified bacteria. The extracted protein profiles are used for this analysis representing each bacteria labelled with different colours; Bacteria of same strain and origin source clustered in the same group; PCA was used with the Varimax rotation method and Kaiser Normalization. 196
Figure 5.23. Treated wastewater correlated bacteria PCA plot, showing bacterial strains in lagoons (L) and groundwater (F). MALDI-TOF-MS produced unique protein profiles acting as a fingerprint for each identified bacteria. The extracted protein profiles are used for this analysis representing each bacteria labelled with different colours; Bacteria of same strain and origin source clustered in the same group; PCA was used with the Varimax rotation method and Kaiser Normalization. 197

Figure 7.1. A picture of an example of a lagoon in Qatar, attached with the survey 205

List of Tables

Table 1.1 Summary of the urban water cycle in Qatar describing each stage, the activities undertaken and the institution responsible to conduct each activity. 10
Table 1.2. USEPA suggested values to calculate typical areal loading rates for WW influents and effluents(USEPA, 2000b). 17
Table 1.3. USEPA recommended guidelines for faecal bacteria based on the type of irrigation (USEPA, 2000b). 18
Table 1.4. This Research main objective, questions, and the research process used to achieve the main project objectives and aims. 26
Table 2.1. Lagoons sampled in both summer and winter with X and Y coordinates. 31
Table 2.2. The sampled wells area location and the X and Y coordinates 33
Table 3.1 Survey questions ID number with each question answer choices and SPSS numerical values 51
Table 3.2. Chi-square test showing the relationship between public knowledge of lagoons in Qatar and the independent demographic variables. 57
Table 3.3 Survey participant answers for questions ID 4 – 9, with the percentage of each response 57
Table 3.4. Chi-square test showing the relationship between public respondents to the survey questions related to lagoons knowledge in Qatar and independent demographic variables. 58
Table 3.5. Chi-square showing the relationship between survey questions related to public attitude toward lagoon safety responses and independent demographic variables 64
Table. 3.6. Chi-square showing the relationship between the survey questions related to public attitudes toward lagoons benefits Qatar and the demographic independent variables. 67
Table. 3.7. Chi-square showing the relationship between the survey questiond related to public desires to be involved in the management decisions around lagoons and the demographic independent variables. 68
Table 3.8. Chi-square test showing the relationship between the survey questions related to public attitude toward TWW reuse and independent demographic variables. 70
Table 4.1. The relative weight of chemical and physical variables chosen for WQI and their sub-indices. 86
Table 4.2. Quality measure (qi) limit values calculated for the indicated variables for each class (Meireles et al., 2010; Muniz et al., 2020; Batarseh et al., 2021). 89
Table 4.3. The relative weightings (w_i) of the IWQI variables. (Muniz et al., 2020; Batarseh et al., 2021) 89
Table 4.4. Farms and lagoon soil principal components, PC1 to PC7 had cumulative eigenvalues of more than 80% and a total of more than 1. 91
Table 4.5. Tests of Normality (Kolmogorov-Smirnov and Shapiro-Wilk) for all the Lagoon variables, If the significant level (Sig.) value of the test is greater than 0.05, the data is normal. If it is below 0.05, the data significantly deviate from a normal distribution (highlighted in grey). 94
Table 4.6. Lagoon water Data KMO and Bartlett's Test results. 94
Table 4.7. Lagoon water principal components. PC1 to PC4 had cumulative eigenvalues of more than 80% for summer and winter. Bold values were correlated to each other in the same PC. 95
Table 4.8. Results of GLM showing a significant correlation between lagoon variables and the seasonal variation between summer and winter. 97

Table 4.9 Summary of the lagoon (n=10) water variables (mean, minimum, maximum and standard deviation), with the number of violations to the different standards highlighted in grey 99
Table 4.10. The different field descriptions divided by a Chadha diagram with their water types, and the number of lagoon sources represented in each field both in summer and winter 104
Table 4.11. Tests of Normality (Kolmogorov-Smirnov and Shapiro-Wilk) for all the groundwater variables, If the significance level (Sig.) value of the test is greater than 0.05, the data is normal. If it is below 0.05, the data significantly deviate from a normal distribution 107
Table 4.12 Groundwater data KMO and Bartlett's test results 108
Table 4.13 Groundwater principal components. PC1 to PC8 had cumulative eigenvalues of 80% for summer and winter. 109
Table 4.14. Results of GLM showing a significant correlation between groundwater variables and seasonal variation between summer and winter ($p<0.05$) highlighted in grey 111
Table 4.15 Results of GLM showing a significant correlation between groundwater variables and distance to the coast ($p<0.05$) highlighted in grey 111
Table 4.16 Summary of the sampled groundwater (summer n=53 and winter n=57) water variables (mean, minimum, maximum and standard deviation), with the number of violations to the different standards highlighted in grey 113
Table 4.17. Chadha diagram water types, and the number of groundwaters (summer n=53 and winter n=57) represented in each field both in summer and winter (description of each water type is in Table 4.10). 117
Table 4.18. Results of GLM showing a significant correlation between summer and winter groundwater variables to the distance of the closest lagoon ($p<0.05$) highlighted in grey. 122
Table 4.19. Summary of scores and water classifications for lagoons (n=10) summer and winter. Including SAR, Na%, PI, PS, Chloride and IWQI in meq L^{-1}. 127
Table 4.20. Water quality classification based on the computed WQI value, with the number of wells in each classification (summer n=53 and winter n=57) 128
Table 4.21. Water classification for the investigated sites based on SAR (summer n=53 and winter n=57) 128
Table 4.22. Classification of groundwater quality for the investigated sites based on Na% (summer n=53 and winter n=57) 129
Table 4.23. Classification of groundwater quality for the investigated sites based on PI (summer n=53 and winter n=57). 130
Table 4.24. Classification of groundwater quality for the investigated sites based on PS (summer n=53 and winter n=57). 130
Table 4.25. Classification of groundwater quality for the investigated sites (summer n=53 and winter n=57) based on Chloride (meq L^{-1}) 130
Table 4.26. Classification of groundwater quality for the investigated sites (summer (S) n=53 and winter (W) n=57) based on IWQI, with recommendation for the water type usage for both soil and plants 131
Table 4.27. Tests of normality (Kolmogorov-Smirnov and Shapiro-Wilk) for all the farm and lagoon soil variables; if the significant level (Sig.) of the test is greater than 0.05, the data is normal. 133
Table 4.28. Farms and lagoon soil data: KMO and Bartlett's Test results. 134
Table 4.29. Farms and Lagoon soil principal components; PC1 to PC5 had cumulative eigenvalues of more than 80%. 134

Table 4.30. Results of GLM showing the soil variables that were significantly different between farm and lagoon soil ($p<0.05$) highlighted in grey. 136
Table 4.31. Results of GLM showing the soil chemical variables that were significantly correlated between farm variables to the distance of the closest lagoon ($p<0.05$) highlighted in grey. 136
Table 4.32. Summary of the farm (n=53) and lagoon (n=10) soils' variables (mean, minimum, maximum and standard deviation), with the number of farms and lagoons soil violating EU and WHO (highlighted in grey). 137
Table 4.33. Soil classification based on SQI, with the percentage of the lagoon (n=10) and farm (n=53) soil in each classification. 141
Table 4.34. Tests of normality (Kolmogorov-Smirnov and Shapiro-Wilk) for all the farm and lagoon soil variables; if the significant level (Sig.) value of the test is greater than 0.05, the data is deemed normal. 142
Table 4.35. Farm and lagoon plant data KMO and Bartlett's test results. 143
Table 4.36. Farm and lagoon plants principle components showing a correlation between the chemical variables; PC1 to PC6 had cumulative eigenvalues of more than 80%. 143
Table 4.37. Results of GLM showing the plant variables that have significant differences between farm and lagoon plants ($p<0.05$) highlighted in grey 145
Table 4.38. Results of GLM showing the plant chemical variables that have significant correlation between farm variables to the distance to the closest lagoon ($p<0.05$) highlighted in grey 145
Table 4.39. Summary of the farms (n=53) and lagoons (n=10) measured plant variables (mean, minimum, maximum and standard deviation), with the number of farms (F) and lagoons (L) plants violating the EU standards for products intended for animal feed (highlighted in grey). 146
Table 4.40. Bioconcentration factors for all the chemical variables measured in plant and soil from farms and lagoons, the values highlighted in grey were greater than one and indicate plant accumulation 148
Table 5.1. Summary of the lagoons (n=9) and groundwater (n=13) 'identified' and 'not identified' bacterial strains using MALDI-TOF-MS with the measured variables (mean, minimum, maximum and standard deviation). 160
Table 5.2. Results of GLM showing the lagoon and groundwater variables with significant differences ($p<0.05$) between winter 2019 and winter 2020. 161
Table 5.3. Bacteria strains identified using MALDI-TOF-MS in both lagoon and groundwater samples with the bacterial phylum, class, order, family, and genus name. Underscore denotes bacteria found in groundwater only; bold denotes bacteria found in lagoon only; the rest were found in both lagoons and groundwater. 162
Table 5.4. Tests of normality (Kolmogorov-Smirnov and Shapiro-Wilk) for all the lagoon and groundwater bacterial and chemical variables; if the significance level (Sig.) of the test is greater than 0.05, the data is normal; if it is below 0.05, the data significantly deviate from a normal distribution. 167
Table 5.5. Lagoon water data: KMO and Bartlett's test results. 168
Table 5.6. Lagoon bacterial profiles PCA 3D plot for the bacterial strains and the water chemical variables. 168
Table 5.7. Groundwater proteins profiles PCA 3D plot for the bacterial strains, the water chemical variables and the groundwater distance to the closest lagoon in km. 170
Table 5.8. Lagoon and groundwater protein profiles spearman correlation matrix between bacterial strains and the water chemical variables. 171

Table 5.9. Bacterial strain summary of lactose fermentation, pathogenic, CB group and bacteria affiliation to lagoons in this research. Underscore denotes bacteria found in groundwater only; bold denotes bacteria found in lagoon only; the rest were found in both lagoons and groundwater. 187
Table 5.10. Coliform bacteria in lagoons and groundwater, with the maximum allowable standards for Qatar quality criteria for treated WW and WHO. 188
Table 5.11. Lagoon principle components showing correlation between CB and chemical variables with PC1 to PC4 had a cumulative eigenvalues of more than 90% 189
Table 5.12. Groundwater principal components showing the correlation between CB and chemical variables with groundwater distance to the nearest lagoon in km; PC1 to PC5 had cumulative eigenvalues of more than 85%..... 191
Table 5.13. GLM estimates CB as the response for the different factors (groundwater distance to the closest lagoon, Al and Fe) with normal Probability distribution and Identity Link function 194
Table 5.14. GLM estimates CB as the response for the different factors (groundwater distance to the closest lagoon, Al and Fe) with normal Probability distribution and Identity Link function 195
Table 5.15. GLM estimates for five selected bacteria strains (A. veronii, E. cloacae, E. coli, K. pneumoniae and P. aeruginosa) as a response to the different factors (groundwater distance to the closest lagoon) with a normal probability distribution and identity link function..... 195
Table 7.1. Summary of groundwater and lagoon median, range and interquartile range for both summer and winter. ... 210
Table 7.2. Microbial survey sampling site location and coordinates, with the bacteria colonies count (CFU ml^{-1}) in the different selective media, with the number of colonies identified and not identified by MALDI-TOF-MS. 211
Figure 7.3. Microbial survey sampling site location bacterial strains identified by MALDI-TOF-MS, with the identification scores >1.70. 212
Table 7.4. Coliform bacteria principle components showing bacteria strains in lagoons and groundwater correlate based on the extracted protein profiles with PC1 to PC6 had a cumulative eigenvalue of more than 98%. 213
Table 7.5. Wastewater correlated bacteria principle components showing bacteria strains in lagoons and groundwater correlate based on the extracted protein profiles with PC1 to PC6 had a cumulative eigenvalue of more than 97%. 213

List of Acronyms, Abbreviation and Units of measurement

3D Plot	=	Three Dimensional Plot
ANOVA	=	Analysis Of Variance
BOD	=	Biological Oxygen Demand
EC	=	Electric Conductivity
EMB	=	Eosin Methylene Blue Agar
EPA	=	The Environmental Protection Agency
EU	=	European Commission
FAO	=	The Food And Agriculture Organization Of The United Nations
GCC	=	Gulf Cooperation Council
GIS	=	Geographic Information System
GLM	=	Generalized Linear Model
HCA	=	Hierarchical Cluster Analysis
IC	=	Inorganic Carbon
ICP-MS	=	Inductively Coupled Plasma Mass Spectrometry
IDW	=	Inverse Distance Weighting
IWQI	=	Irrigation Water Quality Index
MALDI-TOF-MS	=	Matrix-Assisted Laser Desorption/Ionization-Time Of Flight
MANOVA	=	Multiple Analysis Of Variance
MDS	=	Minimum Data Set
Na %	=	Sodium Percent
PC	=	Principle Component
PCA	=	Principle Component Analysis
PHREEQE	=	A Program For Geochemical Calculations
PI	=	Permeability Index
PS	=	Potential Salinity
p-value	=	Measure Of The Probability
SAR	=	Sodium Adsorption Ratio
sig.	=	Significant Figure
SPSS	=	Statistical Package For The Social Sciences
SQI	=	Soil Quality Index
SSP	=	Soluble Sodium Percentage
TC	=	Total Carbon
TDS	=	Total Data Set
TDS	=	Total Dissolve Solids
TN	=	Total Nitrogen
TOC	=	Total Organic Carbon
TWW	=	Treated Wastewater
WHO	=	World Health Organization
WQI	=	Water Quality Index
WW	=	Wastewater

Units

mg L^{-1}	=	milligram per litre
mg kg^{-1}	=	milligram per kilogram
µs cm^{-1}	=	micro Siemens per centimetre
ds m^{-1}	=	deciSiemens per metre
mmol L^{-1}	=	millimoles per litre
meq L^{-1}	=	milliequivalent per litre
CFU	=	Colony Forming Unit

Chapter.1. Introduction and Background to the Research

1.1 Introduction

As the global human population has increased over the last five decades the pressure on safe water and sanitation has also increased. Water is essential for domestic use, agriculture, industry, infrastructure, etc. Thus, providing good quality water is as important as maintaining a healthy natural water cycle. Earth's water represents 71% of its surface area; it is in constant movement and exists in all three physical states (ice, water vapour and liquid water). The process of water movement within the natural hydrological cycle is described, comprising evaporation, condensation, precipitation, infiltration and runoff. However, the natural cycle does not include the anthropological impact on water such as human extraction, discharge, point and non-point pollution sources; these processes can drastically affect the natural water cycle. On the other hand, an urban water cycle is more sensible to use for water management to illustrate the actual human impact on the natural hydrological cycle and how it is altering the natural water quantity and quality at certain places.

A successful urban water cycle ensures that sufficient quantity and quality of water is provided for human consumption with safe discharge to the environment without any near future degradation of the providing or receiving environment (Marsalek *et al.*, 2008; UN-Water, 2021). Although 60% of water bodies measured in 89 countries have good ambient water quality, globally, over 80% of wastewater (WW) is likely to be released into the ecosystem without sufficient treatment (UN-Water, 2021). Furthermore, only 52 of the 89 countries with water quality data have details on groundwater, which is troubling since groundwater accounts for the majority of the freshwater resources for many countries (UN-Water, 2021)

A significant part of the urban water cycle is both treating and discharging WW, and both of those steps typically utilize lagoons and wetlands. Those manmade structures are built either for WW treatment, enhancement of treated wastewater (TWW), or final discharge of treated or untreated wastewater back to the natural hydrological water cycle (Marsalek *et al.*, 2008; Zou *et al.*, 2018).

The Qatar urban water cycle is interesting given the lack of freshwater bodies, such as rivers and reservoirs, as well as low rainfall. Qatar's water supplies are especially significant given that only three types of water are available: desalinated water, groundwater, and recycled water (Darwish *et al.*, 2013); all of these are inefficiently utilized but are essential for the Qatari urban water cycle. In 2015, 533 million m^3 of desalinated water were generated, increased from 362 million m^3 in 2010. Desalinated water production is mainly reliant on oil and gas, and it has several environmental consequences that the Ministry of Municipality and Environment monitors. Accelerated population

growth, lifestyle changes, high per capita income, urbanization, and other factors all contribute to this high pressure on the Qatari water cycle. (MDPS, 2019)

An unusual feature in Qatar is the use of lagoons, as artificial lakes, for storing and discharging surface water, treated and untreated wastewater. Qatar like most of the gulf region uses lagoons as storage for TWW because the recycling of that water is extremely limited due to a cultural perception of it being 'dirty' (Al-Mohannadi, 2004; Ibrahim *et al.*, 2015). This has led to excess TWW being accumulated in lagoons and left to evaporate or infiltrate into the groundwater. Most studies were done on TWW lagoons in the region discuss the applicability of using the water for irrigation instead of disposing of it in lagoons (Al-Rawahi *et al.*, 2014; Al-obaid *et al.*, 2017; Abed *et al.*, 2018; Al-Amro *et al.*, 2018); they also discuss the environmental impact of lagoons on the groundwater and discuss direct irrigation with TWW (Candela *et al.*, 2007). Moreover, Zou (2018) argues that the inefficient use of TWW in irrigation, instead of disposal in lagoons, has led to considerable stress on groundwater resources (Zou *et al.*, 2018). Thus, the main aim of this research is to assess the impact of the lagoon system on groundwater, using Qatar as a case study.

Chapter one is divided into three main sections, starting with the background to the study where the state of Qatar and its water management is introduced including the direct and indirect reasons for a lagoon system to be the adopted practice in the country. The second part is a literature review, where different types of lagoons are described and previous studies tackling the impact of lagoons on groundwater are considered. Finally, research gaps are identified leading to the research aims and objectives of this study and a summary of the thesis structure.

1.2 Study Area Background

1.2.1 Introduction

This research investigates the storage of treated and untreated wastewater in lagoons as a major issue affecting groundwater quality in Qatar. Thus, this section will provide an overview of Qatar's geology, geography and climate, population lifestyle and trends affecting water consumption including direct and indirect water resources management issues and complications that put pressure on the Qatari water system. Information will largely be drawn from reports published by the Planning and Statistics Authority of Qatar for the period 2011 – 2019; other sources include reports published by the Ministry of Municipality and Environment (MME) and General Electricity and Water Corporation "KAHRAMAA".

1.2.2 Geographical location and climate of the country

The state of Qatar is a peninsula of 11,500 km^2 in the Arabian Gulf with a few small offshore islands. It is located in the Middle East between Saudi Arabia, with which it shares a land border, and share seawater boarder with Iran, UAE and Bahrain. It is characterised by an extremely arid desert climate with an average temperature of 37°C, reaching >45°C in summer and high evaporation rates (annual average 2200 mm), strong winds and average humidity of 58%. Evapotranspiration varies greatly from less than 2 mm d^{-1} in winter to more than 10 mm d^{-1} in summer (PSA, 2019).

Precipitation is uncommon, difficult to predict, and occurs exclusively in winter between November and May (FAO, 2008). The average precipitation of c. 80 mm yr^{-1} was observed between 1962 and 2007, insufficient for irrigation and agriculture, however, rainfall represents the main source of groundwater recharge.

1.2.3 Geology and groundwater

Qatar has a mostly flat topography, its elevation varies from 100 m above sea level in the south to less than 50 m in the north. In addition to moving sand dunes of up to 40 m in height, it also has almost 850 separate depressions across the country (Al-Saad, 2005; FAO, 2008; GSDP, 2008) resulting from karstification. Karstification is a consequence of the dissolution of carbonate rock by water. Figure 1.1 illustrates different karstification processes that produce three types of sinkholes in Qatar.

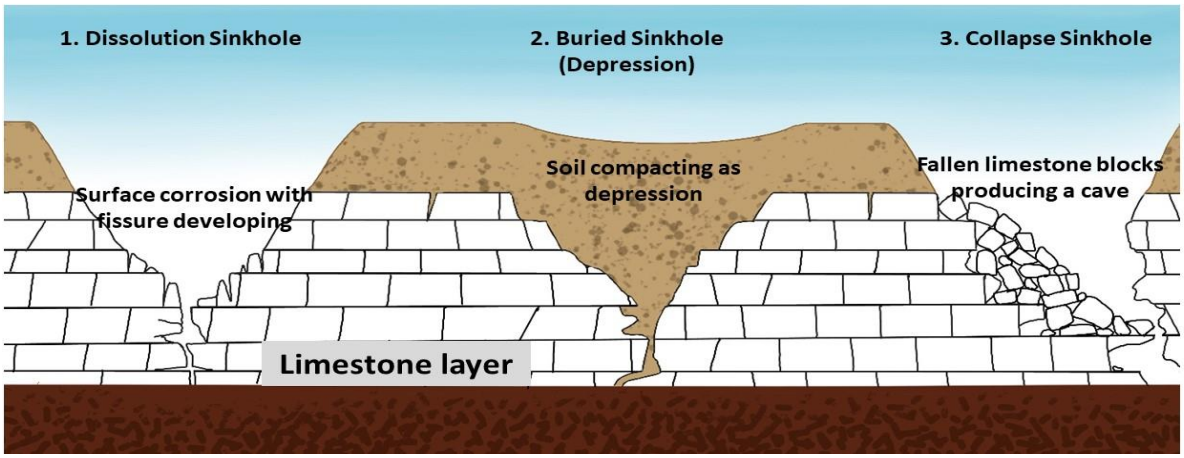


Figure 1.1. Cross-section showing karstification processes producing three types of sinkholes (1.dissolution, 2.buried depression and 3.collapse), (adapted from (Al-Yousef, 2003; Duggan et al., 2014; Rivers et al., 2019).

The karstification rate is dependent on the type and solubility of the rock minerals, the degree of water saturation of the rocks and the time of water-rock interaction. All factors contribute to the

water aquifer drainage and depression formation (Al-Yousef, 2003; Duggan *et al.*, 2014; Rivers *et al.*, 2019)

Figure 1.2 illustrates the main Paleogene rocks that make up the near-surface geology of Qatar including the Dammam Formation of the Middle Eocene, the Rus formation of the Lower Eocene and the Umm er Radhuma Formation. Almost 80% of Qatar's surface is composed of sedimentary rocks of lower and middle Eocene age.

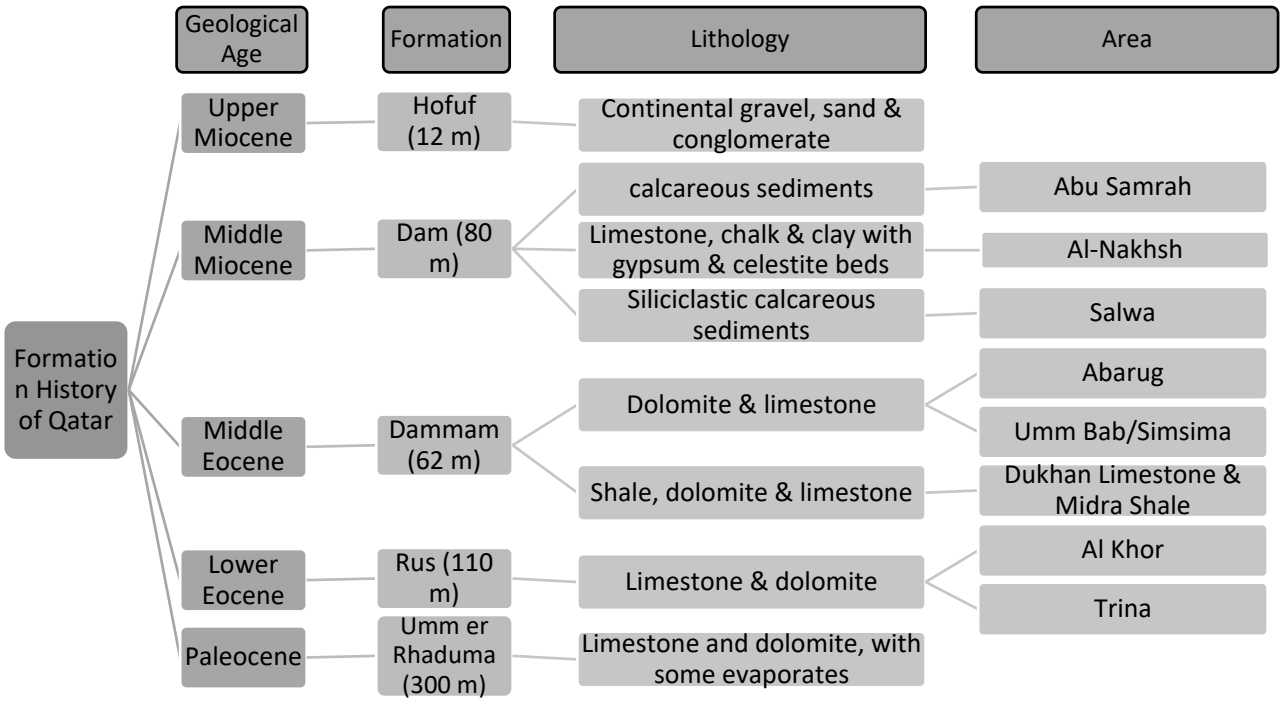


Figure 1.2. Schematic summarizing the geological structure of Paleogene rocks formation history of Qatar (adapted from Al-Yousef, 2003).

The Umm er Radhuma Formation acts as a significant aquifer with a thickness between 100 and 370 m but generally over 300 m. The formation mainly contains dolomitic limestones with harder vesicular dolomite beneath it. This formation usually has calcareous layers in the eastern and central parts of Qatar and argillaceous, gypsitic and dolomitic layers in the west. Overlying the Umm er Radhuma Formation is the Rus Formation, which varies in thickness from a minimum of 15 m in the Dukhan area to a maximum of 122 m in south-western Qatar. It has three sub-divisions; a dolomitic, evaporitic and chalky limestone unit. The dominant geological unit is the Dammam Formation lying above the Rus formation. This formation ranges from 30 m to 62 m in thickness and consists mostly of limestone and dolomite (Al-Yousef, 2003).

Soils locally termed ‘rodat’ exist where overlying limestone rubble and bedrock and colluvial soils composed of calcareous loams, sandy loams, and sandy clay loams have accumulated to depths ranging from 30 cm to 150 cm in depressions. These soils are the country's primary agricultural soils and the locations of rainfall recharge. Highly saline depression soils known as ‘Sabkha’ are also found, primarily along the coastal line to the east and south (FAO, 2008).

There are two primary groundwater reservoirs, the Northern and Southern reservoirs, with three secondary basins in the southwest named Abu Samra, Doha, and the Aruma deep groundwater basin (Fig 1.3). The Northern reservoir is the primary source of water for agriculture, this basin has been determined to be of sufficient quality for agricultural uses because of its low salinity ranging from 500 to 3,000 mg L^{-1}. Both main reservoirs are reported to increase in salinity in summer (Shamrukh, 2014a; Baalousha, 2016b).

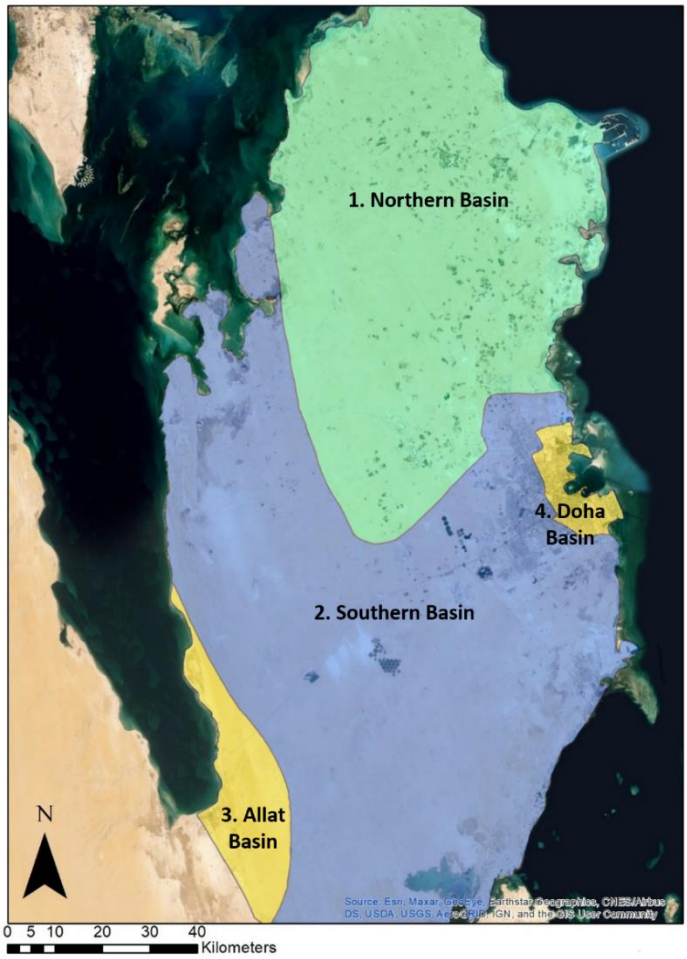


Figure 1.3. Qatar’s four main hydrological basins. Produced from data taken from Qatar MME ArcGIS documents (PSA, 2019).

Groundwater extraction in 2016 was 319 million m^3 y^{-1} with natural recharge of 217 million m^3 y^{-1}, resulting in a depletion rate of c.102 million m^3 y^{-1}. Groundwater use has been reported to exceed recharge by five times (MDPS, 2019). Continued over-pumping can affect groundwater quality and common irrigation methods in Qatar include immersion and irrigation of grass and other water-consuming plants. Preservation of groundwater can be achieved by farms installing modern irrigation systems, growing crops that consume less water, improving irrigation methods, and regulating abstraction from wells. The Qatari government is trying to rectify the issue of over-abstraction by banning the drilling of any new wells and encouraging the adoption of more modern irrigation systems and approaches including the use of TWW for fodder irrigation (GSDP, 2009, 2011).

1.2.4 Demographic and socio-cultural structure

Demographic changes, including a sudden increase in the population in Qatar in recent years (Fig 1.9), has had a substantial impact on the country's environment and natural resources. The impact is due to changes in lifestyle and development needed to cope with the growing population, creating greater stress on water and sanitation resources. Those changes include: (i) greater demand for food, and thus an increase in agriculture and animal production, (ii) an increase in the demand for desalinated water (drinking water, food preparation, washing, cleaning and garden irrigation), and thus an increase in the energy required for desalination operations and the operation of the turbines needed to generate electricity, and (iii) an increase in the water required for the extraction of raw materials and cooling as well as increasing the demand for water necessary for activities including urban development and the building of freshwater reserves to mitigate against crises and emergencies (GSDP, 2008; Ibrahim *et al.*, 2015; Jasim *et al.*, 2016; Fromm *et al.*, 2019)

The population growth is mainly caused by immigration needed to provide labour for development and infrastructure projects that are directly linked to the economic boom witnessed over the last 30 years. This influx of expatriate workers accompanied by their families, resulted in an average annual growth rate of 11.3% during the period 2000-2011 (Darwish *et al.*, 2013; Ibrahim *et al.*, 2015) with substantial additional pressure on water resources. Thus, addressing the increasing water demand as a consequence of population growth is becoming urgent.

1.2.5 Land and water use

Demand for the provision of water supplies and septic connections has arisen due to significant increases in the number of infrastructure projects has occurred between 2010 and 2019 (Fig 1.4) (Permanent Population Committee, 2018). For example, industrial projects alone increased demand from 2.5 million m^3 in 2002 to 11.62 million m^3 in 2016, the highest demand rate ever registered in Qatar (PSA, 2018).

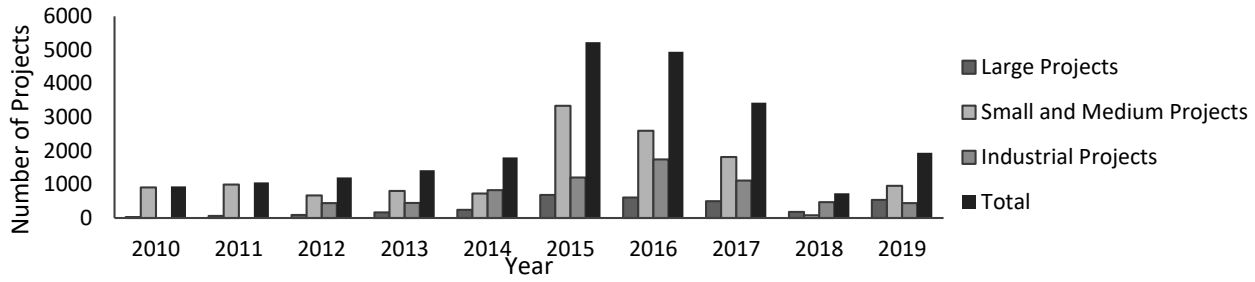


Figure 1.4. Infrastructure projects in Qatar 2010 – 2019. Produced from data published by the Qatar planning and statistical authority (PSA, 2019).

Land use

The agriculture sector can only supply c. 15% of the food requirements of the population this is due to (i) the scarcity of natural water for irrigation, (ii) the dominant soil type lacking essential nutrients to support plant growth, and (iii) the harsh climatic conditions. However, the agriculture consumes c. 40% of the water used in the economic sector, c. 272 million m^3. In 2011, c. 92% of the groundwater usage was by privately owned farms (Fig 1.12). The water produced increased to match the population increase, while the agriculture production remained unchanged (Fig 1.5). The country is aiming for more sustainable agricultural policies to achieve national food sufficiency with more emphasis on research towards water-efficient agricultural technologies.

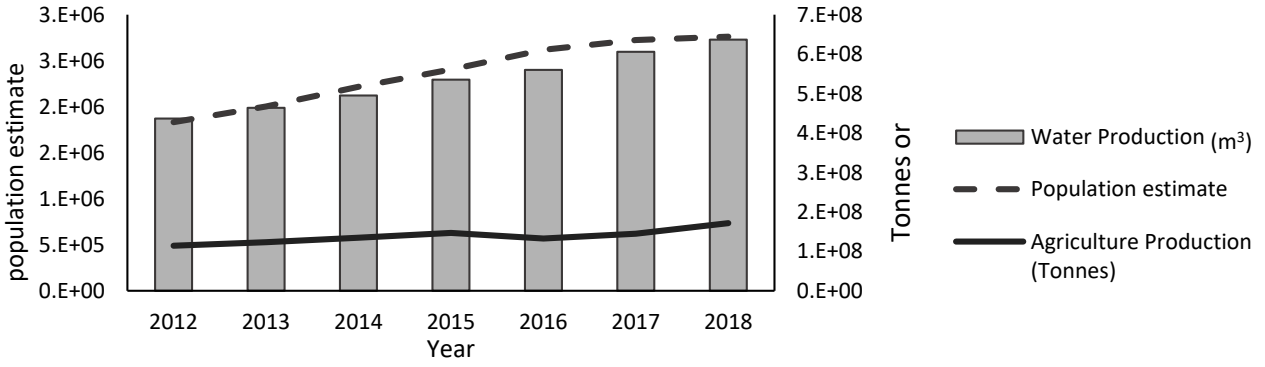


Figure 1.5. Comparison of water in million m^3 (Bar) and agricultural production in tonnes (broken line) as a function of population growth (solid line). Water and agriculture productions are represented on the left Y-axis, and population on the right Y-axis. Produced from data published by the Qatar planning and statistical authority (PSA, 2019).

The area suitable for farming in Qatar is c. 650 km^2, however, only 122 km^2 (18%) is currently being used for agriculture with green fodder production (284,190 t) dominating the majority of local production (constituting about 78.5%) followed by vegetable production (53,351 t), with a relative importance of 14.7%. The production of fruits and dates was 22526 t, (6.2%) and the production of cereals was 2052 t (0.6%).

Water production, abstraction and use

Water sources in Qatar are limited to the abstraction of fresh and saline groundwater, seawater desalination and re-use of treated sewage effluent. Figure 1.6 shows the trends in percentage consumption from each source. In 1990 the two main water sources were groundwater abstraction (65%) and desalinated seawater (35%), however, with increasing demand, seawater desalination has increased substantially and groundwater use has remained constant (for agricultural purposes).

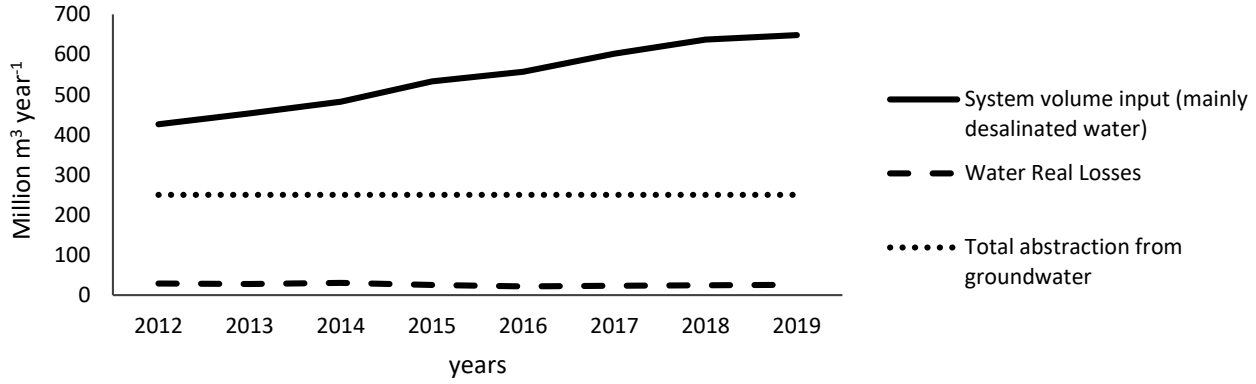


Figure 1.6. Water volumes from desalination production, groundwater abstraction and water losses (million m^3 $year^{-1}$) in Qatar between 2012-2019. Figure produced from data published by the Qatar planning and statistical authority (PSA, 2019).

Wastewater management and treatment has also changed substantially in the last 10 years (Fig 1.7). In 2012 it was reported that 22 million m^3 of untreated wastewater was disposed of in lagoons, decreasing to only 1 million m^3 in 2019. Simultaneously, WW treatment has increased from 142 million m^3 to 287 million m^3 by 2019; the majority going into tertiary treatment.

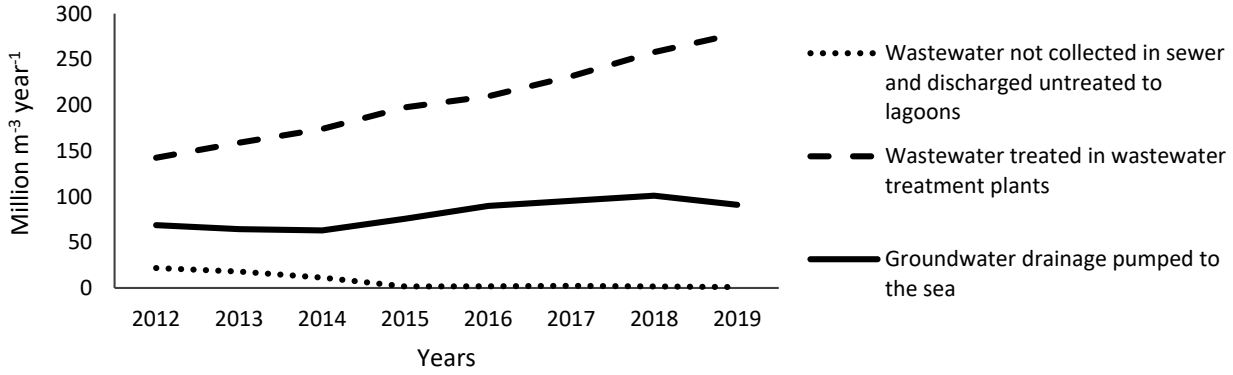


Figure 1.7. Wastewater statistics between 2012-2019 for Qatar, show the amount of wastewater disposed of in untreated lagoons, treatment plants, and surface water pumped to the sea (million m^3 $year^{-1}$). Produced from data published by the Qatar planning and statistical authority (PSA, 2019).

Treatment of WW began in 1971 and it is considered to be a significant 'unconventional' source. It is the only source of water where there is a surplus quantity that is difficult to dispose of. A major issue

with the reuse of TWW is farmers' lack of awareness about the water problems and the TWW quality required for irrigation; most farmers refuse to irrigate with TWW because of concerns regarding health, environmental, psychological and religious reasons (Al-Mohannadi, 2004; Darwish *et al.*, 2013; FAO *et al.*, 2016). It is estimated that TWW in 2019 was about 278 million m^3 but only 86 million m^3 was used for agriculture (mostly fodder production) with 76 million m^3 for green spaces, 79 million m^3 for groundwater injection and 33 million m^3 discharged to lagoons (Fig 1.8).

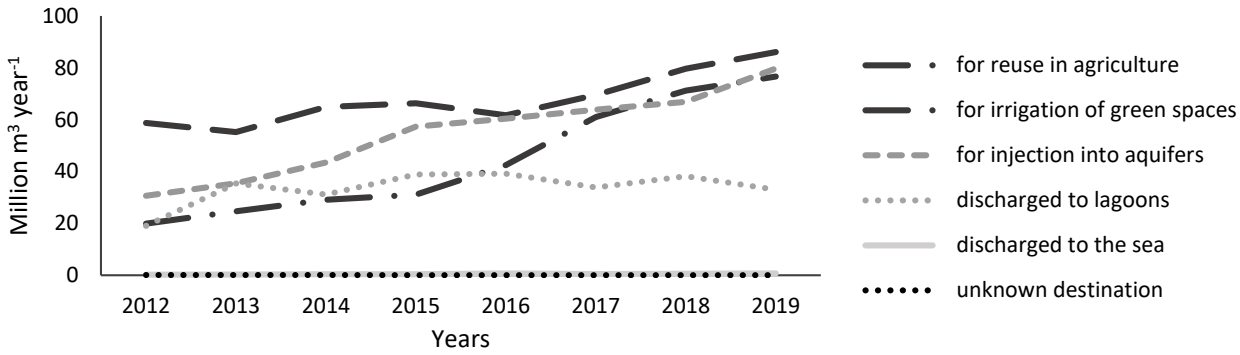


Figure 1.8. Treated waste water (TWW) final discharge statistics (million m^3 $year^{-1}$) for Qatar between 2012-2019. Figure produced from data published by the Qatar planning and statistical authority (PSA, 2019).

Qatar is in a unique situation with water production, domestic water supply, and water sanitation for Qatari citizens being free, and subsidized for expatriates. Groundwater is at risk of being depleted in the foreseeable future because of the practice of flood irrigation on most farms where farmers pay no or very small fees for pumping an unlimited amount of groundwater, with few farms using dripping method. Excessive pumping of groundwater, and salinization due to the intrusion of seawater into the groundwater, have resulted in a decline in the productivity of some agricultural lands (Al Yousef *et al.*, 2000).

1.2.6 Qatar urban water cycle description

The Qatari urban water system starts with water abstraction which is mostly seawater for desalination plants; the water is then consumed, then treated, ending up with disposal in one of the lagoons. Table 1.1 gives a brief overview of how the urban water system operates and the institution responsible to carry out each process. Wastewater treatment in Qatar is reported to produce high-quality effluent (GSDP, 2011; MDPS, 2019). As seen in Figure 1.9 the influent goes through pre-treatment by screening and grit removal, followed by conventional biological treatment of anaerobic and aerobic tanks, then finally tertiary treatment of ultrafiltration, chlorination or UV disinfectant, depending on the treatment plant (Keppel Seghers, 2015; SUEZ, 2021)

Table 1.1 Summary of the urban water cycle in Qatar describing each stage, the activities undertaken and the institution responsible to conduct each activity.

Urban Water Cycle Stage	Activities	Institution Responsible
Water source	For domestic supply desalination is the only source, while groundwater is extracted and used for flooded irrigation. TWW is used for: deep aquifer injection, irrigation for livestock, landscape, and industrial (QNDS, 2016).	The water supplier is Qatar Electricity and Water Company (QEWC) which is a private sector company responsible of the generation of electricity and desalination of water in Qatar.
Distribution	The current distribution coverage is 98%, where the rest are supplied using tankers with high network losses up to 30%–35% (QNV, 2009)	Qatar General Electricity and Water Corporation "KAHRAMAA" was founded to regulate and maintain the supply of electricity and water to all of the customers in Qatar (KAHRAMAA, 2009).
Wastewater	Wastewater is collected by the sewer system (information about sewer leakages or septic tanks could not be found, thus the assumption here this issue does not exist in Qatar)	Ashghal is the responsible agency here, and then the WW is sent to several treatment plants around Qatar (Figure.2) (Emadi et al., 2014)
Treatment	The treatment plants are private.	Ministry of Energy and Industry (MEI), set permits for the disposal of WW Ministry of Municipality and Environment (MME) overall responsibility to ensure the treatment and disposal does not have a negative impact on the environment Ashghal is responsible for the treatment (Emadi et al., 2014)
Effluent disposal	The TWW disposal methods are shown in Figure 1.8	Ashghal is responsible for the regulation of TWW disposal

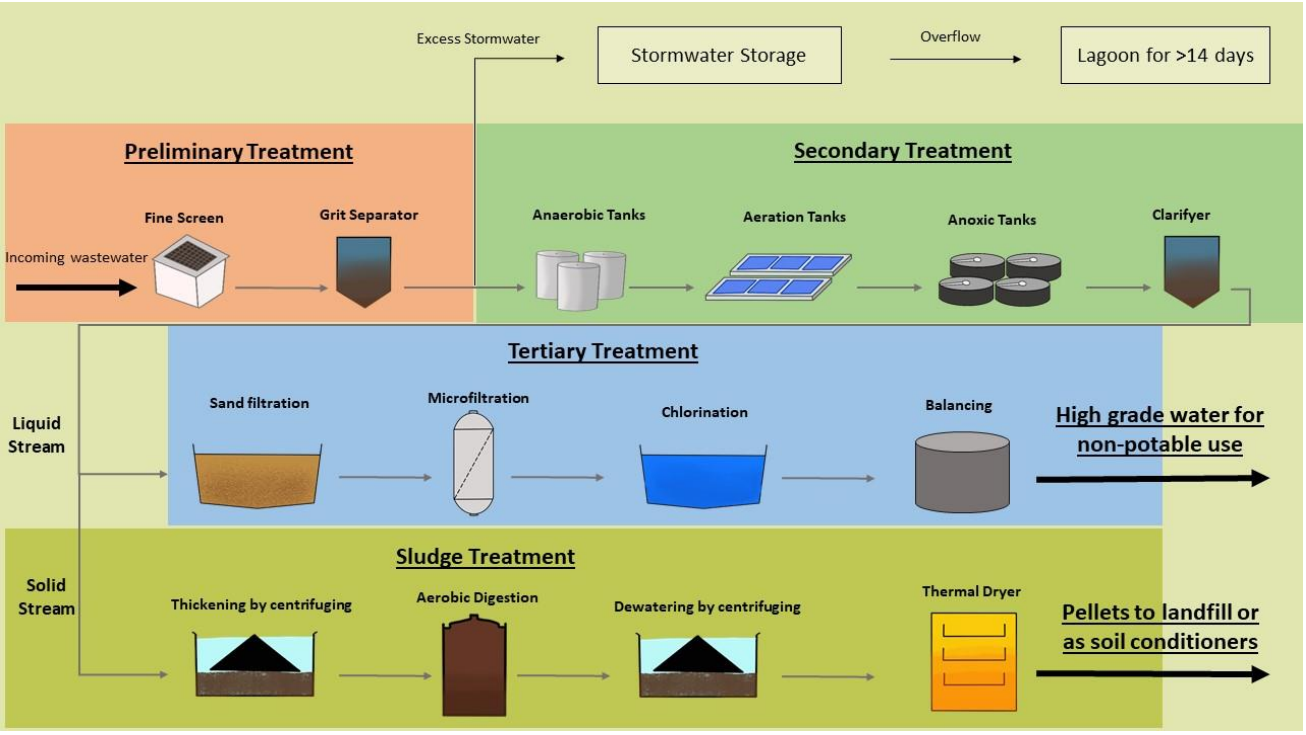


Figure 1.9. An example of WW treatment plant processes flow diagram for Qatar where the resulting water quality is rated as 'high-grade' *(*adapted from (SUEZ, 2021)).

Qatari ministries and governmental institutions' roles in the Urban Water Cycle

- Ministry of Municipality and Environment (MME)

Responsibilities include: (i) setting plans and programs related to assessing the status of all types of water resources management, development, protection and follow-up of programme implementation; (ii) research and estimation of the water balance of the various water basins in the country; (iii) reviewing environmental impact assessments for major projects, including desalination plants and treated sewage plants; (iv) issuing permits for drilling and maintaining wells; (v) conducting studies related to the management, development and protection of water resources.

- Ministry of Energy and Industry

Responsibilities include: (i) ensuring that the country's need for energy, electricity and water is secured permanently and regularly studying the available alternatives to secure it; (ii) regulating tariffs and charges for desalinated water; (iii) producing desalinated water for industrial purposes in Qatar.

- Qatar General Electricity & Water Corporation – Kahramaa

Responsibilities include: (i) buying, selling and distributing electricity and water from the Qatar Electricity and Water Company; (ii) providing partnerships and technical support to establish seawater desalination projects; (iii) construction, operation and maintenance of the desalinated water distribution network; (iv) storing safe drinking water, providing it, and securing the country's need for it; (v) owning and maintaining transmission and distribution facilities and networks electricity and water; (vi) production, distribution and sale of electricity and water to consumers.

- The Public Works Authority – Ashghal

Responsibilities include: (i) implementation, management, operation and maintenance of sanitation and water projects involving surface, underground and TWW; (ii) management and maintenance of sewage networks projects; (iii) collecting and treating WW and distributing TWW to its final disposal place.

- Ministry of Public Health

Responsibilities include: (i) monitoring and following up on the health aspects related to drinking water and WW use; (ii) monitoring the water produced from desalination plants (production, storage and distribution) for drinking water and adherence to international standards for desalinated water; (iii) analysis of chemical and biological pollutants in bottled drinking water.

- Ministry of Development Planning and Statistics

This ministry is responsible for follow-up programs and projects related to the water sector within a strategy for the national development of the State of Qatar.

1.2.7 Qatar water resources problems

The UN-Water (2021) report analysed the water systems of different countries using water and sanitation-related indicators. A positive trend meant the changes moved closer to achieving the relevant sustainable development goal (SDG) and vice versa. Trends were measured as changes in indicator values (status) between 2018 and 2019; changes of less than 5 per cent were displayed as no change. Ideally, the indicator value should increase to reach the global target. Qatar was shown to have negative trends three times. Once, where the goal related to increased water-use efficiency over time (USD m^3). Second, the measure of 'water stress' (%) showed higher levels of freshwater withdrawal as a proportion of available freshwater resources. Lastly, the proportion of hydrological basins shows large changes in surface water extent (%).

Qatar's main problem is in achieving SDG 6 where water use efficiency shows a negative trend (UN-Water, 2021). Qatari water statistics show one of the highest per-capita water consumption rates in the world, at nearly 50 L d^{-1}. Furthermore, the Qatar National Development Strategy (QNDS) predicts that water consumption will rise by nearly 5.4% for Qataris and 7% for expats by 2025 as a result of rising population and water use, as well as the ongoing scarcity of natural potable water (Hofste *et al.*, 2019). The Qatari water system was also was seen as deficient in relation to ensuring water and sanitation for all by 2030 (UN-Water, 2021). Water stress caused by freshwater withdrawal was also negative with Qatar topping the list of countries with extremely high baseline water stress with a score of 5.0 out of 5.0. Countries rated as "extremely high" had levels of baseline water stress in which irrigated agriculture, industries and municipalities withdraw more than 80% of their available supply on average every year (Hofste *et al.*, 2019). Additional challenges faced by the Qatari urban system include water loss and flooding events (GSDP, 2009), both covered in detail in the next section.

Water losses

Water loss in Qatar is one of the highest per capita in the world; desalination is a cost-intensive process and desalinated water loss accounts for 1 billion QR per year. There is an estimated network water loss of 30%-35% on average. Groundwater extraction is estimated at 250 million m^3 yr^{-1} for irrigation including field-flooding, with most of the water lost through evaporation (GSDP, 2009). Figure 1.10 shows if network loss is not reduced demand will inevitably exceed the supply causing water scarcity in the near future.

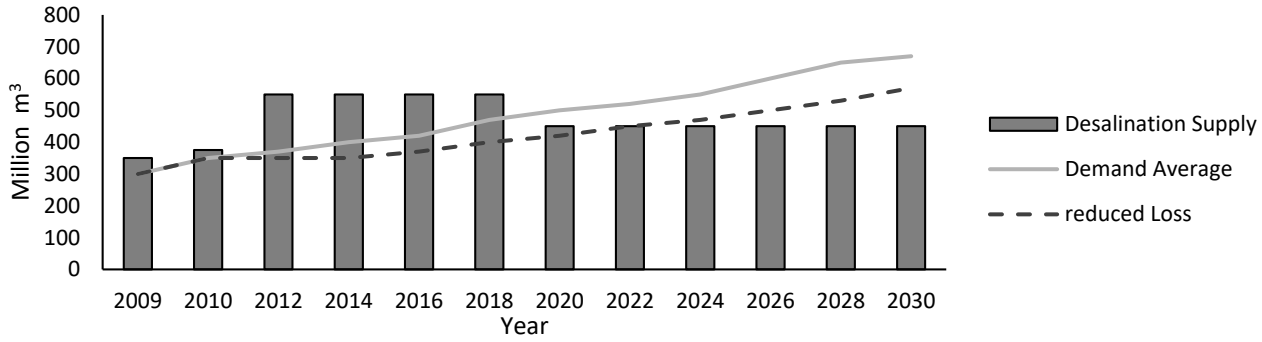


Figure 1.10. Desalination water supply and demand, actual and projected, 2009-2030 (Adapted from QNV, 2009).

Flooding

Flooding problems have followed rainfall events in Qatar, partly because there has been rapid urbanization and construction of pavements so that surface runoff has increased. However, the main reason is leakage from the utility network causing a rise in the shallow groundwater table, decreasing the infiltration capacity, and causing flooding (Al-Mamoon *et al.*, 2016).

All the literature covering floods in Qatar links flooding events to flash rainfall directly causing surface runoff (Al Mamoon *et al.*, 2015; Al Mamoon, 2020) impacting the lagoons by raising the local water table (Fig 1.11). Issues relating to flooding around lagoons have been reported for nearly 15 years. Despite residents' attempts to communicate with the relevant authorities to request a solution to this problem, the situation remains unchanged. An additional problem associated with the floods is the proliferation of mosquitoes that spread in residents' homes and harm children and the elderly (AbuNada, 2021).



Figure 1.11. Rising water table around the Abu-Nakhla lagoon creating surface water pools next to residential areas (AbuNada, 2021).

1.3 Literature Review

Wetlands are broadly defined as "*those areas that are inundated or saturated by surface or groundwater at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions*" (USEPA, 2000b). The focus in the current study is on wetlands considered by the USEPA as 'Artificial', defined as "*wetlands that have been built or extensively modified by humans, such as filling, draining, or altering the flow patterns or physical properties of the wetland*." (USEPA, 2000b). Anthropological modifications to construct wetlands are intended to enable: (i) the treatment of WW including municipal and agricultural runoff, (ii) the polishing of TWW including secondary or tertiary treatment), or (iii) final discharge of treated or untreated WW.

1.3.1 Definition of a Lagoon

Lagoons, wetlands, ponds, artificial lakes, evaporation lakes, urban lakes and lakes are all names to describe what is referred to in this study as a 'lagoon'. Additionally, the term 'lagoon' will be used to refer to a water body that has formed as a consequence of human activities including the accumulation of surface discharge. This would not be termed a 'wetland' as this designation is used to describe an appropriately designed basin containing water, with a lining and vegetation to help remediate contaminated water (DuPoldt *et al.*, 1996; García *et al.*, 2003; Ahmed *et al.*, 2008; Arden *et al.*, 2018) which is not always the case in Qatar.

1.3.2 Lagoon water sources, quality and standards

The water source for lagoons can be TWW (Healy *et al.*, 2002; García *et al.*, 2003; Weller *et al.*, 2017), untreated wastewater (Quiñónez-Díaz *et al.*, 2001; Kaplan *et al.*, 2011), surface water or a mixture of all these (ávila *et al.*, 2013; Verlicchi *et al.*, 2014). In most cases, the water source for constructed wetlands is untreated wastewater where wetlands are a major low-cost technology treatment process (Faulwetter *et al.*, 2013; Rana *et al.*, 2018; Bauer *et al.*, 2021). By contrast, non-constructed wetlands and lagoons are mainly used for the final processing step in the disposal of TWW (Breitholtz *et al.*, 2012; Hussein *et al.*, 2016).

Untreated wastewater

Lagoons or wetlands that contain untreated wastewater are common in developing countries and represent a treatment step within engineered or constructed, wetlands (Kivaisi, 2001; D. Zhang *et al.*, 2014; Arden *et al.*, 2018; Hickey *et al.*, 2018). In rural areas and locations with small communities, the lagoon/wetland is used as the sole water treatment step where treatment plants are not feasible (Kivaisi, 2001). Studies have shown a high removal rate of organic contamination, for example, Verlicchi (2014) highlighted the efficiency of constructed wetland to remove pharmaceuticals from

untreated wastewater which is hard to achieve in typical WW treatment plants (Verlicchi *et al.*, 2014). Moreover, Quiñónez-Díaz (2001) showed that constructed wetlands replaced treatment plants and were effective in removing 90% of pathogens and indicator microorganisms from domestic sewage (Quiñónez-Díaz *et al.*, 2001). Sloey (2021) also discussed how wetlands can be used as a tertiary treatment step for the efficient removal of both N and P instead of employing more expensive treatment processes at the WW treatment plant (Fig 1.12) prior to discharge to the environment whether for irrigation, waterways or groundwater recharge (Sloey *et al.*, 2021).

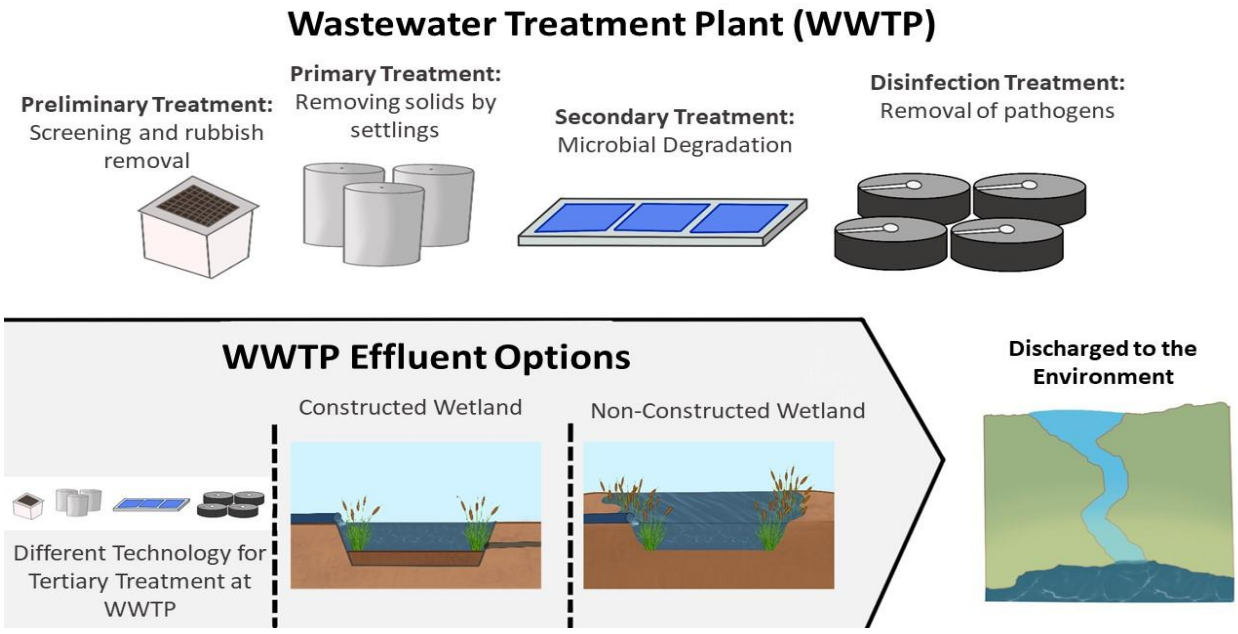


Figure 1.12. Diagram illustrating typical water treatment plants, with three options for tertiary treatment, before discharging water into the natural environment with constructed and non-constructed wetlands as a water polishing step (Adapted from (Sloey *et al.*, 2021).

Treated wastewater

Lagoons can be used as a final disposal option for TWW (Ayaz, 2008; Ruiz *et al.*, 2010; Naidoo *et al.*, 2013), or to polish TWW (Kaseva, 2004; Uusheimo *et al.*, 2018). It has been observed that even after WW has been treated using traditional WW treatment methods, considerable Chemical oxygen demand, Biological oxygen demand and faecal bacteria may remain and that the use of wetland/lagoons reduces these pollutants (Kaseva, 2004; Hunter *et al.*, 2009; Naidoo *et al.*, 2013; Uusheimo *et al.*, 2018).

Surface water lagoons

Surface water lagoons contain water derived from heavy rain or flooding; usually, this water is considered less polluted than WW. For such a water source, Mendes (2018) argued that constructed

wetlands were an appropriate intermediate step to remove pollutants before the water is used in agriculture (Mendes *et al.*, 2018). Additionally, Wang (2021) showed that using constructed wetlands for urban runoff or storm water treatment was effective in the removal of faecal coliform (by 68%) and particulate phosphorus (72%), followed by total P (42%) and N (35%). Concentrations of metallic pollutants including cadmium (Cd), lead (Pb), chromium (Cr), and copper (Cu) were mostly below the detection limit (<1 µg L^{-1}) except for zinc (Zn), where the concentration was reduced by 23% (Wang *et al.*, 2021).

1.3.3 Lagoon Construction

Lagoons are typically labelled as either engineered (constructed lagoons) or assimilation (unconstructed lagoons).

Constructed or engineered Lagoon

According to the USEPA, a constructed lagoon is made up of a well-designed basin with water, a substrate, and vascular plants (USEPA, 2000a) so may be employed as a treatment step for WW. The most important aspect of the constructed lagoon is the substrate lining the bottom of the lagoon preventing pollutants from leaching into the groundwater. The substrate can be sand, gravel, clay or a plastic lining (USEPA, 2000a) A cross-section through a constructed lagoon is shown in Figure 1.13.

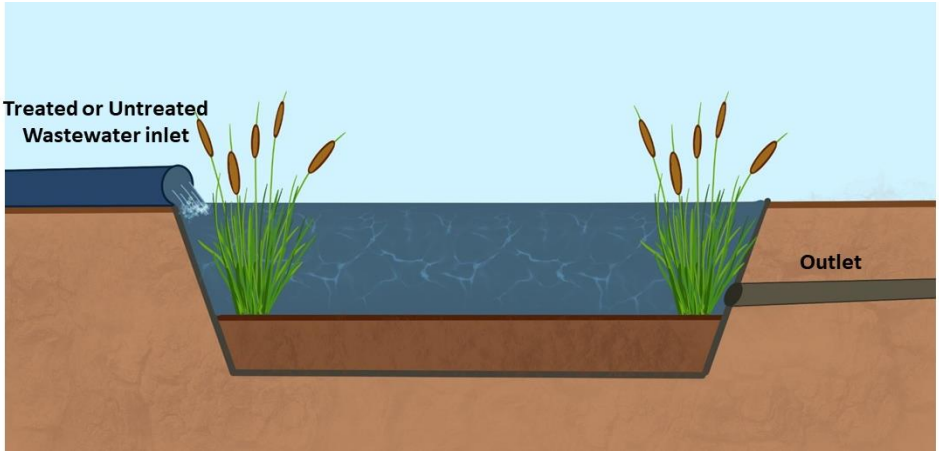


Figure 1.13. Cross-section through a typical constructed wetland, with inlet for the water source, outlet to discharge the water into the natural environment and protective lining (Adapted from (Parde et al., 2021)).

Unconstructed or assimilation lagoons

Unconstructed or 'assimilation' lagoons/wetlands are made without any lining. They have a reputation for failing to prevent pollution of groundwater nor is there any management to ensure that the WW is fully remediated, Figure 1.14 shows an example of such a lagoon. Those lagoons have normally been formed by humans and receive excess water from municipal or industrial infrastructure (Palta *et al.*, 2017).

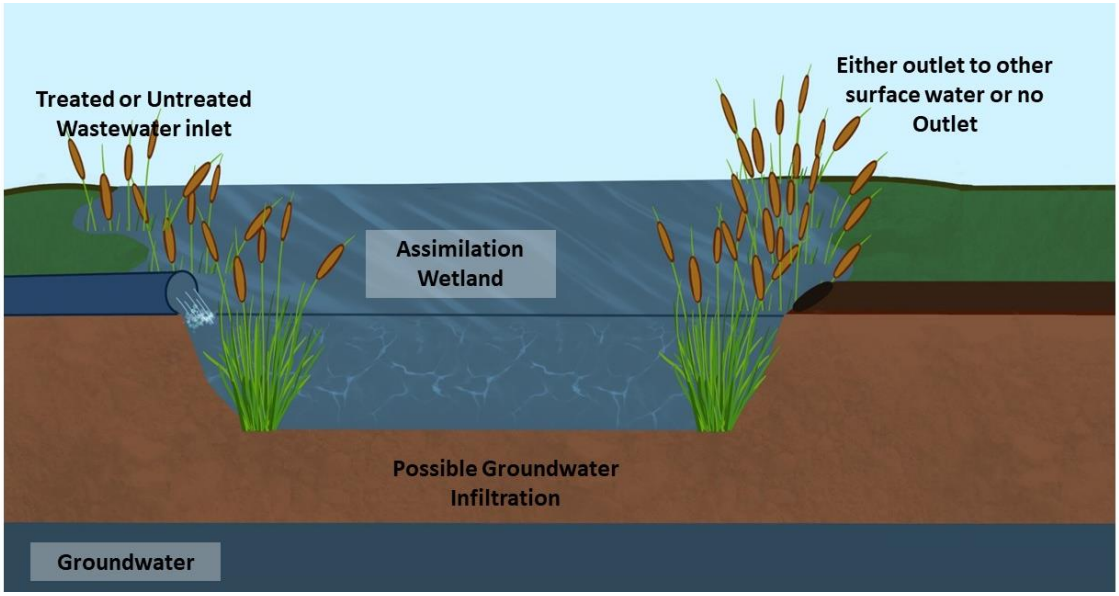


Figure 1.14. A cross-section through a typical unconstructed wetland, with inlet for the water source, outlet to discharge the water into the natural environment and without protective lining (Adapted from (Hunter et al., 2009)).

The main issue with unconstructed lagoons is the potentially unknown source of the lagoon water. A study of unplanned urban lagoons (non-constructed wetlands) by Horvat (2021) suggested that along with the lack of management, and inappropriate infrastructure, such wetlands can receive illegal and unknown sources of water (Horvat *et al.*, 2021).

1.3.4 Lagoon water quality standards

The USEPA has published recommendations for the construction, operation and maintenance of wetlands (USEPA, 2000a) together with suggested standards for influents and effluents (Water *et al.*, 2000), Table 1.2.

Table 1.2. USEPA suggested values to calculate typical areal loading rates for WW influents and effluents(USEPA, 2000b).

Constituent	Typical Influent Conc. (mg/L)	Target Effluent Conc. (mg/L)
Hydraulic Load (cm/day)	1 - 10	-
BOD	5 - 100	5 - 30
Total Suspended Solids (TSS)	5 - 100	5 - 30
NH_3 /NH_4 as N	2 - 20	1 - 10
NO_3 as N	2 - 10	1 - 10
TN	2 - 20	1 - 10
TP	1 - 10	0.5 - 3

Most studies of the efficiency of constructed wetland for WW treatment, whether the WW was municipal, urban runoff or from industrial activity, have used the parameters listed in Table 1.2 to assess treatment efficiencies (Verhoeven *et al.*, 1999; Chen *et al.*, 2006; Vázquez *et al.*, 2013; Nivala

et al., 2018; Edo *et al.*, 2020; Wang *et al.*, 2021). In terms of microbiological quality of wetland effluent, most authors discuss pathogenic contamination in terms of either removal rate (Quiñónez-Díaz *et al.*, 2001; Vega *et al.*, 2003; Okoh *et al.*, 2007; Baram *et al.*, 2014) or against national standards adopted from either the WHO or the USEPA (Sanders *et al.*, 2013; Fathi, 2014; Arden *et al.*, 2018). The USEPA recommended guidelines for faecal bacteria are outlined in Table 1.3.

Table 1.3. USEPA recommended guidelines for faecal bacteria based on the type of irrigation (USEPA, 2000b).

Wetland Irrigation	USEPA guidelines for faecal bacteria
Unrestricted irrigation	41000 faecal coliform bacteria/100 mL
Restricted irrigation	4105 faecal coliform bacteria/100 mL
Flood irrigation or children are exposed	4103 faecal coliform bacteria/100 mL
Nematode eggs	40.1 egg/L

In the Electronic Code of Federal Regulations document of the USEPA regulations, it is also recommended that there should not be a fixed set of standards for all cases as each lagoon or wetland is unique. According to the USEPA, authorized parties should consider the Agency's national recommended water quality criteria when developing their management criteria, however, it is also advised, where appropriate, to adopt other scientifically defensible criteria that may differ from the USEPA's recommendations regarding discharge amount, the receiving water body's current condition and environmental services (USEPA, 2000b).

The USEPA criteria requirements list for state and authorized party listing water reuse quality under 40 CFR 131.11(a)(1) include the following criteria:

- It must be based on reliable scientific rationale.
- It must contain the necessary parameters and factors to protect the chosen use.
- It must support the most sensitive chosen use environment.

Moreover, it is advised that a controlling authority should manage the concentration limits suitable for their environment and produce alternative concentration limits using equation 1.1 (Electronic Code of Federal Regulations, 2000):

$$C_T = \left[\frac{\sum_{i=1}^{N} C_i F_i}{\sum_{i=1}^{N} F_i}\right]\left[\frac{F_T - F_D}{F_T}\right] \qquad 1.1$$

Where:

C_T = the alternative concentration limit for the combined waste stream; C_i = the categorical pretreatment standard concentration limit for a pollutant in the regulated stream I; F_i = the average

daily flow (at least a 30-day average) of the stream i to the extent that it is regulated for such pollutants; F_D = the average daily flow (at least a 30-day average F_T = the average daily flow (at least a 30-day average) through the combined treatment facility (includes F_i, F_D and unregulated streams); N = the total number of regulated streams.

1.3.5 Effects of lagoons on groundwater

While most literature on lagoons and wetlands is concerned with the technology for the removal of chemical and biological contaminants, some articles do address the issue of how, over time, lagoons have an impact on underlying groundwater. Most of these focus on the dynamics concerning how the wetland recharges the groundwater. Bekele et al. (2019) in a study to examine the groundwater dynamic near a WW infiltration lagoon in Australia, showed both a significant rise in groundwater table from infiltration from the lagoon, but also that >34% of the uppermost 30 m of the groundwater consists of a high proportion of lagoon water (Bekele *et al.*, 2019). Figure 1.15 illustrate how the infiltrated water from surface wetlands and lakes increased the groundwater table.

Moreover, the wetland structure by having outlet point showed varying groundwater recharge rates. Hayashi et al. (1998) studied a wetland without an outlet and observed a 75% re-charge of the shallow groundwater aquifer with no transfer to deeper underlying aquifers (Hayashi *et al.*, 1998). By contrast, a study by Choi and Harvey (2000) suggested that 31% of wetland water was actively recharging the groundwater when the constructed wetland had both an inlet and an outlet (Choi *et al.*, 2000).

Chemistry

A recent study by Wu *et al.* (2020) demonstrated the contradiction of the obvious benefits of using constructed wetlands for water treatment with the negative potential impact of water infiltration on underlying groundwater. Wu *et al*. (2020) illustrated that major pollutants were below relevant water quality standards in the wetland, but that groundwater contamination increased over time to exceed permissible standards. The main reason for this was that the wetland did not have an anti-seepage layer to protect the groundwater reservoir (Wu *et al.*, 2020). A further example of this problem was shown by Ackerman et al (2015) who studied nutrient removal from TWW seeping from a constructed wetland into groundwater (Figure 1.15). They showed that 100% of phosphate was removed by adsorption before reaching the aquifer, but only 30% of nitrate was removed with some nitrate reaching the underlying aquifer.

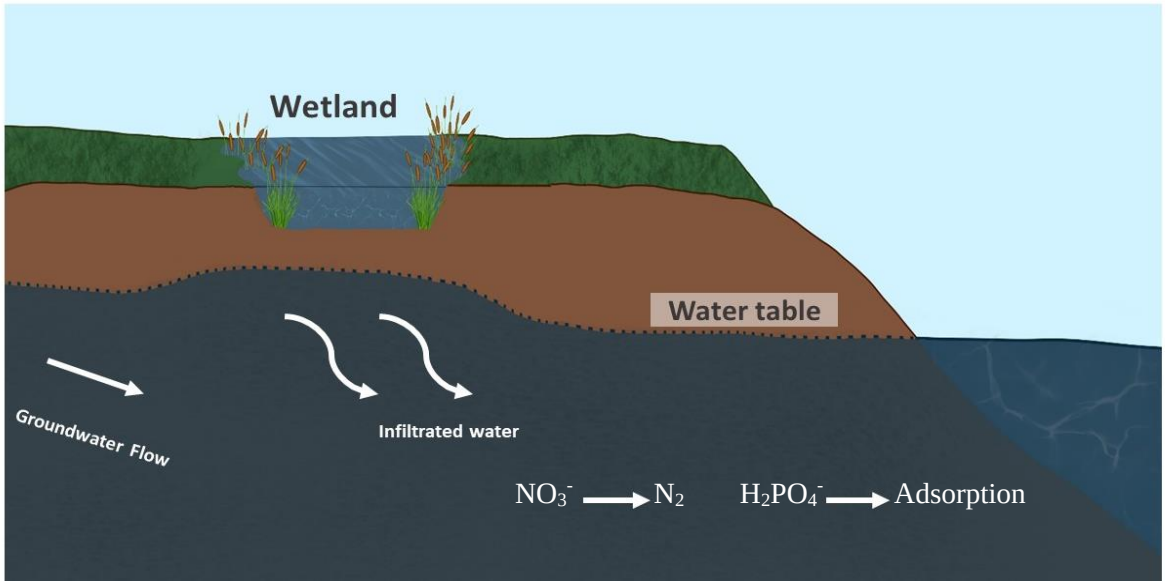


Figure 1.15 Diagram shows a conceptual model of (i) nitrate reduction to dinitrogen and (ii) phosphorus sorption from water moving from wetland to groundwater (Adapted from Ackerman et al., 2015)

Oestrogen and testosterone concentrations in groundwater and their distribution in sediments below a dairy-farm WW lagoon were studied by Arnon *et al* (2008). Both oestrogen and testosterone were detected in sediments to depths of 45 and 32 m respectively. Groundwater samples also displayed elevated concentrations of nitrate, chloride, testosterone, and oestrogen when compared to a reference site located up-gradient of the farm suggesting that the groundwater was directly impacted by the presence of the dairy farm (Arnon *et al.*, 2008). Baram (2014) used spatial correlation employing a geographic information system (GIS) to understand containment concentration in relation to groundwater proximity to dairy farm lagoons and concluded that a dairy lagoon was not the main source of increased Cl^- and NO_3^- contributing only 6.0% and 12.6% respectively of the total mass in the aquifer. The study suggested that the infiltration from lagoons into groundwater was the main reason for the Cl^- and NO_3^- concentration increase (Baram *et al.*, 2014).

Biology

The biological understanding of the impact of lagoons/wetlands on groundwater aquifers is relatively poorly studied. Hafner (2016) showed the influence of a dairy lagoon on underlying groundwater, observing that 7% of lagoon water reached the underlying groundwater within a few days, contaminating the water with the antibiotic regularly used to enhance feed efficiency. The antibiotic was also detected in wells near the dairy lagoon (Hafner *et al.*, 2016). Vega *et al.* (2003) investigated the transport and survival of both WW bacteria and viruses through wetland remediation and a sand filtering system using *Salmonella* as a bio-indicator. They showed that there was a low possibility of

viral contamination but also that *Salmonella* sp. was not significantly reduced during the wetland treatment suggesting a high possibility of contamination of the surrounding environment, depending upon wetlands processes such as adsorption, desorption and inactivation in the water (Vega *et al.*, 2003).

Cameron et al. (2003) measured the removal efficiencies of contaminants in a wetland treating municipal sewage. The effluent had lower biochemical oxygen demand (34%), ammonia and ammonium (52%), total Kjeldahl nitrogen (37%), total suspended solids (93%), total phosphorus (90%), *ortho*-phosphate (82%), faecal coliforms (52%) and *E. coli* (58%). However, nearby groundwater wells showed a higher percentage of contaminants, with the detection of both faecal bacteria and *E. coli*, suggesting further monitoring of lagoon and wetland impact on the groundwater aquifer was required (Cameron *et al.*, 2003).

Candela (2007) showed that coliform bacteria decreased in TWW when disinfected before disposal in a lagoon. The bacteria were detected only in the top 5-10 cm of soil, indicting a very low risk of microbial contamination of the aquifer, which could be due to bacterial die-off resulting from soil-water interaction (Candela *et al.*, 2007). A second study by Kausch (2020) used the analysis of 16s rRNA genes to detect groundwater contamination resulting from dumping WW in surface water nearby. The study found that more than 67% of samples had antibiotic-resistant bacteria and 80% had faecal indicator bacteria. However, the concentration of both were low and could have been from point source contamination rather than WW dumping. Both studies concluded that further research was required to better understand the source of groundwater contamination (Kausch *et al.*, 2020).

1.3.6 Lagoons' advantages and disadvantages to the environment

Different types of lagoons have a range of impacts on the surrounding environment, whether the impact is physical, chemical, biological or economic.

Lagoon advantages

A well-managed and engineered wetland can benefit both the surrounding environment and human socio-culture. For example, the UK Environment Agency has invested in developing the water purification capability of reed beds in constructed wetlands around England and Wales to clean up contaminated mine water (Scholz, 2016). A report on the ‘Economics of Ecosystems and Biodiversity for Water and Wetlands’ discusses the major role of wetlands in water management and water security, where lagoons/wetlands provide clean water storage, WW treatment and groundwater recharge(Russi *et al.*, 2012). Furthermore, wetlands are often considered attractive landscapes and

biodiverse ecosystems, thus providing an essential aesthetic, educational and recreational environment that contributes to public welfare, cultural identity and economy (Russi *et al.*, 2012).

If wetlands are designed as part of an integrated urban plan they can be used as effective water reuse projects for green space irrigation such as golf courses and public parks, or safe groundwater recharge by natural filtration. Wetlands also provide social benefits to public recreation, such as bird watching and amenity purposed walking paths (Metcalfe, 2018). An example of how wetlands with TWW can be used as 'green space' is Tres Rios Constructed Wetland in Phoenix. This wetland was constructed as a final storage location for TWW from a nearby large conventional treatment plant mixed with urban runoff. This set-up was to act as storage and polishing for final effluent coming from the treatment plant but, with further development, it started to act as a means of flood control, habitat restoration, public recreation, water storage for future reuse and a carbon footprint equalizer (Stefanakis, 2019). Another positive example of lagoons and wetlands benefiting the environment can be seen in the long-term effect of assimilated wetlands in Louisiana where disinfected municipal effluent has been discharged to five different assimilated wetlands for 20 to 75 years. Day *et al* (2019) showed a great improvement in vegetation growth and enhancement in woody growth; the establishment of a highly productive floating marsh ecosystem with a net primary production > 4000 g dry wt m^{-2} yr^{-1} (Day *et al.*, 2019).

Lagoon disadvantages

Xu (2018) argues that while constructed wetlands can be effective for the removal of metal from solution by sulphide precipitation and adsorption to solid organic matter, conditions in wetlands also produce elevated bioavailability of both soluble Cu-FA and Zn-FA complexes which has a negative impact on the environment (Xu *et al.*, 2018). The USEPA handbook on constructed wetlands discuss in detail the limitations of constructed wetland: (i) they mostly require a large land area; (ii) conditions can change seasonally; (iii) the lagoon can become toxic if there is a surge of highly contaminated water which will make the lagoon hard to decontaminate; (iv) the bacteria responsible for biodegradation and macrophytes cannot withstand sudden uncontrollable changes in the environment (DuPoldt *et al.*, 1996)

Lagoons can also have a direct and negative impact on human populations, especially when situated in a residential area. A poorly managed lagoon can have flooding issues saturating the nearby ground, pests issues (e.g. mosquitos, rodents, cockroaches), and also an unpleasant smell due to anaerobic processes (Metcalfe, 2018). Mosquitos problems are especially important in hot climates where they present a hazard to human populations (USEPA, 2000a). However, these problems can be mitigated by water level control and the introduction of mosquito-eating fish (Knight *et al.*, 2003).

1.3.7 Lagoon case studies

Compared to lagoon/wetland research globally, the lagoon situation in Qatar is possibly unique. Only a few studies conducted in Saudi Arabia and Oman describe a similar situation. While few studies were found about one lagoon in Qatar (Abu-Nakhla Lagoon)

Saudi Arabia

Saudi Arabia is the largest of the six countries in the Gulf Cooperation Council (GGC) which includes Qatar. Many studies have investigated different types of lagoons/wetlands based in Saudi Arabia, however, few of these involve coastal situations and TWW discharge (Turki, 2007; Zhu *et al.*, 2014; Ali *et al.*, 2017; Rasiq *et al.*, 2018); many are studies of inland lagoons containing TWW (Al-Sheikh *et al.*, 2010; Fahmy *et al.*, 2011; Abdel-moneim, 2014; Fathi, 2014; Al-Amro *et al.*, 2018; Picó *et al.*, 2020), and one investigation was of natural spring water with WW contamination (Abdel-moneim *et al.*, 2012).

The lagoon in Saudi Arabia that was found to be most similar to those in Qatar is located in Al-Hassa oasis called Al-Asfar Lake which contains drainage water from agricultural activities. Another similar lagoon located in the same area is the Al-Uyoun Lake outside. While both lagoons contain water from a groundwater source, they also hold water from various municipal and industrial activities including TWW (Mahmoudi *et al.*, 2011; Hussein *et al.*, 2016). Adel (2016) discussed heavy metal pollution in the lagoons and recorded high concentrations of both Cu and Cd (Hussein *et al.*, 2016). Other studies of these lagoons also report contamination including: carbendazim, atorvastatin, caffeine, etori- coxib, lorazepam, metformin, paracetamol, salicylic acid and tramadol with a high density of micro plastic (Picó *et al.*, 2020). The Al Asfar lake also suffers from heavy metal contamination at concentrations higher than permissible limits (Al-Sheikh *et al.*, 2010; Abdel-moneim, 2014)

Oman

Oman is also one of the six countries of the GCC and there are many published studies concerning the use of constructed wetlands for WW treatment in rural areas and a simple design of a two-step treatment process (Abed *et al.*, 2014, 2018; Al-Rawahi *et al.*, 2014; Stefanakis *et al.*, 2017; Shidi *et al.*, 2018; Yadav *et al.*, 2018). Only one study of a lagoon that has TWW similar to those in Qatar was found (Kacimov *et al.*, 2016). The lagoon called ‘the Haya’ is located in the Oman capital city of Muscat and was built in 1986 to act as a discharge reservoir for TWW where it is assumed it will infiltrate the unsaturated zone. Alongside the lagoon is the Al-Ansab wetland receiving the same water. Ongoing work is attempting to predict the water infiltration rate from the lagoon to the

groundwater with surface geophysics, drilling data, pumping tests and observations of the water level required (Kacimov *et al.*, 2016).

Qatar

The only previous study of lagoons in Qatar concerns the Abu-Nakhla lagoon; other lagoons have not been studied or mentioned in the literature. The Abu-Nakhla lagoon is an 'assimilation lagoon' without underlining, formed in 1985 after the disposal of TWW and WW in a natural depression on the outskirts of the Qatari capital, Doha. Seven studies were found investigating this lagoon (Elhag *et al.*, 2002; Sweileh *et al.*, 2002; Al-thani, 2003; Claus *et al.*, 2016; Kardousha, 2016; Elobaid *et al.*, 2019; Hussein *et al.*, 2020). Moreover, in the local news, this lagoon was consistently the subject of public complaints with the first complaint seen in 2011 (Ahmed, 2011). The public complaints were due to the fact the unlined lagoon caused the over-saturation of the top layer in residential areas, creating small surface ponds attracting mosquitos and the need for dewatering the surface prior to any infrastructure projects (Ahmed, 2011; Al shareq, 2014; Nada, 2019). Research into this lagoon started in 2002 and showed that the lagoon contained heavy metals concentrations and coliform bacteria levels above the recommended standards (Elhag *et al.*, 2002; Sweileh *et al.*, 2002; Al-thani, 2003). However, a study undertaken in 2014-2015 showed that all the contaminants in the lagoon were present at levels below the standards. The same study investigated the lagoon infiltration to the groundwater; it was found that the local hydrological structure of cracks and fissures under the lagoon caused the groundwater table to rise. However, the chemical and biological impact on the groundwater was not shown (Claus *et al.*, 2016; Elobaid *et al.*, 2019). Conversely, studies also showed the positive impact of the rich biodiversity hub created by the lagoon which attracted a range of local and migrating birds taking shelter in the lagoon, including birds and insects that were new to the area (Kardousha, 2016). Moreover, there was uncertainty regarding the water source for this lagoon with one study suggesting untreated sewage (Hussein *et al.*, 2020), and others stating it was highly treated TWW (Elhag *et al.*, 2002; Sweileh *et al.*, 2002; Al-thani, 2003; Claus *et al.*, 2016; Kardousha, 2016; Elobaid *et al.*, 2019).

1.4 Research Background

1.4.1 Lack of water reuse

Desalinated water is four times more expensive to produce than TWW but for reasons of social and infrastructure in Qatar, water reuse remains limited with a large percentage of TWW entering artificial lagoons. Those lagoons are sometimes over-pressured by the daily amount of water they receive causing a danger of flooding and rising water table in Qatar.

1.4.2 Research gap

Understanding the nature of TWW lagoons and their effect on surrounding soil and groundwater reservoirs is generally lacking both globally and in Qatar. One reason is that Qatari lagoons of this type are not very common since most countries have lagoons that receive untreated water, recycle more of their water, or use wetlands instead. Moreover, the study of lagoons in Qatar is limited to the Abu-Nakhla lagoon (Tollenaere, 2015) which dried up four years. Other lagoons are not studied. Therefore different institutions involved with water cycle management in Qatar are keen to obtain (i) a better understanding of the lagoons' environmental impact and (ii) recommendations on how to manage the lagoons.

A further concern is that in the Gulf region, especially in Qatar, when the lagoon has untreated wastewater then it is highly likely to be an 'accidental' or illegal lagoon (Hussein *et al.*, 2016). Fridrich (2014) argued that having a barrier between the lagoon and the groundwater (in their study there was a clay barrier layer) may prevent infiltrating into the groundwater (Fridrich *et al.*, 2014) but as many lagoons are illegal they have no barriers, which could lead to degradation of groundwater quality. Long term dumping of untreated wastewater into unlined lagoons will eventually allow pollutants to infiltrate the groundwater Arnon (2008).

Information about lagoon construction and their water sources in Qatar is extremely limited. However, field studies and communication with policymakers, indicated that the lagoons in Qatar have variable construction types and water sources with most receiving TWW, but a few receiving WW, surface water, storm water, or seawater. Lagoons are also built within residential areas, causing complaints about mosquitos, odours, rodents and drowning hazards (Al-oqedi, 2015, 2016; Al-shareq, 2015; Suliman, 2016; Nada, 2019; AbuNada, 2021) hence understanding the public perception of lagoons was also needed to report back to the relevant ministries.

1.4.3 Aim, Objectives and Research Questions

The hypothesis underpinning this research is that the quality and quantity of water in lagoons and TWW reuse practices are having an impact on the groundwater reservoirs in Qatar. To investigate this hypothesis, the study has three main objectives:

1. Establishing a hydrogeochemical survey of lagoons and surrounding wells;
2. Establishing microbial survey of lagoons and surrounding wells;
3. Understanding public and policymakers' views of the lagoon system in Qatar.

The specific research questions asked to achieve the research objectives are listed in Table 1.4.

Table 1.4. This Research main objective, questions, and the research process used to achieve the main project objectives and aims.

	Research Questions	Research Process
1	How are lagoons viewed by policymakers? How are lagoons viewed by the public?	- the public knowledge about lagoons in Qatar - the public knowledge about the benefits and hazards of lagoons - the public interest in TWW reuse options and having lagoons as recreational places - policymakers' awareness of the current lagoon water quality and quantity situation. - policymakers' awareness of who is managing the lagoons - policymakers' concerns about lagoon impact on groundwater - policymakers' views on public involvement in lagoon management
2	Does the lagoon water infiltrate the groundwater reservoirs? Does it change its chemical characteristics? Does lagoon water impact soil and plant irrigated with this water?	- current chemical and physical water quality of lagoons and groundwater - spatial and temporal changes in chemical and physical water quality in both lagoons and groundwater samples - spatial changes in chemical and physical soil and plants quality in both lagoons and groundwater samples - statistical test to determine lagoon chemical and physical water quality impact on groundwater
3	Does the lagoon infiltration change the microbiological characteristics of the groundwater?	- current microbiological water quality of lagoons and groundwater - identifying faecal and E. coli bacteria in both lagoons and groundwater in terms of the species name and actual quantity of the bacteria in the water - statistical test to determine lagoon chemical and physical water quality impact on groundwater

1.4.4 Approach and thesis layout

This thesis comprises three main chapters covering social, chemical and microbiological aspects of Qatari lagoons in addition to an introduction to the current state of knowledge (Chapter 1) and a chapter on the methodologies used (Chapter 2). Chapter 2 presents all the techniques, instruments and software used for the study and includes details of the statistical tests applied to the data. Chapter 3 presents the survey findings on public and policymaker perceptions about lagoon management in Qatar. Chapter 4 discusses the hydrogeochemical investigations, discussing lagoon and adjacent groundwater chemistry with information on nearby soil and plants. Chapter five presents the microbiological investigation of lagoons and adjacent groundwaters. Chapter 6 summarises the main findings of the work and presents recommendations for better management of lagoons in Qatar.

2.1 Introduction

This chapter starts with a discussion of the research design, describing the research aims and activities required to fulfil the project aims and experimental objectives. Methodologies are described, following the main research objectives; the discussion is divided into three main sections. The methodologies used for the chemical and microbiological analysis are presented in this chapter since both share the same sampling methods while the social investigation methods are included in the 'social perception' chapter (Chapter 3), as it is necessary to present the interview and survey questions in the same chapter as the results for discussion purposes.

2.2 Research Design

This research started with an intensive literature review and desk study from which the reasoning for the research aims was derived. The literature review also revealed the gaps in knowledge regarding lagoons in arid environments and their impact on groundwater reservoirs. The methodologies required were then decided and the study areas were chosen. The overall aim of the project can be summarised as an investigation intended to provide a better understanding of the challenges of urban water management in Qatar. Field site surveys were then conducted for both lagoons and groundwater wells with the primary goal of evaluating the practices of using lagoons as TWW storage areas. All the lagoons in Qatar were located and sampled twice in summer and winter. Groundwater wells around lagoons were then chosen in different proximities to the lagoons and sampled for the range of analyses required.

Following the completion of data collection, the resulting information was interpreted in the light of relevant literature, previous studies in the area and both WHO-recommended drinking-water quality standards and local guidelines. The goal was to determine the extent of contamination in the lagoons and whether, or not, it had reached groundwater aquifers.

With both the hydro-physiochemical and microbiological analyses for both lagoons and groundwaters, it was decided that, for this research to fully cover the lagoon impact, it was also necessary to include a social study examining the role of policy makers and the public perception of lagoons in Qatar. Semi-structured interviews were used to understand how policymakers manage lagoons in relation to groundwater. In addition, public knowledge of the lagoon situation in Qatar and popular opinions about the current lagoon situation were investigated. Finally, some recommendations for contamination prevention and control of lagoon infiltration to groundwater reservoirs in Qatar were established.

2.3 Research Methods

This research comprises three main methodologies for data collection (Fig 2.1) but only two will be discussed below while the third one (the social study) will be presented in chapter.3, since its exclusive to the social analysis.

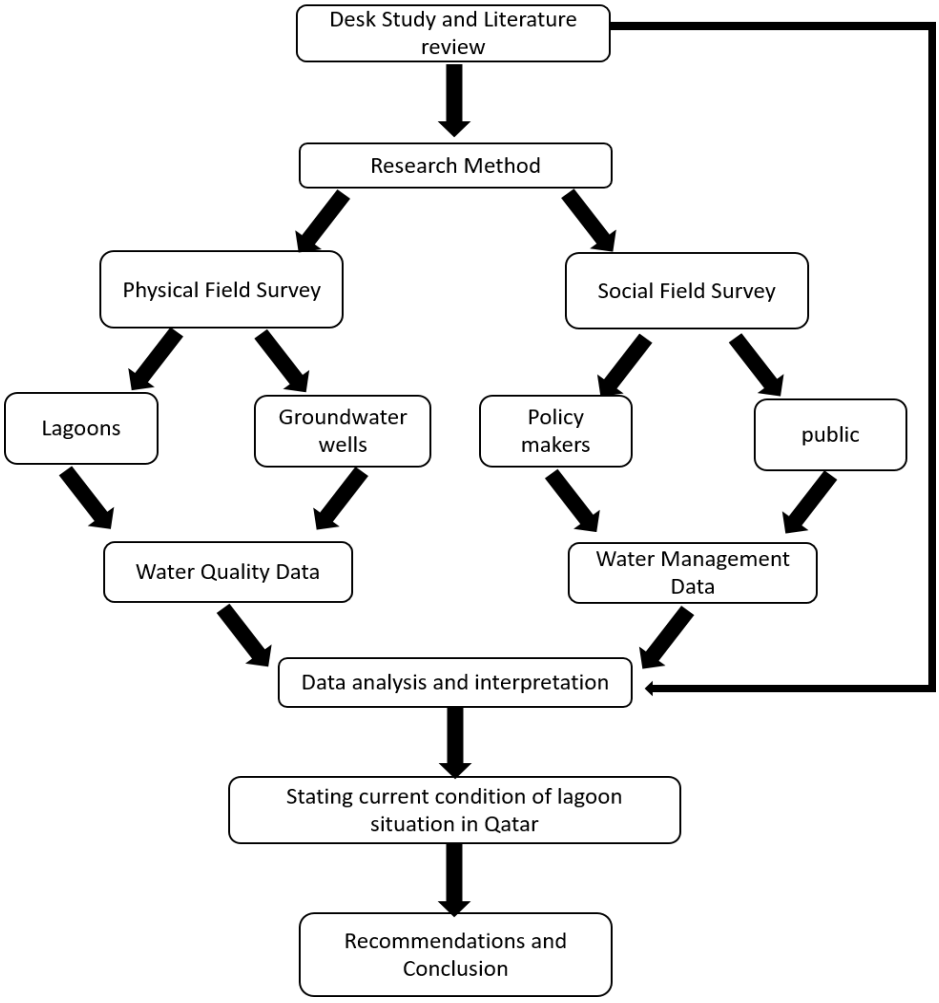


Figure 2.1. A research design flowchart showing the main types of data collection and their sequence within the research project.

2.4 Sampling sites selection and sample collection processes

To achieve the research objectives of the project, samples were required from the different lagoons distributed around Qatar and also from groundwater wells at a range of distances from the lagoons. The methods used to select sample locations and sampling methods are described below.

2.4.1 Lagoons

Lagoon locations were determined using Google Maps; by examining the most recent satellite images of Qatar the locations of artificial water bodies were recorded. Since Qatar is a desert with no

natural water bodies, all the sites located were assumed to be artificial lagoons; this premise was later confirmed with the field study. The reason this method was used was because there were no official records of the existence or locations of lagoons in Qatar. Also, because some lagoons are illegal and 'accidental' their location effectively changed based on the season and flooding events. Because of this, the (current) locations of lagoons were confirmed twice a year through satellite images and field work (Fig 2.2). The X and Y coordinates and the lagoon given name based on the area it is located or the treatment plant adjacent to it is shown in Table 2.1.

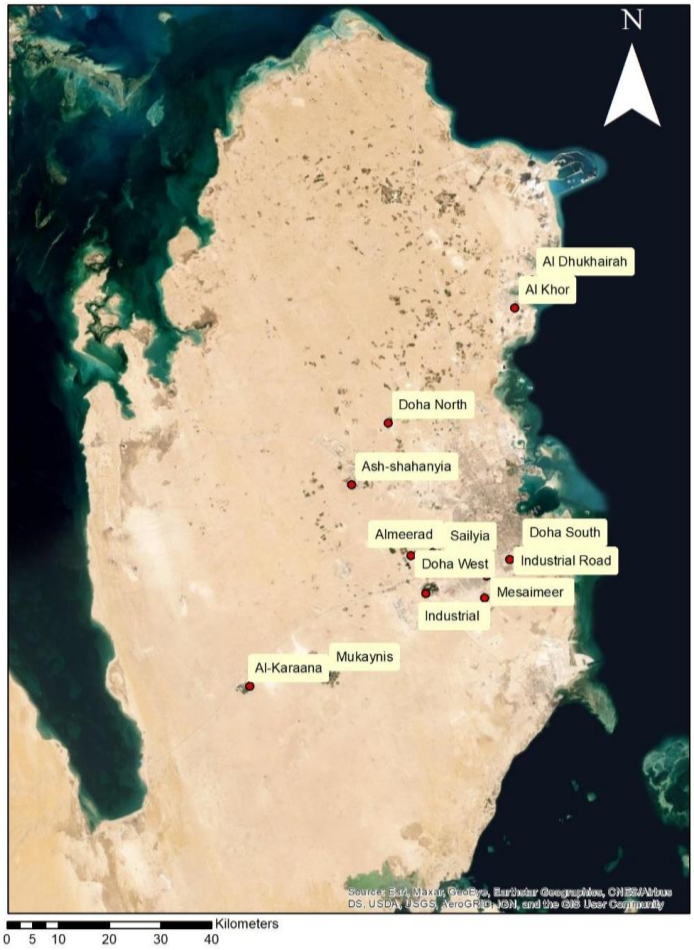


Figure 2.2. Map showing the sampled lagoon locations and names in Qatar.

For some of the lagoons, access requires official approval from several government ministries, especially for the lagoons located adjacent to the water treatment plants. Access required health and safety training by each treatment plant before sampling was permitted. Other lagoons were between houses and next to streets with no boundary fencing – in which case access for sampling was straightforward.

Table 2.1. Lagoons sampled in both summer and winter with X and Y coordinates.

Lagoon ID	Name	POINT_X	POINT_Y
1	Al-Khore treatment plant	51.46970772	25.66496544
2	Al-Dhukhairah treatment plant	51.546715	25.7124751
3	Al-Karanna	51.04959136	24.98474995
4	Mukayinas fodder irrigation	51.182758	25.0048107
5	Doha west treatment plant	51.332953	25.218275
6	Doha north treatment plant	51.2928791	25.456258
7	Ash-Shahanyyia treatment plant	51.22847521	25.34546283
8	Mesaimeer surface water	51.4659061	25.1817851
9	Industrial area	51.4628017	25.1425157
10	Mesaimeer area	51.371787	25.2241338

2.4.2 Wells

For groundwater samples, a list with inventoried wells locations around Qatar was used from a previous study in 2009 (Schlumberger water Services, 2009). The list is not entirely up to date and so a field survey was also needed to confirm the location and the condition of the chosen wells. Wells locations for this study were chosen based on their proximity to the lagoons, ranging from 0.5 km to 10 km away from the closest lagoon. The research required wells adjacent to lagoons and located far from lagoons for an effective comparison (Fig 2.3). To validate the chosen sites as representative of the study objectives a geo-statistics specialist (Prof Murray Lark, University of Nottingham) was consulted.

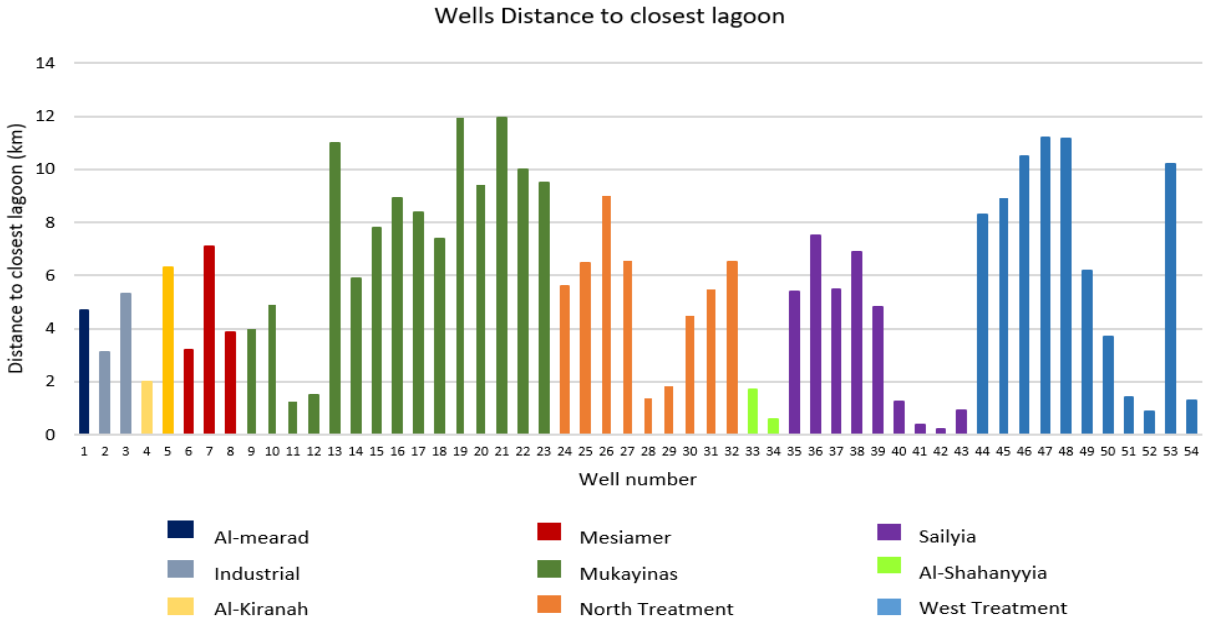


Figure 2.3. Wells distribution in the different areas around Qatar and their proximity to the closest lagoon.

The final wells and lagoons sampled locations are shown in Figure 2.4. It is seen that two lagoons in the north did not have any wells sampled around them, there are two reasons for that. First, there is

no farming activity around those lagoons, and the second is that both lagoons are directly next to the sea shore, with one lagoon pumping into the sea directly, with that the assumption is there would not be any water infiltration into the groundwater aquifers.

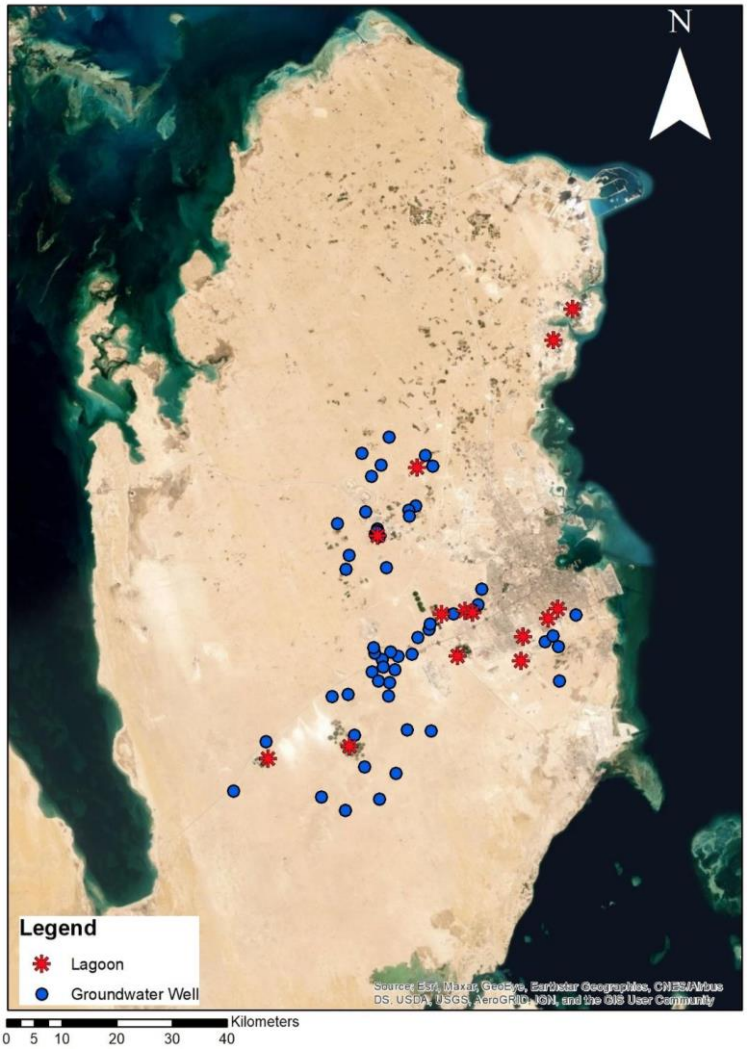


Figure 2.4. Map of Qatar with sampling locations for the hydrogeochemistry survey section. Red symbols show the location of all the lagoons; blue symbols indicate wells that were sampled.

2.4.3 Sample locations

For each sample location pictures and site information were taken; details covering vegetation, construction material, animals observed, fencing, pipes or any other relevant observations were recorded during the field visit. Wells exact X and Y coordinates were recorded and shown in Table 2.2.

Table 2.2. The sampled wells area location and the X and Y coordinates

Well ID	Area	X	Y	Well ID	Area	X	Y
1	Khreeb	51.23388	25.46005	**28**	Kharara	51.17537	24.90124
2	Khreeb	51.24666	25.50551	**29**	Kharara	51.13652	24.92294
3	Khreeb	51.20295	25.47918	**30**	Kharara	51.27692	25.03155
4	Khreeb	51.21849	25.44206	**31**	Salwa	51.28428	25.15433
5	Mukaynis	51.1537	25.08533	**32**	Abu Nakhla	51.29407	25.18156
6	Mukaynis	51.18046	25.0888	**33**	Abu Nakhla	51.31251	25.19452
7	Mukaynis	51.19048	25.02296	**34**	Abu Nakhla	51.31422	25.203
8	Khreb	51.30655	25.47632	**35**	Mukaynis	51.25625	25.12917
9	Khreb	51.31819	25.45852	**36**	Mukaynis	51.24764	25.10828
10	Umm Gehab	51.29073	25.39406	**37**	Mukaynis	51.24618	25.08629
11	Karanna	51.04604	25.01229	**38**	Mukaynis	51.23727	25.13292
12	Karanna	50.99259	24.93275	**39**	Mukaynis	51.21959	25.12575
13	Salwa	51.26148	25.15101	**40**	Mearad	51.22946	25.1104
14	Salwa	51.24947	25.15728	**41**	Mearad	51.39857	25.25944
15	Salwa	51.23568	25.14588	**42**	Mukaynis	51.3923	25.23396
16	Salwa	51.22314	25.15564	**43**	Mearad	51.38428	25.22573
17	Salwa	51.22193	25.1646	**44**	Mearad	51.35216	25.21946
18	Umm Gehab	51.27877	25.38727	**45**	Shahanyyia	51.22795	25.35674
19	Umm Gehab	51.2797	25.37785	**46**	Shahanyyia	51.22473	25.3481
20	Rwdat Rashed	51.24276	25.29406	**47**	Shahanyyia	51.23123	25.3447
21	Rwdat Rashed	51.17645	25.29168	**48**	Shahanyyia	51.22724	25.35363
22	Rwdat Rashed	51.18148	25.31454	**49**	Wakra	51.50201	25.17428
23	Rwdat Rashed	51.16224	25.36568	**50**	Wakra	51.51507	25.18347
24	Rwdat Rashed	51.20891	25.38509	**51**	Wakra	51.52381	25.16617
25	Kharara	51.31599	25.02945	**52**	Wakra	51.52505	25.11092
26	Kharara	51.2579	24.9613	**53**	Wakra	51.55212	25.21783
27	Kharara	51.23129	24.91907				

2.4.4 Sample collection

Two types of water samples and one soil sample were collected from each sample location. Because of access difficulties in some situations, a bucket with a rope was used for water samples. The bucket was rinsed with the water sampled before each collection.

Four sterilized universal tubes were used to collect water at each sample location. Two out of the four were filtered with a syringe filter (0.22 µm pore size), using 60 ml syringes, to eliminate bacteria and algae that could degrade the sample prior to chemical analysis. The tubes were filled to the top leaving no air gap between the sample and the tube covered to avoid changes in CO_2 partial pressure.

In addition, topsoil samples (0–15 cm) were collected using a shovel which was rinsed with water between each sample collection. The samples were collected in a plastic bag and subsequently air-dried and sieved (<2 mm) in the lab (Edwards, 2010)

Each farm had a different range of crops. Samples were mostly taken from leaves, from four to five random locations on the farm in an attempt to cover the majority of crop types growing. Moreover, dead plants and leaves were not sampled, nor were plants damaged by heat, dehydration or insects. Plant samples were rinsed with clean water, oven-dried at 70-80°C for 6 to 8 hours and stored in paper bags wrapped in plastic bags for transportation and storage before analysis (Peacock, 1992; Ernst, 1995).

Sample transportation & storage

After collection in the field, all samples were immediately stored in an icebox, with ice inside, then stored in a refrigerator at 4°C. Samples were also stored in the icebox with frozen gel packs for transportation from Qatar to the UK.

2.4.5 Labs used for sample analysis

Depending on the sample types different labs were used. For samples able to be transported from Qatar to the UK, analysis was undertaken in the University of Nottingham labs. For the biological samples, that need to be analysed within 24 hours, Qatar university labs were used to prepare the samples to be sent later to Sidra hospital labs. Finally, at the beginning of the research, Ashghal labs were used for the analysis of water collected in May 2018, but due to the labs' work priority, they stopped for the rest of the sampling trips. Each lab's affiliations and analyses done in each lab will be mentioned in this section.

University of Nottingham

Laboratory facilities within the University of Nottingham (UoN) were used for all the chemical and physical analyses undertaken on all the samples. Multi-element analysis, major cations and anions, Total Organic Carbon (TOC), Total Nitrogen and iodine analysis was all performed at the Gateway laboratory, School of Biosciences, Sutton Bonington Campus, UoN.

Qatar University

Since biological samples need to be analysed within 24 hours of sample collection, Qatar University labs were used. A collaboration was established with Prof. Nabil Zouri (Professor of Environmental Science, Microbiology, Enzyme Engineering & Bioconversion) in the Department of Biological and Environmental Sciences. All the biological sample handling, isolation, purification and storage was done in the labs at Qatar University.

Sidra Medicine Pathology laboratories

A collaboration with Pathology and the Genomics Core at Sidra Medicine was established in order to use their ‘Matrix-assisted laser desorption/ionisation time-of-flight mass spectrometry’ (MALDI-

TOF MS) instrument for the biological analysis. Sidra Medicine is an institution that provides tertiary healthcare services for women and children. Within Sidra medical centre, lab facilities were formed for Research related to patient health (Sidra Medicine, 2021). The Microbiology Division has collaborated with Qatar University on several research projects using MALDI-TOF-MS for microbial species identification (Mohamad *et al.*, 2019; Tsui *et al.*, 2020).

Ashghal Centre for Research and Development Laboratory

The Public Works Authority 'Ashghal' have overall responsibility for Qatar's infrastructure projects and public buildings, from planning to delivery and asset management. Since the authority needs a laboratory to carry out its monitoring and regulations (Ashghal, 2021). Ashghal-related technical research was formed under the Quality and Safety Department. An unofficial collaboration between this project and the Ashghal Quality and Safety department (Centre for Research and Development) was formed, with a joint interest in the lagoons of Qatar. This department analysed the lagoon samples for the summer of 2018 for *E. Coli*, Faecal Coliform, pH, Alkalinity, residual chlorine, Electric Conductivity (EC), Total Dissolve Solids (TDS), Total Suspended Solids, Ca, Mg, total phosphorus, chemical oxygen demand, ammonia, total Kjeldahl nitrogen, NO_3, NO_2, K, Na, Al, As, Cd, Co, Cr, Ni, Pb and Zn.

2.5 Hydrogeochemical data analysis

Since three types of samples were gathered at each site, three main sets of analyses were conducted. Firstly, water analysis was performed within three weeks of sample collection. Afterwards, soil and plant samples were dried and analysed. The protocol for each analysis is described below.

2.5.1 Water analysis

All the instruments used for the water analysis will be mentioned in this section.

Water Physical analysis

pH, EC, TDS, and temperature were measured on-site, to capture the results before any changes occurred during storage and transportations, using a Hanna HI-98130 meter. It was calibrated using solutions 4.0, 7.0 and 10.0 for pH and 12.88 mS cm^{-1} solution for EC

Water Chemical analysis

Multi-element analysis of diluted solutions was undertaken by ICP-MS (Thermo-Fisher Scientific iCAP-Q; Thermo Fisher Scientific, Bremen, Germany). The instrument was run employing three operational modes, including (i) a collision-cell (Q cell) using He with kinetic energy discrimination (He-cell) to remove polyatomic interferences, (ii) standard mode (STD) in which the collision cell is evacuated and (iii) hydrogen mode (H_2-cell) in which H_2 gas is used as the cell gas. Samples were

introduced from an autosampler (Cetac ASX-520) incorporating an ASXpress™ rapid uptake module through a glass nebulizer (Thermo Scientific, Bremen). Internal standards were introduced to the sample stream on a separate line via the ASXpress unit and included Ge (10 µg L^{-1}), Rh (10 µg L^{-1}) and Ir (5 µg L^{-1}) in 2% Primar Plus™ grade (Fisher Scientific, UK) HNO_3. External multi-element calibration standards (Claritas-PPT grade CLMS-2 from SPEX Certiprep Inc., Metuchen, NJ, USA) included Ag, Al, As, Ba, Be, Cd, Ca, Co, Cr, Cs, Cu, Fe, K, Li, Mg, Mn, Mo, Na, Ni, P, Pb, Rb, S, Se, Sr, Tl, U, V and Zn, in the range 0 – 100 µg L^{-1} (0, 20, 40, 100 µg L^{-1}). A bespoke external multi-element calibration solution (PlasmaCAL, SCP Science, France) was used to create Ca, Mg, Na and K standards in the range of 0-30 mg L^{-1}. Phosphorus, boron and sulphur calibration utilized in-house standard solutions (KH_2PO_4, K_2SO_4, and H_3BO_3). In-sample switching was used to measure B and P in STD mode, Se in H_2-cell mode and all other elements in He-cell mode. Sample processing was undertaken using Qtegra™ software (Thermo-Fisher Scientific) utilizing external cross-calibration between pulse-counting and analogue detector modes when required. For iodine, the matrix was 1% TMAH, the internal standard was Re and analysis was with the ICP-MS in STD mode (evacuated Q-cell).

To measure total organic carbon (TOC) and inorganic carbon (IC) a TOC-VCPH (PC-controlled Total Organic Carbon Analyzer high-sensitivity model) was used. To determine total carbon concentration (TC) a carrier gas (purified air) is passed at a controlled flow rate of 150 mL min^{-1} through an oxidation catalyst-filled TC combustion tube, heated to 680°C. When the sample pre-treatment/delivery system injects the sample into the combustion tube, the TC in the sample is oxidized to carbon dioxide. The carrier gas carrying the combustion products from the combustion tube is cooled and dehumidified in the dehumidifier unit before passing via a halogen scrubber into the sample cell of a non-dispersive infrared detector (NDIR), where the carbon dioxide is assayed. The NDIR analogue signal forms a peak, and the data processor calculates the peak area.

To calibrate the instrument, the relationship between the TC concentration and peak area (calibration curve) is predetermined using a TC standard solution. TC comprises the sum of TOC and IC. The acidified sample is sparged with the carrier gas (purified air) to convert only the IC in the sample to carbon dioxide. This carbon dioxide is detected by the NDIR detector and the sample IC concentration is measured in the same way as TC. The IC is a combination of carbonate and bicarbonate. To then determine TOC the IC concentration is subtracted from the TC concentration (TOC = TC-IC).

2.5.2 Soil and Plants analysis

All the instruments used for the soil and plants analysis will be mentioned in this section.

Soil and Plants Physical analysis

Soil pH was determined in the lab, after shaking a soil: water suspension (1:2.5 ratio; MilliQ water) for 30 min, using a pH meter (Mettler Toledo FE20/EL20).

Soil and Plants Chemical analysis

Subsamples of the sieved soils (< 2 mm) were ground in an agate planetary ball mill (Model PM400; Retsch GmbH & Co., Germany). For multi-element analysis, approximately 200 mg of finely-ground, air-dried soil was digested using 2.5 ml hydrofluoric acid (HF; 40% AR), 2.0 ml HNO_3 (70% Primar Plus™), 1.0 ml $HClO_4$ (70% AR) and 2.5 ml H_2O in a 48-place Teflon-coated graphite block digester (Model A3, Analysco Ltd, Chipping Norton, UK) with PFA digestion vials. Multi-element analysis was undertaken by ICP-MS (Thermo-Fisher Scientific iCAP-Q; Thermo Fisher Scientific, Bremen, Germany) The instrument was run employing a collision-cell (Q cell) using He with kinetic energy discrimination (He-cell) to remove polyatomic interferences. Internal standards included Sc (50 µg l^{-1}), Rh (10 µg l^{-1}) and Ir (5 µg l^{-1}) in 2% Primar Plus™ HNO_3.

External multi-element calibration standards (Claritas-PPT grade CLMS-2, SPEX Certiprep, Stanmore, UK) included Cd, Pb, and Zn; the certified reference material NIST 2711 (Montana soil) was used for quality control purposes (% recoveries were 98.1% Zn, 92.4% Pb and 92.9% Cd). For measuring inorganic carbon samples of the ball-milled soil were accurately weighed to 50-100 mg into acid-washed and furnace ceramic boats. Acid (25% H_3PO_4) was added to the boat using a Zipette (0.7 mL) and the boat was introduced into the furnace and the acidified sample was sparged with the carrier gas (purified air) to convert only the IC in the sample to carbon dioxide.

2.5.3 Hydrogeochemical data analysis

Pre-processing

Since results were produced from different instruments, all the data was converted to compatible units and summarized in MS-Excel for all the statistical analyses to be performed.

Moreover, Level of Detection (LOD) is used to eliminate the variables measured in the different instruments, but their values were detected at negligible concentrations. Thus, values below LOD were excluded. LOD is determined by equation 2.1 (Shrivastava *et al.*, 2011)

$$LOD = 3 \times SD_{blank} \qquad 2.1$$

Where, SD is the standard deviation of the blank (instrument noise values), and S is the slope of the calibration curve (Shrivastava *et al.*, 2011)

Hydrogeochemical data validation

Data quality was assured by using accredited calibration standards, replicate analyses and certified reference materials (CRMs) for all instruments. Moreover, to ensure the syringe filters used for water samples did not leach any DOC to the samples the filters were tested by filtering Milli-Q water and analysing the sample using the TOC analyser; no DOC was leached to the water indicating that the filtered samples were representative of the lagoon water for TOC. Examining cation-anion balances also supported the accuracy of the sample analyses, Figure 2.13 shows a relationship close to a 1:1 trend, suggesting the validity of the analysis.

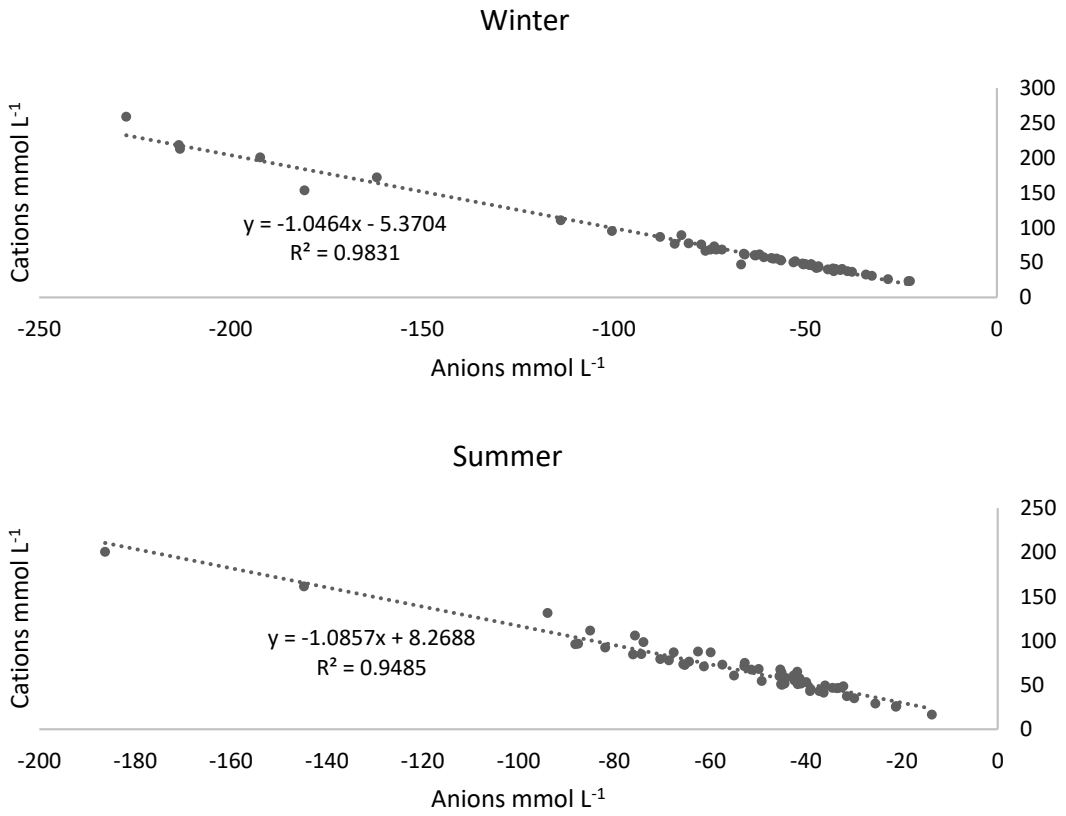


Figure 2.5. Plot showing cations-anions balances with R^2 more than 0.9. Anions: Chloride, Nitrate, Sulphate, Bicarbonate, and Cations: Sodium, Magnesium, Potassium, Calcium

2.6 Multivariate statistical analysis

For most statistical analyses a data set is required to be normally distributed. However, environmental data is often not normally distributed, even after lognormal transformation (Andrews *et al.*, 2002; Faulwetter *et al.*, 2013; Alvarez-Guzmán *et al.*, 2020; Suchy *et al.*, 2020; Narikkatan *et*

al., 2021). Many environmental data sets are skewed, with outliers, so the statistical techniques used have to be adapted to fit the non-normality of the data set (Filzmoser, 1999).

For this research, a log transformation was conducted in an attempt to achieve normality. However, it was clear that, even with removing outliers, the data should be treated as skewed data and not normal. Two tests of normality were used, Kolmogorov-Smirnov and Shapiro-Wilk, both given the same results.

SPSS software was used for the microbiological analysis. The software was chosen for its versatility in performing PCA analysis. PCA was used for the chemical analysis data as a first step to understanding how the variables interacted with each other.

For biological analysis, PCA is the most widely used statistical test for MALDI-TOF-MS data. PCA is suitable for this research objective since it shows the link between the protein profile between different bacterial species and the source of those bacteria (lagoon and groundwater).

Data were analysed using SPSS employing cluster analysis and constructing a correlation matrix. Multivariate statistical analysis of the spearman correlation method was conducted on the data. A Dendrogram of the data was constructed to show how the different variables correlate with each other in the lagoon and wells samples. Therefore, observing how the variables cluster into different classes.

2.6.1 Principal component analysis (PCA)

Principal component analysis (PCA) is an unsupervised linear transformation technique that is used to find linear combinations that accounts for as much variability as possible. PCA reduces the number of dataset dimensions or variables by creating new variables (principal components) for further types of analysis. The objective of PCA is to produce the fewest possible principal components which describe as much of the data variance as possible. It is a popular tool in hydrochemical studies to understand and visualize the relationship between variables to show the different water processes in any water system. Which summarize a large number of measured variables to three-dimensional visualization of their complex interaction.

Before preforming a PCA analysis a Kaiser-Meyer-Olkin (KMO) measure for sampling adequacy. This test is needed to insure the suitability of the PCA, especially for non normal data set. . KMO values greater than 0.8 are considered desirable, implying PCA will be beneficial for this data set. This is common when the majority of the zero-order correlations are positive. When the majority of the zero-order correlations are negative, KMO values will be less than 0.5. KMO values less than 0.5

necessitate corrective action, either through the deletion of the offending variables (variables that were either highly correlated or close to zero values) (IBM SPSS Statistics, 2020).

Another important step for PCA is choosing the rotation needed for the data set. Rotation is a change of coordinates used to maximize the sum variance, it is to ensure the final plot represent the best way to illustrate the data. There are two types of rotation used in PCA: the first one is orthogonal and oblique rotation orthogonal used when it is not known if the variables correlated to each other. Oblique rotation is used if it is known that the variables are correlated to each other (Dean, 2009). The identity matrix is compared to an observed correlation matrix in Bartlett's Test of Sphericity. It tests to see if there is enough redundancy between the variables to be able to summarize them with a small number of variables. The test's null hypothesis is that the variables are orthogonal ($p < 0.005$) that is, uncorrelated. If that is the case then Varimax rotation will be used, which is the most used rotation for non-parametric results (Kang, 2013).

After conducting both KMO and Bartlett's test, with results showing that PCA is appropriate for data reduction, a standardization is suggested. When the data contains variables with different units or on different scales, standardization is recommended to remove large differences for the weight value to be more accurate. A standardization data set is produced as described in Eq. 2.2.

$$z = \frac{x - \underline{x}}{SD} \qquad 2.2$$

Where, x is the value, $\underline{x}$ is the variables mean, SD is the variable standard deviation

After standardization centring the dataset, the mean of the variables will be zero and the SD will be equal to 1.

After standardization PCA is performed using equation 2.3.

$$PCA = \propto_1 x_1 + \propto_2 x_2 \qquad 2.3$$

Where, $\propto_1^2 + \propto_2^2 + \propto_3^2 + \cdots = 1$

$\propto$: is eigenvalue for each variable

x: is the mean for each variable

After PCA is conducted variables were then divided by principal components (PCs). Usually, variables are divided using PC1 and PC2, and sometimes PC3 as well to make 3D plots. However, the number of PCs used to divide the variables is used either by selecting the least number of PCs that hold up 80% to 90% of the total variances (Kaiser Criteria) or by using a scree plot, with the variance or the eigenvalues on the Y-axis and PCs on the X-axis. The scree plot is used to select the

last PC on the steep point of the plot. In addition, Component loadings values indicate the strength of the correlation. PCs are classified as strong (>0.75), moderate (0.5-0.75) and weak (0.3-0.5) for the relationship between variables for both positive and negative signs (Nathan *et al.*, 2017; Ravikumar *et al.*, 2017).

2.6.2 The hierarchical cluster analysis (HCA)

The most common clustering method is hierarchical cluster analysis (HCA). The dissimilarities or 'distances' between objects are used to form the clusters in hierarchical clustering; these dissimilarities can be based on a single dimension or multiple dimensions. Starting with each observation as a separate cluster, HCA uses agglomerative methods to join clusters together until one cluster of size n remains (Wunsch *et al.*, 2009; Singh, 2021).

The methods used for clustering continuous data are versatile. There are no strict rules for choosing specific methods for individual data sets. The HCA approach was used to analyse both hydro geochemical data and the gene expression data from MALDI-TOF-MS. The hydro geochemical data indicated that the most appropriate approach would be the Euclidean distance method (Wunsch *et al.*, 2009; Shirkhorshidi *et al.*, 2015).

Euclidean distance is the most widely used measurement method when clustering data. The only disadvantage is that large scale features dominate the other variables. However, that problem can be solved with standardisation of the data, as undertaken for PCA.

A Dendrogram refers to any graphical representation that depicts a taxonomic system as a tree. A Dendrogram is a two-dimensional graphic that illustrates a tree of relationships between any variables regardless of their source; a Dendrogram shows clustering observations at each stage and their similarity levels into different clades. The degree of resemblance is plotted on the vertical axis (also the degree of separation) while the observations are arranged horizontally (Wunsch *et al.*, 2009).

2.6.3 Correlation matrix

A correlation matrix shows if there is a quantitative relationship between variables and the strength of that relationship. Two common correlation matrices are Spearman's rho and Pearson's r. Since the data set for this research is not normally distributed, then Spearman's rho will be used as the nonparametric test for the correlation matrix (Rayner *et al.*, 2006)

A positive sign in front of a correlation coefficient indicates a positive direction; a negative sign denotes a negative or inverse direction. Moreover, A Spearman's rho value between 0.60 and 1.00 indicates a strong and reliable correlation and weak and insignificant values would be between 0 and

0.39. when the values are positive then it is a positive correlation, when the values are negative, then it is a negative correlation (Rayner *et al.*, 2006; Weaver *et al.*, 2018).

2.6.4 Generalized linear models (GLM)

To study the effect of a pollution source on groundwater, or to analyse the spatial and temporal variation of water quality, most literature uses multivariate analysis of variance (MANOVA) (Tanty *et al.*, 2014; Nathan *et al.*, 2017; Mello *et al.*, 2018). However, MANOVA is considered a parametric test and, since the current data set is considered non-parametric, a generalized linear model was considered more appropriate to use for more robust results.

The Generalized Linear Model (GLM) was developed in 1972 by John Nelder and Robert Wedderburn as an advanced semi-parametric statistical modelling tool, later popularized by McCullagh and Nelder (1982, 2nd edition 1989). It is considered a flexible test for data normality since there are several models under the umbrella term that allow the response variable 'y' to have an error distribution different from a normal distribution (Davidian, 1989; Shewhart *et al.*, 2001; Chen *et al.*, 2018).

GLM is widely used in linear regression to model a continuous response variable given continuous and/or categorical predictors (covariates) so that the dependent variable is linearly related to the factors and covariates determined in the study (Bickel *et al.*, 2007).

A general linear model test with a gamma probability distribution, as a model for continuous but non-parametric data (Davidian, 1989; Chen *et al.*, 2018) was used to determine:

- Chemical and microbial Spatial and temporal variation of groundwater and lagoon water;
- The associations between groundwater Chemical and microbial quality and groundwater proximity to both the lagoons and the coast

2.7 GIS analysis using Inverse distance weight (IDW) analysis

A geostatistical analysis is used to illustrate and predict the chemical and physical variables of groundwater on a geological map. It has been used in many published studies for predicting variables concentration in groundwater aquifers. Interpolation using Inverse Distance Weighting (IDW) is commonly used for demonstrating spatial variation in groundwater aquifers (Setianto *et al.*, 2013; Ahmad *et al.*, 2020; Elumalai *et al.*, 2020; Ghazaryan *et al.*, 2020; Batarseh *et al.*, 2021; Tefera *et al.*, 2021a). IDW presumes that near values are more connected than further values. Thus, IDW works by calculating the unknown sample amplitude as a weighted sum of its nearest neighbours. The estimated value of the unknown location is a weighted mean of nearby observations by its inverse

distance. As a result, the closer the known sample is to the final value of the unknown amplitude, the more weight it carries (Marvasti, 2001; Artiola *et al.*, 2004). IDW is calculated from Eq. 2.4.

$$\hat{z}(x) = \frac{\sum_i^n w_i z_i}{\sum_i^n w_i} \qquad 2.4$$

Where:

x = is an unknown value at a location to be determined

z_i = known point value

w_i = is an inverse distance of a point to each known point value that is used in the calculation (Marvasti, 2001)

Another well-known Geostatistical analysis tool is Kriging. However, kriging needs a spatial correlation between two variables for the prediction of the spatial distribution. While IDW uses only one variable and its distance weight to predict the unknown spatial distribution (Setianto *et al.*, 2013).

Chapter.3. A perceptual study of lagoons and groundwater in Qatar

3.1 Introduction

With the increase of the global population in recent years, there has been a concurrent increase in demand for clean water. However, natural water resources are becoming less available which has encouraged the option of using TWW for potable and non-potable water supplies globally (Peprah *et al.*, 2018). Conversely, traditional views regarding what constitutes an acceptable source of water present a challenge to the use of TWW supplies. This is known as the 'wisdom of repugnance', essentially a deep-seated feeling that such water is dirty and cannot be used for human consumption (Hamilton *et al.*, 2007; Peprah *et al.*, 2018). Thus, knowledge regarding public attitude towards TWW has been found to be important in many cases dealing with TWW reuse (Demnati *et al.*, 2012; A. K. Sharma *et al.*, 2016; Alves *et al.*, 2018).

Previous literature has documented the importance of understanding public attitudes when it comes to urban water management. However, few studies were found to illustrate public perception about the reuse of TWW, especially in farming or indirect contact with people (Mojid *et al.*, 2010; Al-Shenaifi *et al.*, 2015; Hagen *et al.*, 2017; Akpan *et al.*, 2020; Khanpae *et al.*, 2020). Moreover, most literature dealing with TWW wetlands, or WW in general, explore the idea of farmers' willingness to pay or willingness to understand the best practices for treated and untreated waste water reuses (Starkl *et al.*, 2015; Abdelrahman *et al.*, 2020; Camus *et al.*, 2020; Deh-Haghi *et al.*, 2020; Ricart *et al.*, 2021).

Hence, opinions are affected by geographical locations, culture, religion and ethnic background; different studies have shown varying conclusions regarding perception around TWW. Most case studies showed farmers' acceptability of the TWW increased with greater awareness of the environmental and economical benefits of using that water (Mojid *et al.*, 2010; Baawain *et al.*, 2020; Deh-Haghi *et al.*, 2020; Khanpae *et al.*, 2020) However, in some cases, even with such awareness, low acceptability was reported regardless of factors such as age and education (Mu'azu *et al.*, 2020). Moreover, some studies reported different behaviour depending on the uses of the TWW. For example, attitudes differ depending on whether the TWW was meant for consumption or uses with no direct contact with human beings, such as fodder or landscape irrigation (Deh-Haghi *et al.*, 2020).

Countries with a similar cultural background to that of Qatar reported low acceptability of TWW regardless of the intended use. In Saudi Arabia, the study showed that in general the public had positive acceptability towards greywater over TWW and this was influenced by educational level, gender, age, and residential location, with a greater acceptance with higher education, and a greater

acceptance by men compared to women (Mu'azu *et al.*, 2020). Another country similar to Qatar is Kuwait, where it was reported that 55–77% showed acceptance of TWW usage for non-potable purposes and the majority (78%) opposed direct use by people (Alhumoud *et al.*, 2010). Similar results were also seen in Oman where the survey showed that using TWW as drinking water was the least popular option. However, the public community were positive about the prospect of reusing TWW for irrigation for non-edible crops, urban uses, groundwater replenishment and industrial activities (Baawain *et al.*, 2020). It is important to note that in Qatar this kind of public survey of opinions regarding TWW use has either never been undertaken or never published.

On the other hand, regarding lagoons or wetlands, studies have shown that the public is concerned about WW discharge to wetlands, when the wetland was formed naturally or artificially for flood and surface water control, as the wetlands are perceived as clean, unlike WW (Maulan, 2006; Bikangaga *et al.*, 2007; Smith *et al.*, 2016). Other literature discusses wetlands as bodies of water containing untreated sewage and focuses on public contact with that water and the awareness of health consequences arising from direct contact with contaminated wetland water (Anh *et al.*, 2007; Demnati *et al.*, 2012). However, based on the current author's survey of the literature, an investigation of the Qatar lagoon receiving TWW and the public attitude to that have not been found.

Furthermore, literature concerning policymakers as stakeholders were mostly found in research related to the reuse of WW. Those studies' main findings were that the most important factor in sustainably managing TWW is the willingness of stakeholders to:

- listen to and engage with the public, especially farmers' needs in the TWW management (Baggett *et al.*, 2006; Bixio *et al.*, 2006; Chen *et al.*, 2015; Saliba *et al.*, 2018);
- participate in forming economic instruments and the set-up of water reuse guidelines (Bixio *et al.*, 2006);
- enhance communication and inter-stakeholder relationships between institutions managing the TWW and water resources management (Khan *et al.*, 2006; Hennessy, 2009; Goodwin *et al.*, 2019; Massoud *et al.*, 2019).

Unlike the public perception studies, investigations into policymakers' attitudes have not been conducted in Qatar or similar countries.

While no published articles were found about public perception toward lagoons in Qatar, over the years the public has raised their concern about flooding and the presence of mosquitoes from nearby lagoons (Al-shareq, 2015; Suliman, 2016; Nada, 2019)

In conclusion, the situation of having lagoons as a storage option for TWW in a desert climate is unique and seen only in Qatar and adjacent countries. There have been no studies showing public and policymaker's perceptions about using lagoons and how this may affect the groundwater and wider environment, which makes this research a unique opportunity to fill this knowledge gap.

Thus, this research is designed to fill existing knowledge gaps over lagoon management influencing the groundwater reservoir in Qatar. Lagoon management is controlled by different policymakers in the water managing institution in Qatar; in addition, groundwater and lagoon co-existence and their management are likely to have an effect on public health and their satisfaction with the overall Qatar water management system. Hence, social science approaches will be used in this chapter to understand the wider picture by understanding policymakers and public perceptions of the technical, economic and social issues. In particular, policymakers and local residents will be asked, through an online survey and interviews, respectively, to share their views on lagoons and their management. This social science mixed-method approach will provide insight into perceptions of lagoons and preferences for management, which may only be determined through contact with a range of respondents. Quantitative data on public perception of lagoons will be collected and statistically analysed from the online surveys. Qualitative data, in the form of interview transcripts, will be analysed after face-to-face interviews have been conducted with policymakers.

The goal of this study is to obtain stakeholder perspectives on the usage of lagoons, public perceptions on lagoon impact on the environment and health, and to compare the difference between the perceptions of the public and policymakers. The following study objectives are listed below.

1. Identify and compare public and policymakers' knowledge of lagoons and their understanding of lagoon types, locations and the reasons for constructing them.
2. Identify public concern about having lagoons near their residences and determine their views about lagoon impact on public health.
3. Determine the roles of both public and policymakers in using lagoons instead of other approaches of TWW reuse.
4. Understand if the policymakers are willing to accept public involvement in decision making for TWW reuse to decrease the number of lagoons in residential areas.
5. Based on the research outcomes propose recommendations for future handling of lagoons in terms of planning, design and public involvement for better water management in Qatar.

Information obtained from this study will be communicated to the different ministries dealing with lagoon and water management in Qatar to aid in better decision making for lagoon construction and

monitoring in the future. Moreover, together with the results derived from the chemical and biological analysis parts of this study, this social survey will provide a holistic understanding of the environmental issues arising from building lagoons around Qatar.

3.2 Methodology

This section explains the processes utilized to develop this research chapter and the methods used to conduct the research. While the literature strategy was described in Chapter 2, this section will describe the detailed methodology used for conducting the social science investigation. In addition, the approach paradigm followed in this study will be discussed in this chapter. This research project has both a quantitative and qualitative component; the main purpose of the qualitative component is to gain in-depth insight into the current attitude of the policy makers in the government ministries managing water and WW in Qatar as well as public knowledge about the presence of lagoon and their perception about lagoon management in Qatar. This is research structure is shown in Figure 3.1, where the research design is divided between public and policy makers with each having different data collection and analysis discussed separately.

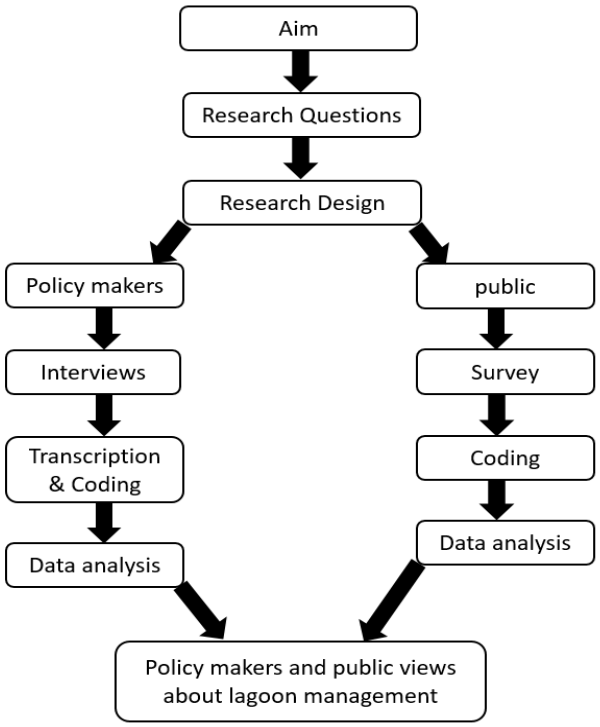


Figure 3.1 Flow chart showing the social study chapter research design flowchart illustrating the main types of data collection

For the social research to be conducted a research paradigm and design had to be chosen, ethical approval needed to be obtained, the data collection method needed to be chosen and designed, all those steps are explained in this section, to gather information from both policy makers and public.

3.2.1 Research paradigm and design

There are two known paradigms in social sciences: in an **Inductive** approach, the theory comes first and is either proven or rejected after observations; with a **Deductive** approach, a theory is developed following observations and experiments (Bryman, 2012). This research is partially inductive; the initial theory is that the public perceives TWW reuse negatively - hence the increase in TWW being stored in lagoons. An additional theory is that the policymakers are unaware of the possible impact lagoons have on the groundwater reservoir. However, it is expected that analysing data from public surveys and policymakers' interviews will enable the development of more specific theories. Those theories, after testing, will be the main outcomes of this chapter. This approach has been described by Bryman (2012) as an '**iterative** paradigm', which is commonly used in human perception studies (Bryman, 2012).

This research design combines both qualitative and quantitative methods. The information gathered from the public survey will be quantitative and the data will be analysed using quantitative statistical techniques. However, the policymakers' interviews will be analysed using qualitative methods of coding and thematic analysis. Comparing the two methods should enhance the validity of the research; the two approaches will complement each other to produce a more comprehensive picture of the social views of lagoons in Qatar.

3.2.2 Ethical approval

Before reaching out to both public and policy makers two ethical approvals were needed. The first one was from the University of Nottingham, as any research involving human beings, their data and/or tissue requires an ethical assessment and permission. A summary of the research was provided and questions about the research ethics were answered. The same process was conducted to obtain ethical approval from Qatar University. Ethical approval from Qatar University was required because the author is a lecturer with that institution. This also has some advantages when approaching stakeholders, as it provides some assurance knowing the researcher is from a local university. The author also informed stakeholders about her affiliation with the University of Nottingham.

3.2.3 Public perception survey

This section of the chapter provides details of the methods used to understand public perception in Qatar, including: (i) the type of design chosen for the survey; (ii) the target population; (iii) how interviewees will be contacted; (iv) how consent will be obtained. Finally, this section will cover how the gathered data will be recorded, stored, processed and analysed.

Justification for choosing quantitative methods

To meet the set objectives for this chapter, a representative number of the public had to be surveyed. There is no set number for sample size but between 200 and 400 is typically needed to give a realistic picture of public perception. Considering the resources and time available to the author a qualitative form of interviews or a focus group would not be possible. Thus, an online survey was chosen as the quantitative method to reach as many people in Qatar as possible.

Survey design

The public survey and consent form is attached in the appendix section (Appendix A), here the reasoning for the survey structure is outlined. This survey was designed to collect information about the following topics.

Demographic data

Public perception studies have shown that the public's socio-economic background influenced their knowledge of lagoons and TWW reuse management, benefits and importance. It also affected their acceptance of the use and locations of lagoons and their future management in the country (Demnati *et al.*, 2012; Ricart *et al.*, 2021). To address that aspect, the survey collected information about nationality, age and education, as those were determined to be highly influential parameters in perception studies in Qatar and the GCC region (Muqeem, 2016; Al-Ghanim, 2017; Tohid *et al.*, 2017; Baawain *et al.*, 2020).

Public knowledge of the lagoon situation in Qatar

To meet the study objective of understanding the impact of lagoons on the groundwater and the wider environment, the opinions of people who live locally should be understood. In addition, in the local newspapers lagoons have been a source of complaints (Al-oqedi, 2015, 2016; Al-shareq, 2015; Suliman, 2016; Nada, 2019; AbuNada, 2021). For those reasons, this survey will include questions intended to determine whether the public is aware of the lagoons' existence, structure, locations, volumes and management.

Public attitude toward lagoons' health and safety risks

When lagoons were discussed in the newspaper by the public there were always complaints about perceived health risks that lagoons may impose on the local population; most complaints concerned mosquitos, odours, rodents and drowning hazards (Al-oqedi, 2015, 2016; Al-shareq, 2015; Suliman, 2016; Nada, 2019; AbuNada, 2021). Thus, this survey included a Likert scale asking the public about the common risks listed in the local newspapers.

Public attitude toward lagoons benefits

The lagoons existence is an essential part of the Qatar urban water system, and recently the Public Works Authority in Qatar, Ashghal, announced the conversion of the most polluted Al-Karanna lagoon to a green landscape for different types of local ecosystems, bird watching and cycling; this opened to the public in 2019 (Al-shareq, 2019). Thus, the survey used a Likert scale to understand the public willingness to use, accept and visit the transformed lagoons.

Public desire to be involved in the management decisions around lagoons

In the local newspapers the public has complained that they were not being heard (Suliman, 2016; AbuNada, 2021). This is indicative of their expectations of being involved in lagoon management decisions and issues related to their environment impacting their health. The survey therefore includes questions aimed at understanding their desire to be involved and on what matters they want to be consulted.

Public attitude toward TWW reuse

Treated wastewater reuse is always considered a taboo topic in Qatar (Al-Mohannadi, 2004; Stefanakis, 2020), with no studies showing the public acceptance of reusing TWW for green landscape or animal fodder. The survey therefore explored the public acceptance of these reuse options currently practiced in Qatar.

Target research group

The target group are either Qataris above the age of 18 or people who are permanently living in Qatar. The population of Qatar is 2.7 million. However, in Qatar a large proportion of the population are external labour coming with short contracts for a specific job and living in ‘labour designated accommodations’ (FAO, 2008). Thus, the targeted population were counted from the total number of individuals living in households, which is 955,769 individuals in 2020 (Population & Housing Census, 2020).

Access to participants

For public perception, the internet site ‘www.qualtrics.com’ was used to collect, store and analyse data. Qualtrics is GDPR compliant (https://www.qualtrics.com/support/survey-platform/getting-started/qualtrics-gdpr-compliance/).

Online surveys were completed by members of the public who were asked to take part in this study; a link was circulated through social media, including ‘WhatsApp’ and ‘Snapchat’, as well as emails; participants were directed to the URL where the survey was housed. The survey was distributed through the researcher’s relatives and friends to a range of social groups on ‘WhatsApp’. On

'Snapchat', local social influencers were contacted to post the survey. Moreover, the survey was circulated to all staff and students at Qatar University.

Participant consent

For the online survey, a consent form comprised the first question. Participants were asked to sign it before starting the actual survey – if this was not signed the participant was unable to continue.

Data recording and storage

For the online survey, the data was stored on the website using anonymous ID codes. Data was also downloaded from the website for analysis, again using anonymous ID codes, and stored securely on the University of Nottingham server.

Data processing and analysis

Data first was coded to numerical values as a requirement for statistical analysis using SPSS (Table 3.1) where each category containing the survey choice was given a number starting with 1, when the question was not answered the label (no answer) was given with the respective number.

Before analysing the scale questions in the survey, the response reliability would be assessed using Cronbach's Alpha test. Cronbach's Alpha is a statistical tool that measures the internal consistency of a set of scale items or how well the scale items vary together as a group (Trobia, 2011). This test has a value between 0 and 1, the higher the value the more the chance a respondent would offer the same score on a measure if the variable were administered to the same respondent repeatedly. According to some experts, a crucial value for the alpha of 0.70 indicates that the scale is credible. If the value is less than that, it is advised that the scale be altered (Trobia, 2011; Al-Ghanim, 2017; Khanpae *et al.*, 2020).

Table 3.1 Survey questions ID number with each question answer choices and SPSS numerical values

ID	Survey Choices Codes
Q1	**1**= 18-25, **2** = 26-35, **3**= 36-45, **4**= 46-60, **5**= 61 & above, **6**= Prefer not to say, **7**= No answer
Q2	**1**= Middle school, **2**= High school, **3**= Bachelor degree, **4**=Postgraduate degree, **5**= Prefer not to say, **6**= No answer
Q3	**1**= Qatari, **2**= GCC countries, **3**= Middle east, **4**= Other**, 5**= Prefer not to say, **6**= No answer
Q4	**1**= Yes, **2**= No, **3**= No answer
Q5	**1**= In the past five years, **2**= In the past 10 years, **3**= Cannot recall, **4**= No answer
Q6	**1**= 1 or 2, 2 = Around 5, **3**= Less than 10, **4**= More than 10, **5**= I don't know, **6**= No answer
Q7	**1**= Yes, there is one in my city, **2**= No, we do not have any lagoons in my city, **3**= I don't know, maybe there is a lagoon in my city, **4**= No answer
Q8	**1**= Rainwater, **2**= Groundwater, **3**= Wastewater, **4**= Treated wastewater, **5**= Seawater, **6**= I don't know, **7**= No answer
Q9	**1**= Ashghal, **2**= Ministry of Municipality and Environment, **3**= Kahramaa, **4**= I don't know, **5**= No answer
Q10	**1**= Disagree, **2**= Somewhat disagree, **3**= Neither agree nor disagree, **4**= Somewhat agree, **5**= Agree, **6**= I do not know, **7**= No answer
Q11	
Q12	**1**= Comment about lagoon, **2**= Questions about lagoon, **3**= Irrelevant comment, **4**= No answer

Furthermore, the statistical analysis chosen in the methodology chapter was based on the data type related to physical, chemical and biological data, which is continuous. However, social data are mostly categorical, so the data are either nominal or ordinal (Bryman, 2012). Thus, a different statistical test was chosen for this chapter. The coded data were evaluated with descriptive statistics such as frequencies and percentages then graphed as bar charts to show survey responses. Pearson Chi-square was chosen for its suitability in estimating the likelihood of statistically significant differences in opinion between two or more independent groups (Sirkin, 2011), this is similar to GLM in the continuous data analysis.

Chi-Square was found to be the most common type of relationship test used in questionnaire type studies (Manuel, 2003; Møller *et al.*, 2012; Abdelrahman *et al.*, 2020; Akpan *et al.*, 2020; Mu'azu *et al.*, 2020) when the concept of a certain independent category is thought to affect another ordinal (Segura *et al.*, 2018; Dery *et al.*, 2019; Michetti *et al.*, 2019) or even continuous dependent variable (Singh, 2021). A p-value of $p < 0.05$ was used to test the null hypothesis and the chi-square statistic was used to determine there was a difference in the dependent value based on the independent value.

3.2.4 Policy makers interviews

This section covers the qualitative methodology, showing the interview design and identifying the targeted experts and policymakers related to the lagoon and water quality. Also, it covers how the experts consulted were located and contacted and how the data is stored, analysed and reported.

Justification for choosing a qualitative method

Policymakers and experts in the field of water resource management in Qatar obtain valuable and beneficial information that could not be gathered through a literature review or field observation. This was an incentive to conduct one-to-one interviews, not only to answer the research question of the policymakers' attitudes towards lagoons but also to give each expert the chance to provide their expertise and knowledge around the topic.

Interview design

The policymaker's interview questions are provided in the appendix section (Appendix B). The reasoning for the interview structure is discussed below.

Interview structure. The interview questions were designed to fulfil the research aims. The questions were designed as a semi-structured interview, but certain questions were added during the interview when a point needed to be clarified and where more information regarding the question topic was required.

Participant information sheet. Each interview began with a brief introduction to the research scope, the nature of the questions asked, a brief introduction to lagoons in Qatar and a copy of the Participant Information Sheet was shared before every interview.

Duration of the interview. It was recognized that interviewers are busy people with little free time; thus, the interview was planned to last between 10 and 40 minutes, depending on the interviewee's responses.

Language. While English is spoken by the majority of those in the industry, some are not native speakers. A translation of the interview questions into Arabic was developed and the choice between Arabic and English was offered before every interview.

Interview question themes. The Interview questions were divided into three main themes.

- Lagoon theme (9 Questions): this started with general knowledge about lagoons, then the policy makers were asked about their professional perception of lagoon management in Qatar
- Groundwater theme (3 Questions): they were asked about their knowledge about the current groundwater quality, and their thoughts on lagoon impact on the groundwater
- Public theme (4 Questions): they were asked if they think the public are involved or if they should be involved and surveyed with the lagoon management in Qatar

Interview questions arrangement. The questions began with a broad context (years of experience) to let the interviewee relax, then the interview progressed to a deeper level, with general questions about lagoons then concluding with the interviewee's perspective of the lagoon's impact on the environment and groundwater quality.

Target research group

All of the collection sites for the interviews were Ministries in Qatar. Experts on water quality in Qatar ministries are involved in the operation of the whole water cycle, starting with ministries dealing with drinking water to ministries dealing with sewerage treatment and disposal.

- Qatar General Electricity & Water Organization (KAHRAMAA)
- Ministry of Municipality and Environment (MME)
- Public Works Authority (Ashghal)
- Engineers in treatment plants
- Individuals dealing with water management in the oil and gas sector

The number of policymakers was limited by the number of people holding these roles in Qatar, and hence the results will reflect only the views of this small, but highly informed and influential group.

Access to participants

Contact information for the policy makers being interviewed was obtained by contacting the human resource (HR) department in each ministry first. The official letters and required documentation were prepared and then, after approval, the HR personnel nominated 3 or 4 individuals from their ministries dealing with water management to be interviewed.

The interviews were generally conducted using video calls because of Covid restrictions but, because some participants were unavailable, a few phone interviews were conducted as well.

Participant privacy and consent

Since the interviews were mostly done by video chat, written consent could not be obtained from the interviewee. However, the consent form was sent to them by email requesting approval to conduct the interview as well as to record the interview for transcription purposes only. Some participants were anonymously quoted – names were not used. However, if the participant affiliation needed to be mentioned in the results only the ministry name was provided, but not the department, so the participant cannot be identified.

Data Recording and storage

For face-to-face or video call interviews, a voice recording was taken if the respondent consented; if not then only notes were written. Interviews were recorded, transcribed and subsequently translated into English for analysis. No names or affiliations were stored with interview data, and respondents were given anonymous ID codes. Audio data, transcripts, and translations were stored securely on the University of Nottingham servers.

Data processing and analysis

Coding is the starting point for the majority of qualitative data analysis techniques, in which a category is identified in the data that corresponds to the research questions and ultimately provides the research with the theoretical foundation necessary to contribute to the literature on the research topic (Creswell, 1997; Bryman, 2012). Thematic Coding steps may be summarized as follow:

- **Step 1:** transformed the audio material to text through transcription
- **Step 2:** chose main codes based on the study objectives and questions
- **Step 3:** read the transcript looking for emerging and repeated codes
- **Step 4:** related the emerging codes to the study objectives
- **Step 5:** merged similar codes and set the final codes list (Bryman, 2012)

Final themes or codes were discussed as qualitative data to recognize concepts and establish relationships between them and to link how the interviewees perceive lagoons and lagoon management in Qatar.

3.3 Results and discussion

First, results from the public survey will be stated and analysed, followed by the policymakers' interviews.

3.3.1 Public perception of lagoons: current situation and management

This section will discuss the results obtained from the public survey in Qatar investigating their perception of lagoons, specifically regarding the current situation and future management plans. Since the survey was distributed via social media as a link, the exact number of the survey sent is unknown, but of the questionnaires that were sent out, 466 were returned. However, because of incomplete survey forms and non-consented responses, a total of 128 participants were not included in the data analysis. Finally, 338 responses were included in the study, which is equivalent to a 72.5% response rate. This is a fairly common rate with research using online surveys of the public asking about water management in their country (Abdelrahman *et al.*, 2020; Akpan *et al.*, 2020; Mu'azu *et al.*, 2020; Ricart *et al.*, 2021).

Before discussing the survey results, a Cronbach's alpha test was performed on the Likert scale questions 10 and 11 (Table 3.1) and produced an alpha value of 0.886, concluding the Likert scale responses were highly reliable (Alpha>0.7) and the statistical analyses conducted on the respondents' answer were appropriate (Trobia, 2011)

In addition, a chi-square test was done to determine the relationship between public attitude and knowledge of lagoons' safety risks, benefits, management decisions regarding lagoons and TWW reuse practices. In addition, how perceptions were influenced by demographic characteristics of the respondents was assessed, including the effects of nationality, age and education.

3.3.1.1 Demographic data

The age group 18-25 had the largest number of respondents (46% of total respondents) while the age group 26-35 was the second-highest; the percentage of respondents decreased with age (Fig 3.2). This matches the Qatari population census; the Qatari population has the highest percentage of the population within the age group of 20 – 35 (Population & Housing Census, 2020). Moreover, other social research conducted in Qatar had the same respondent age group distribution with 20 – 35 as

the highest respondent age group (Al-Ghanim, 2017; Cheema *et al.*, 2017; Tohid *et al.*, 2017; Abdmouleh *et al.*, 2018; AbdulRahim *et al.*, 2020).

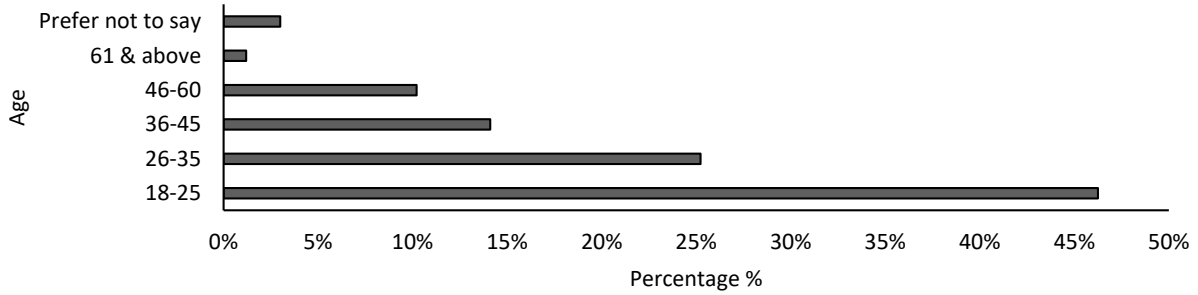


Figure 3.2. Survey participant age distribution percentage.

Regarding respondents' education, the highest response for the educational level was a bachelor degree (46%), with the second postgraduate and third was high school degree (Fig 3.3), comparing these results to other survey studies in Qatar, or globally, it shows that the educational level of the highest respondent group is always either high school or graduate and postgraduate (Cheema *et al.*, 2017; Tohid *et al.*, 2017; Abdelrahman *et al.*, 2020).

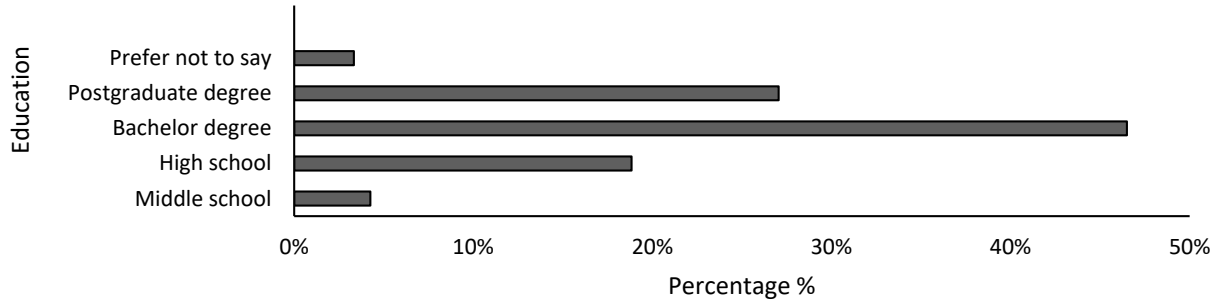


Figure 3.3. Survey participant education distribution.

In terms of respondent nationalities (Fig 3.4) Qatari citizens respondents had the highest percentage of 47%. This was almost double all the other nationalities with the second highest being 'Middle Eastern' at 25%. Other public perception studies done in Qatar have classified the population as either 'Qatari' or 'non-Qatari', where non-Qatari had the highest percentage (Tohid *et al.*, 2017; Abdmouleh *et al.*, 2018). Thus, if all other nationalities are summed up (a total of 50%) then the current research will match previous studies done in Qatar and the current population census of Qatar which indicates that Qataris were fewer than non-Qataris (FAO, 2008). Therefore, with further data analysis, the nationality response will be recoded to "1=Qatari, 2=non Qatari and 3= prefer not to say''

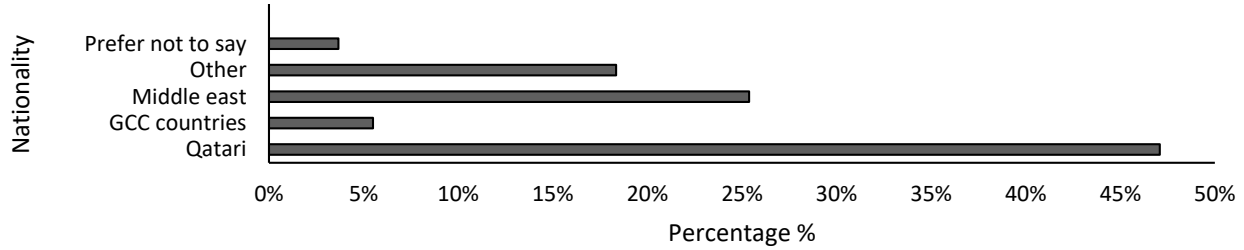


Figure 3.4. Survey participant nationality distribution.

Moreover, public demographic characteristics of age, nationality and education could influence each other, since the educational level is likely to increase with age; there could also be an effect of nationality on educational level. Thus, to truly understand the demographic background influence on the public perception of lagoons, education, age and nationality should be tested by chi-square to determine possible correlations. Table 3.2 shows that there was no influence of each variable on the other. Therefore, it is appropriate to assume each demographic influence is independent of the other demographic variables.

Table 3.2. Chi-square test showing the relationship between public knowledge of lagoons in Qatar and the independent demographic variables.

Question (dependent)	Independent variables	Mean Square	DF	Sig.
Nationality	**Age**	36.307	10	0.080
Age	**Education**	169.9	20	0.329
Education	**Nationality**	48.67	8	0.165

3.3.1.2 Public knowledge of the lagoon situation in Qatar

The survey showed that more than 56% of the public in Qatar were aware of lagoons, before the survey, and within that almost half of the participants stated that had known about the lagoons for at least the past five years (Table 3.3).

Table 3.3 Survey participant answers for questions ID 4 – 9, with the percentage of each response

ID	Survey Choices					
4	**Yes** 56.7%			**No** 43.3%		
5	**In the past five years** 46.8%		**In the past 10 years** 38.3%		**Cannot recall** 14.9%	
6	**1 or 2** 17%	**Around 5** 23.4%	**Less than 10** 11.7%	**More than 10** 9.6%	**I don't know** 38.3%	
7		**Yes** 34.9%		**No** 28.5%	**Maybe** 37%	
8	**Rainwater** 21%	**Groundwater** 15.0%	**Wastewater** 22.75%	**Treated wastewater** 19.5%	**Seawater** 12.9%	**I don't know** 8.8%
9	**Ashghal** 17.4%	**MME** 65.9%		**Kaharamma** 9.1%	**I don't know** 7.6%	

However, respondents who had never heard about the lagoons before were curious to know more. This is seen in the comments question at the end of the survey where 21 respondents asked questions about the lagoons' whereabouts and reasons for their existence; there were also requests for videos and pictures of the lagoons. The main questions concerning lagoons are listed below.

- What is the purpose of the lagoons?
- Are they used for construction projects?
- What are the benefits and disbenefits of their existence?
- How can lagoons be removed?

This demonstrates that the public is interested to learn more about the current conditions and management of lagoons in Qatar.

A Chi-square test has shown that there was no significant influence of respondent nationality on the public knowledge of lagoons in Qatar, but there was an apparent effect of education and age ($p<0.05$) (Table 3.4).

Table 3.4. Chi-square test showing the relationship between public respondents to the survey questions related to lagoons knowledge in Qatar and independent demographic variables.

Question (dependent)	Independent variables	Mean Square	DF	Sig.
Before this survey, have you heard about lagoons before?	**Nationality**	2.897	2	0.235
	Age	25.3	5	0.006
	Education	14.805	4	0.005
When did you first hear about Lagoons?	**Nationality**	8.58	4	0.072
	Age	39.74	10	0.001
	Education	27.48	8	0.002
Based on your knowledge how many lagoons do we have in Qatar?	**Nationality**	607	8	0.647
	Age	23.52	20	0.78
	Education	34.45	16	0.005
Are you aware of any lagoons in your city?	**Nationality**	4.8	4	0.307
	Age	4.21	10	0.937
	Education	17.67	8	0.022
What do you think is the main water source in the lagoons?	**Nationality**	38.22	8	0.554
	Age	56.12	20	0.625
	Education	68.70	16	0.005
Which ministry is responsible for the lagoons?	**Nationality**	23.12	12	0.072
	Age	37.958	30	0.150
	Education	52.67	24	0.001
Are all lagoons the same?	**Nationality**	8.33	10	0.596
	Age	47.74	25	0.090
	Education	43.47	20	0.160

The influence of the respondent's age and education on their knowledge of lagoons can be seen in Figures 3.5 and 3.6, where 86% of the middle school group knew about lagoons; this is higher than all the other groups. Previous studies showed that a higher educational level was correlated with

greater knowledge of current water management (Alhumoud *et al.*, 2010; Zhu *et al.*, 2018). Thus, the middle school having the highest positive response is unexpected. It is worth mentioning, respondents with middle school levels of education, showed a variation in the age groups, so it cannot be assumed that they were also younger than all the other education groups. This was shown with the GLM results illustrating that there was no significant influence of age on the education group (Table 3.2)

Moreover, of people who were 61 and older, 100% knew about the lagoons prior to this survey. This result is expected since they have had a greater life experience.

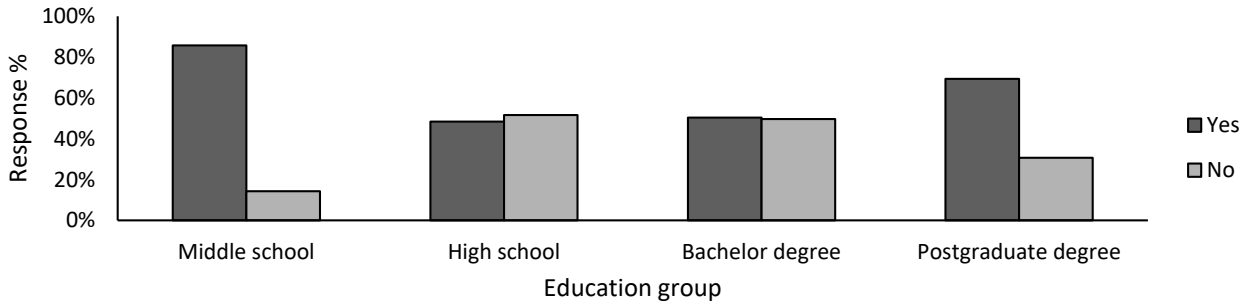


Figure 3.5. The survey question "Heard about lagoons before?'' responses divided into different educational groups.

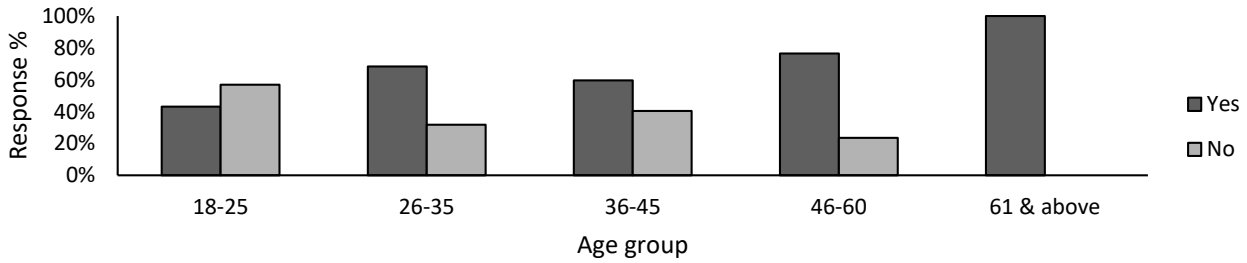


Figure 3.6. The survey question "Heard about lagoons before?'' responses divided into different age groups.

Regarding when the public first heard about lagoons, 46% said in the last five years; the chi-square test showed that there was no significant influence of nationality but education and age significantly influenced the answers provided ($p<0.05$). In the middle school group, 92% answered 'in the past 5 years' whereas the other groups responded equally to 'in the past 5 years' and 'in the past 10 years' (Fig 3.7). By contrast, each 'age' group responded differently (Fig 3.8), with the 36-46 group giving the most accurate answers of "in the past 10 years'' since the lagoons started in the 1970s based on the historical images extracted from google maps, but the public only started complaining about them in 2011 (Ahmed, 2011).

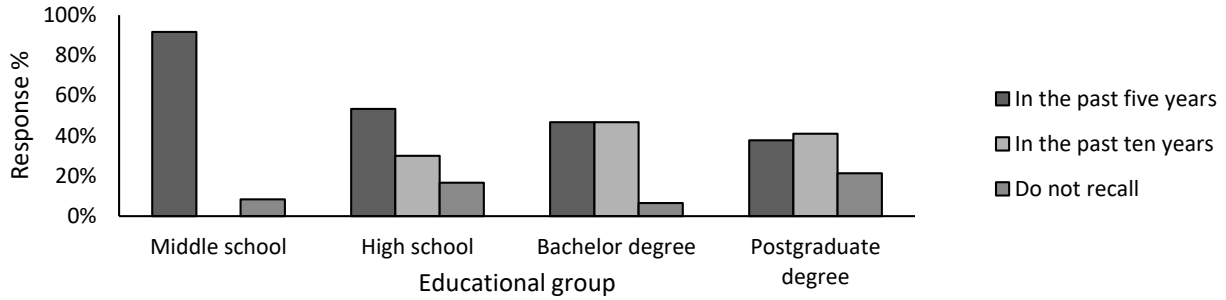


Figure 3.7. The survey question "When did you first hear about Lagoons?" responses divided by the different educational groups.

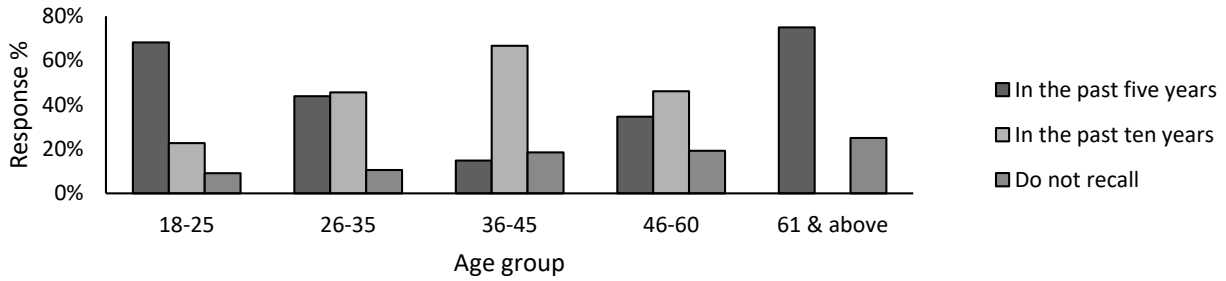


Figure 3.8. The survey question "When did you first hear about Lagoons?" responses divided by the different age groups.

Additionally, the survey revealed that mostly participants did not know how many lagoons there are in Qatar (37%), with only 9% knowing the correct answer, i.e. more than 10 lagoons. Moreover, the chi square test determined that there was no impact of age or nationality on the responses. By contrast, education level influenced respondent answers ($p<0.05$), where 58% of middle school believed that there were 1 or 2 lagoons, 35% of the bachelor degree group thought there were around 5, and the other educational groups highest response was they did not know (Fig 3.9).

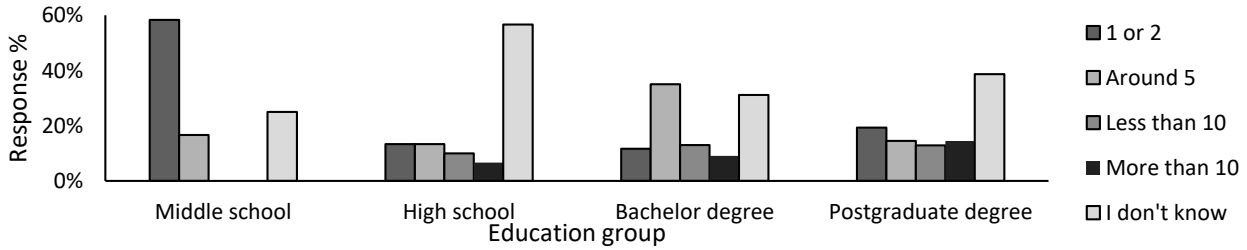


Figure 3.9. The survey question "How many lagoons are there in Qatar?" responses divided by the different educational groups.

In addition, when asked about their knowledge of a lagoon in their city, almost equal proportions of participants stated "Yes", "No" and "maybe", with the chi-square test showing no significant influence on the responses of age or nationality but a significant influence of education level ($p<0.05$); the middle school group produced a different response rate, with more than 80% of them

answering “Yes” while the other educational groups responded almost equally to all the options (Fig 3.10).

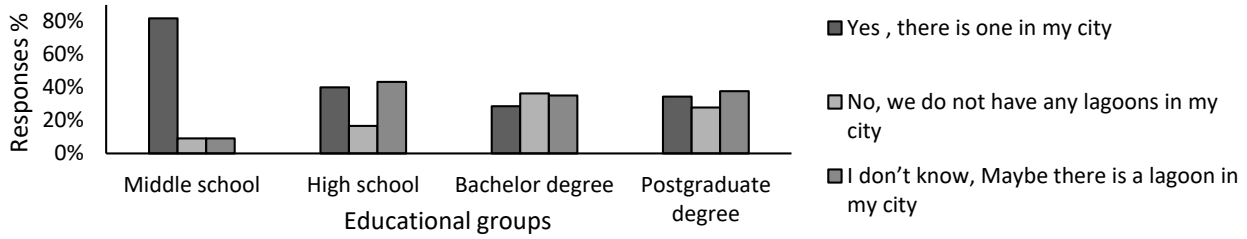


Figure 3.10. The survey question “Are you aware of any lagoons in your city?” responses divided by the different educational groups.

Regarding lagoon water source, WW, rainwater and TWW were mainly chosen with 22%, 21% and 19% respectively; this would have been seen in newspapers article where the water source is categorised using these terms (Al-oqedi, 2015, 2016; Al-shareq, 2015, 2019; Suliman, 2016; Nada, 2019; AbuNada, 2021). Moreover, 22% of respondent choosing WW indicates that people have concerns that lagoons contain untreated sewage and carries a possible health hazard. The Chi-square test showed that there was no relationship between the source of lagoon water selected and nationality or age but there was a relationship with education level ($p<0.05$) (Fig 3.11) with the middle school group selecting rainwater as the most common source, and postgraduates choosing all sources equally.

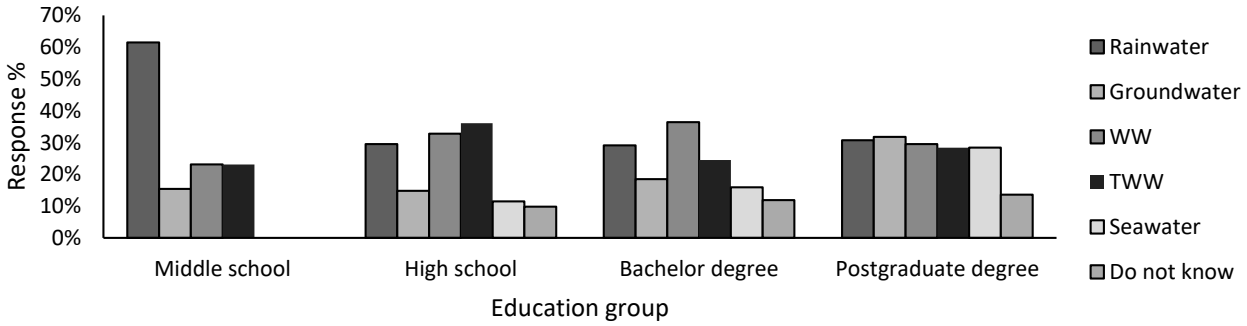


Figure 3.11. The survey question “Lagoon water source” responses divided by the different educational groups.

Ministry of municipality and environment (MME) was the most popular selection, with almost 66% of respondents naming this ministry as being responsible for lagoons management; Ashghal was the second most popular selection with only 18% of the selections. This shows that the public were largely unaware that Ashghal is the ministry responsible for managing water infrastructure and the disposal of TWW in the artificial lagoons; nationality and age did not affect the responses. However,

Figure 3.12 shows the influence of education on the response choices; middle school respondents were the group with the most accurate answer of ‘Ashghal’.

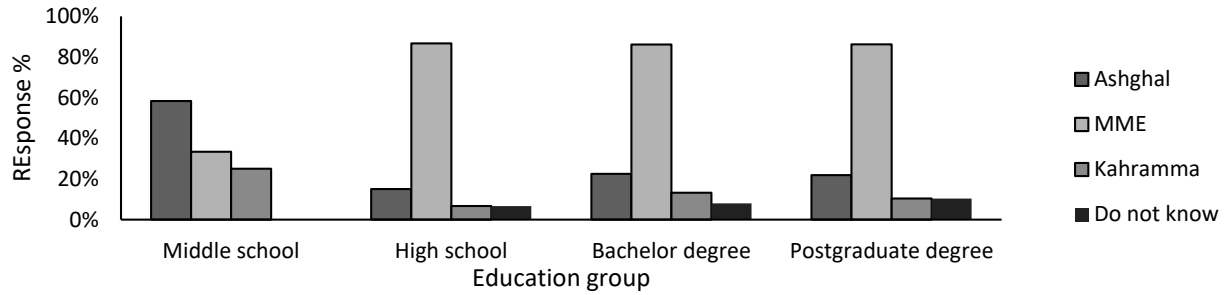


Figure 3.12. The survey question “Ministries responsible for lagoons management’’ responses divided by the different educational groups.

Using the Likert scale (Fig. 3.13), the public were asked if they perceive all lagoons as similar in nature and function; this was to investigate whether the public were aware of the variation in lagoon construction and water source. Most respondents disagreed with the statement that lagoons are ‘the same’ indicating they have some awareness of differences in lagoons’ structure and purpose; those responses were not impacted by nationality, age or education.

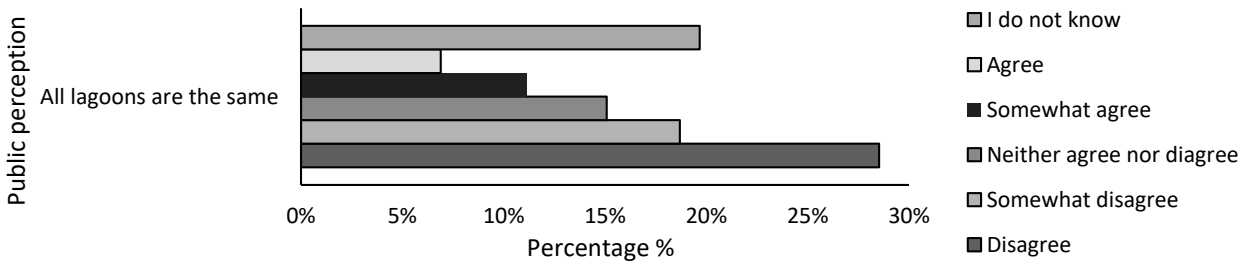


Figure 3.13. Survey Likert scale responses for the survey question “all lagoons are the same?’’.

In conclusion, respondents with middle school education had more knowledge about the existence and locations of lagoons, and the ministry responsible for lagoons. This has not been reported before in the literature (Alhumoud *et al.*, 2010; Muqeem, 2016; Zhu *et al.*, 2018; Mu’azu *et al.*, 2020).

3.3.1.3 Public attitude toward lagoon health and safety risks.

This highest number of responses were in agreement on the importance of security mitigation measures around lagoons (Fig 3.14), indicating the public view that there are risks associated with having lagoons around Qatar. In the local media the public has voiced their concerns over the drowning hazard and the presence of dangerous animals (Al-oqedi, 2016; Suliman, 2016; Nada, 2019).

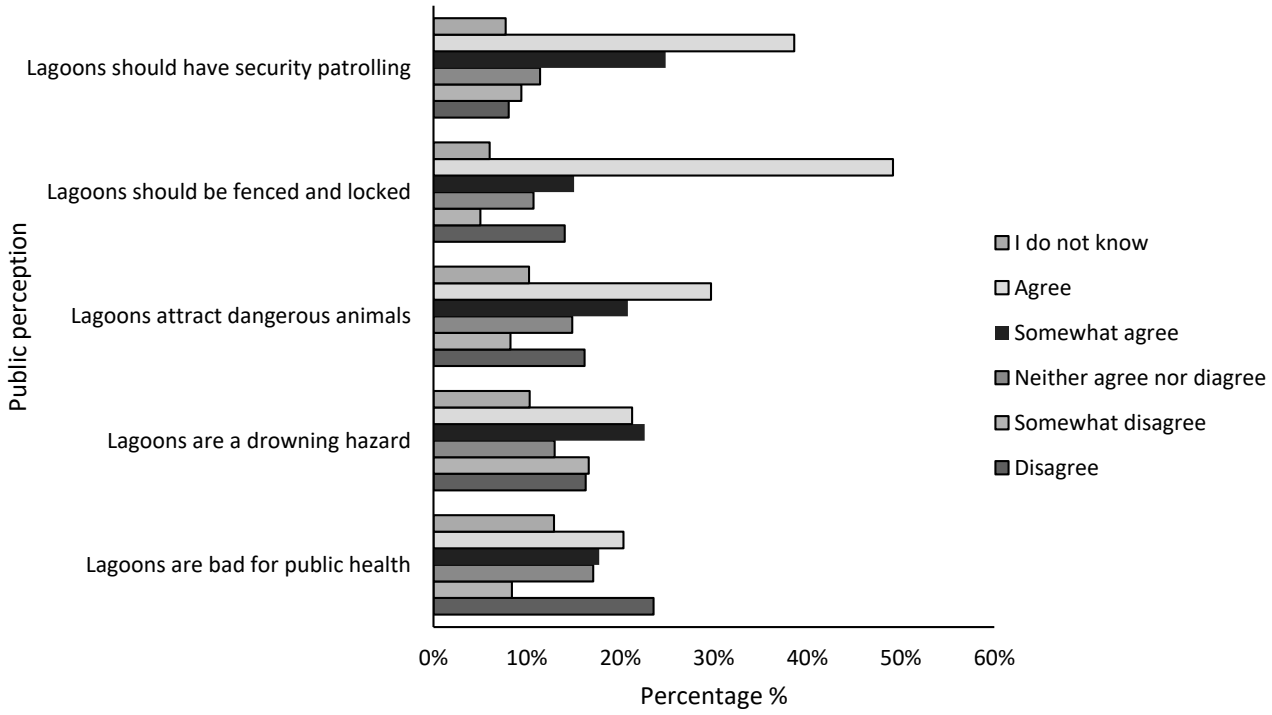


Figure 3.14. Survey Likert scale responses for the survey questions related topublic attitude toward lagoons health and safety risks.

Looking at the survey response, this is revealed by the majority (more than 50%) who "agree'' or "somewhat agree'' with all existing lagoon risk and mitigation measures (Fig 3.14). Thus, in the survey's comments section the risk of dangerous animals was mentioned four times - e.g. (i) *"Lagoons are beautiful to have in our country but the government should check it every month to be sure that it doesn't hold dangerous creatures"* and (ii) *"Stagnant lagoon water may host mosquitoes which may spread vector-borne diseases"*

On the other hand, when asked if the lagoons are bad for public health there was an equal percentage of respondents choosing "agree" and "somewhat agree" as those selecting "disagree'' and "somewhat disagree". This could indicate that the public were not necessarily against the presence of lagoons but they expect a more strict management regime to protect the residents living in the same area as lagoons.

An examination of the respondents' demographic background suggested that nationality had a significant influence ($p<0.05$) on their perception of lagoon safety risks from dangerous animals, drowning hazards and general safety (Table 3.5).

Table 3.5. Chi-square showing the relationship between survey questions related to public attitude toward lagoon safety responses and independent demographic variables.

Question (dependent)	Independent variables	Mean Square	DF	Sig.
Lagoons should have security patrolling	**Nationality**	15.47	10	0.116
	Age	20.997	25	0.693
	Education	27.53	20	0.121
Lagoons should be fenced and locked	**Nationality**	16.39	10	0.089
	Age	30.70	25	0.199
	Education	58.71	20	0.261
Lagoons attract dangerous animals	**Nationality**	25.56	10	0.004
	Age	26.00	25	0.407
	Education	32.15	20	0.042
Lagoons are a drowning hazard	**Nationality**	24.03	10	0.004
	Age	26.594	25	0.376
	Education	22.45	20	0.322
Lagoons are bad for public health	**Nationality**	15.47	10	0.116
	Age	20.99	25	0.693
	Education	27.52	20	0.121
Public attitude toward lagoons' health and safety risks	**Nationality**	20.488	10	0.025
	Age	28.13	25	0.302
	Education	47.41	20	0.001
	Have you heard about lagoons before	19.87	5	0.001

Figures 3.15, 3.16 and 3.17 illustrate that the Qatari population agreed highly (60%) with lagoons having a safety risk, in contrast with non-Qataris' response of 40%. This could indicate that non-Qataris have greater acceptance of lagoons, either because of cultural differences or their positive exposure to lagoons in their own country. However, this statement cannot be conclusive since some non-Qataris are born and raised in Qatar.

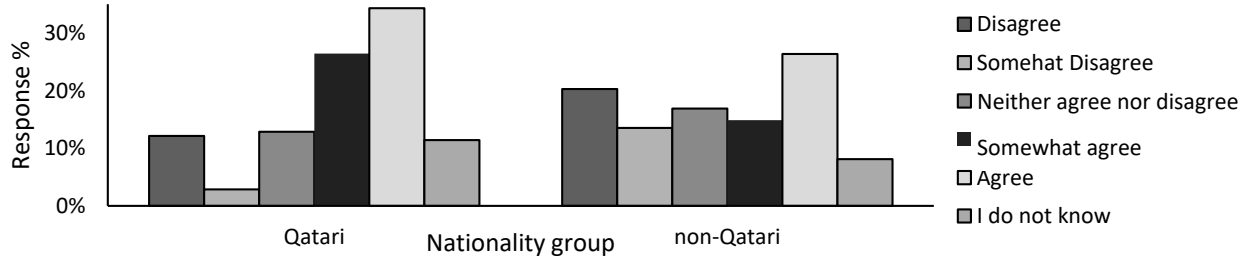


Figure 3.15. The survey question "Lagoons attract dangerous animals'' responses divided by the different nationality groups.

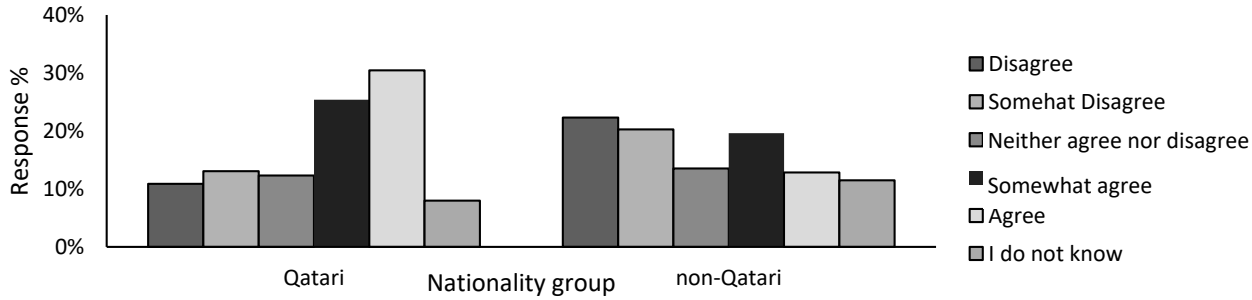


Figure 3.16. The survey question "Lagoons are a drowning hazard'' responses divided by the different nationality groups.

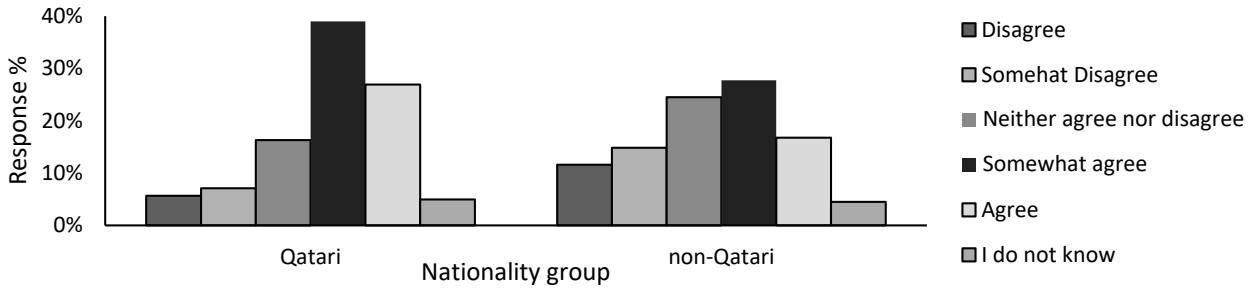


Figure 3.17. The survey question related to public attitude toward lagoon health and safety risks divided by the different nationality groups.

In addition, exploring the relationship between education level and safety risk perception (Fig 3.18) it is clear that middle school responses differed from the other classifications as they were the only group in which 50% disagreed with the premise that lagoons are a safety hazard and require mitigation measures. All the other groups showed greater agreement (more than 25%) and much lower disagreements (less than 15%).

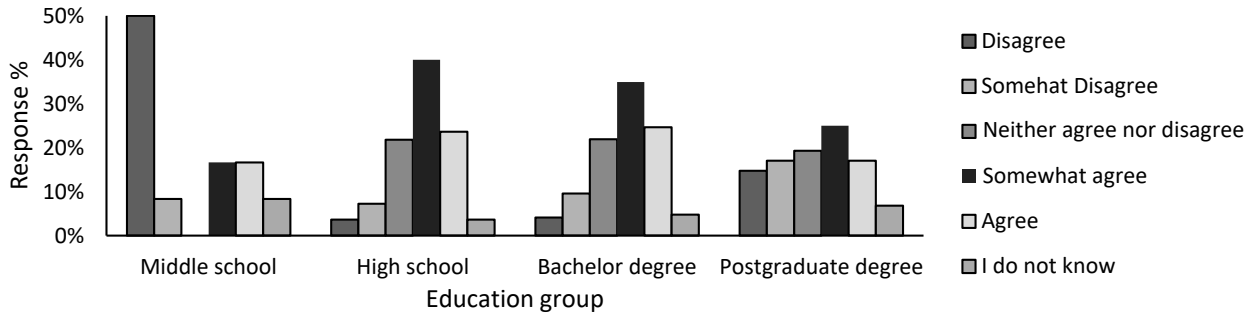


Figure 3.18. The survey question related to public attitude toward lagoons' health and safety risks divided by the different education groups.

These results are important since the public acceptability of lagoons rendered any discussion a taboo topic in the local news and research. Understanding public expectations of mitigation measures may lead to better acceptance by the public of lagoons and water reuse practices and may help Ashghal to understand how to convert lagoons into a healthier environment.

3.3.1.4 Public Attitude toward lagoons benefits

Considering Ashghal's plans to convert lagoons into public leisure places, it is important to understand the public's knowledge of the lagoons and their degree of willingness to visit and engage with the lagoons (Al-shareq, 2019).

Of all the respondents, 39% showed interest in visiting lagoons, while 20% did not wish to visit lagoons, indicating a major inconsistency in public opinion (Fig 3.19). Moreover, 40% disagreed with the premise that the lagoons were a good place for bird hunting or bird watching.

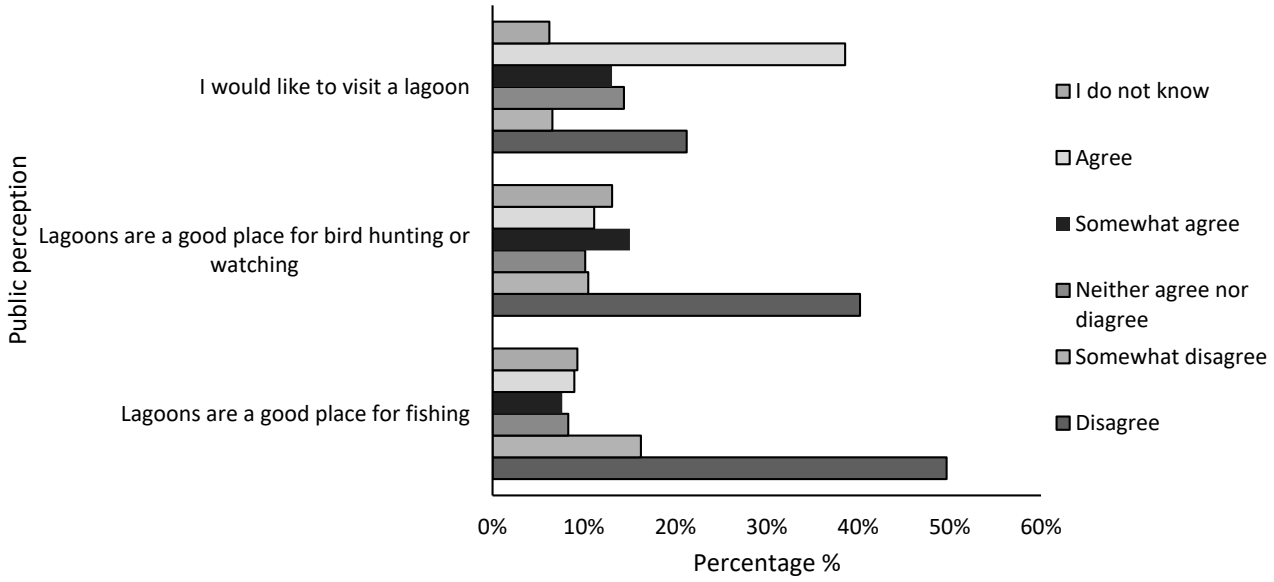


Figure 3.19. Survey Likert scale responses for survey questions related to public attitude toward lagoons' benefits.

These results indicate that the public were still unwilling to regard the lagoons as a venue for leisure activities, which could be due to their reservations regarding lagoon safety as discussed in Section (3.3.1.3). An example of this was seen in the survey comment section with one comment stating: *"Lagoons are beautiful to have in our country but the government should check it every month to be sure that it doesn't hold dangerous creatures"*

However, a few comments showed interest in lagoons, for example: *"Lagoons enrich biodiversity, keep them"* and *"They could be highly useful for environmental restoration and erosion".* These quotations show the dichotomous nature of public willingness to regard lagoons as recreational and environmental assets.

During a field visit to the lagoons fishing activities were observed, but the Ashghal ministry has stated that they consider this an illegal activity, since the fish quality is questionable (Aljabiry, 2019). For this reason, questions about fishing activities were included in the survey; 68% of respondents disagreed and somewhat disagreed that lagoons were a good place for fishing, whereas 18% agreed and somewhat agreed. This could reassure the ministries that illegal fishing is perceived negatively by the public.

There was no relationship between respondents' demographic characteristics and their views on the possible benefits of lagoons, in contrast to previous sections (Table 3.6).

Table. 3.6. Chi-square showing the relationship between the survey questions related to public attitudes toward lagoons benefits Qatar and the demographic independent variables.

Question (dependent)	Independent variables	Mean Square	DF	Sig.
lagoons are a good place for fishing	**Nationality**	11.29	10	0.337
	Age	22.83	25	0.587
	Education	23.18	20	0.280
lagoons are a good place for bird hunting	**Nationality**	17.65	10	0.061
	Age	37.19	25	0.055
	Education	32.96	20	0.340
I would like to visit a lagoon	**Nationality**	20.43	10	0.250
	Age	42.37	25	0.160
	Education	24.595	20	0.217
public attitude toward lagoons benefits	**Nationality**	19.18	10	0.138
	Age	30.97	25	0.190
	Education	34.89	20	0.221
	have you heard about lagoons before	4.96	5	0.420

3.3.1.5 Public desire to be involved in the management decisions around lagoons

Previous studies have shown that public involvement in decision making on water management matters is likely to aid policymakers in successfully implementing future TWW reuse or leisure lagoons programs (Chen *et al.*, 2015; Alves *et al.*, 2018; Lemée *et al.*, 2018). Here the public desire to be involved in the management decisions around lagoons was shown in a Likert scale. The majority of respondents (75%) agreed that the public should be informed about lagoon water sources and 72% felt that the public should know about lagoons located near them; 50% agreed when asked if they did not want to live next to a lagoon (Fig 3.20).

In addition, in the comments section many respondents asked to be informed more about the benefits and possible harmful impacts or effects of lagoons, indicating their wish to be generally better informed on lagoons matters – e.g. quotation: *"Lagoon in my country not treated well it can be more productive if there are good plans and management"*

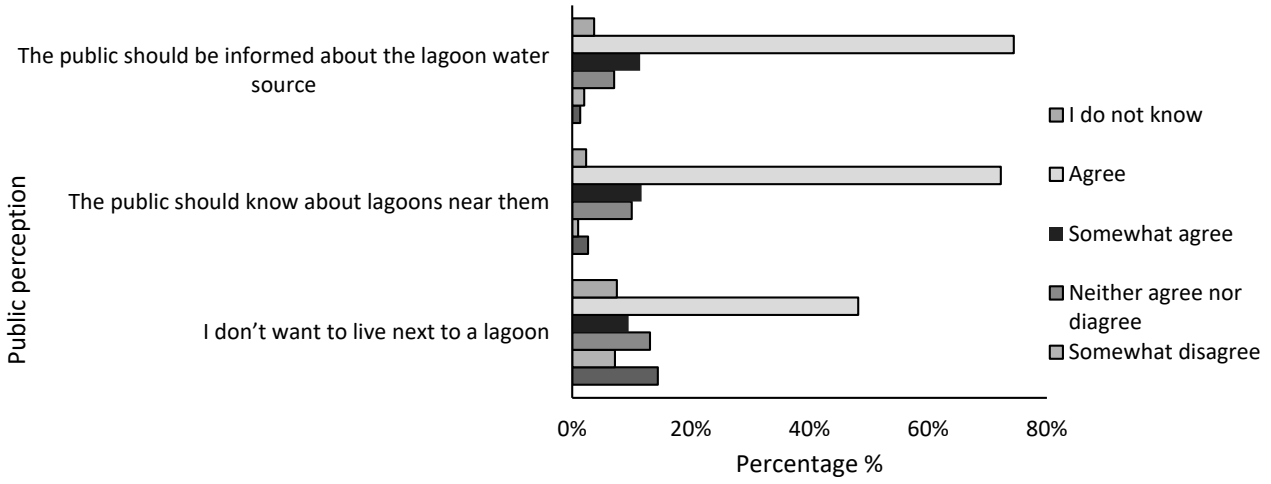


Figure 3.20. Survey Likert scale responses for the survey questions related to "Public desire to be involved in the management decisions around lagoons".

The public desire to be involved in management was significantly ($p<0.005$) influenced by education, but not by age or nationality (Table 3.7). Figures 3.21 and 3.22 show that respondents with a middle school educational level expressed a different perception of the need for public involvement, with only 27% in favour, while the other educational classes agreed from 65% to 88%.

This again shows that respondents with the lowest education level had a different perception about lagoons in Qatar compared to respondents with a higher educational qualification. This is consistent with previous studies about the influence of education on public involvement (Zhu *et al.*, 2018; Deh-Haghi *et al.*, 2020).

Table. 3.7. Chi-square showing the relationship between the survey questiond related to public desires to be involved in the management decisions around lagoons and the demographic independent variables.

Question (dependent)	Independent variables	Mean Square	DF	Sig.
I don't want to live next to a lagoon	**Nationality**	10.948	10	0.362
	Age	21.86	25	0.643
	Education	16.08	20	0.712
The public should be informed about the lagoons near them	**Nationality**	9.25	10	0.530
	Age	33.40	25	0.121
	Education	76.14	20	0.001
The public should be informed about the lagoon water source	**Nationality**	8.335	10	0.596
	Age	47.74	25	0.057
	Education	43.46	20	0.011
Public desire to be involved in the management decisions	**Nationality**	21.6	10	0.017
	Age	37.64	25	0.082
	Education	41.63	20	0.003
	have you heard about lagoons before	14.48	5	0.013

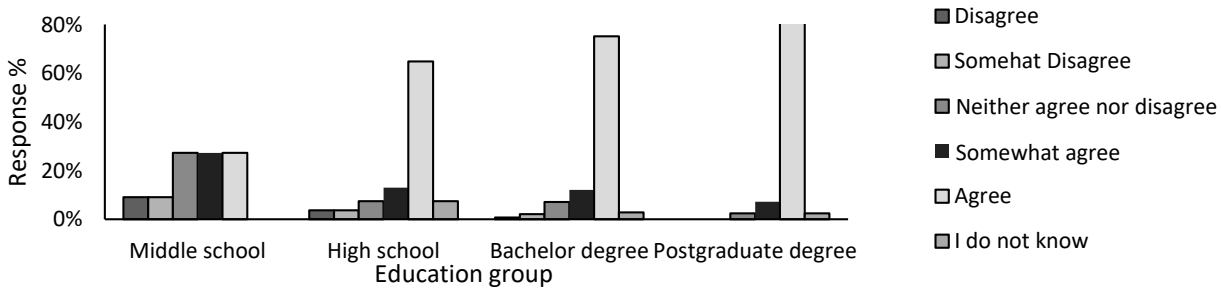


Figure 3.21. The survey question "Lagoon water source" responses divided by the different education groups.

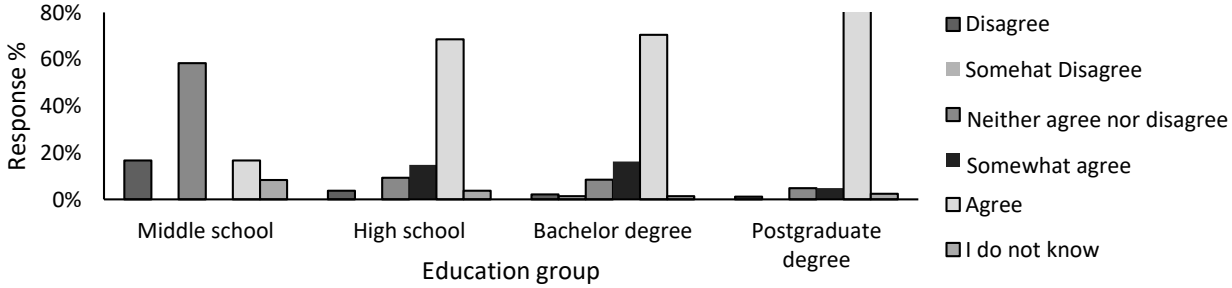


Figure 3.22. The survey question related "Public should know about lagoons near them" responses divided by the different education groups.

3.3.1.6 Public attitude toward TWW reuse

The main cause of the flooding of TWW being stored in lagoons is the limited current reuse options and practices in Qatar (MDPS, 2019). This was reported in a study done in 2004 as being due to the combined effects of culture, psychological aspects and religious constraints where the public have the impression that the water is ‘’dirty’’ (Al-Mohannadi, 2004). However, the current research results suggest that the public may be more willing to accept TWW reuse now: 64% “agreed and somewhat agreed” that TWW should be used for further reuse options and less than 16% “disagreed and somewhat disagreed” on that (Fig 3.23). Comparing these results to other studies done in the Gulf Region this is broadly the same acceptability rate as Saudi Arabia, Kuwait, Oman and UAE which all have a reuse acceptance rate between 55% and 70% for non-potable reuse options (Alhumoud *et al.*, 2010; Abdelrahman *et al.*, 2020; Baawain *et al.*, 2020; Mu’azu *et al.*, 2020)

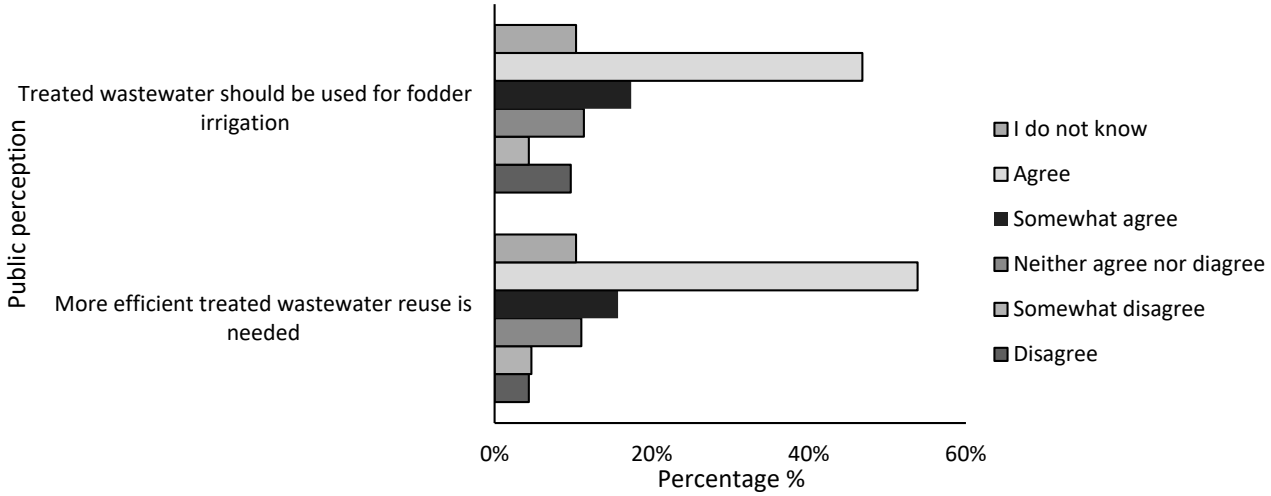


Figure 3.23. Survey Likert scale responses for the survey questions related to public attitude toward TWW reuse.

Moreover, one of Qatar's national development strategies is to have more efficient TWW reuse (MDPS, 2019). When this was raised in the survey, 69% “agreed and somewhat agreed” that there should be efficient TWW reuse and less than 5% and 9% “disagreed and somewhat disagreed”.

This illustrates the public’s willingness to integrate TWW into urban water management, which is contrary to previous studies showing public resistance to accepting TWW for future water management (Al-Mohannadi, 2004; Darwish *et al.*, 2013; FAO *et al.*, 2016). This could be seen in the survey comments section, where reuse was suggested for lagoon water: e.g. (i) “*believe more should be done in the artificial waterways to establish plant life”* and (ii) “*more reuse options should be implemented like using greywater that is seen in the UK*”

Additionally, a chi-square test was done to assess how demographic background, and current knowledge about lagoons, influenced the reuse perceptions of respondents (Table 3.8). It was

observed that only the level of education impacted the perception of the need for more efficient TWW reuse: a higher level of education was associated with greater acceptance of the need for reuse (Fig 3.24). Education has been seen in other studies to influence the acceptability of non-conventional water reuse, where people with higher education were more understanding of the need for reuse practices (Alhumoud *et al.*, 2010; Garcia-Cuerva *et al.*, 2016; Zhu *et al.*, 2018; Michetti *et al.*, 2019)

Table 3.8. Chi-square test showing the relationship between the survey questions related to public attitude toward TWW reuse and independent demographic variables.

Question (dependent)	Independent variables	Mean square	DF	Sig.
More efficient treated wastewater reuse is needed	**Nationality**	17.78	10	0.060
	Age	20.85	25	0.701
	Education	30.93	20	0.046
Treated wastewater should be used for fodder irrigation	**Nationality**	8.55	10	0.575
	Age	35.29	25	0.083
	Education	17.56	20	0.616
Public attitude toward treated wastewater reuse	**Nationality**	12.94	10	0.227
	Age	23.39	25	0.554
	Education	28.16	20	0.105
	Previous knowledge about lagoons	14.63	5	0.012
	lagoon water type	47.56	30	0.220

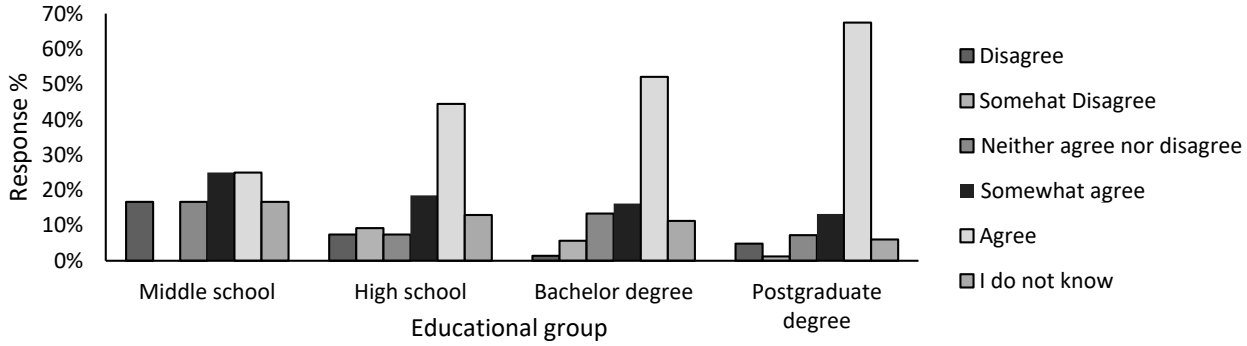


Figure 3.24. The survey question "More efficient treated wastewater reuse is needed" responses divided by the different educational groups.

The general public's perception of TWW reuse was also influenced by previous knowledge of the lagoons' existence. Figure 3.25 shows that respondents who had heard about the lagoons more readily agreed (55%) with TWW reuse, while only 45% of respondents who were unaware of the lagoons agreed with reuse and 17% answered that they do not know. This could show that educating the public about the flooding of TWW and lagoons in Qatar could increase public willingness for TWW reuse.

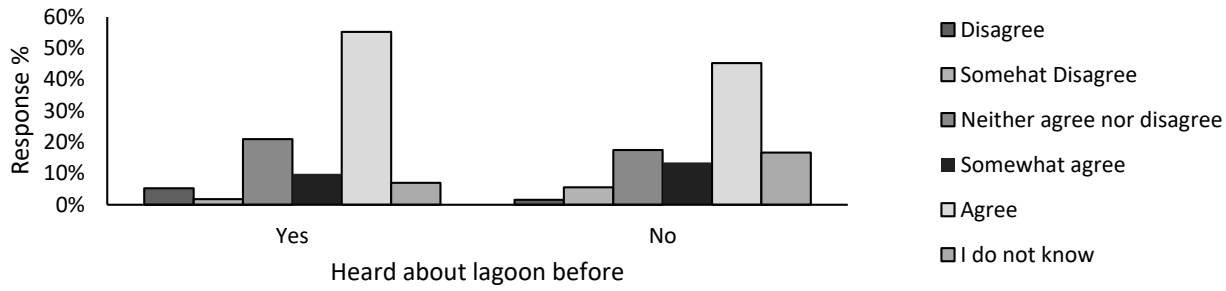


Figure 3.25. The survey question "Public attitude toward treated wastewater reuse'' responses divided by the public's previous knowledge of lagoons' existence.

3.3.2 Policymakers perception of lagoons current situation and management

Policymakers in the various ministries dealing with water management in Qatar were interviewed to document and analyse their perception of lagoons – specifically, their current situation, management practices, opinions about public perceptions and their current understanding of groundwater quality. Moreover, undocumented information about lagoons and groundwater in Qatar were also gathered and reported in this section.

A total of 12 interviews were conducted in the year 2021; all the interviews were done through either Zoom or MS Teams, because of the Covid restrictions. This was the preferred method for all interviewees. The goal was to conduct interviews with all the ministries dealing with lagoon and groundwater in Qatar. However, for the ministry responsible for groundwater quality, approval was not granted. For the other ministries, researchers working in the university and oil and gas sectors were all interviewed after getting their head of department approval.

After transcription of the interviews thematic codes were chosen based on the study objective:

- **Lagoon:**
  - Lagoons water source
  - Lagoon construction
  - Lagoons quantity
  - Lagoon impact
  - TWW reuse

- **Groundwater:**
  - Groundwater quality
  - Lagoon impact on groundwater
  - Recommendations to protect groundwater from lagoons

- **Public:**
  - Public perception of lagoons
  - Public involvement
  - Public survey

On the other hand, during the coding process other thematic codes emerged that were also relevant to the study objectives:

- Lagoons Monitor
- Lagoons examples
- Treatment plants
- Qatar geology and infrastructure
- Policymakers interest
- Public complaining
- Recommendation for water management
- New technology

Some of those thematic codes were used as this section's headings, to discuss the policy maker's interview interpretation, the rest will be discussed within each subsection.

3.3.2.1 Policymakers background information

All the policymakers interviewed stated that they work in the field of water management in Qatar, their duties ranged from compliance assurance, treatment plant management, issuing lagoon permissions and research about TWW or groundwater. When asked about dealing with lagoons, seven interviewees stated that they dealt with lagoons in their daily work duties, four said they were not directly involved with lagoons but they dealt with WW compliances or environmental projects where they could encounter lagoons. Only one stated that they only work with environmental compliances related to water quality, but they were aware of lagoons through their work. Thus, the majority of policymakers in the water management field had either directly dealt with, or encountered, lagoons.

3.3.2.2 Policymakers general knowledge about lagoons in Qatar

Policymakers' knowledge and understanding of the current lagoon situation, processes and responsible stakeholders has been the focus of studies dealing with enhancing wetland management (Steyaert *et al.*, 2007; Cools *et al.*, 2013; Johnston *et al.*, 2013). This section will discuss the policy maker's awareness of the current lagoons' situation, understanding of groundwater quality and their interest regarding lagoons, groundwater and the overall Qatar water system.

Locations

Lagoon locations were investigated in interviews but were mentioned by several interviewees as examples of current lagoons in Qatar. One lagoon that was mentioned eight times was the Abu-Nakhla lagoon, which is probably the subject of most complaints by the public in local newspapers (Al-shareq, 2015; Suliman, 2016; Nada, 2019; AbuNada, 2021). It is worth mentioning that this lagoon was announced to be dried up by Ashghal and, during four field visits by the author it was

found to be completely dry. However, a recent satellite image of the lagoon shows that it had water (Fig 3.26), but is not filled to the capacity seen before the announcement that it was dry in the year 2014 (Al-shareq, 2014). In the interviews, three stated that the lagoon is dried up and moved to other locations, while the rest believed the lagoon is still working at full capacity.

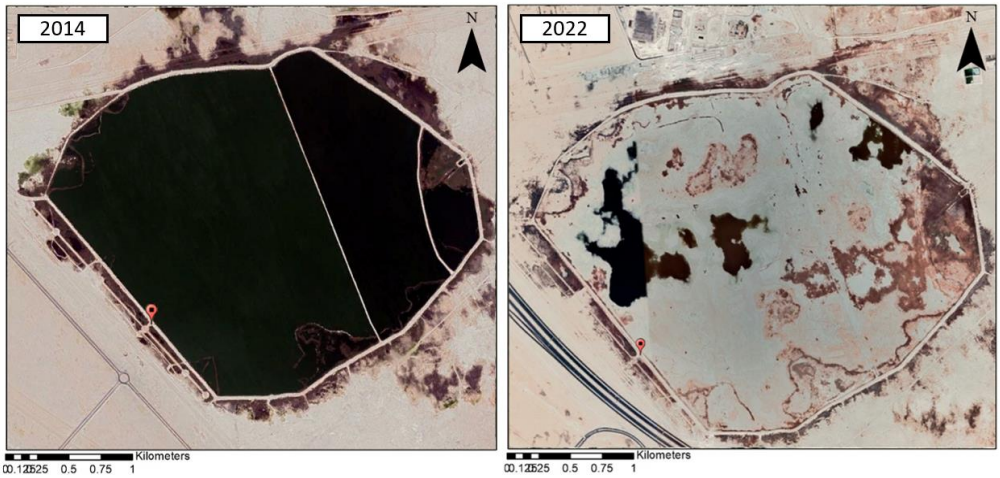


Figure 3.26. Abu Nakhla lagoon, satellite image taken in the year 2014 (left) and 2022 (right)

Another lagoon mentioned three times was the Al-Karanna lagoon (Fig 3.27), where it was stated that a huge transformation project had been undertaken to convert it to a clean water body open to the public for leisure activities (Al-shareq, 2019). Other lagoons mentioned were the North Doha lagoon adjacent to the north treatment plant and an industrial area lagoon that received mostly surface water.

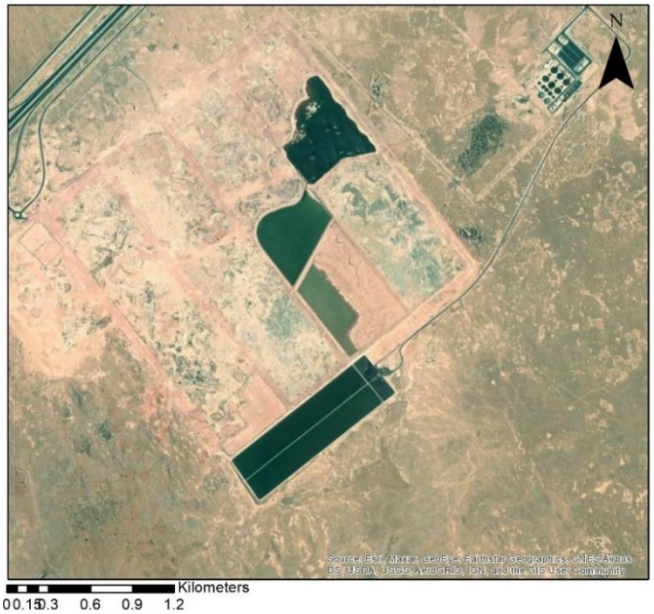


Figure 3.27. Al-Karanna lagoon, satellite image taken on 14th August 2021.

Number

Interviewees were asked to estimate the number of lagoons in Qatar to understand if they were aware of all the lagoons in Qatar or only the ones shared with the public in the local news. Eight of them answered with non-committal statements such as "*I don't have records for the number of lagoons but there are many*" showing their knowledge of the many lagoons scattered around Qatar even though the actual number is unknown. A few respondents suggested that there were 2, 3 or 4 lagoons but all stated there could be more of which they were not aware.

Moreover, while the lagoons are the responsibility of Ashghal it was stated that not all lagoons are managed by them since some of them are from improper disposal of WW, described as (e.g.) *"people with low awareness dumping waste in an improper way"*

The illegal or unmanaged dumping in established lagoons or to produce a new lagoon has been reported in several countries dealing with wetlands, where stakeholder perception studies have shown that they were aware of the issue (Dalahmeh *et al.*, 2009; Clare *et al.*, 2011), but they do not have the power to investigate those responsible or stop this happening; this is also seen in Qatar.

Water source

Five water sources were mentioned in the interviews: TWW, WW, groundwater, surface water and seawater. Figure 3.28 illustrates that TWW was chosen as the lagoon source 11 times, where it was believed that the purpose of lagoons in Qatar was to dispose of surplus TWW from treatment plants. Surface water and WW were mentioned five times, in both cases, it was suggested that the water does not get reused but is left to evaporate with time. Lagoons are also used for emergencies when, for example, projects require storage for WW or need to dewater surface water.

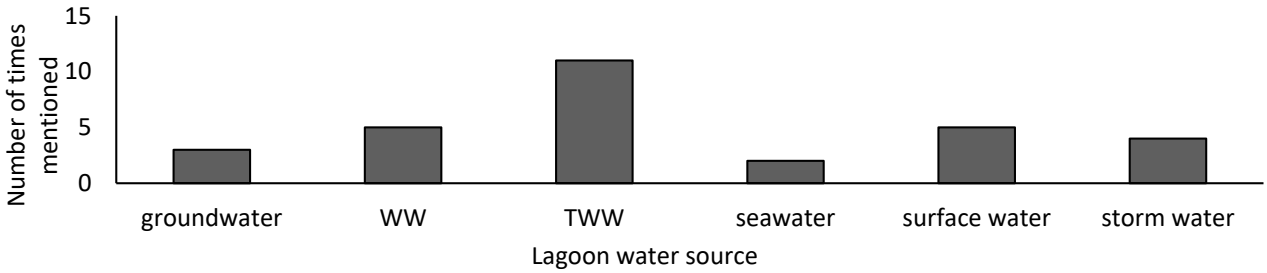


Figure 3.28. Interviews responses on the lagoon water source, showing the water source and number of times it was mentioned.

Storm water was mentioned, when policymakers believed that lagoons are to store water after heavy rainfall events, and seawater was mentioned when discussing lagoons near the coast (Al-Khore and Al-Dhukhariah lagoons); seawater intrusion to the lagoons is mixed with TWW.

Groundwater was mentioned only three times. However, on those occasions the groundwater was thought to be of poor quality, which is why it was dumped in a lagoon and not used for irrigating – e.g. quotation: "*groundwater always contains insects and residues*". This shows some policymakers were unaware of the difference between surface water and groundwater, they perceive groundwater as contaminated and a nuisance water source. Furthermore, they described three groundwater aquifers in Qatar: one was near the surface causing lagoons issues; the second is a deeper aquifer used in agriculture; the third is very deep and is a high salinity aquifer. In fact, the last two aquifers are as described but the superficial aquifer is surface water being oversaturated by network pipeline leakage and lagoon water seepage.

Lagoon construction

All the interviewees understood that the lagoons were not lined, and some stated that lagoons had formed in natural depressions in places far away from the cities. Some also specified the need for the lagoons to be more highly engineered to enable the water to mostly evaporate without impacting the groundwater.

Responsible ministry

Seven interviewees said Ashghal was the responsible ministry for lagoon management; three regarded MME as jointly responsible while one thought MME was solely responsible; two interviewees believed that Kahramaa was in charge of lagoons. This illustrates that while most policymakers in the Qatari ministries understand that Ashghal is the ministry responsible for lagoon management in Qatar, not all were aware of that. In addition, Kahramaa was also mentioned twice when discussing groundwater quality, which shows that they also understand which ministry is responsible for groundwater quality.

3.3.2.3 Policymakers perception of lagoon impact on the environment

During the interviews policymakers were asked about their opinions on lagoon impact on groundwater; responses varied between (i) negative only, (ii) positive only or (iii) both.

Negative impact

Only two respondents regarded the impact as negative only, where the lagoon was of questionable quality and was thought to pollute groundwater as well. In such circumstances, the lagoon is a nuisance to residents living in the same area, because of the bad smell and mosquitos it produces and the raised surface water table causing small ponds around houses with the consequent danger of drowning.

Positive impact

Three interviewees' respondents suggested the impact was only positive, stating that lagoon water is of high quality and is used to improve groundwater quality when it is allowed to infiltrate the aquifers. Also, the lagoons are regarded as an ecosystem for migrating birds and for people to visit and enjoy, mentioning the Al-Karanna lagoon as an example.

Both negative and positive impacts

The majority of interviewees believed lagoons have both positive and negative impacts, determined by the lagoon water source, location and construction style. An interviewee responsible for lagoon monitoring stated that initially the impact was negative but after a restoration programme that included inputting only high-quality TWW the impact become positive. Eventually, they suggested this will be applied to all the lagoons in Qatar. The other respondents felt that the impact was positive if the lagoon was far from residential areas and can be used for recreational purposes, but negative if situated close to residential areas because of the drowning, insect and rodent risk to the residents. Moreover, it was noted that if the lagoon is lined then the groundwater is protected but if not lined then the TWW will infiltrate and contaminate the groundwater. Unlined lagoons will also cause the surrounding surface area to be saturated with water raising the water table and causing a problem for infrastructure and small ponds to form in residential areas causing mosquitos and odour issues.

Most policymakers' understood the dual impact of lagoons, with the majority agreeing that with proper management lagoons could be transformed into a healthy ecosystem without the negative impact on the groundwater and the public. This understanding is shown to be an integral part of wetland management (Wattage *et al.*, 2005; Clare *et al.*, 2011).

3.3.2.4 Policymakers perceptions of public opinion and involvement with lagoon management

Policymakers were asked about public opinion and involvement in lagoon management and TWW reuse practices; they were also asked if they agree with involving the public in the future, including surveys to ask about their current perceptions.

Policymakers opinions on the current public perception of lagoons

The majority thought that the public were not happy about the current state of lagoons because of their perception of TWW as 'dirty water'. Moreover, they also felt that lagoons have caused public dissatisfaction because of mosquitos, odour, ground saturation and drowning hazards. Thus it is evident that policymakers were aware of all the public complaints.

Policymakers opinions on involving the public in decision-making regarding lagoon management.

The majority stated they think the public were not involved (nine out of twelve), while three maintained that if the public complained about a lagoon then the ministries would address their concerns and change circumstances accordingly – e.g. quotation: *"Complaints about Lagoons are heard".* This appears to indicate that public 'involvement' is manifested only through complaints to authority.

In addition, all the interviewees agreed that there should be greater effort to involve the public in lagoon management. It was thought that this would make the public more willing to accept lagoons and water reuse practices in Qatar, as they would be likely to feel that they had some power over the management practices.

In terms of surveying the public, the majority agreed it would be helpful to survey the public for awareness, as well as to use their feedback and integrate it into future lagoon management. However, only two stated that the public is not sufficiently aware of the issues to be surveyed, and the survey could cause unhelpful opinions to be reported. There was also the suggestion that only educated people should be interviewed in order to obtain more meaningful and informed opinions.

3.3.2.5 Policymakers opinions about TWW reuse

All the interviewees agreed strongly on the need for more reuse practices for lagoon water. However, their individual recommendations for reuse options were different. Four thought that the lagoon water is of high quality and should be used for groundwater recharge either by direct injection or infiltration since groundwater is of relatively lower quality having been contaminated with seawater. The remaining interviewees disagreed on groundwater recharge because of the need to protect the Qatar aquifers and, instead, suggested using lagoon water for fodder and landscape irrigation, industrial cooling, and recreational lined lagoons for migrating birds and human entertainment. This shows that there were markedly contrasting beliefs, and available information, regarding the need to protect groundwater resources and the best management strategies to adopt.

3.3.2.6 Policymakers recommendations regarding lagoon and general water management

Policymakers' contrasting interests were evident in the interviews. Their primary interests were either the need for groundwater to be protected, or that lagoon water should be of higher quality so that it could be used to improve the groundwater. Six interviewees focussed on the importance of groundwater protection and felt that lagoon infiltration should be stopped, even if the TWW was of higher quality since pollutants accumulate with time. In contrast, four stated that TWW is of a higher quality than groundwater and so infiltration would improve the Qatar aquifers; thus water should be

injected into groundwater aquifers to stop the marine intrusion and for future water storage. Moreover, two interviewees stated that TWW quality cannot affect the groundwater considering the Qatar lithology, which includes a rocky and impermeable layer, so lagoon water infiltration is impossible. This shows contradicting views and misinformation concerning Qatar's lithology and the natural water cycle, indicating that Qatar needs to ensure policymakers impacting lagoon management decisions need to be working on the same agenda. Stakeholders having the same interests and objectives was shown to be of high importance in previous literature (Opio, 2008; Romanelli *et al.*, 2011; Jenkins, 2021), and its application in the Qatar context would aid the understanding and protection of the whole Qatar water cycle, including the protection of groundwater and better exploitation of lagoon water.

When broader environmental issues were discussed three interviewees discussed new technologies for TWW improvement and whether Qatar is using the latest technology to manage the water cycle – e.g. quotation: "I think all the new improved technology we were bringing it to Qatar". This is also evident in previous stakeholder studies that have shown when environmental issues arise the policymakers tend to seek new remedial technologies to solve the problematic symptoms rather than tackling the problem from its roots (Clare *et al.*, 2011; Gardezi *et al.*, 2020).

Finally, although a few interviewees mentioned illegal lagoons, only one discussed law and policy enforcement, which should be an integral part of successful environmental protection and management strategies (Opio, 2008; Clare *et al.*, 2011)

3.3.3 Linking public and policy makers' perceptions

Policymakers were more knowledgeable than the public about the current lagoon situation and the ministries responsible for lagoon management. However, the policy makers' views about public perception did not match the results from the public survey. The policymakers thought that the public were either unaware of the lagoon situation or their views were entirely negative. Moreover, the policymakers felt that the public were not in favour of TWW use and they will not accept it. However, in the survey, the public agreed with the importance of using TWW for a range of irrigation reuse practices.

On the other hand, policymakers believed that the lagoons could be converted into a recreational facility that could attract the public; this was confirmed by the fact that the public showed curiosity and a desire to visit lagoons.

Concluding, both the public survey and policymaker interviews were important to clarify which aspects of the lagoon management need to be changed or improved. Also, participation of both

public and policymakers clearly enriches the management's capacity to respond to public needs and demands (Herath, 2004; Clare *et al.*, 2011).

3.4 Conclusions

In general, knowledge about the public perception about lagoon, and policymakers views regarding lagoon and lagoon management was acquired in this chapter, that has never been reported in Qatar and globally before.

The demographic characteristics of the survey respondents matched the general Qatar population as well as respondents from other perception studies undertaken in Qatar. Participants in the survey shared their desire to have more knowledge about lagoon locations, water sources, benefits and safety risks.

Respondents with middle school education had more knowledge about the lagoons' current situation and management, which is contrary to other literature stating that higher educational qualifications were associated with more knowledge in the public domain about the current water management systems. However, middle schools were less inclined to encourage the involvement of the public in the future management of lagoons. This is in alignment with previous literature about education and public involvement. In addition, the public were shown to have knowledge about the benefits and hazards of lagoons in Qatar. Also, not all the public were interested in visiting lagoons for leisure activities, and the majority of public agreed on future public involvement in lagoon management.

TWW and lagoon water reuse was encouraged by the survey responses and also suggested in the survey comment section. This indicates that Qatar could integrate this public acceptance into publicising and expanding its TWW reuse programmes.

Knowledge about lagoons was shared between policymakers in Qatar, in terms of lagoons number and lagoon respoinsbile ministry. However, policymakers gave varying answers regarding lagoon water source and different perspectives on lagoon impact on the groundwater and the environment: some believe lagoon had a negative impact, others positive, with a few agreeing that there were both negative and positive impacts.

Policymakers were keen to involve public opinions and needs in the management of lagoons, and they agreed on the need to survey the public to spread awareness and then integrate their perceptions into the water management in Qatar. However, the policymakers believed the public are not aware of importance of TWW reuse, thinking the public are gainst it. While, the public survey showed the opposite. In addition, the policymakers converting lagoons to leisure places for public without knowing the public are still hesitant on vising lagoons as what the survey showed

Moreover, policymakers' interest in which aspect of the water cycle to be protected should be clarified and agreed, to enable Ministries to be able to work together on the protection and restoration of groundwater and better utilization of lagoon water.

Finally, data collected from this survey could contribute to the development of a holistic approach to understanding using artificial lagoons as a final step for WW treatment and their impact on groundwater aquifers. Likewise, sustainable management of water resources in Qatar does not require only the newest technology to treat WW and manage lagoons, but also requires the inclusion of public opinion and policymakers' technical views, since they have a real impact on the water resources management in Qatar.

Chapter.4. HydroGeoChemical survey of lagoons and surrounding wells

4.1 Introduction

Globally groundwater is a valuable and fragile water source used mainly for drinking or agricultural uses. Groundwater aquifers have a long turnover time and so a global effort was put in place for their protection (U.S. EPA, 2017). In Qatar groundwater is used for farming activities; fodder and hay are irrigated during summer and a range of vegetables are grown in winter when the temperature is suitable for vegetables and fruits to grow (Kalra *et al.*, 2011; QGDP, 2016). While the main use of groundwater in Qatar is irrigation, in a few unreported cases groundwater is still used for human consumption (Aljabiry, 2019).

Few articles were found regarding the current Qatari groundwater quality. The existing research could be divided into two categories. First, there is research regarding the hydrochemical quality of the different aquifers in Qatar (Shamrukh, 2014b, 2014a; Kuiper *et al.*, 2015; Shomar, 2015; FAO *et al.*, 2016; Lachaal *et al.*, 2016; Al-Naimi *et al.*, 2018; Ahmad *et al.*, 2020). The second branch of research concerns the natural recharge rate from the rare rainfall events in Qatar, the locations of the recharge areas and how to improve recharge (Shamrukh, 2014a; Baalousha, 2016b, 2016a). The research has shown that the main issues facing Qatari groundwater include:

- overexploitation of groundwater by private farms (Darwish *et al.*, 2013; Shomar *et al.*, 2014; Mohieldeen *et al.*, 2019);
- groundwater salinization caused by seawater intrusion (Baalousha, 2016b; Al-Naimi *et al.*, 2018; PSA, 2018);
- insufficient natural recharge to maintain the groundwater quality (Vecchioli, 1976; Streetly *et al.*, 1998)
- high concentrations of molybdenum and boron in the aquifers from natural geological processes (Kuiper *et al.*, 2015; FAO *et al.*, 2016)

It is important to note that groundwater studies in Qatar usually were done with just one season's sampling. No research was found to show temporal variation in aquifers by sampling in summer with extreme heat and winter after rainfall events. Moreover, most of the studies focus on either recharge zones or the north aquifer in Qatar because it has less salinization and a higher recharge rate, thus being most affected by agricultural activities (Vecchioli, 1976; Streetly *et al.*, 1998; Elobaid, 2000; Sadiq *et al.*, 2002; Mamoon *et al.*, 2017; Al-Naimi *et al.*, 2018). Only one study was found to cover the majority of Qatar (Ahmad *et al.*, 2020). Therefore, this research will cover spatial and seasonal

variation, including sampling in summer and winter and sampling to cover the middle aquifer in Qatar, where the lagoons are located.

In addition, with an increasing number of municipal or industrial treatment plants, the impact of discharged water on the natural aquifers has been the concern of many researchers. However, research about TWW in Qatar and the impact of its disposal on groundwater aquifers has not been studied, nor mentioned in any published literature. In addition, the TWW and lagoon water quality in Qatar has not been studied. Only a few publications have mentioned the Abu-Nakhla lagoon (Tollenaere, 2015). However, this lagoon is not the main lagoon in Qatar anymore.

Since Qatar relies on Groundwater for all agriculture activities and TWW for landscape and fodder irrigation (Jasim *et al.*, 2016) understanding how the disposal of TWW in different lagoons in Qatar and the reuse of TWW impact on the Qatari aquifers is important for the environmental sustainability of water resources in Qatar.

To achieve this aim, the following objectives have been developed for this part of the study:

- analysis of groundwater samples from pumping wells around the lagoons and the farms using TWW for irrigation;
- analysis of the physical and chemical characteristics of the TWW used for irrigation water and stored in lagoons;
- understanding of lagoon infiltration consequences on Qatar groundwater reservoir;
- Recommending how to improve the urban water cycle management in the state of Qatar.

To achieve these objectives this chapter will describe in detail the hydrogeochemical quality of lagoon and groundwater using international and national standards, to determine which variables the lagoon and groundwater wells have violated for either drinking or irrigation purposes. This chapter will also include a statistical analysis of lagoon and groundwater results for the hydro-geostatistical variables, with a section on the major water processes dominating both water systems, including salinization, water/rock interaction, and oxidation-reduction processes. Then, the relationship between wells and lagoons will be analysed and discussed. Several measured characteristics will be used to convert numerical variables to categorized descriptions that summarise the water quality. Since the main use for groundwater in Qatar is irrigation, and in rare cases, human consumption, the Irrigation Water Quality Index (IWQI) and Water Quality Index (WQI) will be used to determine the suitability of the groundwater for those purposes. Moreover, other criteria that were used in the literature, and by decision-making institutions, will be employed to categorize the water based on its effect on agriculture activity. Those criteria include Sodium adsorption ratio (SAR), Soluble Sodium

Percentage (SSP) or Sodium Percent (Na%), Permeability Index (PI), Potential salinity (PS) and Chloride concentration (meq L^{-1}). Finally, data for plant and soil samples will be presented and discussed, to understand pollutant accumulation from lagoon and groundwater to soil and plants

4.2 Methodology

Chapter 2 of the Methodology for this thesis has covered most of the analysis used in this chapter and chapter 5. However, few methods were exclusively used for this chapter's results analysis and interruption, which will be covered in this section.

4.2.1 Modelling and visualising water type, precipitation and mineral saturation

Literature covering groundwater quality has utilized several models and diagrams to analyse, plot, and report hydro-geochemistry and water quality (FAO *et al.*, 2016; Ahmad *et al.*, 2020; Ismail *et al.*, 2021; Q. Zhang *et al.*, 2021; Şener *et al.*, 2021). Also, those tools have been discussed in publications related to water chemistry to visualize and classify water quality (Helsel *et al.*, 1992; Appelo *et al.*, 1993; Hounslow, 1995; Kumar, 2004).

Piper diagrams have two distinctive axes: one for major cations (say Ca^{2+}+ Mg^{2+}) and one for major anions (say Cl^- + SO_4^{2-}). Piper Diagrams plot the sampled water as % milli-equivalences of the major anions and cations on two triangles and a diamond, producing a dot on the diagram representing the water classification for each sample analysed (Appelo *et al.*, 1993; Hounslow, 1995).

Piper diagrams classify water into four main types based on the position of samples within the diagram. Classifications include:

- Permanent hardness water high in both (Ca^{2+}+ Mg^{2+}) and (Cl^- + SO_4^{2-})
- Temporary hardness water high in (Ca^{2+}+ Mg^{2+}+ SO_4^{2-})
- Alkali carbonate water with high (Na^+ + K^+ and HCO_3^- CO_3^{2-})
- Saline water with high (Na^+ + K^+ and Cl^- + SO_4^{2-})(Kumar, 2004)

Additionally, Gibbs Diagrams were used to determine the link between water composition and lithological properties of the groundwater aquifer. The Gibbs diagram demonstrates three separate dominant water processes, including precipitation, evaporation and rock–water interaction. Gibbs Diagrams illustrate the relationship between TDS and (Na^+ + K^+)/ (Na^+ + K^++ Ca^{2+}) and/or (Cl^- + HCO_3^-) ratios. The diagrams show the dominant mechanism controlling groundwater chemistry (Appelo *et al.*, 1993; Kumar *et al.*, 2020). Three water systems can be demonstrated by Gibbs diagrams:

- Seawater intrusion when the chemistry is dominated by high Na^+, Cl^- and TDS

- Rainfall recharge when the chemistry is similar to diluted seawater but with low TDS
- Terrestrial water seepage water high in Ca^{2+} and HCO_3^- because of water interaction with soil during infiltration (Akshitha *et al.*, 2021; Dixit *et al.*, 2021)

Moreover, The Chadha Diagram is another tool to illustrate water interaction with aquifers rocks in the groundwater. It uses the difference between alkaline earth (Ca^{2+} + Mg^{2+}) and alkali metals (Na^++ K^+) for cations, and the difference between weak acidic anions (HCO_3^- + CO_3^{2-}) and strong acidic anions (Cl^-+ SO_4^{2-}) to show the water-rock processes (Chadha D., 1999).

Saturation indices plots, calculated using PHREEQC speciation software, may be used to indicate the dissolution and precipitation of minerals within the groundwater aquifers. Estimating speciation, ion activity products (IAPs), and solubility saturation indices (IAP/Ks) using PHREEQC requires, as inputs, the sampled water temperature and composition, including concentrations of Dissolved organic carbon (DOC), Na^+, K^+, Cl^-, SO_4^2, Mg^{2+}, As, Fe, and Mn (Schmidt *et al.*, 2007). After running PHREEQC, $\log_{10}$ saturation indices with a positive value indicate oversaturation of the analysed mineral, so that the dominant process is mineral precipitation. While, Saturation indices with a negative value indicate undersaturation of the analysed mineral, and the mineral's tendency to dissolve. Thus, when the saturation indices for the sampled water are plotted the data can show the active processes in the groundwater aquifer (Appelo *et al.*, 1993; Horst D. Schulz, 2000; Schmidt *et al.*, 2007). The solubility product of gypsum was compared with the Ion Activity Product (IAP) $_{gypsum}$ in equation 4.1

$$(\text{IAP}) = [Ca^{2+}][SO_4^{2-}] \qquad 4.1$$

Where the ion activity IAP of both Ca^{2+} and SO_4^{2-} ions are used

4.2.2 Water quality indices

Water quality index (WQI)

The water quality index (WQI) was first introduced by Brown (1979), as a tool to summarize various selected water variables as a percentage indicating the suitability of the water for its chosen purpose. In his study, Brown (1970) contacted several experts in water quality asking them which variables to measure for monitoring water quality; they were also asked to list those variables depending on their importance. Using the data collected Brown developed the concept of a WQI as a tool to convert quantitative data to qualitative information describing the water quality depending on its use (Brown *et al.*, 1970). In the Literature the WQI is mostly used to indicate the suitability of groundwater as a source of potable water (Talat *et al.*, 2019; Banda *et al.*, 2020).

With time, the WQI was customized and used with different variables depending on the water sources and usage (Şener *et al.*, 2021). Thus, WQI has become a nonparametric classification system that uses an algorithm to establish a multivariate ranking pattern that uses a chosen set of observations according to standards set by a water quality authorization party, usually WHO or the national water standard of the study area country (Wills *et al.*, 1996). Examples of those variables are: Dissolve oxygen, pH, TOC, TDS, turbidity and concentrations of calcium, magnesium iron, fluoride, zinc, sulphate and nitrate. Therefore, it was found suitable to be used in this study.

There are four stages involving the formulation of WQI models, as described below (Uddin *et al.*, 2021).

Step 1. The selection of water variables to be used.

In most literature, the relevant variables were determined based on the research data availability and the opinion of the authors as to the variables most important for their water use (Wills *et al.*, 1996; Feng *et al.*, 2017; Uddin *et al.*, 2021). Thus different literature sources used different variables. However, the majority included the basic water quality variables (temp, pH, TDS, TOC and EC) (Uddin *et al.*, 2021). Moreover, most of the literature could not include faecal bacteria as it is an expensive and time-consuming variable to measure (Uddin *et al.*, 2021), which was the case for this research where faecal bacteria was measured in only 13 wells out of 57 (discussed in chapter.5). All the 57 samples were measured twice in winter and summer all the heavy metals were below national and WHO standards. The variables that failed the standards most frequently were: pH, EC, TDS, TOC, and chloride and sulfate concentrations (discussed in detail in section 4.3). The variables which were added, since they are very critical in drinking water quality, included: nitrate, magnesium and iron concentrations.

Step 2. Calculating sub-indices (q_i) for each variable.

Since each water variable measured has a different value range, it would not be realistic to simply sum their numerical value to determine the WQI (Brown *et al.*, 1970). For example, chloride concentrations ranged in this study from 177 to 6330 mg L^{-1} while nitrate had a range of 0 to 39 mg L^{-1}. Therefore sub-indices were derived by expressing each variable as a percentage of the standard value whether it is WHO or the National threshold limits. This also normalises the variable where different units are used; for example, pH units is different from chemical variables measured in mg L^{-1}

Step 3. Assigning weight values for each variable (W_i).

Brown (1970) asked several experts which variables were important for water quality and how their values would impact WQI. Thus, each variable chosen in Step one is assigned a number from 1 to 5, where a value of 5 denotes a highly critical factor for drinking water quality; the least critical variables will be assigned a value of 1 (Brown *et al.*, 1970). Different WQI models use different weighing systems. For the current research, the Bascaron Index (1977) is used where the sum of all weighting values are equal to 54 (Uddin *et al.*, 2021).

Step 4. Computing sub-indices (q_i).

Calculating each variable weight (W_i), using the WQI equations, results in a rating scale summarized in Table 4.1 to categorize the drinking water suitability from 'Excellent water' to 'Water unsuitable for drinking purposes' (Şener *et al.*, 2021; Uddin *et al.*, 2021).

The WQI is calculated using Eq 4.2 (Ramakrishnaiah *et al.*, 2009; Uddin *et al.*, 2021) where it is determined by summing the results of multiplying each of the relative weight values (Wi) and the quality rating (qi) values for every variable chosen in Step 1. (Brown *et al.*, 1970)

Table 4.1. The relative weight of chemical and physical variables chosen for WQI and their sub-indices.

Variables (mg L^{-1})	Kahramaa Drinking Standards[1]	Wi[2]	w_i
pH	8	4	0.074074
Total dissolved solids	250	5	0.092593
Total organic carbon	4	1	0.018519
Ca^{2+}	80	3	0.055556
Mg^{2+}	30	3	0.055556
Fe	0.3	3	0.055556
Cl^-	80	5	0.092593
Sulphate	50	5	0.092593
Nitrate	10	5	0.092593
Sodium	80	4	0.074074
potassium	4	2	0.037037
Boron	1	4	0.074074
Lead	0.01	5	0.092593
arsenic	0.01	5	0.092593
Total		54	1

1. Kahramaa Drinking Standards (Lutowski, 2005)
2. Relative weight based on Bascaron Index (Ramakrishnaiah *et al.*, 2009; Uddin *et al.*, 2021)

$$Overall\ WQI = \sum(W_i \times q_i) \qquad 4.2$$

Where:

$$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \qquad 4.3$$

W_i= relative weight

w_i= weight of each variable

n= number of variables; (Ramakrishnaiah *et al.*, 2009; Uddin *et al.*, 2021)

And:

$$q_i = \frac{C_i}{S_i} \times 100 \qquad 4.4$$

q_i= the quality rating

C_i= concentration of each chemical variable

S_i= the drinking water standard for each chemical variable (Table 4.1);

Different studies have chosen different sets of variables depending on the study objectives. Also, the different studies chose either WHO, EPA or their local authority standards to dictate the WQI percentage for their water. In this study the authority responsible for drinking water is Kahramaa and so their drinking water standards were used for the sub-indices (q_i), shown in Table 4.1.

Sodium Adsorption Ratio (SAR)

An important water quality criterion that affects soil permeability is the sodium adsorption ratio (SAR). Both calcium and magnesium were counted in SAR (equation 4.5) since the presence of both in adequate quantities in the soil or water, will assist in maintaining healthy soil qualities by counteracting the impacts of Na^+.(Delgado *et al.*, 2010; Ogunfowokan *et al.*, 2013; Ismail *et al.*, 2021)

$$SAR = \frac{Na^+}{\sqrt{\frac{(Ca^{2+}+Mg^{2+})}{2}}} \qquad 4.5$$

Soil clay particles absorb sodium as an exchangeable cation, in competition with the other major cations (Ca^{2+}, Mg^{2+} and K^+). However, Na^+ encourages clay tactoid dispersion and, thereby, aggregate destruction in topsoils. If an affected soil is dried, it hardens and compacts into a 'massive' (de-aggregated) structure, making water penetration more difficult. Soil with a high clay concentration is particularly susceptible to this process (Wilcox, 1955; Meireles *et al.*, 2010; Dennis W. *et al.*, 2019). Thus, a high concentration of sodium, in relation to calcium and magnesium, affects soil permeability, limiting the amount of water available to crops. Thus, SAR is used as an index to determine the acceptability of irrigation water, where the SAR of water is directly related to the extent of sodium adsorption by soil relative to the divalent cations (Wilcox, 1955).

Soluble Sodium Percentage (SSP) or Sodium Percent (Na%)

Another criterion widely used in literature to measure the impact of sodium on soil permeability is the 'Soluble Sodium Percentage' (SSP) or Sodium Percentage (Na%) shown in equation 4.6. Both terms were used in the literature to describe the concentration of sodium relative to the other cations in the irrigation water (Ravikumar *et al.*, 2011; Thapa *et al.*, 2020; Tefera *et al.*, 2021b). High

Sodium concentration makes the soil sticky and viscous when wet, when dry soil becomes hard to till and tough for seeds to germinate. Another important consequence of high sodium is the toxic effect on plants. The difference between SAR and SSP is that SAR is used to understand high sodium levels in soil, while SSP is a better indicator of the likely accumulation of sodium in plant tissue (Wilcox, 1955; Gupta *et al.*, 2003) since SSP is the percentage of soluble sodium in relation to a total cation on an equivalent basis (Wilcox, 1955).

$$Na\% = \frac{(Na^{+}+K^{+})}{(Ca^{2+}+Mg^{2+}+Na^{+}+K^{+})} \times 100 \qquad 4.6$$

Water Permeability Index (PI)

The 'Permeability Index' is a useful criterion used to indicate the ease of irrigation water movement in the soil (equation 4.7), as proposed by Doneen (Doneen, 1964) and currently used by the WHO. The PI is especially important for soils under long term irrigation with water. The PI value is affected by Na^{+}, Ca^{2+}, Mg^{2+}, and HCO_3^{-} ions in the soil; high values of PI indicate possible reductions in soil water permeability (Aravinthasamy *et al.*, 2020; Thapa *et al.*, 2020; Batarseh *et al.*, 2021).

$$PI = \frac{(Na^{+}+\sqrt{HCO_3}\times 100}{(Ca^{2+}+Mg^{2+}+Na^{+}+K^{+})} \qquad 4.7$$

Water Potential Salinity (PS)

Potential salinity was proposed by Doneen (1964) as a better measurement criterion for salts in irrigation water (equation 4.8) since both Cl^{-} and SO_4^{2-} are considered high soluble salts that directly increase salinity in the soil, in contrary to soluble salts that have low solubility and just accumulate with each irrigation event (Doneen, 1964). Those salts are vital to monitor since excessive salt in the soil raises the osmotic pressure of the soil condition, which can cause a physiological drought environment. As a result, even though the soil in the field looks to be damp, the plants will wilt from dehydration. Because of the high osmotic potential of soil water, plant roots are unable to absorb it. As a result, water lost by transpiration from the plant shoot cannot be replaced (Doneen, 1964; Ogunfowokan *et al.*, 2013; Aravinthasamy *et al.*, 2020).

$$PS = Cl^{-} + \frac{SO_4^{2-}}{2} \qquad 4.8$$

Water Chloride Level

While chloride is essential for plant growth, excessive concentrations are very toxic to sensitive plants; at very high concentrations (Above 10.15 meq L^{-1}), caused by marine intrusion, chloride is

likely to be toxic to the majority of vascular plants. Also, Plants will be dehydrated and their growth will be inhibited (Dennis W. *et al.*, 2019)

Water Irrigation Water Quality Index (IWQI)

As discussed in the literature review, Qatar uses groundwater and TWW mainly for irrigation purposes. Thus, IWQI will categorize the sampled water into classes describing suitability for irrigation and the likely impact on both soil and plants irrigated. First, q_i is calculated using equation 4.9.

$$q_i = q_{max} - \left(\frac{(x_s - x_{lo}) \times q_{amap}}{x_{amap}}\right) \qquad 4.9$$

Where:

q_{max} = the class upper value of the corresponding q_i , seen in Table 4.2

X_s = the sample variable value

X_{lo} = the lower limit value of the class to which the observed variable belongs, seen in Table 4.2

q_{amap} = the class amplitude for qi classes, seen in Table 4.2

X_{amap} = the class amplitude to which the variable belongs, seen in Table 4.2; (Meireles *et al.*, 2010; Muniz *et al.*, 2020; Batarseh *et al.*, 2021)

Table 4.2. Quality measure (qi) limit values calculated for the indicated variables for each class (Meireles *et al.*, 2010; Muniz *et al.*, 2020; Batarseh *et al.*, 2021).

qi	EC (µS cm^{-1})	SAR (meq L^{-1})	Na^+(meq L^{-1})	Cl^-(meq L^{-1})	HCO_3^-(meq L^{-1})
85–100	200–750	<3	2–3	<4	1–1.5
60–85	750–1500	3–6	3–6	4–7	1.5–4.5
35–60	1500–3000	6–12	6–9	7–10	4.5–8.5
0–35	<200 or >3000	>12	<2 or >9	>10	<1 or >8.5

Finally, IWQI is calculated using the equation 4.10

$$IWQI = \sum_n^n q_i w_i \qquad 4.10$$

In Eq.4.10, *n* is the number of variables, q_i calculated values were multiplied by w_i values shown in Table 4.3 Those values were determined in previous studies produced to develop the best IWQI measurement (Batarseh *et al.*, 2021; Q. Zhang *et al.*, 2021; Şener *et al.*, 2021).

Table 4.3. The relative weightings (w_i) of the IWQI variables. (Muniz *et al.*, 2020; Batarseh *et al.*, 2021)

Variables	w_i
EC	0.211
Na^+	0.204
HCO_3	0.202
Cl^-	0.194
SAR	0.189
Total	1.000

4.2.3 Soil Quality Index

The Soil Quality Index (SQI) is described as a set of variables that provide numerical data about a soil's ability to perform one or more functions. It is used by many studies to examine the health of the soil for agriculture purposes following irrigation with polluted water (Abd-Elwahed, 2018; Aravinthasamy *et al.*, 2020; Jahany *et al.*, 2020) When the main purpose of soil use and management goals were established the SQI steps should follow. The SQI requires three main steps: (1) selecting acceptable indicators from a 'total data set' (TDS) for a 'minimal data set' (MDS); (2) converting indicator scores; (3) calculating each MDS variable weight; (4) combining indicator scores to produce an index (Biswas *et al.*, 2017; Rezapour *et al.*, 2021). In this research, the SQI will be used to evaluate soil quality following irrigation with groundwater, TWW and lagoon water.

(1) Selecting acceptable indicators.

The main soil variables to monitor when comparing groundwater and TWW are soil macronutrients (N, P, and K), micronutrients (Fe, Mn, Zn, and Cu), pH and potentially toxic heavy metals. All of these were measured and represent the TDS. To reduce the number of the variables to the most important and influential variables in assessing soil quality, TDS should be minimized to the MDS. This is done by performing PCA where the PCS with an eigenvalue of more than 1 that explains at least 5% of the data variation were chosen (Biswas *et al.*, 2017; Rezapour *et al.*, 2021). Only soil variables with weighted loadings of more than 0.700 were chosen (Table 4.4).

When multiple variables show high scores in the same PC, a Pearson correlation should be performed between the variables; the correlated variables will be dismissed and only the variable with the higher score will be included in the MDS. In case there is no correlation between the variables all will be used in the MDS (Biswas *et al.*, 2017; Abd-Elwahed, 2018; Jahany *et al.*, 2020).

For PC1 the variables with high PC values were Ti, Li, Al, V, Cr, Mn, Fe, Co, Ni and As; after Pearson correlation was performed on those variables it was found that all of them were highly correlated to each other ($p>0.01$); Thus, Fe was chosen out of all of them since it had the highest PC value of 0.973.

For PC2 the chosen variable was K^+ only; for PC3 it was P only; for PC4 it was both S and Sr, a correlation test was done showing that these were correlated ($p>0.01$) so Sr with the highest PC value was chosen; for PC5 it was Na^+ and EC but a correlation test showed a high correlation ($p>0.01$) so Na^+ with the highest PC value was chosen; for PC6 both Zn and Ba were selected as they were not correlated ($p>0.01$); lastly for PC7, only pH was selected.

Table 4.4. Farms and lagoon soil principal components, PC1 to PC7 had cumulative eigenvalues of more than 80% and a total of more than 1.

	1	2	3	4	5	6	7	Communalities
Total	10.485	3.457	2.467	2.264	1.745	1.349	1.062	
Cumulative %	37.44	49.79	58.6	66.69	72.92	77.74	81.53	
pH	-.021	-.228	-.332	-.135	.170	-.404	**.552**	0.369
EC	-.194	-.192	-.177	.319	**.748**	-.129	-.025	0.740
C%	-.101	-.758	.422	-.113	-.237	.148	-.016	0.841
I	.134	.108	.301	.072	-.186	-.010	.744	0.127
Na^+	-.193	.272	-.026	.051	**.844**	-.092	.084	0.834
Mg^{2+}	.277	-.617	-.004	-.087	.063	.512	-.077	0.659
P	-.147	-.141	**.878**	-.057	-.068	-.002	-.075	0.727
S	-.048	-.031	.111	**.783**	.331	-.026	-.178	0.917
K	.457	**.859**	.016	-.025	-.032	-.059	-.046	0.999
Ca^{2+}	-.009	-.732	-.211	.458	-.027	-.136	-.003	0.696
Ti	**.887**	.075	-.001	-.033	-.013	.043	-.029	0.785
Li	**.929**	.217	.060	.063	-.011	.011	.016	0.914
Al	**.800**	.539	-.049	-.120	-.081	.026	-.070	0.965
V	**.929**	.071	-.079	.183	-.171	.000	.015	0.961
Cr	**.880**	-.207	-.050	-.124	.049	.022	-.045	0.893
Mn	**.942**	.037	.171	-.069	-.068	.030	-.034	0.923
Fe	**.973**	.102	-.038	.018	-.122	-.013	-.019	0.986
Co	**.960**	.110	.013	.040	-.155	-.042	-.010	0.974
Ni	**.927**	-.070	.076	-.153	-.062	-.034	.044	0.900
Cu	.655	.012	.409	.004	.025	.145	.060	0.565
Zn	.066	-.291	.251	.087	-.062	**.786**	.068	0.759
As	**.773**	.155	-.168	.264	-.282	-.132	-.004	0.972
Rb	.688	.652	.053	-.141	-.020	-.029	-.035	0.926
Sr	-.020	-.117	.062	**.879**	.009	.118	-.022	0.626
Mo	.197	.033	.097	.280	-.230	-.110	-.561	0.137
Ba	-.198	.119	-.394	.009	-.203	**.709**	-.083	0.602
Pb	.550	.209	.183	.360	.204	.328	.152	0.533
U	.196	.121	.767	.273	-.072	.009	.153	0.615

(2) Converting indicator scores.

Using a scoring function approach, data was translated into a dimensionless score ranging from 0 to 1 for each soil indicator (Biswas *et al.*, 2017; Jahany *et al.*, 2020). Soil properties could be divided into three types of standard scoring equations based on indicator sensitivity: first, the "more is better" equation 4.11 was applied to TOC, total N, available P, and exchangeable cations (Ca^{2+}, Mg^{2+}, K); second, the "less is better" equation 4.12 was applied to Na^+, and heavy metals; and finally, the "optimum range" equation 4.13 was applied to pH using a threshold of pH 6 – 7 (Jahany *et al.*, 2020; Rezapour *et al.*, 2021)

$$S_i = \frac{X_i - Mn_i}{M_i - Mn_i} \qquad 4.11$$

$$S_i = \frac{M_i - X_i}{M_i - Mn_i} \qquad 4.12$$

$$S_i = \frac{7 - X_i}{7 - 6} \qquad 4.13$$

In equations 4.11 – 4.13, S_i is the linear score, X_i is the soil variable value, Mn_i is the minimum value of the soil variable, and M_i is the maximum value of the soil variable (Jahany *et al.*, 2020; Rezapour *et al.*, 2021).

(3) Calculating each MDS variable weight.

The SQI weight for each variable was calculated by Common Factor Analysis in SPSS, the resulting communalities values for each variable is the weighting value of the soil (Table 4.4).

(4) Calculating SQI.

The SQI was calculated from Eq. 4.14,

$$SQI = \sum_{i=n}^{n} W_i \times S_i \qquad 4.14$$

where S_i is the indicator score, n is the number of soil indicators in the MDS soil variables and W_i is the weighting value of soil (Biswas *et al.*, 2017; Jahany *et al.*, 2020).

4.2.4 Plant Bioconcentration factor relative to the soil.

The bio-concentration factor (BCF) describes the concentrations of different chemical variables accumulating in plants tissue from the soil the plants were growing in (Eq. 4.15) (Rana *et al.*, 2018; Mehmood *et al.*, 2019; Sharma *et al.*, 2021). This index illustrates the relative ease of movement of the chemical variables measured from water to soil and finally to plant crops (Rana *et al.*, 2018; Mehmood *et al.*, 2019; Sharma *et al.*, 2021).

$$BCF = \frac{[X_i\ Plant]}{[X_i\ Soil]} \qquad 4.15$$

Where the X_i represent the chemical variable measured in both soil and plant in the sampled location. A BCF of greater than 1 implies a greater affinity for the plants than the soil (Rana *et al.*, 2018; Mehmood *et al.*, 2019; Sharma *et al.*, 2021).

4.3 Results and discussion

This chapter covers the water, soil, and plant data for both lagoon and groundwater samples. It also includes a discussion about (i) the influence of the lagoon water on groundwater, soil and plant quality and (ii) the quality of sampled water and soil for agriculture usage.

4.3.1 Qatar artificial Lagoons

Since the main objective of this study is to understand the Lagoon impact on the Qatari groundwater reservoir, the lagoons were first characterized and their temporal and spatial water quality should be stated. This section will cover results and discussions related to artificial lagoons in Qatar. First, the results from the statistical analysis will be stated, then the discussion will be divided into the main water quality in comparison with national and international standards for TWW reuse. Then, the main water processes in the lagoon water will be shown.

4.3.1.1 Lagoon water multivariate statistical analysis.

In previous literature about lagoons and wetlands, multivariate statistical tests were utilized to illustrate how the different chemical variables relate to each other, showing the main water processes governing pollutant transformation. This illustrates the wetland's general quality and how it is influencing and being influenced by the surrounding environment (Leung *et al.*, 2017; Hu *et al.*, 2020; Tan *et al.*, 2020; Xia *et al.*, 2021). Thus, to understand lagoon water quality more fully and how it is influencing the groundwater, some of those statistical tests were adopted and performed. Here results of the multivariate statistical analysis performed on lagoon water are shown. First, the distribution of the chemical variables in the lagoon water has to be determined, thus PCA, HCA and GLM analyses were used. A few measured variables in this study were excluded since they were not detected in all samples or were detected at negligible concentrations below LOD; the variables affected included: B, Pb, Tl, Cs, Cd, Ag, Co, Be, Ti, Se, Cr, Cu, total P and PO_4

Lagoon Normality test.

To assess the suitability of the statistical test used to analyse lagoon data, two normality tests were performed: Kolmogorov-Smirnov and Shapiro-Wilk. After conducting both normality tests, Table 4.5 shows that 21 out of 32 were not normal with the Kolmogorov-Smirnov test and 20 out of 32 with Shapiro-Wilk Test ($p<0.05$). Thus, to conduct a reliable multivariate analysis, the assumption should always be that the data is not normally distributed. So, using non-parametric tests or data transformation was recommended.

Table 4.5. Tests of Normality (Kolmogorov-Smirnov and Shapiro-Wilk) for all the Lagoon variables, If the significant level (Sig.) value of the test is greater than 0.05, the data is normal. If it is below 0.05, the data significantly deviate from a normal distribution (highlighted in grey).

	Kolmogorov-Smirnov			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
General water Quality Variables						
EC	0.4	10	0	0.653	10	0
IC	0.247	10	0.084	0.852	10	0.061
TDS	0.4	10	0	0.653	10	0
TN	0.195	10	.200	0.814	10	0.021
TOC	0.257	10	0.06	0.884	10	0.143
Anionic and cationic variables						
Ca^{2+}	0.365	10	0	0.685	10	0.001
Cl^-	0.391	10	0	0.603	10	0
I	0.288	10	0.019	0.775	10	0.007
K^+	0.386	10	0	0.68	10	0
Mg^{2+}	0.421	10	0	0.624	10	0
Na^+	0.372	10	0	0.657	10	0
NO_3^-	0.347	10	0.001	0.705	10	0.001
S	0.368	10	0	0.655	10	0
SO_4^{2-}	0.362	10	0.001	0.647	10	0
Metal and metalloid variables						
Al	0.349	10	0.001	0.76	10	0.005
As	0.223	10	0.175	0.886	10	0.151
Ba	0.195	10	.200	0.816	10	0.023
Fe	0.191	10	.200	0.9	10	0.217
Li	0.431	10	0	0.606	10	0
Mn	0.294	10	0.014	0.791	10	0.011
Mo	0.309	10	0.008	0.784	10	0.009
Ni	0.195	10	.200	0.881	10	0.133
Rb	0.316	10	0.005	0.808	10	0.018
Sr	0.358	10	0.001	0.656	10	0
U	0.364	10	0	0.615	10	0
V	0.201	10	.200	0.922	10	0.373
Zn	0.425	10	0	0.422	10	0

Lagoon Principal Component Analysis (PCA).

PCA has been used by many researchers to study water processes in wetlands, lakes and other surface water contexts, it is often used to illustrate the interaction between heavy metals and identify possible links between the chemical variable and the contamination source (Hu *et al.*, 2017, 2020; Leung *et al.*, 2017; Ogunlaja *et al.*, 2019; Huang *et al.*, 2020; Tan *et al.*, 2020; Xia *et al.*, 2021). In this research, the data was shown not to be normally distributed. Thus, a KMO and Bartlett's Test was done before PCA with results of (0.596; Table 4.6) which indicates that the data set is acceptable to conduct a PCA analysis, without any corrections.

Table 4.6. Lagoon water Data KMO and Bartlett's Test results.

KMO and Bartlett's Test		
KMO measure of sampling adequacy.		.596
Bartlett's Test of Sphericity	**Approx. Chi-Square**	1892.82
	df	498
	Sig.	.000

A PCA was then carried out using varimax rotation with Kaiser Normalisation to identify the relationship between the measured variables. Table 4.7 shows that only 4 PCs were needed to explain 90% of the total variance, where PC1 explained 56% for summer and 45% for winter.

Both summer and winter data were resolved into three distinctive groups, with almost the same variables correlating to each other. The first group (A) was the same for both summer and winter and has Cl^-, Na^+, EC, K, Ca^{2+}, Sr, SO_4^{2-}, Mg^{2+}, Li, TDS, and Mo. However, a difference noticed between the two seasons was that Ba and U moved from group A in the summer to group B in the winter. The

second group (B) for both summer and winter included: TOC, IC, TN, NO_3^-, Al, V, Ni and Zn, and group C consisted of just Mn and I. However, Fe, As, and Ba moved to other groups between summer and winter (Fig 4.1).

It was noted that TN and NO_3^- were found to be in the same group, but there was no clear correlation between them with having similar scores on PCs. This signifies that the NO_3^- does not represent the majority of TN in the lagoon. Furthermore, concerning the Sulfur species, there was a clear correlation between total S and SO_4^{2-}, with both having high scores on PCs; this signifies that the majority of S in the lagoons is SO_4^{2-}.

Table 4.7. Lagoon water principal components. PC1 to PC4 had cumulative eigenvalues of more than 80% for summer and winter. Bold values were correlated to each other in the same PC.

	Summer				Winter			
	PC1	**PC2**	**PC3**	**PC4**	**PC1**	**PC2**	**PC3**	**PC4**
Cumulative %	56	73	84	90	45	64	77	86
General water quality variables								
EC	**0.975**	0.061	0.178	-0.005	**0.967**	0.109	0.123	-0.012
IC	-0.365	-0.208	**-0.868**	0.028	-0.296	0.014	0.072	0.063
pH*	-	-	-	-	-0.122	-0.38	-0.22	**-0.835**
TDS	**0.975**	0.061	0.178	-0.005	**0.845**	0.073	0.176	-0.045
Temp*	-	-	-	-	-0.363	0.14	-0.142	0.439
TN	-0.355	-0.216	**-0.842**	-0.111	-0.122	-0.38	-0.22	**-0.835**
TOC	0.023	-0.143	-0.43	0.411	-0.058	-0.124	-0.034	0.094
Anionic and cationic variables								
Ca^{2+}	**0.905**	0.344	0.229	-0.036	**0.874**	0.293	0.337	0.071
Cl^-	**0.968**	-0.026	0.175	-0.109	**0.937**	-0.057	-0.132	-0.121
I	0.419	**0.816**	0.312	-0.073	0.36	**0.66**	**0.592**	0.118
K^+	**0.983**	-0.064	0.151	-0.01	**0.862**	-0.383	-0.081	-0.239
Mg^{2+}	**0.899**	0.406	0.001	0.076	**0.848**	0.228	0.447	-0.027
Na^+	**0.966**	-0.068	0.188	-0.01	**0.923**	-0.162	-0.127	-0.104
NO_3^-	-0.283	-0.238	-0.047	-0.138	-0.167	-0.245	0.079	**0.833**
S	**0.905**	0.406	0.112	0.002	**0.879**	0.255	0.378	0.021
SO_4^{2-}	**0.875**	0.469	0.062	-0.015	**0.869**	0.26	0.39	0.026
Metal and metalloid variables								
Al	-0.234	-0.185	**-0.509**	0.391	-0.529	-0.387	-0.273	0.5
As	**0.685**	0.387	0.459	0.157	0.483	**0.821**	-0.002	-0.055
Ba	**0.662**	0.646	0.081	0.294	0.176	**0.949**	0.087	-0.086
Fe	-0.108	0.118	-0.172	**0.751**	-0.347	**0.537**	-0.222	0.225
Li	**0.979**	0.142	0.129	-0.007	**0.875**	0.155	0.437	0.109
Mn	0.056	**0.821**	0.349	-0.08	-0.32	**0.921**	-0.107	-0.001
Mo	**0.948**	-0.014	0.259	0.048	**0.837**	-0.131	0.317	-0.337
Ni	0.28	0.205	-0.278	**0.838**	0.489	0	**0.802**	-0.018
Rb	**0.719**	-0.642	0.039	-0.082	-0.166	-0.744	-0.427	-0.375
Sr	**0.911**	0.389	0.126	0.011	**0.811**	0.265	0.507	0.049
U	**0.769**	0.612	-0.011	0.07	**0.6**	0.15	**0.779**	-0.034
V	0.092	0.095	**0.839**	-0.433	0.02	-0.083	**0.696**	0.106
Zn	-0.138	-0.18	0.104	**0.942**	-0.185	-0.189	-0.25	**0.922**

- Temperature and pH measurements were not taken during the summer period

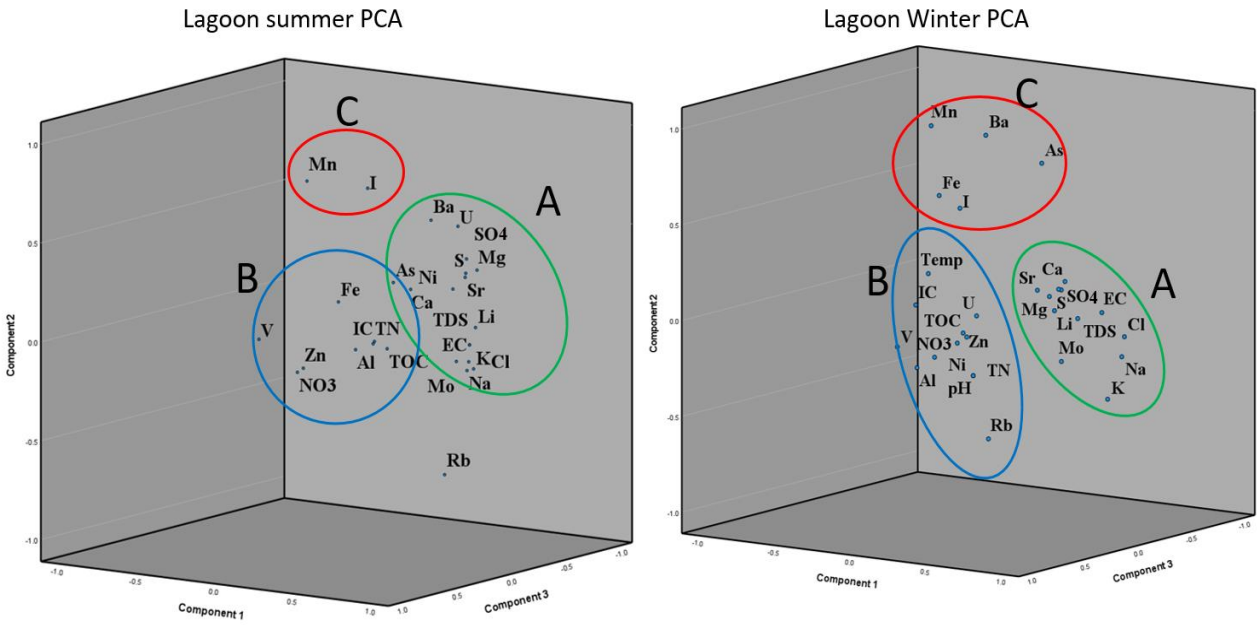


Figure 4.1. Lagoon water PCA 3D plot for 32 physical and chemical variables (summer: left, winter: right). Varibles clustered in the same group showen by three circules labled A,B and C. PCA was used with the Varimax rotation method and Kaiser Normalization.

Lagoon Hierarchical Cluster Analysis (HCA)

Like PCA analysis, HCA has also been applied in previous studies to understand the water quality of wetlands, as well as to reduce large data sets to a Dendrogram showing the relationship between wetlands pollutants (Tan *et al.*, 2020; Dar *et al.*, 2021). For that, HCA analysis was applied to lagoon water data to show how the different variables clustered in relation to each other. Lagoon variables clustering is shown in Figure 4.2. The analysis produced three clades for summer and two clades for winter, with the clades having more or less the same variables correlating together. Variables in clades A & B in summer were seen in clade B in winter except for Mn, As and Ni. Moreover, clade C in summer is similar to clade A in winter.

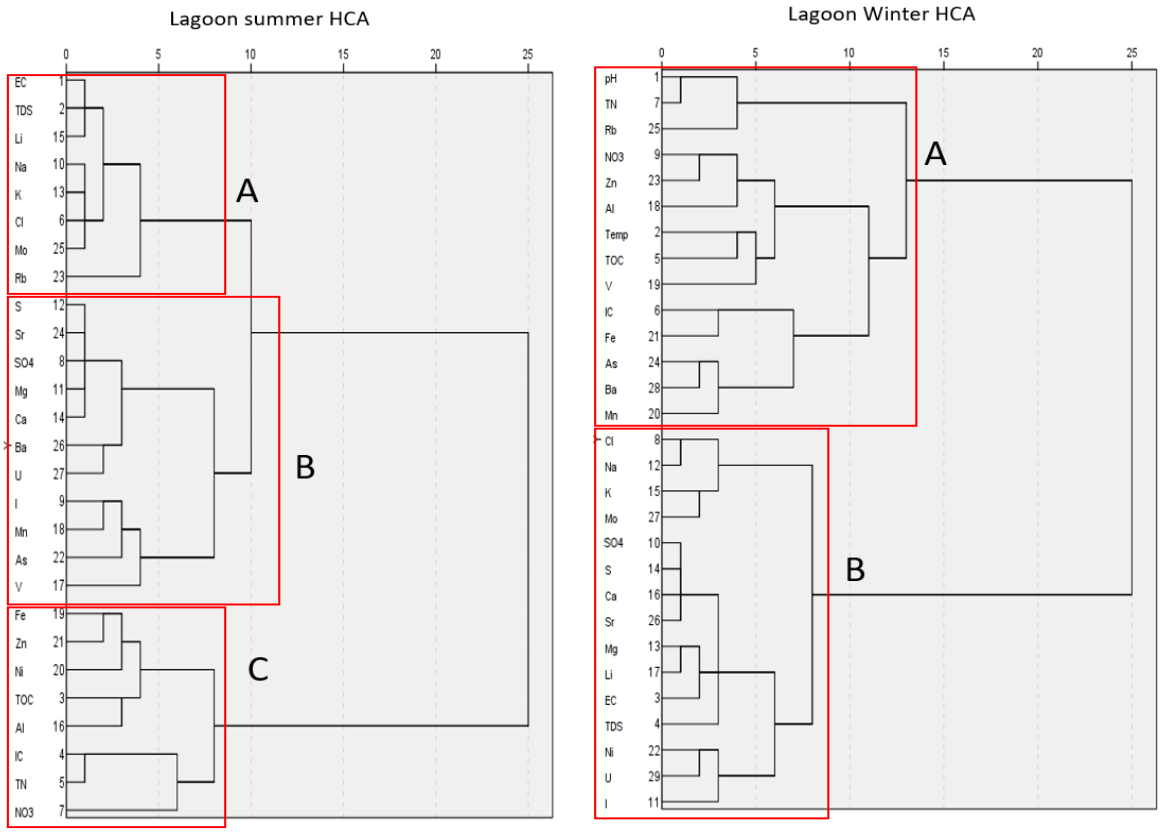


Figure 4.2. Lagoon Dendrogram, produced from HCA, using ward linkage, with Euclidean distance measurement with Z score standardization transformation. Varibles clustered in the same group showen by the squares labled A,B and C. (Summer: left, winter: right)

Lagoon Generalized Linear Model (GLM)

GLM is used by many studies to show the influence of fixed factors on the measured dependent variables. Here temporal variation is the fixed factor and GLM analysis will test its influence on the lagoon water data. Table 4.8 shows that none of the variables was influenced by the seasonal change (P>0.005).

Table 4.8. Results of GLM showing a significant correlation between lagoon variables and the seasonal variation between summer and winter.

Dependent Variable	Mean Square	F	Sig.	Dependent Variable	Mean Square	F	Sig.
General Water Quality Variables				**SO_4^{2-}**	169228.12	0.9	0.356
EC	24188.46	0	0.963	**Metal and metalloid variables**			
IC	473.56	2.93	0.104	**Al**	81.79	2.66	0.12
TDS	418050.92	0.1	0.757	**As**	0.19	0.21	0.651
TN	28597.97	484.31	0.568	**Ba**	360.28	1.72	0.206
TOC	589.12	1.38	0.255	**Fe**	153.44	1.27	0.274
Anionic and cationic variables				**Li**	1834.85	0.99	0.334
Ca^{2+}	2000.24	0.03	0.866	**Mn**	5514.62	1.25	0.279
Cl^-	1528125.5	1.26	0.276	**Mo**	0.09	0	0.952
I	1047.88	0.97	0.337	**Ni**	0.18	0.2	0.66
K^+	415.79	0.61	0.446	**Rb**	50.12	0.59	0.451
Mg^{2+}	3596.78	0.42	0.524	**Sr**	24970193	0.41	0.531
Na^+	218789.99	0.85	0.368	**U**	1.27	0.16	0.696
NO_3^-	5.98	0.18	0.68	**V**	8.7	0.87	0.365
S	55105.82	0.39	0.54	**Zn**	25003.52	1.85	0.191

4.3.1.2 Lagoon water quality compared to international and national standards.

Lagoon water data for winter and summer sampling (n=10) are summarized and compared to Qatar's national water standards in Table 4.9, the data median, range and interquartile range attached in the appendix section (Appendix C). In official Qatari documentation, three types of standards were found: 1) the Qatari irrigation standards used for irrigation water monitoring, usually applied to groundwater, 2) Qatar TWW reused for irrigation, and 3) Qatar TWW point source discharge to marine water. Since TWW from lagoons has been found to be used for irrigation and discharge to marine water as well, the results were compared to both standards.

General water quality

It is observed three of ten lagoons that pH was above the standard range of 6-9, with a maximum value of 9.4. When it comes to nitrogen and organic matter removal, the pH of the WW can have a significant impact on the success of the treatment. During nitrification, for example, high alkalinity consumption lowers the system's nitrogen removal efficiency significantly (Yin *et al.*, 2016). Moreover, with reusing TWW for irrigation the pH values of the TWW are critical. Low pH values in irrigation water can result in acidification of soil, which can lower the availability of nutrients, such as Mo and P and increase the solubility of potentially toxic elements such as Mn and Al, affecting plant growth and productivity. Similarly, high soil and water pH values limit the availability of micronutrients such as Mn, Zn and Fe (Almuktar *et al.*, 2018). As a result, not all lagoons were suitable for irrigation depending on their pH value.

Five out of ten lagoons were above the permissible level for TDS with a maximum of 8389 mg L^{-1}. TDS is a measure of salinity in water systems. Furthermore, soil salinity has been linked to and is often determined by, water salinity. Thus, it is important to monitor TDS for TWW use for irrigation; the correlation between TDS and EC was significant ($P < 0.05$) in lagoon samples.

Major anions and cations

The dominant cations and anions in the lagoon water were $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ and $Cl^- > SO_4^{2-} > NO_3^- > PO_4^{3-}$, which is similar to the cations and anions distribution in previous Qatari groundwater studies (Kuiper *et al.*, 2015; Ahmad *et al.*, 2020). In addition, previous studies have shown that cation and anion distribution in wetlands depends on the local water-rock interactions (Dixit *et al.*, 2021; Joshi *et al.*, 2021). This is seen in the current research as well, where salinization and dissolution of carbonate and gypsum reported in the area has clearly influenced lagoons cations and anions species.

Furthermore, the chemistry of lagoon samples was similar to reports about groundwater in Qatar, having high concentrations of sulphate and boron. It was noticed the three lagoons with the highest concentrations were lagoons constructed to contain surface water, not TWW. Thus, the water characteristics were likely to be similar to that of groundwater.

Table 4.9 Summary of the lagoon (n=10) water variables (mean, minimum, maximum and standard deviation), with the number of violations to the different standards highlighted in grey

	Mean		Min		Max		SD		TWW for irrigation[1]			TWW for marine water[2]			Crop irrigation[3]		
	S	W	S	W	S	W	S	W	STD	violations S	violations W	STD	violations S	violations W	STD	#violations S	#violations W
General water quality variables (mg L^{-1}); Except EC in µs cm^{-1} and pH no unit																	
EC	3240	3170	473	1330	13100	7660	4280	1970	-	-	-	-	-	-	-	-	-
pH	NA	8.2	NA	7	NA	9.4	NA	0.9	6-9	NA	3	6-9	NA	3	6-9	NA	3
TDS	2070	1780	302	690	8380	3850	2740	982	1500	5	5	1500	5	5	2000	3	4
TN	6.3	82	1	70	20	95	6	9	35	1	10	5	6	10	35	1	10
TOC	7	9	1	4	17	16	5.7	3	40	0	0	50	0	0	75	0	0
Anionic and cationic variables (mg L^{-1})																	
B	0.7	0.5	0	0.2	2	1	0.3	0.5	1	2	1	2	2	0	2	1	0
Ca^{2+}	253	233	34	49	841	742	200	151	-	-	-	-	-	-	-	-	-
Cl^{-}	897	344	51	90	4690	813	1530	241	-	-	-	-	-	-	-	-	-
I	24	38	3	3	72	100	38	30	-	-	-	-	-	-	-	-	-
K	35	26	9	14	122	40	7	22	-	-	-	-	-	-	-	-	-
Mg^{2+}	76	49	2	11	370	132	40	64	-	-	-	-	-	-	-	-	-
Na^{+}	508	299	80	107	2230	608	168	538	-	-	-	-	-	-	-	-	-
NO_3	4	4	0	0	11	20	5	7	-	-	-	-	-	-	-	-	-
P	1	0.7	0	0	3	4	1	0	-	-	-	-	-	-	-	-	-
PO_4^{2-}	0.1	0	0	0	1	0	0	0	30	0	0	-	-	-	30	0	0
S	332	227	16	49	1380	751	213	190	-	-	-	-	-	-	-	-	-
SO_4^{2-}	362	178	13	32	1720	632	587	183	400	2	1	-	-	-	400	2	1
F	0	0	0	0	0	0	0	0	15	0	0	-	-	-	15	0	0
Metal and metalloid variables (µg L^{-1})																	
Ag	0	0	0	0	0	0.1	0	0	-	-	-	5	-	-	-	-	-
Al	8	4	2	0.8	23	9	7	3	5000	0	0	3000	0	0	1500	0	0
As	1	2	0.3	0.6	3	3	0.9	1	100	0	0	100	0	0	100	0	0
Ba	20	29	9	13	51	67	13	16	1000	0	0	1000	0	0	2000	0	0
Be	0	0	0	0	0	0	0	0	-	-	-	-	-	-	-	-	-
Cd	0	0	0	0	0	0	0	0	10	0	0	50	0	0	50	0	0
Co	0.1	0.2	0.1	0.1	0.2	0.3	0	0.1	200	0	0	100	0	0	200	0	0
Cr	0.4	0.2	0.3	0.1	0.8	0.4	0.1	0.1	100	0	0	100	0	0	10	0	0
Cs	0.1	0.1	0	0	0.7	0.2	0.2	0.1	-	-	-	-	-	-	-	-	-
Cu	0.9	0.7	0.3	0.3	2	2	0.5	0.5	200	0	0	200	0	0	200	0	0
Fe	17	11	7	0.6	35	36	8	13	1000	0	0	500	0	0	1000	0	0
Li	39	20	2	8	165	45	60	11	-	-	-	-	-	-	-	-	-
Mn	9	42	0.7	1.2	33	306	9.9	94	50	0	1	200	0	1	50	0	1
Mo	6	6	0.5	0.8	18	13	6	4	-	-	-	-	-	-	-	-	-
Ni	2	2	2	1	3	5	0.5	1	200	0	0	200	0	0	200	0	0
Pb	0	0	0	0	0.1	0.1	0	0	100	0	0	100	0	0	100	0	0
Rb	18	15	3	3	43	30	10	8	-	-	-	-	-	-	-	-	-
Se	0.2	0.3	0.1	0.1	0.6	0.8	0.2	0.2	-	-	-	20	0	0	-	-	-
Sr	6790	4550	120	843	28300	13900	10200	4120	-	-	-	-	-	-	-	-	-
Tl	0	0	0	0	0	0.1	0	0	-	-	-	-	-	-	-	-	-
U	2	1	0	0.1	11	5	4	2	-	-	-	-	-	-	-	-	-
V	4	5	0.4	0.6	9	12	3	4	-	-	-	-	-	-	-	-	-
Zn	79	8	18	2	544	29	164	8	500	1	0	1000	0	0	500	1	0

1. Qatar quality criteria for TWW used for irrigation (Mesaieed industrial city, 2011)
2. Qatar quality criteria for TWW discharged to marine water (Mesaieed industrial city, 2011)
3. Qatar drinking and irrigation water standards(Schlumberger water services, 2009)

Metal and metalloid concentrations

All the metal concentrations were below the different standards, except Mn, which violated all the standards in winter only. However, only one lagoon violated the Mn standard, that lagoon is Al-Mearad receives storm water and surface water, suggesting that this increase may be related to point source pollution and does not represent all lagoons.

4.3.1.3 Lagoon water processes and rock-water interactions.

Lagoons' water is sourced from TWW, WW, groundwater, surface and storm water, but it is stored in unlined depressions which will affect the environmental conditions of the lagoon. In particular, the solubility of contacting rock layers will influence the water characteristics, through dissolution and precipitation reactions (Dixit *et al.*, 2021; Joshi *et al.*, 2021). This section will discuss the main processes exhibited in the lagoons as suggested by PCA and HCA multivariate analysis. The processes discussed in the sequence include: (i) salinization; (ii) interactions between water and rock; (iii) saturation minerals; (iv) oxidation and reduction processes.

Salinization in Lagoon water.

The lagoon PCA results suggested minimal changes in most metals between summer and winter, where the correlations of the variables yielded the same groups (Fig 4.1). The chemical variables indicating salinization (Cl^-, Na^+, EC, Li^+, and K^+) clustered tightly together in both summer and winter (Fig 4.1). Those variables were also seen to belong to the same group in the HCA Dendrogram (Fig 4.2). The lagoon chemistry was therefore dominated by salinization, regardless of season, as found in groundwater studies reported in previous studies in Qatar (Shomar, 2015; Ahmad *et al.*, 2020).

Piper diagrams were mostly used in groundwater evaluation studies to understand the relative importance of salinization and carbonate dissolution in aquifers (FAO *et al.*, 2016; Elumalai *et al.*, 2020; Narikkatan *et al.*, 2021). Piper plots provide a means of collectively visualizing a number of common ions in water samples. While other plot types can display the abundance of ions in groundwater, this plot type is particularly popular in water quality research because it allows arranging many samples of water on the plot to show their water type as a group in terms of cation and anion species (Walter *et al.*, 2017; Dixit *et al.*, 2021; Joshi *et al.*, 2021). The Piper diagram (Fig. 4.3) shows that eight out of ten lagoons were shown to be of 'Na^+- Cl^- type' in summer and four out of ten in winter; the majority of the lagoons were 'Na^+- Cl^- type' in both summer and winter. Nevertheless, two lagoons were shown to have fresh water characteristics but with calcium bicarbonate type, those two lagoons (Doha west and Ash-Shahanyyia) have a constant flow of

TWW. This demonstrates that not all lagoons were affected by salinization conditions in Qatar; a few lagoons were still considered fresh or non-saline.

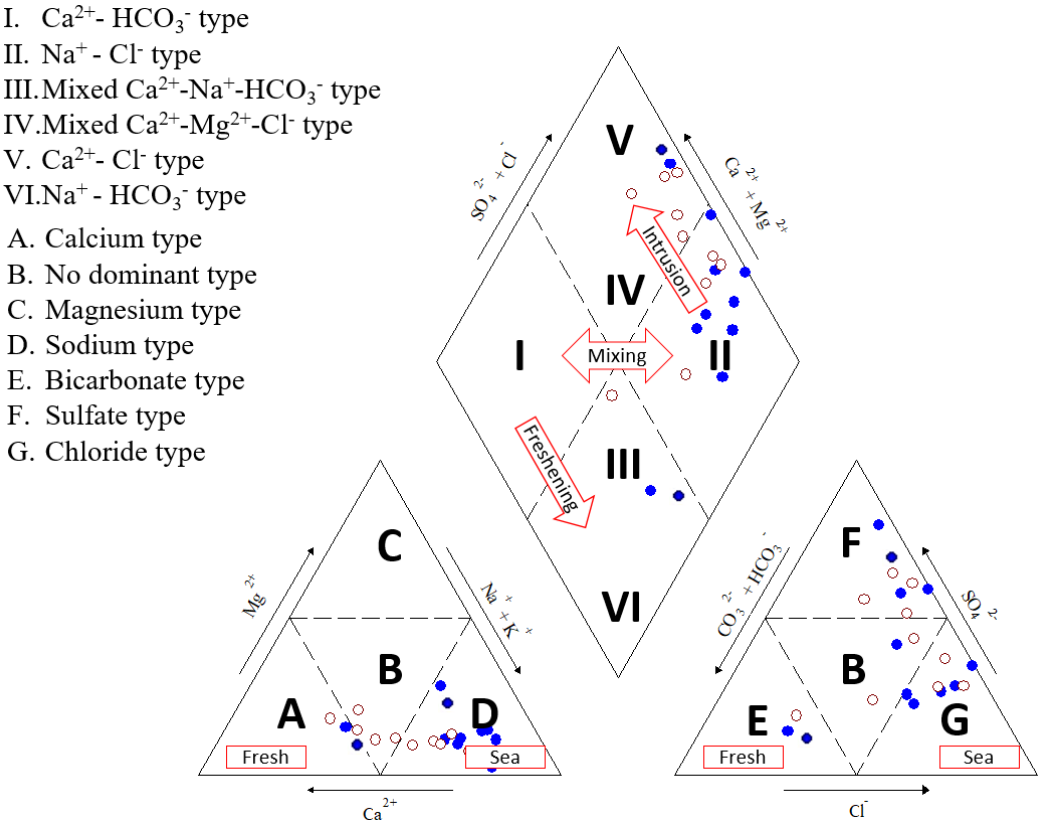


Figure 4.3. Piper diagram showing different water types of lagoons based on the major cations (Ca^{2+}, Mg^{2+}, Na^+ and K^+) and major anions (HCO^{-3}, Cl^- and SO_4^{2-}) in meq L^{-1} (Left: summer, right: winter)); the ion exchange processes are shown in the red arrows, with typical seawater or freshwater processes illustrated.

Rock-water interactions in lagoon water.

Both PCA and HCA illustrated a correlation between chemical variables reported to be linked to water/rock interactions in Qatar (Kuiper *et al.*, 2015; FAO *et al.*, 2016), those variables were SO_4^{2-}, Ca^{2+}, Mg^{2+}, and Sr^{2+}. In winter those variables correlated with salinity but in summer formed a separate group (B) with other metals.

Moreover, the Piper diagram not only showed salinization in lagoon water but also demonstrated rock water interactions with five lagoons being Ca^{2+}- Mg^{2+}- HCO^-_3 types. Nonetheless, water/rock interactions will be shown in more detail with the Gibbs plot and Chadha diagram. Furthermore, the Gibbs plot is developed to show three processes altering surface water chemistry in lakes, rivers, and wetlands, with those processes expressed on the plot (Cirelli *et al.*, 2004; Zhang *et al.*, 2008; Sharma *et al.*, 2016). Thus, it is used here to show the evaporation, precipitation and rock weathering processes in the lagoon and the difference between summer and winter samples (Fig 4.4)

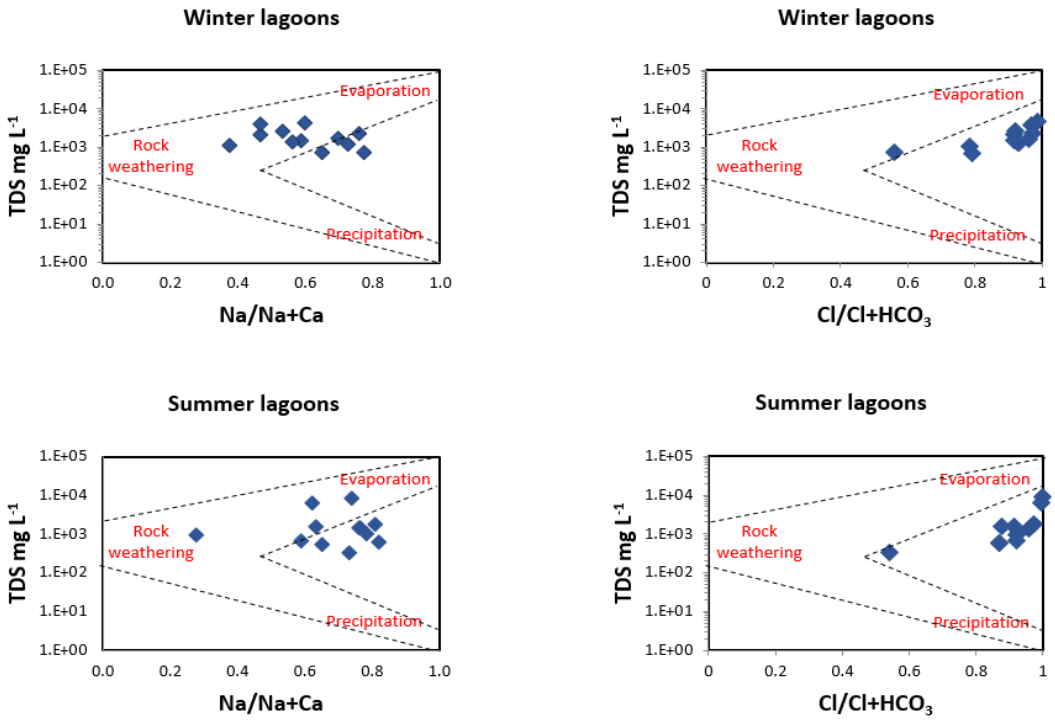


Figure 4.4. Gibbs plot showing lagoon water summer and winter evaporation, precipitation and rock weathering processes based on $Na^+/Na^+{+}Ca^{2+}$ relation and $Cl^-/Cl^-{+}HCO_3^-$ relation with TDS in mg L^{-1}.

It is seen that all data points falling within the Gibbs boomerang are explained by one of the three processes. Looking at Figure 4.4 for the ($Na^+/Na^+{+}Ca^{2+}$) plot, the majority fell within the boomerang near the evaporation-crystallization lines showing the lagoon is dominated by the evaporation of water which is expected for the extremely arid Qatar conditions. However, the data points move more to the area outside the boomerang in summer. This shows the increase in Na^+ concentration and indicates the introduction of halite dissolution in the water increasing the salinity. For the ($Cl^-/Cl^-{+}HCO_3^-$) plots, for both winter and summer, the data fell outside the Gibbs boomerang, illustrating the high concentration of Cl^- because of salinization. Conversely, this result of salinity for the lagoons was not expected since the lagoon's main water source is municipal TWW and surface water with a low salinity, which could indicate that perhaps surface water is of high salinity and is also mixed in the lagoons. Moreover, the Gibbs plot is mostly used in the literature to show water/rock interaction; here the high Na^+ and Cl^- values showed only the evaporation points in winter when the samples fell within the boomerang, preventing the plot from showing the other water/rock interaction.

The influence of salinization on the water/rock variables is seen in both PCA and HCA, in which the salinization variables were correlated with rock/water variables in the same group. Nevertheless, summer HCA separated the two into different groups, which could be due to the increase in

salinization leading to a higher correlation of the salinity variables separating them into a different group. Another tool that can be used to show the rock/water process is the Chadha diagram. While the Chadha diagram was found to be used less often than the Gibbs plot in hydrochemistry research, it is proposed in the literature that it more effectively illustrates the water/rock interaction in the presence of high concentrations of Na^+ and Cl^-.

In summer, the lagoons were found to be in four Chadha water types (Figure 4.5 and Table 4.10). One lagoon was in type 5, a Ca^{2+} –Mg^{2+} –HCO_3^- type, which is regarded as recharging water. Four lagoons in winter and one lagoon in summer were in type 6 (Ca^{2+} –Mg^{2+} –Cl^- type), known as reverse ion-exchange water, where Na^+ is replaced by Ca^{2+} and Mg^{2+}. All the lagoons with this water type were receiving surface water (Mesaimeer, Al-Mearad, Industrial and Al-Karanna), this explains the lagoon moving to type 6 in winter because of the increasing amount of surface water after rainfall events which has been in contact with gypsum. Two in summer and winter were type 7 (Na^+ – Cl^- type), subject to the influence of seawater; both those two lagoons lay adjacent to seawater (Al-Khore and Al-Dhukhariah).

Lastly, five lagoons in winter and nine lagoons in summer were type 8 (Na^+ – HCO_3^- type) which is the base ion-exchange type; if this water was used for irrigation then it would deposit residual sodium carbonate causing soil structural damage. This shows that lagoons with TWW were mostly influenced by ion exchange with Na^+ and not direct salinization (Na^+ – Cl^- type). In addition, the reservations of using each water type are shown in Table 4.10, where all the lagoons water was shown to have either hardness or sodium accumulation problems on irrigated soil.

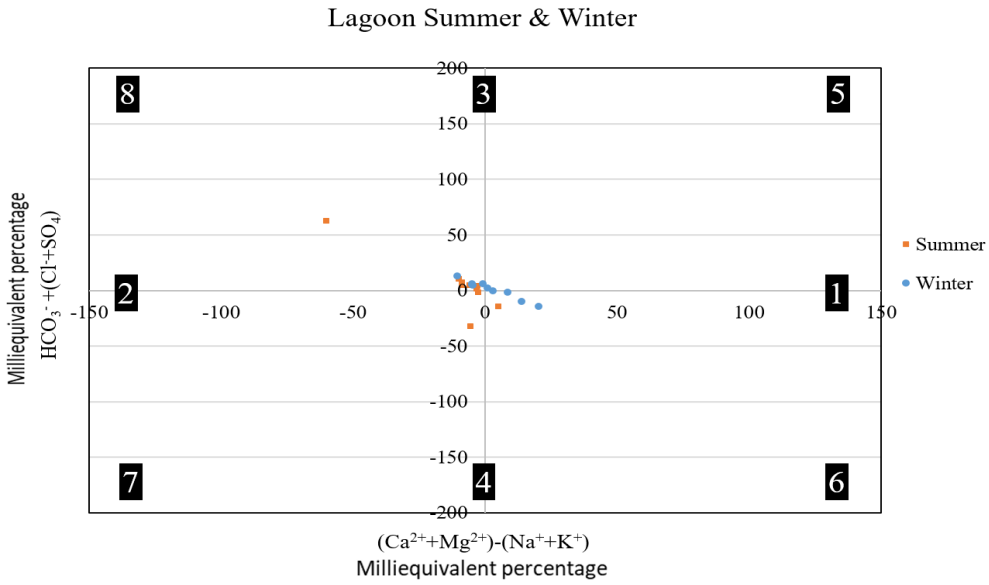


Figure 4.5. A Chadha diagram illustrating the lagoon water-rock process difference between summer and winter, with each section on the diagram labelled from 1 to 8 showing different processes

Table 4.10. The different field descriptions divided by a Chadha diagram with their water types, and the number of lagoon sources represented in each field both in summer and winter

#	Field description*	Water type*	Summer	Winter
1	Alkaline earths were dominants and surpass alkali metals	Ca^{2+} + Mg^{2+}	0	0
2	Alkali metals were dominants and surpass alkaline earths	Na^{+} + K^{+}	0	0
3	Weak acidic anions were dominants and surpass strong acidic anions	HCO_3^{-} + CO_3	0	0
4	Strong acidic anions were dominants and surpass weak acidic anions	Cl^{-} + SO_4^{2-}	0	0
5	Alkaline earths and weak acidic anions were dominants and surpass both alkali metals and strong acidic anions, respectively. For that, the water has temporary hardness.	Ca^{2+} – Mg^{2+} – HCO_3^{-} type, Ca^{2+} – Mg^{2+} dominant HCO_3^{-} type, or HCO_3^{-} dominant Ca^{2+} – Mg^{2+} type waters	0	1
6	Alkaline earths were dominants and surpass alkali metals and strong acidic anions exceed weak acidic anions. For that, the water has permanent hardness and will not add residual sodium carbonate to irrigated soil.	Ca^{2+} – Mg^{2+} –Cl^{-} type, Ca^{2+} – Mg^{2+} dominant Cl^{-} type, or Cl^{-} dominant Ca^{2+} – Mg^{2+} type waters	1	4
7	Alkali metals were dominants and surpass alkaline earths and strong acidic anions exceed weak acidic anions. For that, the water will likely cause salinity problems for irrigation and drinking uses.	Na^{+} – Cl^{-} type, Na_2SO_4 type, Na^{+} -dominant Cl^{-} type, or Cl^{-} dominant Na^{+} type waters	2	2
8	Alkali metals were dominants and surpass alkaline earths and weak acidic anions exceed strong acidic anions. For that, the water will deposit residual sodium carbonate in irrigation soil and could cause soil structure damage.	Na^{+} – HCO_3^{-} type, Na^{+} dominant HCO_3^{-} type, or HCO_3^{-} dominant Na^{+} type waters	9	5

* Adopted from (Chadha D., 1999)

Mineral saturation in lagoon water

The saturation index (SI) is used to demonstrate a solution's thermodynamic condition in relation to equilibrium with solid-phase minerals in any water system. Thus, it has been utilized by much hydrochemical research on groundwater using SI to understand mineralization in the aquifers (Cirelli *et al.*, 2004; Zaidi *et al.*, 2015; FAO *et al.*, 2016). Since both lagoons and groundwater were influenced by local lithology, SI will also be used to illustrate mineralization in lagoons, where PHREEQC was used to calculate SI values for gypsum, calcite, aragonite, and anhydrite (Fig 4.6 and 4.7).

Lagoons were dominated by gypsum and anhydrite dissolution, as also reported for groundwater in Qatar (Cirelli *et al.*, 2004; Zaidi *et al.*, 2015; FAO *et al.*, 2016). Also, lagoons were dominated by the oversaturation of both aragonite and calcite. Calcite oversaturation and precipitation were reported in

previous studies for wetlands with alkaline water in a calcareous environment similar to that of Qatar (Sadiq *et al.*, 2002; Dill *et al.*, 2007; Rivers *et al.*, 2019).

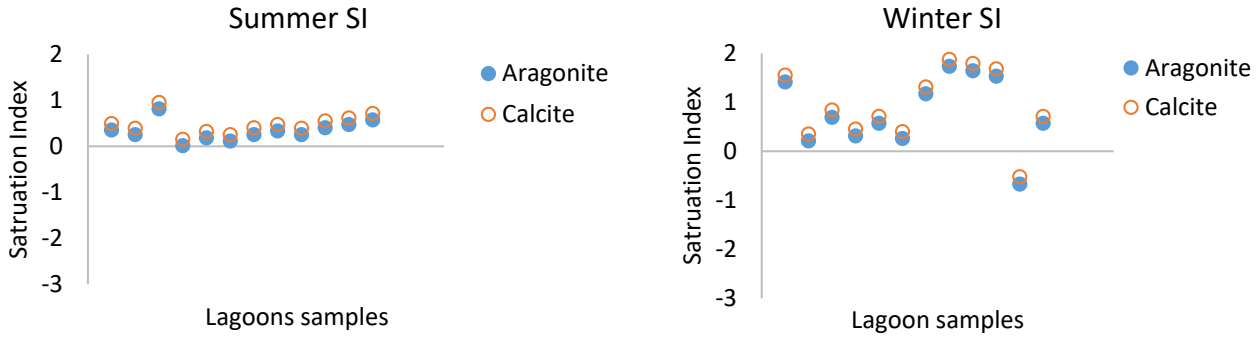


Figure 4.6. Lagoon water Aragonite and Calcite Saturation indices for summer (left) and winter (right).

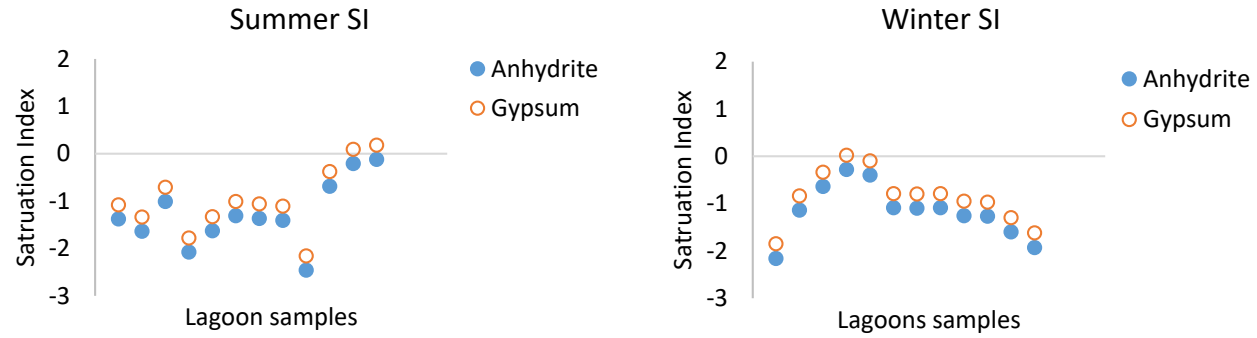


Figure 4.7. Lagoon water anhydrite and gypsum saturation indices for summer (left) and winter (right).

In addition, log of the ion activity products (log_{10} (IAP)) for Ca^{2+} and SO_4^{2-} were calculated to reveal that gypsum dissolution is active in the lagoon during both summer and winter. As the Ca^{2+} ion activity increased, the system approached gypsum saturation ($-log_{10}Ks = 4.6$), as shown in Figure 4.8. The results indicate that gypsum solubility is controlling Ca^{2+} and SO_4^{2-} activities in the lagoon (IAP Ks) in both summer and winter. This finding is consistent with earlier groundwater studies in the area, indicating lagoons were also affected by gypsum dissolution.

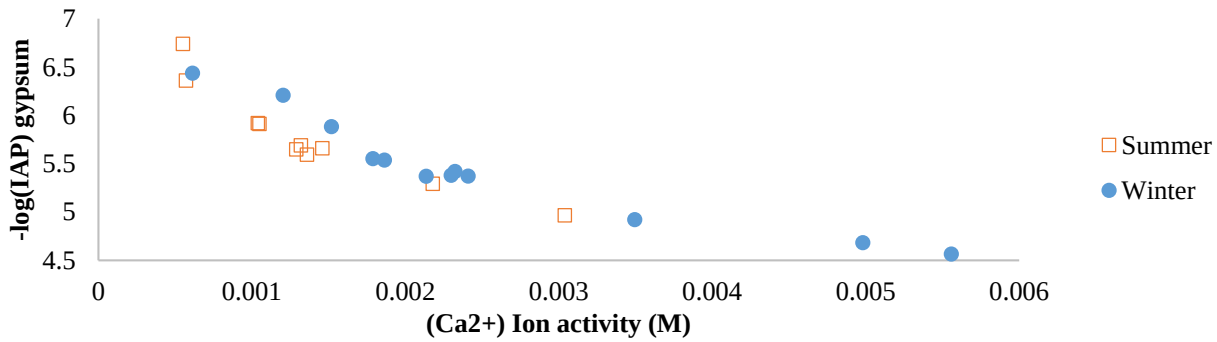


Figure 4.8. Lagoon water summer and winter dissolution processes are shown by gypsum log(IAP) vs Ca^{2+} ion activity with a gypsum saturation point of 4.6 (log_{10}IAP – log_{10}Ks).

Oxidation and Reduction in Lagoon water

Redox reactions in aqueous systems exercise control over the concentration of many chemical species and the availability of some pollutants (Appelo *et al.*, 1993; Smedley *et al.*, 2002). Under reducing conditions, the presence of NO_3^- will result in the process of denitrification and loss as N_2O and N_2 gas. Further reduction will cause Fe^{III} and Mn^{IV} oxides to act as alternative electron acceptors and dissolve, releasing Fe^{2+} and Mn^{2+} ions into the solution along with adsorbed species such as heavy metals and arsenate/arsenite (Smedley *et al.*, 2002; Hsu *et al.*, 2010; Al-Farraj *et al.*, 2013); Those processes were equally significant in a lagoon or aquifer system. Oxidation and reduction processes in wetlands have been studied previously using multivariate statistical analysis, which showed that heavy metals (Fe, Mn, As, Cu, Cd, Cr) were correlated with TOC indicating reduction condition; by contrast, high concentrations of NO_3^- and low concentrations of redox-sensitive metals indicate oxic conditions (Ogunlaja *et al.*, 2019; Huang *et al.*, 2020; Xia *et al.*, 2021). In this research, both PCA and HCA showed a range of correlations where heavy metals such as Fe, Al, Zn and V were associated with TOC, indicating reducing conditions. However, Mn a heavy metal whose solubility is associated with that of Fe in reducing environments (Landajo *et al.*, 2004; Rattan *et al.*, 2005; Barzegar *et al.*, 2015), was seen in a separate group with iodine in both summer and winter, with Fe and As joining the group in winter (Fig 4.1). Moreover, with HCA it was seen that Mn was in the same group as sulphate in summer, but was part of the redox variables group in winter (Fig 4.1)

This could be explained by the ‘reduction ladder’, where in summer conditions were sub-oxic thus Mn was reduced and SO_4^{2-} was available. However, in winter the system becomes sulfidic where Fe^{III}, As^{V} and SO_4^{2-} were all reduced (Kerr *et al.*, 2008; Di Luca *et al.*, 2011; Hansen *et al.*, 2022). This indicates in summer the lagoon water was freshly deposited and in the winter season after a few months had passed the lagoon system had been stagnant sufficiently long for reduction processes to be complete. This was verified using satellite historical views where lagoons were seen to be filled and emptied with water several times during the year. A similar situation was seen in studies of wetland drying and re-flooding influence on the redox chemistry of metals, where at the end of the flooding the wetland would be in a sulfidic condition (Hansen *et al.*, 2022).

4.3.2 Qatar Groundwater Aquifers

This chapter's primary objective is to understand the effects of lagoon water infiltration on groundwater reservoirs. For that, an understanding and characterization of Qatar's groundwater quality must be established. To achieve that, chemical and physical variables must be analysed and

investigated for (i) groundwater chemical processes, and (ii) spatial and temporal variation between the years 2018-2020.

The groundwater in Qatar will be discussed and the results presented in this section. The statistical analysis results will be presented first, followed by a discussion of the primary water quality in comparison to national and international criteria for groundwater drinking and irrigation guidelines. The key water processes in groundwater water will then be discussed.

4.3.2.1 Groundwater multivariate statistical analysis

To understand the relationship between the different chemical and physical characteristics of the groundwater and how they change and respond to each other, multivariate statistical analyses were performed. A few tested variables were excluded from this study since they were not detected in most samples or were detected at negligible concentrations below LOD. Those variables were: Pb, Tl, Cs, Cd, Ag, Co, Be, Ti, P and PO_4^{3-}

Groundwater Normality test

After conducting both normality tests, Table 4.11 shows that 22 out of 32 were not normal ($p<0.05$) according to the Kolmogorov-Smirnov test and 23 out of 32 were not normal using the Shapiro-Wilk test ($p<0.05$). Thus, this data set is not normal.

Table 4.11. Tests of Normality (Kolmogorov-Smirnov and Shapiro-Wilk) for all the groundwater variables, If the significance level (Sig.) value of the test is greater than 0.05, the data is normal. If it is below 0.05, the data significantly deviate from a normal distribution

	Kolmogorov-Smirnov			Shapiro-Wilk				Kolmogorov-Smirnov			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.		Statistic	df	Sig.	Statistic	df	Sig.
General water quality variables							**SO_4^{2-}**	0.131	53	0.023	0.86	53	0
EC	0.258	53	0	0.633	53	0	**Metal and metalloid variables**						
IC	0.058	53	.200	0.983	53	0.626	**Al**	0.153	53	0.003	0.779	53	0
pH	0.097	53	.200	0.985	53	0.725	**As**	0.129	53	0.027	0.877	53	0
TDS	0.258	53	0	0.633	53	0	**Ba**	0.186	53	0	0.892	53	0
Temp	0.099	53	.200	0.990	53	0.725	**Cr**	0.226	53	0	0.728	53	0
TN	0.134	53	0.019	0.953	53	0.035	**Cu**	0.435	53	0	0.172	53	0
TOC	0.165	53	0.001	0.877	53	0	**Fe**	0.454	53	0	0.172	53	0
Anionic and cationic variables							**Li**	0.202	53	0	0.698	53	0
B	0.111	53	0.099	0.905	53	0	**Mn**	0.345	53	0	0.471	53	0
Ca^{2+}	0.07	53	.200	0.985	53	0.764	**Mo**	0.233	53	0	0.78	53	0
Cl^-	0.285	53	0	0.589	53	0	**Ni**	0.201	53	0	0.749	53	0
I	0.057	53	.200	0.973	53	0.283	**Rb**	0.241	53	0	0.669	53	0
K^+	0.239	53	0	0.698	53	0	**Se**	0.187	53	0	0.777	53	0
Mg^{2+}	0.187	53	0	0.796	53	0	**Sr**	0.091	53	.200	0.957	53	0.054
Na^+	0.312	53	0	0.571	53	0	**U**	0.139	53	0.012	0.867	53	0
NO_3^-	0.146	53	0.007	0.874	53	0	**V**	0.103	53	.200	0.96	53	0.076
S	0.089	53	.200	0.962	53	0.088	**Zn**	0.27	53	0	0.693	53	0

Groundwater Principal Component analysis (PCA)

For a better picture of the groundwater characteristics, a PCA was conducted for both summer and winter samples to demonstrate how the variables are correlated; since the data set was not normally distributed, a KMO Bartlett's Test was implemented. The KMO value was (0.594; Table 4.12). This value is acceptable and no data correction is needed.

Table 4.12 Groundwater data KMO and Bartlett's test results

KMO and Bartlett's Test		
KMO measure of sampling adequacy.		.594
Bartlett's Test of Sphericity	**Approx. Chi-Square**	1886.618
	df	496
	Sig.	.000

It was apparent, for both summer and winter data sets, six PCs explain 75% of eigenvalues (Table 4.13). This is a high number of PCs compared to other groundwater studies which usually involves only three PCs. However, those studies have used a smaller number of variables to compare. Few studies dealing with groundwater hydrology have used as many PCs when using a similar number of measured variables (Ravikumar *et al.*, 2017; Rezaei *et al.*, 2021).

For PC analysis a plot (Fig 4.9) was used to analyse 32 physical and chemical variables for groundwater samples in summer and winter. For summer samples there were three groups: Group A included EC, TDS, Na^+, K^+, Cl^-, Ca^{2+}, S, SO_4^{2-}, Mg^{2+}, B, and Rb; Group B has TN, pH, TOC, IC, Se, As, Cu, V, Ni, Al, Fe, Cr, Mn, Mo, Li, I and Se; Group C contained NO_3, TN, V, and Cr. For winter three groups were formed: Group A included EC, TDS, Na^+, K^+, Cl^-, B and Rb; Group B had NO_3, TN, pH, TOC, IC, Se, As, V, Ni, Cu, Al, Fe, Cr, Mn, Mo, Zn, I and Se; Group C contained Ca^{2+}, S, SO_4^{2-}, Li, Sr and Mg; only Ba did not form part of a group.

TN and NO_3 were in the same group; there was a strong association between the two having similar PC ratings. This indicates that NO_3 in the groundwater accounts for the majority of TN. Furthermore, there is a clear association between total S and SO_4^{2-} in terms of Sulfur species, with both having high PC scores; this indicates that SO_4^{2-} makes up the majority of the S in the groundwater.

Table 4.13 Groundwater principal components. PC1 to PC8 had cumulative eigenvalues of 80% for summer and winter.

	Summer						Winter					
	PC1	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**	**PC1**	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**
Cumulative %	31	42	52	59	65	71	29	41	52	61	69	75
General water quality variables												
EC	**0.915**	-0.331	0.084	0.119	-0.067	-0.09	**0.869**	0.33	0.233	0.046	0.067	-0.077
IC	0.026	**0.674**	0.432	0.141	-0.216	-0.092	-0.117	-0.26	-0.101	**0.786**	-0.083	0.117
pH	-0.102	-0.115	0.08	0.13	0.28	0.261	-0.028	0.086	0.427	-0.253	0.245	-0.023
TDS	**0.915**	-0.331	0.084	0.119	-0.067	-0.09	**0.887**	0.221	0.002	-0.067	-0.006	0.013
TN	**0.539**	0.14	-0.402	0.078	-0.292	0.398	0.256	0.208	**0.836**	0.01	-0.063	0.118
TOC	**0.587**	0.385	0.355	0.395	0.021	-0.013	-0.129	-0.07	-0.073	-0.079	0.049	0.088
Anionic and cationic variables												
B	**0.711**	0.048	0.151	-0.299	-0.059	-0.009	0.519	0.299	0.151	0.271	-0.152	**0.422**
Ca^{2+}	**0.647**	0.029	-0.285	-0.118	0.448	0.034	0.201	**0.869**	0.231	-0.06	0.059	-0.112
Cl^{-}	**0.885**	-0.369	0.098	0.158	-0.098	-0.108	**0.949**	0.082	0.154	-0.019	0.038	-0.089
I	0.183	0.132	0.447	-0.339	-0.174	0.44	0.298	0.167	0.08	0.039	0.093	**0.766**
K	**0.862**	-0.219	0.191	0.012	-0.235	0.014	**0.876**	0.105	0.021	-0.023	-0.037	0.238
Mg^{2+}	**0.935**	0.019	0.142	0.071	0.064	-0.111	0.665	**0.579**	0.124	0.302	-0.018	0.131
Na^{+}	**0.897**	-0.312	0.103	0.163	-0.187	-0.056	**0.964**	0.123	0.145	-0.029	0.043	-0.05
NO_3	0.491	**0.565**	-0.379	-0.009	-0.233	0.33	-0.078	0.246	**0.902**	0.087	-0.107	0.098
S	**0.851**	0.108	-0.088	-0.305	0.275	0.105	0.317	**0.897**	0.142	0.051	-0.034	0.077
SO_4^{2-}	**0.552**	0.025	-0.103	-0.482	0.338	0.08	0.315	**0.845**	0.149	0.044	-0.09	0.163
Metal and metalloid variables												
Al	0.336	0.419	0.099	0.212	0.367	-0.202	0.174	0.029	0.02	-0.058	-0.081	-0.73
As	0.172	-0.039	-0.171	0.19	-0.072	0.366	0.063	0.132	0.173	-0.053	**0.904**	-0.037
Ba	0.03	0.198	0.216	**0.665**	-0.437	-0.16	0.065	-0.733	0.184	0.114	-0.01	0.005
Cr	0.348	0.12	**-0.637**	0.276	-0.349	0.207	0.2	-0.117	**0.619**	-0.04	-0.059	-0.249
Cu	0.272	0.598	0.252	0.191	0.429	-0.11	0.409	0.2	0.118	0.147	-0.086	0.055
Fe	-0.021	-0.238	0.268	0.322	0.348	**0.527**	-0.007	-0.057	-0.213	0.009	**0.855**	0.072
Li	**0.63**	0.016	-0.081	-0.194	0.206	-0.14	0.458	**0.698**	0.112	0.347	0.021	-0.042
Mn	-0.138	-0.304	0.391	0.332	0.284	**0.611**	0.003	-0.097	-0.302	-0.166	**0.592**	0.407
Mo	-0.01	-0.091	**0.508**	-0.452	-0.348	0.254	-0.066	-0.099	-0.104	0.252	0.213	-0.07
Ni	-0.15	0.2	**0.662**	0.041	-0.172	0.1	-0.097	-0.014	-0.124	0.164	0.008	0.101
Rb	**0.816**	-0.454	0.186	0.071	-0.044	-0.214	**0.938**	0.14	-0.158	-0.152	0.007	-0.023
Se	0.395	0.453	0.023	-0.275	-0.197	0.003	0.086	0.173	0.246	**0.632**	-0.092	-0.296
Sr	**0.732**	0.201	-0.115	-0.102	-0.002	0.226	0.327	0.605	0.425	0.17	0.209	0.003
U	0.174	**0.743**	0.389	-0.248	-0.034	-0.031	-0.088	0.34	0.012	**0.764**	-0.03	0.189
V	0.153	0.458	**-0.641**	0.191	-0.072	0.074	-0.149	0.064	0.404	0.232	-0.161	-0.239
Zn	0.221	0.289	0.009	0.358	0.47	0.013	-0.007	0.084	0.03	0.004	-0.018	-0.053

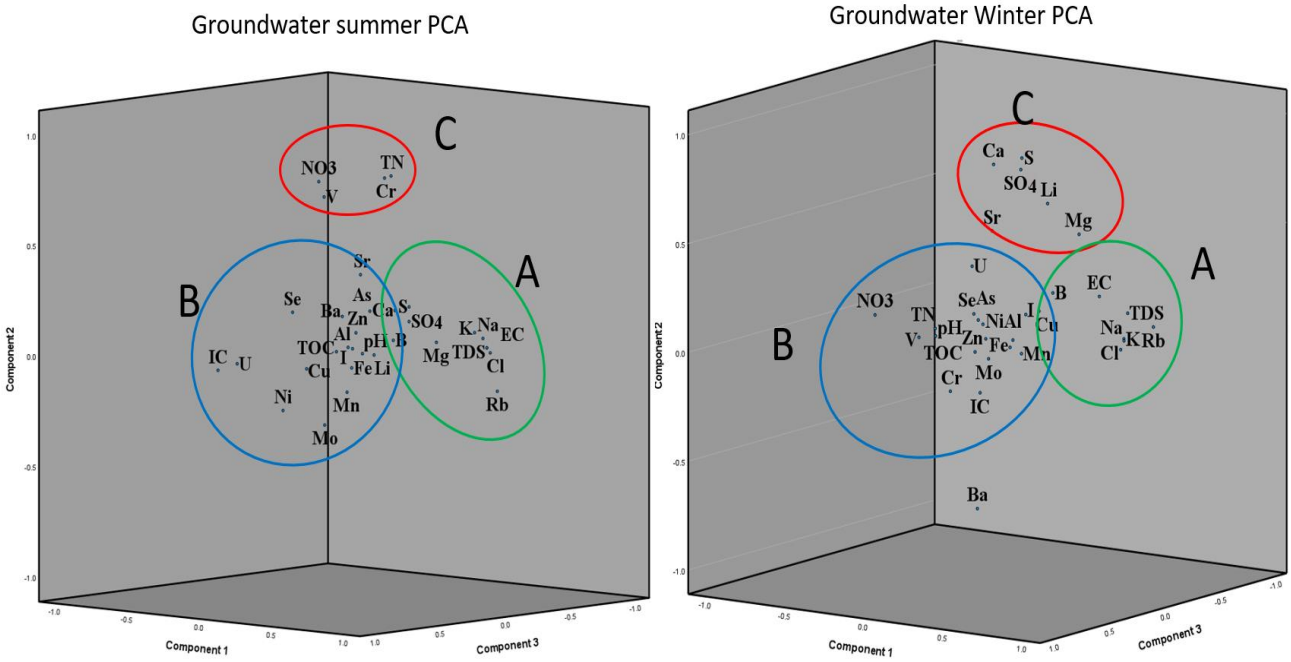


Figure 4.9. Groundwater PCA 3D plot for 32 physical and chemical variables (summer: left, winter: right). Varibles clustered in the same group showen by three circules labled A,B and C. PCA was used with the Varimax rotation method and Kaiser Normalization.

Groundwater hierarchical cluster analysis (HCA)

Clustering analysis has been used in many groundwater quality studies to organize a set of variables in a way that variables in the same cluster were more similar to each other than to those in other clusters (Nathan *et al.*, 2017; Abdelaziz *et al.*, 2020; Egbueri, 2020). Figure 4.10 shows the clustering variables in different clades in the Dendrogram, with clade A in both winter and summer being the same, with the exception of I in winter. Clade B is also similar between the two seasons with the exception of Cu in winter. Finally, clade C is the same between summer and winter

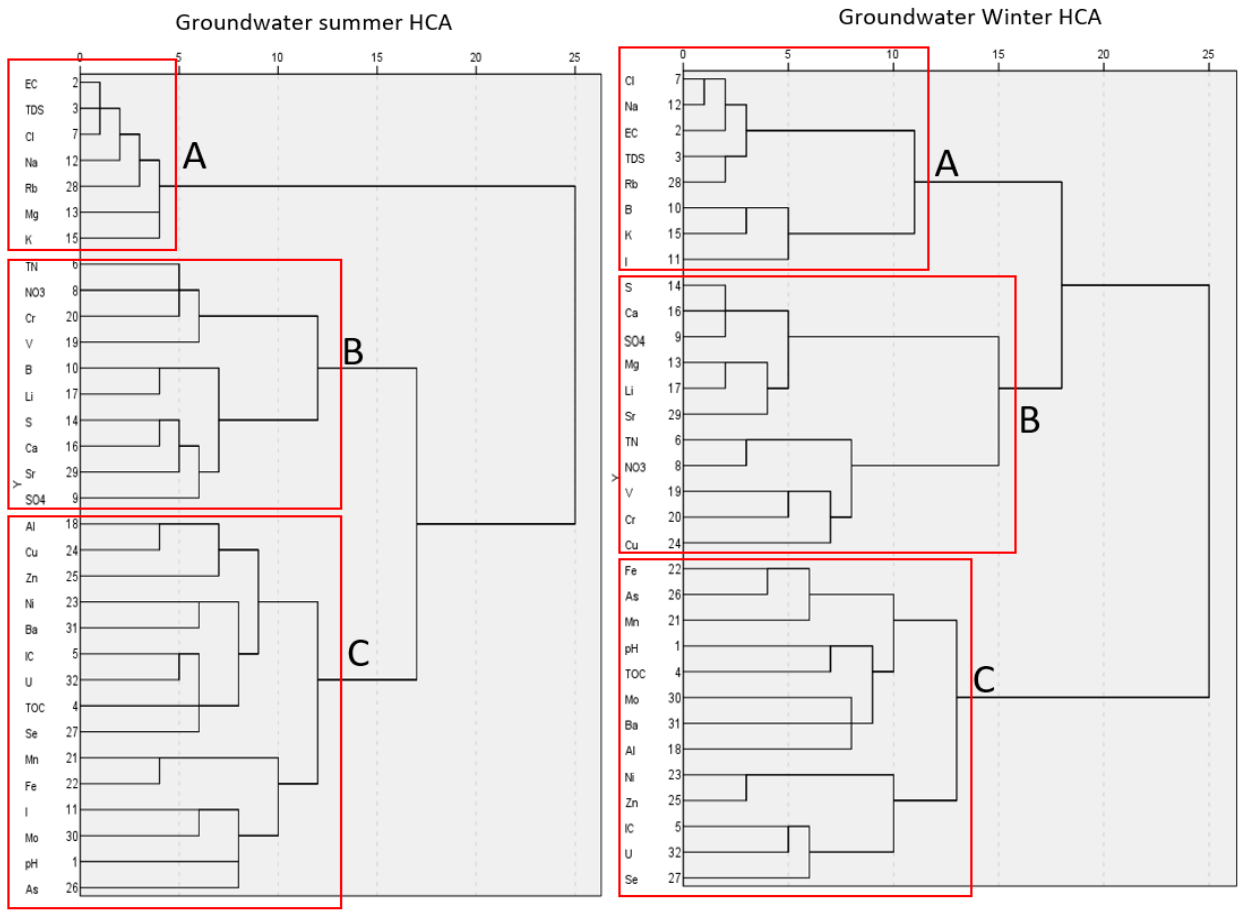


Figure 4.10 Groundwater Dendrogram, produced from HCA, using ward linkage, with Euclidean distance measurement with Z score standardization transformation. Varibles clustered in the same group showen by three squares labled A,B and C. (Summer: left, winter: right)

Groundwater Generalized Linear Model

Spatial and temporal variation in groundwater was statistically tested using a GLM. This approach works by linking the measured variables as dependent values to the fixed factors and measuring the magnitude of the factors' influence on the magnitude of the variables. The fixed factors here will be:

- Seasonal variations were represented by summer (dry season) and winter (wet season)
- Wells' distance to the nearest point on the coast

GLM results for the influence of season on the groundwater variables showed that it has a significant influence ($p<0.05$) on EC, IC, pH, Temp, TOC, Ca^{2+}, I and SO_4^{2-} (Table 4.14). Moreover, GLM analysis on the influence of groundwater proximity to the coast showed a significant influence ($p<0.05$) on EC, TDS, TN, Cl, Na^+, Ca^{2+}, K, Li, Rb, Sr, and U (Table 4.15).

Table 4.14. Results of GLM showing a significant correlation between groundwater variables and seasonal variation between summer and winter (p<0.05) highlighted in grey

Dependent Variable	Mean Square	F	Sig.	Dependent Variable	Mean Square	F	Sig.
General water Quality Variables				**SO_4^{2-}**	157083	5.674	0.019
EC	166.557	17.284	0	**Metal and metalloid variables**			
IC	565.9	4.469	0.037	**Al**	237.996	2.623	0.108
pH	0.823	9.628	0.002	**As**	2.618	1.746	0.189
TDS	1.83E+08	69.811	0	**Ba**	261.188	2.811	0.097
Temp	821.727	88.807	0	**Cr**	1.334	0.116	0.734
TN	52.445	3.092	0.082	**Cu**	120.929	1.203	0.275
TOC	685.645	114.517	0	**Fe**	307.582	0.032	0.859
Anionic and cationic variables				**Li**	16.51	0.006	0.938
B	0.015	0.063	0.802	**Mn**	2.736	0.177	0.675
Ca^{2+}	117416.1	7.655	0.007	**Mo**	1752.914	1.36	0.246
Cl^-	2113509	2.418	0.123	**Ni**	7.56	1.184	0.279
I	6959.718	8.742	0.004	**Rb**	16.348	0.456	0.501
K^+	321.379	0.603	0.439	**Se**	4.064	0.122	0.727
Mg^{2+}	1100.889	0.242	0.624	**Sr**	3417494	0.345	0.558
Na^+	67563.63	0.178	0.674	**U**	118.125	2.338	0.129
NO_3^-	75.475	1.006	0.318	**V**	324.049	1.888	0.172
S	28084.92	0.952	0.332	**Zn**	3197.706	0.678	0.412

Table 4.15 Results of GLM showing a significant correlation between groundwater variables and distance to the coast (p<0.05) highlighted in grey

Dependent Variable	Mean Square	F	Sig.	Dependent Variable	Mean Square	F	Sig.
General water Quality Variables				**SO_4^{2-}**	5126.123	0.185	0.668
EC	70.222	7.287	0.008	**Metal and metalloid variables**			
IC	54.703	0.432	0.512	**Al**	22.367	0.246	0.621
pH	0.001	0.006	0.938	**As**	0.807	0.538	0.465
TDS	16969392.65	6.462	0.013	**Ba**	195.026	2.099	0.15
Temp	2.899	0.313	0.577	**Cr**	8.361	0.729	0.395
TN	97.305	5.737	0.018	**Cu**	81.544	0.811	0.37
TOC	7.144	1.193	0.277	**Fe**	24002.467	2.487	0.118
Anionic and cationic variables				**Li**	10358.315	3.852	0.05
B	0.235	0.988	0.323	**Mn**	47.952	3.096	0.081
Ca^{2+}	63846.19	4.163	0.044	**Mo**	90.589	0.07	0.791
Cl^-	10024926.5	11.467	0.001	**Ni**	8.066	1.264	0.264
I	1068.149	1.342	0.249	**Rb**	457.971	12.776	0.001
K^+	5258.802	9.862	0.002	**Se**	72.292	2.178	0.143
Mg^{2+}	2048.922	0.45	0.504	**Sr**	33157895	3.348	0.07
Na^+	5169330.839	13.647	0	**U**	829.109	16.409	0
NO_3^-	27.031	0.36	0.55	**V**	31.631	0.184	0.669
S	28167.172	0.954	0.331	**Zn**	610.66	0.129	0.72

4.3.2.2 Groundwater quality compared to international and national standards

Table 4.16 presents a summary of the sampled groundwater variables, where the number of wells showing values above the recommended water quality standards of WHO Drinking water, Qatar Drinking and irrigation water is included. The data median, range and interquartile range attached in the appendix section (Appendix C). The variables for which at least one well exceeded the standards included: EC, TDS, TOC, Cl^-, SO_4^{2-}, B, Na^+, Mg^{2+}, Ca^{2+}, Fe, As, Se and U.

General water quality variables

Physical characteristics of the groundwater wells were all within the standards range and within the global groundwater naturally occurring pH range of 6-8.5 (in the absence of coal or iron sulphide minerals) (Herschy, 2012); sample temperatures were always below 45^{o}C.

Anionic and cationic variables.

The dominant cations in the groundwater were $Na^+ > Ca^{2+} > Mg^{2+} > K^+$; the dominant anions were $Cl^- > SO_4^{2-} > NO_3^-$. This is in alignment with previous literature studies of groundwater in Qatar (Shamrukh, 2014a; Kuiper *et al.*, 2015; Shomar, 2015)

Magnesium and Ca^{2+} concentrations were higher than the recommended standards from Qatar drinking regulation for all the wells sampled. In most groundwater, Ca^{2+} and Mg^{2+} are generally in balance (Princela *et al.*, 2021). Magnesium in soil could be mainly in the form of dolomite $CaMg(CO_3)_2$ where the Ca^{2+}:Mg^{2+} atomic ratio is 1:1. Groundwater typically contains calcium as carbonate, bicarbonate, sulfate, chloride, and nitrate. This elevated amount of calcium (average 450 mg L^{-1}) could be due to rock dissolutions which contribute to the permanent hardness of the water (Sahu *et al.*, 2008; Princela *et al.*, 2021).

In addition, variables associated with seawater intrusions (EC, TDS, and Na^+) consistently exceeded the WHO and Qatar Drinking water quality standards indicating, as predicted from the literature review, that the water is too saline for human consumption (Darwish *et al.*, 2013; Jafari *et al.*, 2019; MDPS, 2019).

Metal and metalloid variables

All heavy metals showed values below the maximum allowable limits recommended by both WHO and Qatar drinking regulations. Exceptions included Fe and As with two wells each in violation of the standards in summer and winter. Strontium values always violated the drinking water quality standard. It is recommended by the USEPA that Sr concentration should not exceed 4000 µg L^{-1}. The high level of Sr is discussed in most articles discussing groundwater in Qatar (Shomar, 2015;

Palanivel *et al.*, 2021), where the reason is Qatar's natural stratigraphic composition (Dill *et al.*, 2007)

Table 4.16 Summary of the sampled groundwater (summer n=53 and winter n=57) water variables (mean, minimum, maximum and standard deviation), with the number of violations to the different standards highlighted in grey

	Mean		Min		Max		SD		WHO drinking[1]			Qatar drinking[2]			Qatar irrigation[2]		
	S	W	S	W	S	W	S	W	STD	# violations S	# violations W	STD	# violations S	# violations W	STD	# violations S	# violations W
General water quality variables (mg L^{-1}), except EC in µs cm^{-1} and pH no unit																	
EC	4140	6470	1020	1760	19400	17000	3630	2660	-	-	-	**150-500**	54	57	-	-	-
pH	7	7.2	6	7.3	8	8.4	0.2	0.3	**6.5–8.5**	0	5	**6.5-8.5**	6	7	**6--9**	8	9
TDS	2650	3410	656	870	12400	20000	2320	2760	**600**	54	57	**110-250**	54	57	**2000**	25	0
Temp	30	25	28	16	42	29	3	3	-	-	-	**45**	0	0	-	-	-
TN	7	6	1	0.4	18	22	4	4	-	-	-	-	-	-	**35**	0	0
TOC	8	3	0.3	1.2	20	6	3	0.9	-	-	-	**4**	52	7	**75**	0	0
Anionic and cationic variables (mg L^{-1})																	
B	1.2	1.3	0.5	0.4	3	2.6	0.5	0.5	**2**	2	1	**1**	-	-	**2**	-	-
Ca^{2+}	453	510	221	166	755	805	115	150	-	-	-	**80**	54	56	-	-	-
Cl^{-}	1030	796	174	94	6330	4891	1209	844	**200-300**	45	47	**80**	54	57	-	-	-
F	0	0	0	0	0	0	0	0	**2**	0	0	**2**	0	0	**15**	0	0
I	88	102	30	14	177	147	27	30	-	-	-	-	-	-	-	-	-
K	48	52	17	17	166	121	27	22	-	-	-	-	-	-	-	-	-
Mg^{2+}	140	150	61	49	440	350	76	63	-	-	-	**30**	54	56	-	-	-
Na^{+}	686	656	123	78	4470	2950	796	538	**200**	49	52	**80**	54	56	-	-	-
NO_3	9	11	0	0	39	36	8	9	**50**	0	0	**10**	-	-	-	-	-
P	0	0	0	0	0	0.3	0	0	-	-	-	-	-	-	-	-	-
Po3	0	0	0	0	0	0	0	0	-	-	-	**0**	0	0	**30**	0	0
S	550	570	206	92	1140	943	170	190	-	-	-	-	-	-	-	-	-
SO_4^{2-}	527	445	166	75	1450	724	196	141	250	51	51	**50**	-	-	**400**	43	38
Metal and metalloid variables (µg L^{-1})																	
Ag	0	0	0	0	0.5	0.4	0.1	0.1	-	-	-	**100**	0	0	-	-	-
Al	1	3.7	0	0	6	90	0.9	13	**200**	0	0	**200**	0	0	**1500**	0	0
As	1.3	1.6	0.2	0	5	10	0.8	1.5	**10**	0	1	**10**	0	1	**100**	0	0
Ba	14	19	4	6	36	97	6	15	**700**	0	0	**700**	0	0	**2000**	0	0
Be	0	0	0	0	0.1	0.1	0	0	-	-	-	**4**	0	0	-	-	-
Cd	0.1	0.1	0	0	1	0.5	0.2	0.1	**3**	0	0	**3**	0	0	**50**	0	0
Co	0	0.1	0	0	0.3	0.5	0.1	0.1	**2000**	0	0	**1000**	0	0	**200**	0	0
Cr	2.4	2.7	0	0	0	20	3	3	**50**	0	0	**50**	0	0	**10**	0	0
Cs	0.5	0.7	0	0	3	4	0.6	0.8	-	-	-	-	-	-	-	-	-
Cu	3	0.8	0	0	103	3.6	14	0.7	**2000**	0	0	**1000**	0	0	**200**	0	0
Fe	21	22.1	0.2	0.5	799	606	109	83	**300**	1	1	**300**	1	1	**1000**	0	0
Li	95	91	35	27	440	190	63	40	-	-	-	**50**	45	0	-	-	-
Mn	2	2.2	0	0.1	25	14	4	3	**100**	0	0	**50**	0	0	**50**	0	0
Mo	26	32	8	0.2	98	343	17	46	-	-	-	**70**	-	-	-	-	-
Ni	2	3	0.7	0.2	9	19	3	3	**70**	0	0	**70**	0	0	**200**	0	0
Pb	0	0	0	0	0.6	0.1	0.1	0	**0**	0	0	**10**	0	0	**100**	0	0
Rb	10	11	2.5	2.3	43	39	7	7	-	-	-	-	-	-	-	-	-
Se	26	7	0.6	0.3	973	32	131	5	**40**	1	0	**12**	8	6	-	-	-
Sr	12800	12800	6180	4100	20400	21700	3080	3650	-	-	-	**4000**	54	57	-	-	-
Tl	0.2	0.2	0	0	0.9	1.2	0.2	0.2	-	-	-	**2**	0	0	-	-	-
U	13	14	3	2	42	34	7	8	**30**	2	4	**15**	14	24	-	-	-
V	22	26	0.3	0.1	45	60	12	15	-	-	-	-	-	-	-	-	-
Zn	8	18	0	0	56	701	12	92	**3000**	0	0	**3000**	0	0	**500**	0	0

1. WHO drinking water standards (Herschy, 2012)
2. Qatar drinking and irrigation water standards (Schlumberger water Services, 2009)

Molybdenum concentrations were high, this is in alignment with previous studies based in Qatar and compared to other regions (Kuiper *et al.*, 2015; FAO *et al.*, 2016). In this study Mo concentrations in some of the wells were above Qatar drinking water guidelines of (70 µg L^{-1}) and with mean values higher than FAO irrigation guidelines of (10 µg L^{-1}). The reason for elevated Mo levels has been reported to be a consequence of (i) oxic alkaline conditions in Qatar aquifers which encourage Mo solubility, (ii) demineralization and (iii) anthropological contamination (Kuiper *et al.*, 2015)

4.3.2.3 Groundwater processes and rock-water interactions

Using the results of PCA, HCA and GLM multivariate analysis and hydrochemistry plots analysis, this section will examine the key water processes that occur in the groundwater. First, the most common process of salinization will be discussed, followed by the interactions between water and rock, oxidation and reduction processes and, ultimately, the behaviour of saturation minerals in groundwater.

Salinization in Groundwater

Salinization caused by seawater intrusion is the main problem discussed in literature dealing with the Qatar groundwater system (Shamrukh, 2014a; FAO *et al.*, 2016; Al-Naimi *et al.*, 2018). To show how the salinization is happening in the groundwater, and how it changes between summer and winter, PCA, HCA, and Piper plots were constructed. First, both PCA and HCA demonstrate that summer and winter had the same variables of EC, Cl^-, Na^+, Mg^{2+}, Li^+, Rb correlated in PC1 (Table 4.13); those are variables related to salinization processes in the groundwater. From both the PCA 3D plot (Fig 4.9) and HCA Dendrogram (Fig 4.10), those variables form a distinctive group distinct from the other chemical variables. Moreover, GLM shows the influence of wells' locations on the salinization impact, where groundwater proximity to the closest coastal point was shown to influence the salinization variables, indicating marine intrusion magnitude is greater in wells closer to the coast (Table 4.15).

In addition, the Piper plot has been used in many groundwater studies to show salinization in groundwater. On the Piper plots, each groundwater type was represented on the diagram by an individual point. A Piper diagram showing the hydrochemical facies of the groundwater aquifer system (Fig 4.11) illustrates that the groundwater was mostly of the ‘chloride type’ in summer, which moves to be mostly the ‘sulphate type’ in winter, with seven wells remaining in chloride type in both seasons. This shows the seasonal impact on salinization processes in the aquifers. GLM analysis also showed the influence of the dry summer and rainfall events in winter on groundwater salinization, where the salinization variables were influenced significantly by the seasonal change (Table 4.14).

Moreover, in terms of cations, the majority of groundwaters were not dominated by any water type, with some in the calcium or sodium type; this was also seen in the GLM where the Mg^{2+} concentration was not influenced by seasonal variations.

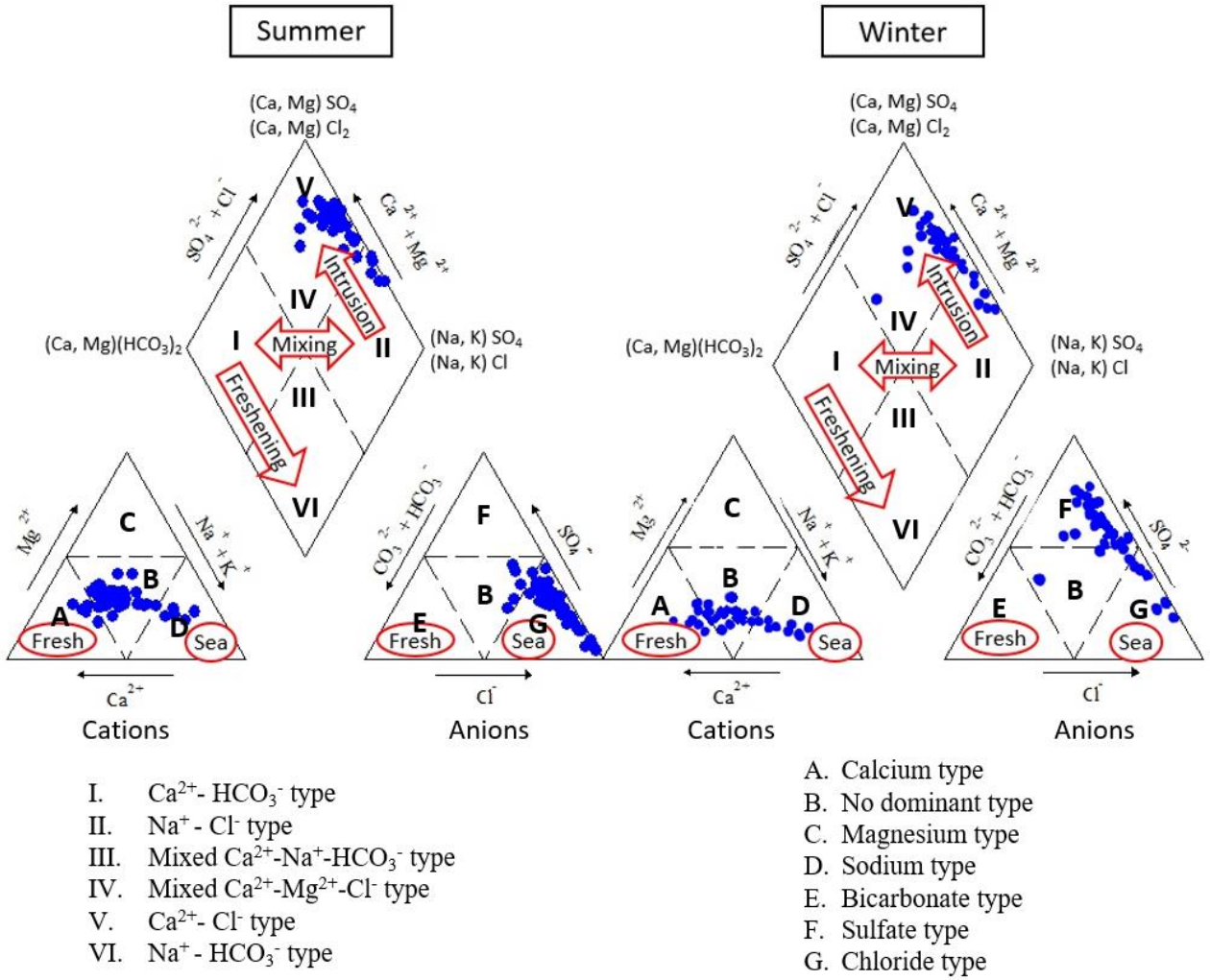


Figure 4.11. Piper diagram showing different groundwater types based on the major cations (Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}) and major anions (HCO_3^-, Cl^- and SO_4^{2-}) in meq L^{-1} (Left: summer, Right: winter); the ion exchange processes are shown in the red arrows, with typical seawater or freshwater processes illustrated.

Moreover, the Cl^- IDW map (Fig 4.12) also illustrates spatial and temporal variation influenced by salinization in the groundwater where, in the winter map, water from the recharge region has Cl^- concentrations of less than 200 mg L^{-1} and is moving from the north to the middle of Qatar. This is because Qatar has a higher recharge rate in the north after the rainy season. Also, the map shows areas closer to the sea coast having higher Cl^- concentrations in both winter and summer. This was also shown by GLM analysis (Table 4.15) where the salinization variables of EC, Cl^-, Na^+, Mg^{2+}, Li^+, Rb were highly correlated ($p<0.05$) with distance to the nearest coastal point - the source of seawater intrusion. Salinization has been discussed as the dominant process in Qatar aquifers in

many studies (Kuiper *et al.*, 2015; Shomar, 2015; FAO *et al.*, 2016). However, the temporal and spatial influence on the salinization process that is shown in this research has not been reported in previous research.

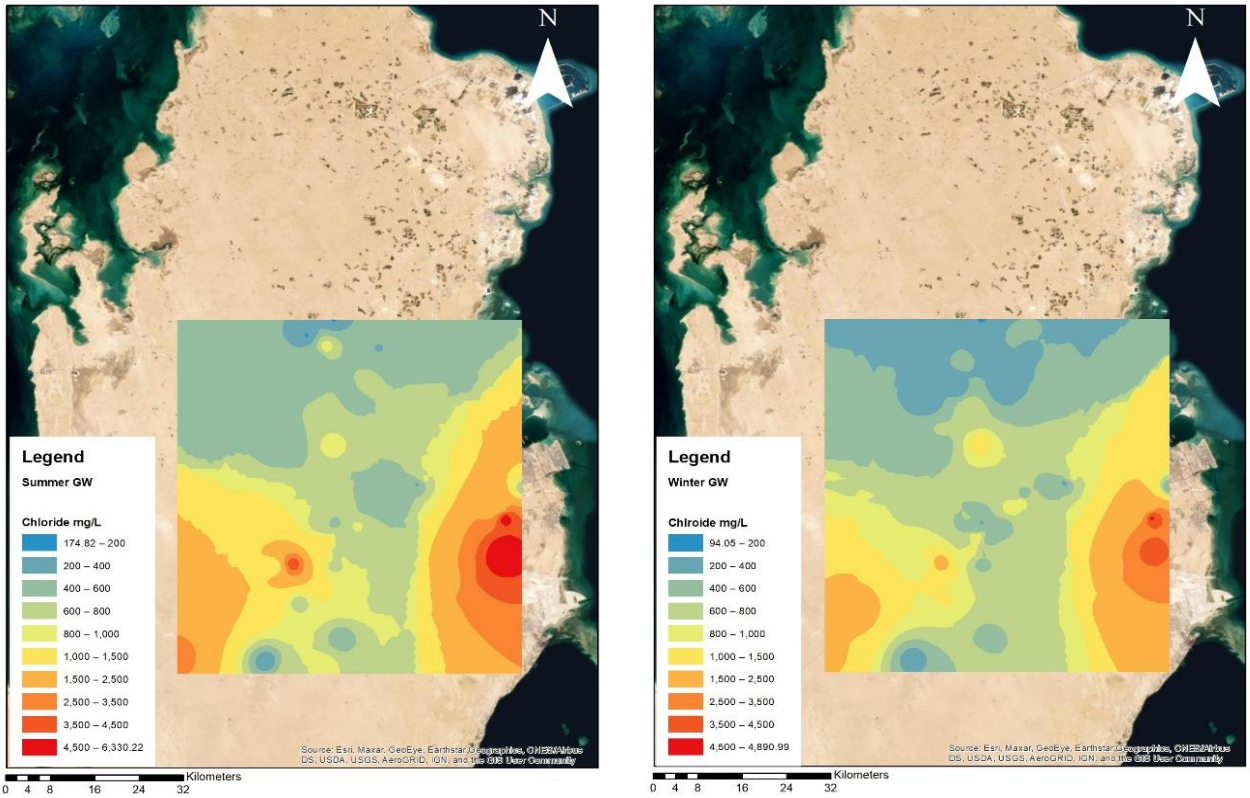


Figure 4.12. Groundwater chloride isoconcentration maps in mg L^{-1} produced with the IDW geostatistical tool.

Rock-water interactions in groundwater.

Various environmental conditions, particularly the position and solubility of rock layers, can impact the concentration of many elements below the ground surface, where solution and/or precipitation reactions can occur (Appelo *et al.*, 1993). Groundwater is always close to numerous solid mineral phases at the same time. Thus, groundwater is rarely in complete equilibrium with the mineral solids that surround it because mineral–solute reactions are slow and water encounters different types of minerals as it travels, where water can either dissolve or precipitate minerals from the matrix, adding mass to the groundwater system. For those reasons, several analyses and diagrams were used to understand the main water processes in groundwater in this section.

To better understand the groundwater chemistry a Gibbs plot was used. Figure 4.13 shows that, for groundwater, evaporation/salinization was the dominant water system in both winter and summer, with slightly greater salinization in summer. For the $Na^+/Na^+{+}Ca^{2+}$ index, most of the groundwater sampled fell within the boomerang showing, as expected, that the water composition in summer was dominated by evaporation due to the hot dry weather; samples closer to the rock weathering zone

reflect gypsum dissolution for both summer and winter as the system is dominated by rock-weathering. However, for $Cl^-/Cl^-+HCO_3^-$ all the groundwater samples were outside the boomerang, this is due to the high concentration of Cl^- in the groundwater for both summer and winter. Therefore, as seen for the lagoon analysis, the Chadha diagram was used to show the rock water interaction.

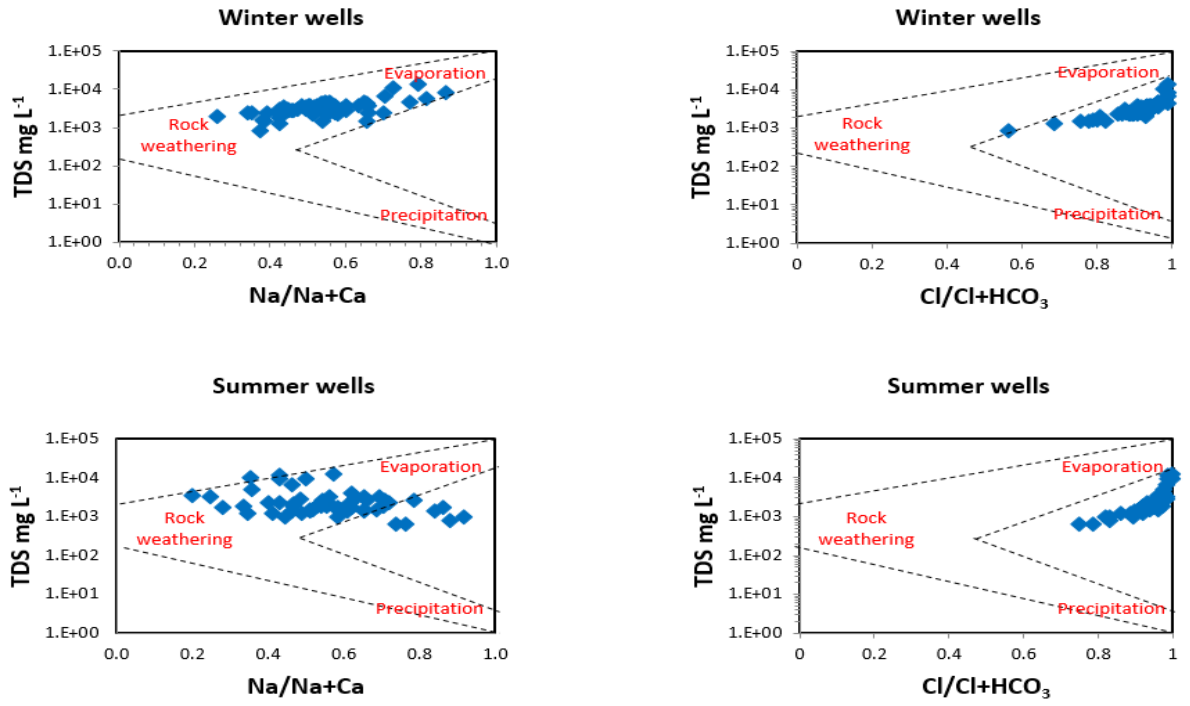


Figure 4.13. Gibbs plot showing groundwater summer and winter evaporation, precipitation and rock weathering processes based on the relationship of TDS (mg L^{-1}) with Na^+/Na^++Ca^{2+} and $Cl^-/Cl^-+HCO_3^-$

Chadha diagrams were used to divide the groundwater into eight different fields (Fig 4.14, Table 4.17) based on the water/rock interactions. The majority of groundwater for summer (43 wells) and winter (40 wells) were water type 6 (Ca^{2+}– Mg^{2+}– Cl^-) with reverse ion exchange, indicating the influence of gypsum in Qatar aquifers (Shamrukh, 2014b; Shomar, 2015; FAO *et al.*, 2016).

Table 4.17. Chadha diagram water types, and the number of groundwaters (summer n=53 and winter n=57) represented in each field both in summer and winter (description of each water type is in Table 4.10).

Water type	Summer	Winter
1	0	3
2	0	1
3	0	1
4	0	0
5	0	1
6	43	40
7	10	0
8	0	7

* Adopted from (Chadha D., 1999)

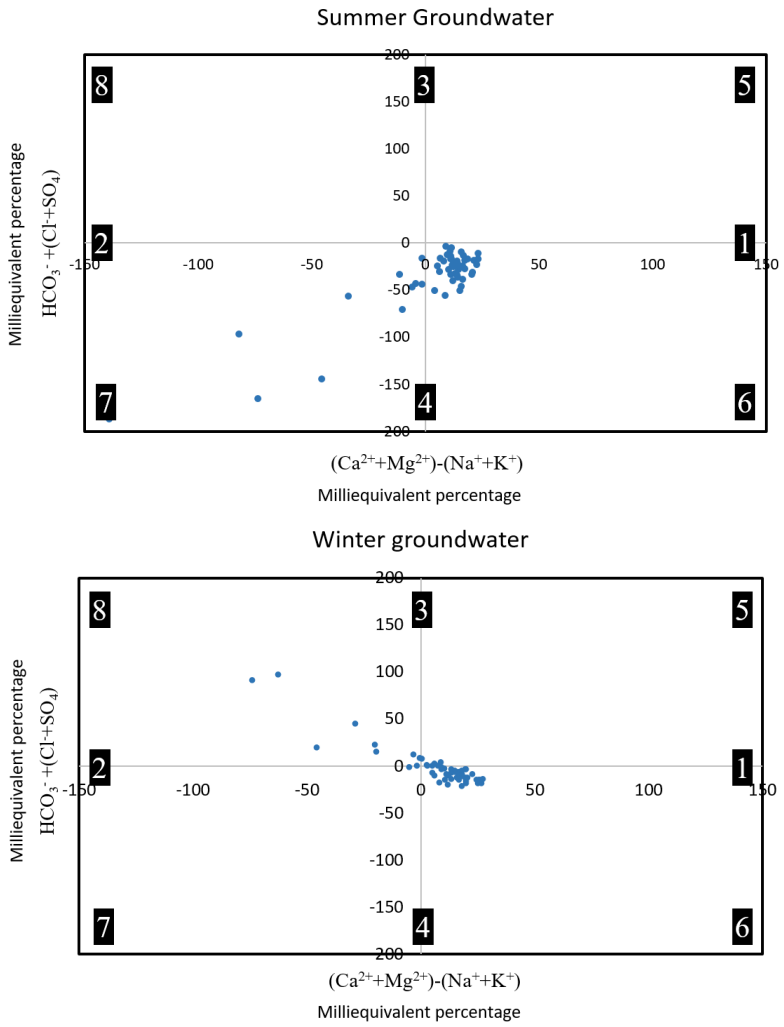


Figure 4.14. Chadha diagram illustrating water-rock process difference between summer and winter, with each section on the diagram labelled from 1 to 8 showing different processes.

Also, ten groundwater in summer where water type 7 (Na^+– Cl^-) where salinization was dominant, and the effect of seawater intrusion was severe. In contrast to the summer results, winter did not show any groundwater in type 7, and in the summer ten wells of type 7, were shown to be types 1, 2, 3, 5 and 8 in winter. Types 1, 3 and 5 shows the recharge of the aquifers, and type 2 and 8 shows ion exchange processes. A few studies have shown a rainfall recharge influence on the groundwater ionic exchange in arid catchments similar to Qatar with similar results (Alyamani *et al.*, 1995; Medjani *et al.*, 2021); this indicates that the Chadha diagram highlighted different types of salinized aquifers recharge seen in winter. Those groundwater wells are shown in the map (Figure 4.15), where 7 out of 10 summer type 7 wells were close to the coast. The three groundwater samples in the middle differed from the wells adjacent to them (Figure 4.15); this could be due to the groundwater structure that caused those wells to be more influenced by the different seasons. In conclusion, the

Chadha diagram was successful in showing the different water/rock interactions in groundwater without the major influence of salinization on the diagram results.

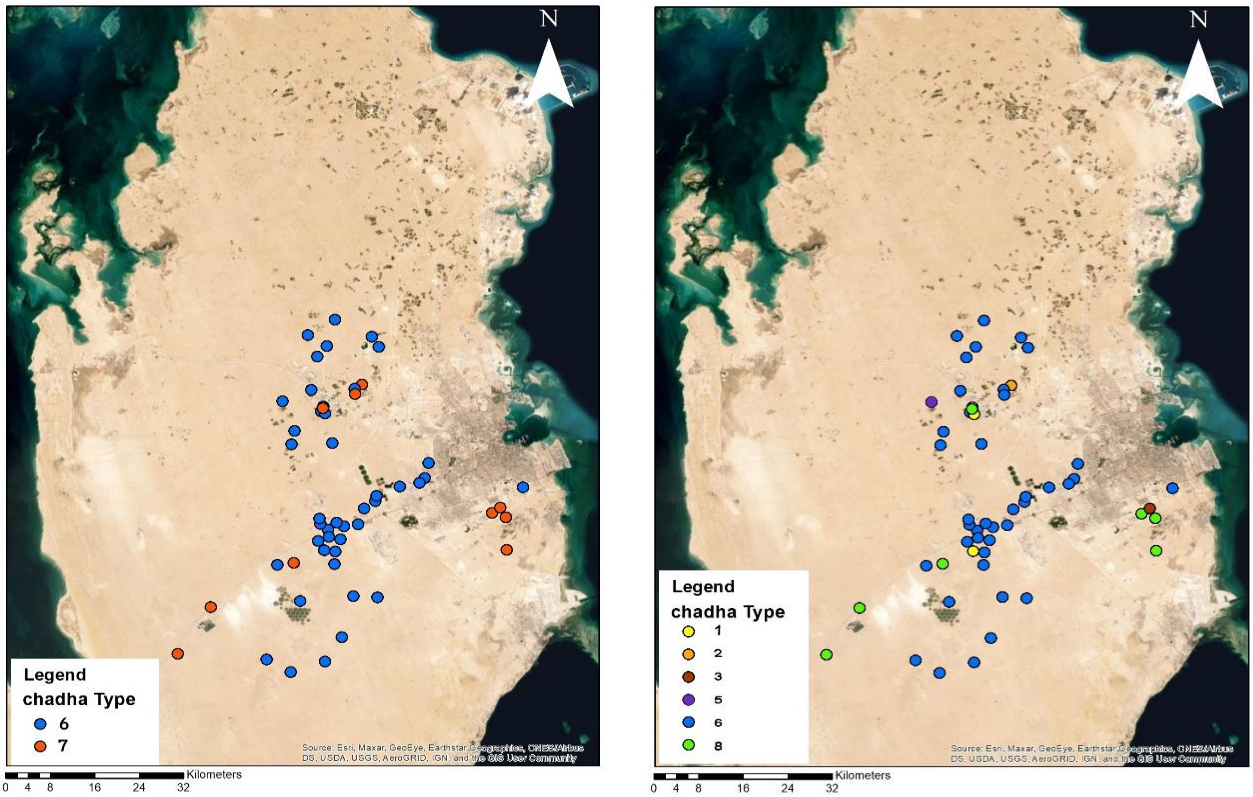


Figure 4.15. Groundwater wells divided based on the Chadha water type (1 – 8 types), summer on the left and winter on the right.

Mineral saturation in groundwater.

The saturation index can be used to express the saturation status of minerals in groundwater (SI) without collecting solid-phase samples and evaluating the mineralogy of the aquifers. Figures 4.16 and 4.17 illustrate saturation indices for the groundwater samples; it shows that all the groundwaters, for both summer and winter samples, were undersatrurated with respect to gypsum and anhydrite. By contrast, for calcite and aragonite, saturation indices fluctuated around the saturation line. This shows that the precipitation of aragonite and calcite increased in winter after the rainfall events, in contrast to the majority of wells, which were undersatrurated with respect to calcite and aragonite. Enhancement of calcite precipitation was reported in previous studies to be a sign of recharge zones in groundwater with the increase in rainfall recharge (Narikkatan *et al.*, 2021; Sarti *et al.*, 2021).

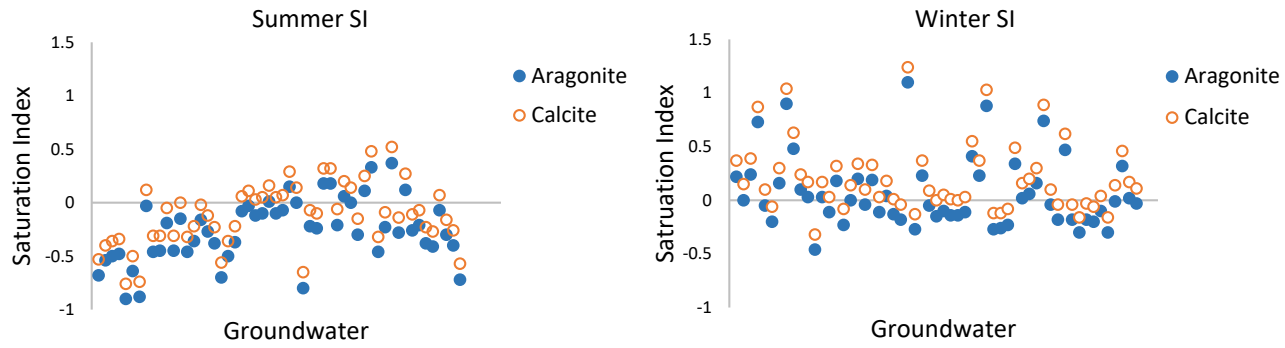


Figure 4.16. Groundwater aragonite and calcite saturation indices for summer (left) and winter (right).

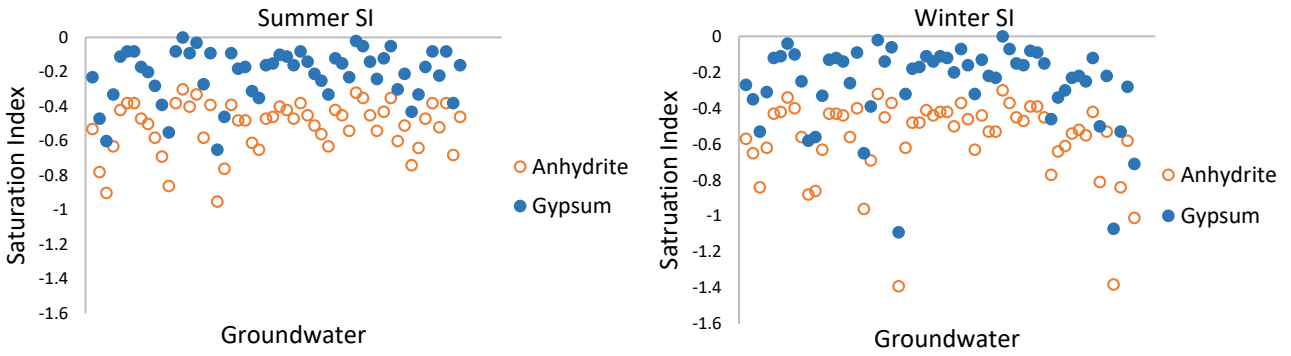


Figure 4.17. Groundwater anhydrite and gypsum saturation indices for summer (left) and winter (right).

In addition, Ion activity for Ca^{2+} and SO_4^{2-} was used to calculate ion activity products ($\log_{10}$ (IAP)) to show that gypsum dissolution is active in the groundwater during both summer and winter. Figure 4.18 shows the system is approaching the gypsum saturation point ($-\log_{10}Ks = 4.6$) as the Ca^{2+} ion activity increases.

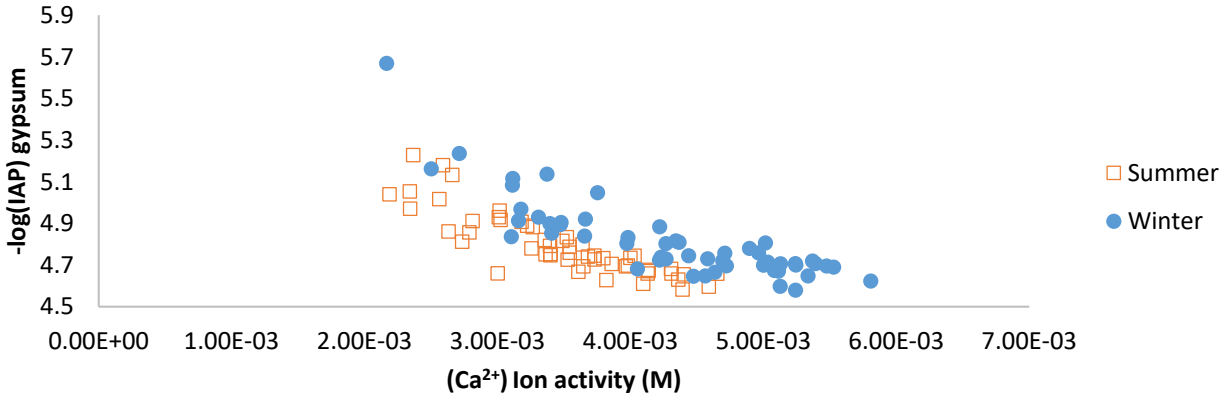


Figure 4.18. Groundwater summer and winter dissolution processes are shown by gypsum $\log_{10}$(IAP) vs Ca^{2+} ion activity with gypsum saturation point ($\log_{10}$Ks) of 4.6.

Results suggest that there is active gypsum dissolution in both summer and winter in the groundwater aquifer (IAP < Ks). This result is in alignment with previous groundwater research done in the area (Saleh *et al.*, 1999; Sadiq *et al.*, 2002; FAO *et al.*, 2016).

Oxidation and reduction in groundwater.

Analysis of PCA and HCA have been used by many groundwater studies to show oxidation and reduction processes in the aquifer system (Carroll *et al.*, 2005; Candela *et al.*, 2007; Jahany *et al.*, 2020); this is evident when the reduced forms of heavy metals show correlations with either TOC or DO in the PCA plot (Fahmy *et al.*, 2011; Fathi, 2014). In the current study the pH, TOC, IC, Se, As, Ni, Cu, Al, Fe, Mn, Mo, Zn, I and Se variables were all correlated in both summer and winter. Those variables were used as redox indicators in many groundwater related studies (Fahmy *et al.*, 2011; Fathi, 2014). However, the NO_3^- and TN correlation differed between summer and winter. This could be because the winter season in Qatar is when farming activities occur when the weather allows it. Thus, because many farmers use nitrate-based fertilizers (Shomar *et al.*, 2013; FAO *et al.*, 2016) it is likely that this is when NO_3^- will seep into the groundwater, increasing the NO_3^- and TN concentrations in winter.

A recent study of groundwater in Qatar illustrated reduction and oxidation activity in the groundwater in Qatar (Ahmad *et al.*, 2020). They showed that the reduction was due to the farming activities in winter; the sampling focused on the north groundwater aquifers, where most of the farming activities occur. However, this area also has no lagoons, thus lagoon infiltration was not considered. The following section will elaborate on the lagoon infiltration hydrochemical impact on the groundwater aquifers in Qatar

4.3.3 Correlation between lagoon water and groundwater composition

This study's objective is to examine the lagoon water and the TWW reuse practice's influence on the groundwater aquifers in Qatar. The previous section discussed the water characteristics of lagoons and groundwater separately. In this section, the lagoon water's influence on the groundwater characteristics will be explored more explicitly.

Temporal and spatial variations of the lagoon's influence on groundwater were seen in the GLM results in Table 4.18 which shows that groundwater variables were significantly influenced by the groundwater well's proximity to the closest lagoon in summer and winter. While 18 variables in summer and 10 variables in winter were shown to be significantly correlated, not all of those will be discussed here.

First, groundwater variables that were shown to be significantly influenced by the sea coast proximity (Table 4.11) were eliminated (EC, TDS, Ca^{2+}, Na^{+}, Sr^{2+}, Rb^{+}, Li^{+}, and U). Moreover, variables that were correlated only in summer were also not discussed (IC, TOC, Mo, and Ni). This

is because lagoon water was shown by GLM to be the same in both summer and winter (Table 4.8), thus the influence on the groundwater should also be the same in winter and summer.

Table 4.18. Results of GLM showing a significant correlation between summer and winter groundwater variables to the distance of the closest lagoon (p<0.05) highlighted in grey.

Dependent Variables	Mean Square	F	Sig.	Mean Square	F	Sig.
	Summer			Winer		
General variables						
EC	52402419	5.708	0.028	1.183	0.115	0.735
IC	15611781	32.348	0	265.401	2.13	0.147
TDS	21105144	5.612	0.029	115341.52	0.041	0.839
TN	28.944	1.291	0.271	0.27	0.015	0.902
TOC	50216503	25.848	0	0.443	0.073	0.787
pH	NA	NA	NA	0.005	0.062	0.803
Temp	NA	NA	NA	0.665	0.072	0.789
Anionic and cationic variables						
B	0.062	0.211	0.65	0.051	0.211	0.647
Ca^{2+}	10495.011	0.169	0.686	70551.036	4.619	0.034
Cl^{-}	3703692.8	3.128	0.094	63831.929	0.066	0.798
I	512064.33	17.368	0.001	14603.111	21.969	0
K^{+}	62.895	0.045	0.834	843.56	1.464	0.229
Mg^{2+}	51460.069	2.102	0.164	15591.028	3.528	0.063
Na^{+}	1270506.5	5.238	0.034	27770.647	0.065	0.8
NO_3^{-}	3804.322	29.434	0	84.522	1.135	0.289
S	549301.49	4.635	0.045	119360.18	4.169	0.044
SO_4^{2-}	391190.66	2.273	0.149	39284.059	1.436	0.233
Metal and metalloid variables						
Al	261.742	9.605	0.006	77.752	0.862	0.355
As	8.906	20.355	0	6.533	4.526	0.036
Ba	2474.076	0.556	0.465	27.488	0.291	0.591
Cr	20.685	1.698	0.379	14.675	1.286	0.259
Cu	133.864	1.378	0.356	122.834	1.226	0.271
Fe	234326.12	11.656	0.003	37396.813	3.927	0.05
Li	552.271	0.213	0.65	22879.384	8.911	0.004
Mn	1357.547	17.908	0.001	163.391	11.373	0.001
Mo	138.396	8.636	0.009	464.303	0.361	0.549
Ni	85038.547	9.359	0.007	0.009	0.001	0.971
Rb	1018.318	17.043	0.001	24.031	0.6	0.44
Se	411.25	10.7	0.006	329.971	10.752	0.001
Sr	230170732	4.369	0.05	13818046	1.369	0.245
U	435.807	4.542	0.047	255.217	4.549	0.035
V	248358.33	10.991	0.004	2108.69	13.925	0
Zn	17275.517	1.275	0.274	4822.677	1.032	0.312

In summer, heavy metals and metalloids such as Al, As, Fe, Mn, Mo, Ni, Sr, U, and V were significantly influenced by the lagoon, whereas in winter only As, Fe, Mn, Sr, U, and V were shown to be influenced by the lagoon. This illustrates the lagoon influence on redox-related variables such as As, Fe, and Mn (Poggenburg *et al.*, 2016; Green *et al.*, 2020) in both summer and winter. Thus, the lagoon's influence on As, Fe, Mn will be discussed here.

Iron and Mn in groundwater are normally the product of reducing conditions and are usually correlated in any water system (Landajo *et al.*, 2004; Rattan *et al.*, 2005; Barzegar *et al.*, 2015). Here they were not influenced by seasonal variation in the groundwater (Table 4.14), but by lagoon

location. This may suggest that the redox processes in the groundwater are more highly influenced by the location of infiltration from lagoons in areas receiving fertilizer from farming activities.

This can be further illustrated using IDW maps for the redox-affected metals. First, the IDW for Fe shows the influence of both farming and lagoons on the Fe concentration in the groundwater (Fig 4.19). In the summer map without farming activity, concentrations of Fe were higher around four lagoons (Ash-Shahanyyia, Mukayinas, Industrial and Mesiamer); this was also seen in winter. In addition, there was an increase in Fe concentration in the north, where the farming activities were concentrated. Thus, Fe reduction and solubility were influenced by both lagoon locations and winter farming activities.

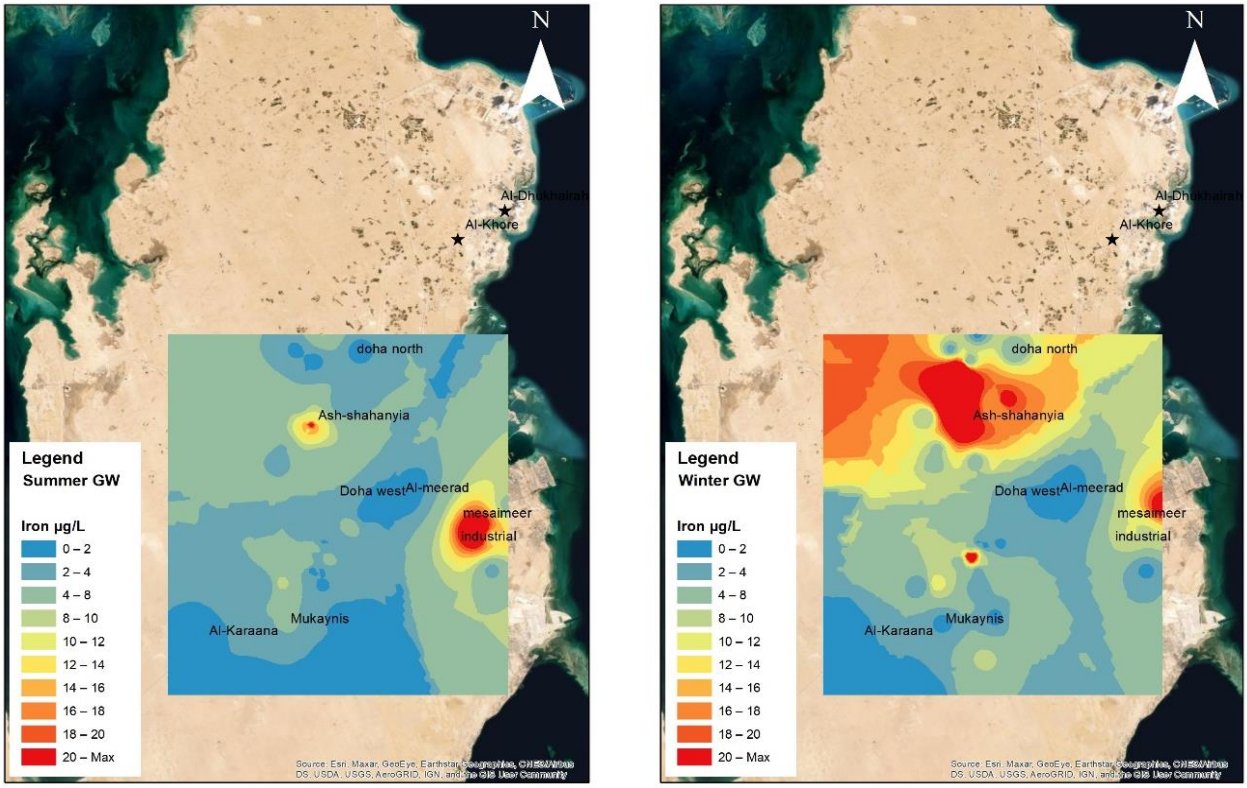


Figure 4.19. Groundwater Iron isoconcentration maps (µg L^{-1}) produced with the IDW geostatistical tool.

Arsenic concentration was not at an alarming level, being below the Qatar crop irrigation guideline (100 µg L^{-1}). However, it was found to correlate significantly to the lagoon locations. This can be seen with the IDW maps (Fig 4.20), where the As concentration is higher around all lagoons except Doha North lagoon, and the As level is seen to be higher in winter as well. Arsenic has been the main potentially toxic element studied by many researchers discussing groundwater contamination (Freikowski *et al.*, 2010; Barzegar *et al.*, 2015). It is an important variable not only because of its availability in groundwater following the reduction of arsenate to arsenite but also because of its

extreme toxicity and carcinogenicity to human populations (Varol *et al.*, 2021). Thus, understanding lagoon influence on the groundwater As level is highly important.

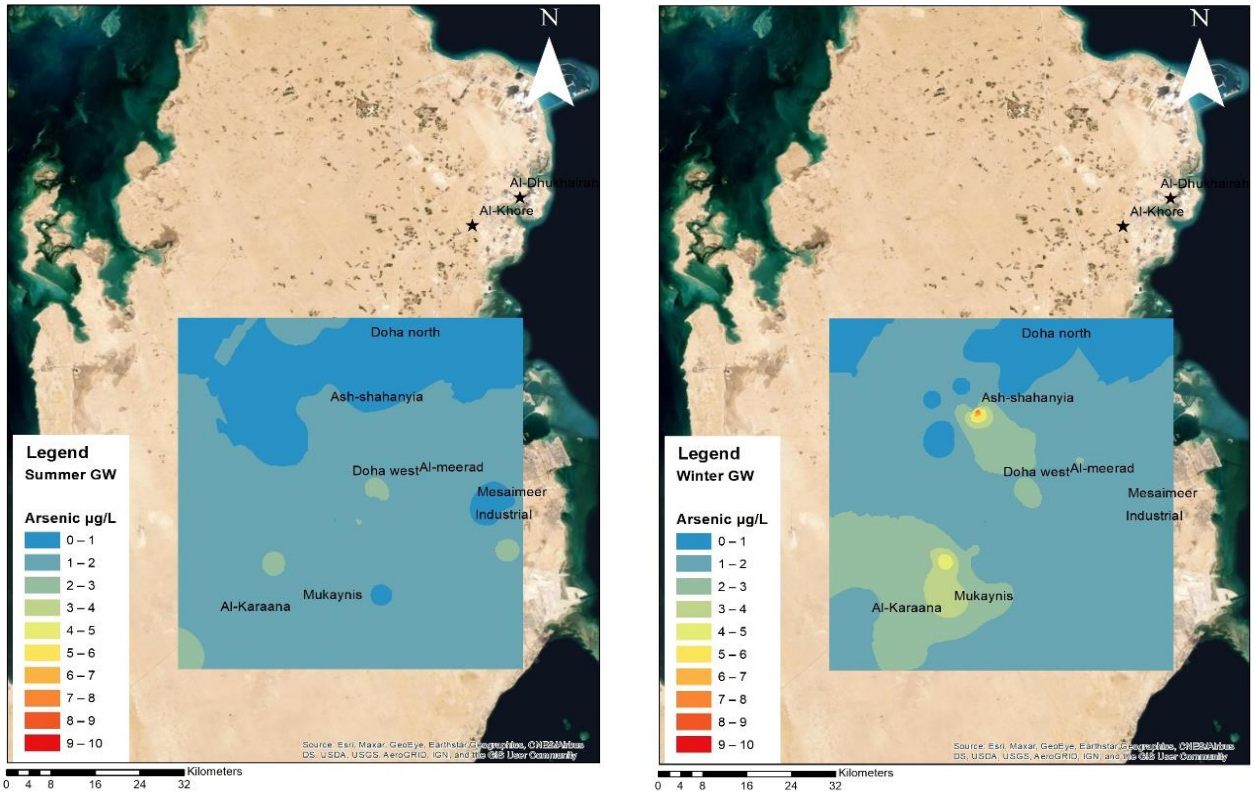


Figure 4.20. Groundwater Arsenic isoconcentration maps (µg L^{-1}) produced with the IDW geostatistical tool.

Iodine was also found to be affected by lagoon locations, I is not suspected to be from seawater intrusion since the average I concentration in the sea is around 50 µg L^{-1}; concentrations were much higher in both lagoons and wells (Fig 4.21). Also, the I in groundwater was not influenced by seasonality (Table 4.14) or the proximity to the sea coast (Table 4.15).

IDW maps (Fig 4.21) illustrate I was higher around two lagoons (Doha North and west) in both summer and winter, and I noticeably increased in winter. Iodine has been reported in previous literature to increase in the groundwater in reducing conditions, as it will increase with surface water infiltration to the groundwater (Smith *et al.*, 2008; Pierce *et al.*, 2016). This indicates I increased with surface water from the lagoon and rainfall events infiltrating the aquifers and not from seawater intrusion.

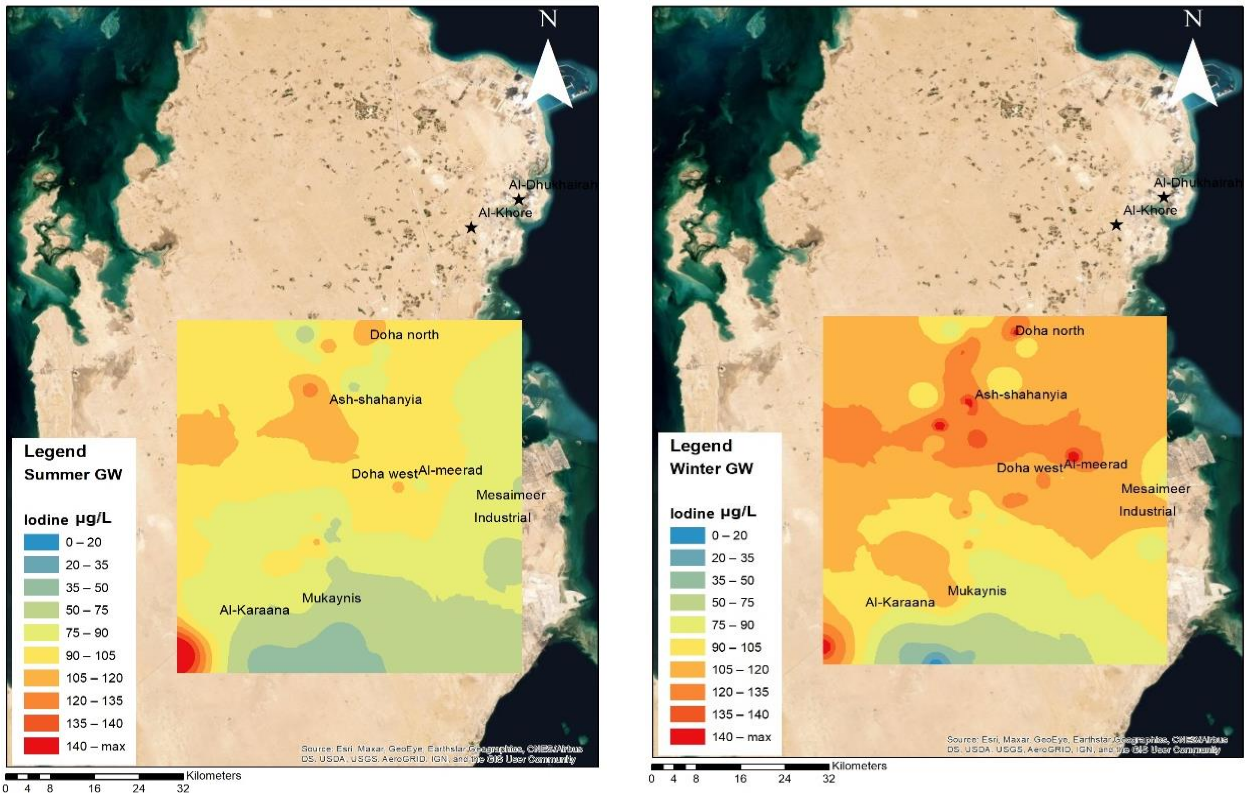


Figure 4.21 Groundwater Iodine isoconcentration maps in µg L^{-1} produced with IDW geostatistical tool

Furthermore, to understand whether NO_3^- in the groundwater was due to farming activities or lagoon location, NO_3^- IDW maps are shown (Fig 4.22). The maps show during both summer and winter NO_3^- was higher around four lagoons (AL-Karaana, Mukayinas, Industrial and Al-Mearad) but not higher in the north where farming activities were concentrated. This indicates that NO_3 could be influenced both by lagoon water infiltration as well as farming activities, as suggested in previous literature (Ahmad *et al.*, 2020).

Finally, GLM and IDW maps have illustrated the different chemical variables in groundwater influenced by the different lagoons in Qatar. Furthermore, the variation in lagoon water chemistry in Qatar could explain why some lagoons influenced some groundwater chemical characteristics but not others.

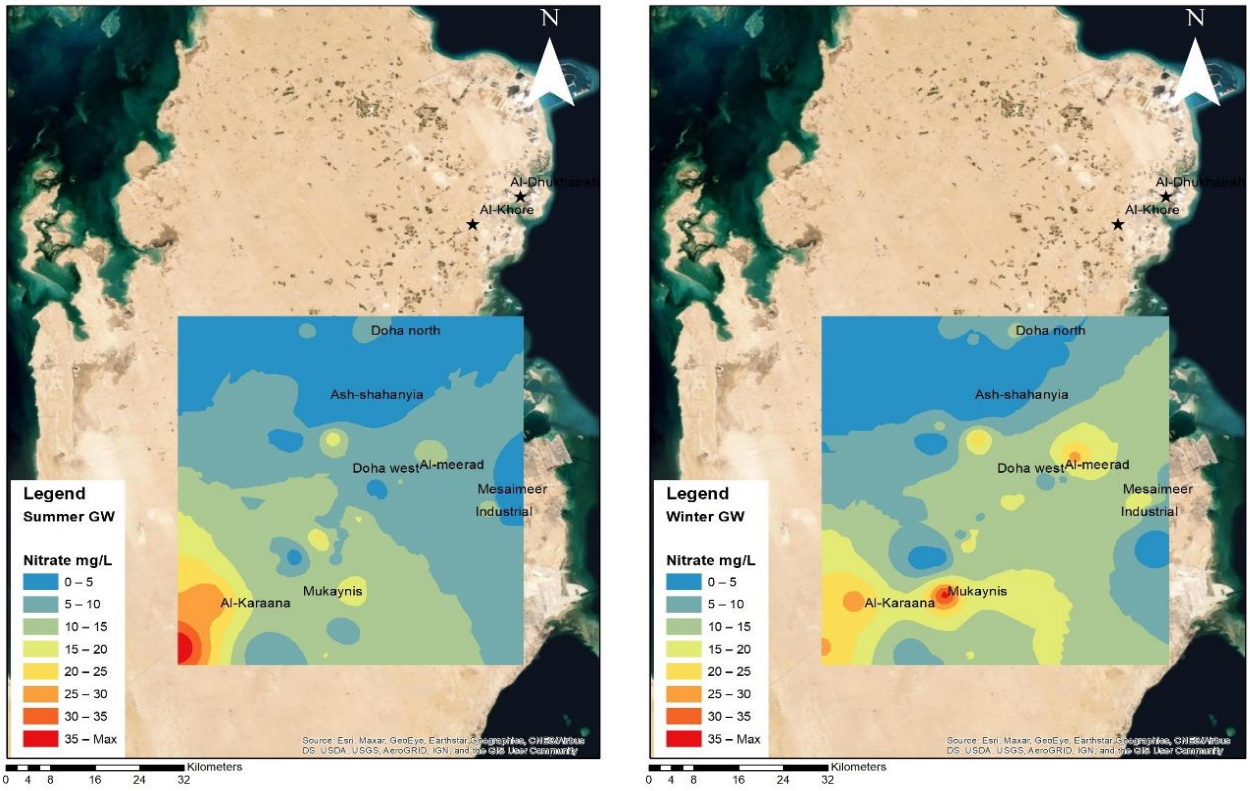


Figure 4.22. Groundwater nitrate isoconcentration maps in mg L^{-1} produced with the IDW geostatistical tool.

4.3.4 Evaluating Lagoon and Groundwater based on their designated usage

Lagoons contain excess TWW in Qatar. However, TWW is used for landscaping and fodder irrigation. While, for groundwater it is reported that the main usage is for crops and fodder irrigation mostly on private farms (FAO, 2008; MDPS, 2017), with few cases of people using it for drinking (Aljabiry, 2019). For that, this section will discuss different water quality indices that evaluate both lagoon and groundwater for their designated usage.

4.3.4.1 Lagoon water quality classifications

Table 4.19 summarize the lagoon water quality indices. The majority of lagoon samples were classified for SAR as excellent or good for both summer and winter. With the exception of two lagoons scoring high SAR value in the summer. For the Na% the majority were between permissible and doubtful, with one in summer and three in winter scored good. Additionally, PS scored 90% Injurious to unsatisfactory indicating lagoons also has an issue with salinity. Especially for the lagoons containing surface water. Which is also seen in the Chloride sample scoring above 4 meq L^{-1}The lagoon permeability index was classified between good and suitable for irrigation, indicating concentrations of Na^{+}, Ca^{2+}, Mg^{2+}, and HCO_3^{-} ions were not the major issue in the lagoon water as it is in groundwater. This is the reason all the lagoons scored goodfor IWQI, with only one lagoon in

winter and summer being classified as severe with major irrigation restriction, this lagoon (Al-Mearad) is a surface water lagoon, not a TWW lagoon. Thus, having higher salts concentrations.

Table 4.19. Summary of scores and water classifications for lagoons (n=10) summer and winter. Including SAR, Na%, PI, PS, Chloride and IWQI in meq L^{-1}.

Quality Criteria	Value Range	Water classification	Number of samples		Percentage (%)	
			Summer	Winter	Summer	Winter
SAR[1]	<6	Excellent	4	7	40%	70%
	6–9	Good	4	3	40%	30%
	>9	Permissible	2	0	20%	0%
Na%[2]	<20	Excellent	0	0	0%	0%
	20–40	Good	1	3	10%	30%
	40–60	Permissible	1	5	10%	50%
	60–80	Doubtful	7	2	70%	20%
	>80	Unsuitable	1	0	10%	0%
PI[3]	>75	Good for irrigation	5	1	50%	10%
	25–75	Suitable for irrigation	5	9	50%	90%
	<25	Unsuitable for irrigation	0	0	0%	0%
PS[4]	< 3.0	Excellent to good	0	0	0%	0%
	3.0–5.0	Good to injurious	1	1	10%	10%
	> 5.0	Injurious to unsatisfactory	9	9	90%	90%
Chloride[5]	Below 2.03	Generally safe for all plants	1	0	10%	0%
	2.03–4.06	Sensitive plants show injury	1	2	10%	20%
	4.07–10.15	Moderately tolerant plants show injury	5	4	50%	40%
	Above 10.15	Can cause severe problems	3	4	30%	40%
IWQI[6]	85 ≤ 100	No restriction needed	1	0	10%	0%
	70 ≤ 85	Low	3	2	30%	30%
	55 ≤ 70	Moderate	2	4	20%	30%
	40 ≤ 55	High	3	3	30%	30%
	0 ≤ 40	Severe	1	1	10%	10%

1. Sodium adsorption ratio classification based on FAO (Ayers, R. S. and Westcot, 1985)
2. Soluble Sodium Percentage (SSP) value range(Wilcox, 1955)
3. Permeability Index value range (Wills *et al.*, 1996; Batarseh *et al.*, 2021; Eldaw *et al.*, 2021)
4. Potential salinity value range (Delgado *et al.*, 2010; Ravikumar *et al.*, 2011; Ismail *et al.*, 2021)
5. Chloride value range (Dennis W. *et al.*, 2019)
6. IWQI categorizes (Muniz *et al.*, 2020; Batarseh *et al.*, 2021; Eldaw *et al.*, 2021)

4.3.4.2 Groundwater Quality Classifications

In the official reports (FAO, 2008; MDPS, 2017; PSA, 2018, 2019), it was not stated that groundwater is used as drinking water. However, during field sampling trips, farmers were asked if they drank the groundwater; in a few cases, this was confirmed (Aljabiry, 2019). Therefore, the eligibility of groundwater as a source of drinking water should be explored.

Groundwater Quality Index (WQI)

As expected from Qatar National reports and previous literature (Darwish *et al.*, 2013; FAO *et al.*, 2016; MDPS, 2017), groundwater has deteriorated as a result of seawater intrusion to the point where it is unacceptable for human consumption. Table 4.20 shows that the majority of the wells

were unsuitable as a source of drinking water (79.9% summer and 87.7% winter) with the rest of the wells producing values between 'very poor' and 'poor' water classifications (Table 4.20). The WQI system has never been practised in the state of Qatar but it has been suggested previously that the water would not be suitable for human consumption, as the main source of drinking water in Qatar has become desalinated seawater (Darwish *et al.*, 2013; Kuiper *et al.*, 2015; PSA, 2018).

Table 4.20. Water quality classification based on the computed WQI value, with the number of wells in each classification (summer n=53 and winter n=57).

Range (meq L^{-1})[1]	Type of water	Number of samples		Percentage (%)	
		Summer	Winter	Summer	Winter
<50	Excellent water	0	0	0%	0%
50–100	Good water	0	0	0%	0%
100–200	Poor water	2	2	3.7%	3.5%
200–300	Very poor water	9	5	16.6%	8.8%
300<	Water unsuitable for drinking purposes	43	50	79.7%	87.7%

1. (Ramakrishnaiah *et al.*, 2009; Uddin *et al.*, 2021)

Groundwater Sodium Adsorption Ratio (SAR)

Most of the water was classified as 'excellent' both in winter and summer (Table 4.21), with few groundwater samples classified as 'good' and 'permissible', but it is observed that in winter 16% of the groundwater change from 'excellent' to 'good' and 'permissible', indicating that SAR increased after rainfall events, and the recharging of the aquifers, which has been reported to be the case with the rainwater infiltrating the soil to the groundwater. Nevertheless, from the Table 4.21 SAR is not the main problem facing Qatari aquifers.

Other literature that used SAR to discuss water quality generally used the US Salinity Laboratory (USSL) diagram to plot the SAR versus the EC to provide a fuller understating of the impact of both sodium and salinity on soil (Aravinthasamy *et al.*, 2020; Batarseh *et al.*, 2021). However, the plot uses an EC range between 100 to 2500 µS cm^{-1}. However, in the current study, most of the samples had EC values in excess of 2000 µS cm^{-1} and therefore out of the diagram range (Fig 4.23).

Table 4.21. Water classification for the investigated sites based on SAR (summer n=53 and winter n=57).

Value Range[1] (meq L^{-1})	Water classification	Number of samples		Percentage (%)	
		Summer	Winter	Summer	Winter
<6	Excellent	39	36	79%	63%
6–9	Good	6	13	9%	23%
>9	Permissible	9	8	12%	14%

1. Sodium adsorption ratio classification based on FAO (Ayers, R. S. and Westcot, 1985)

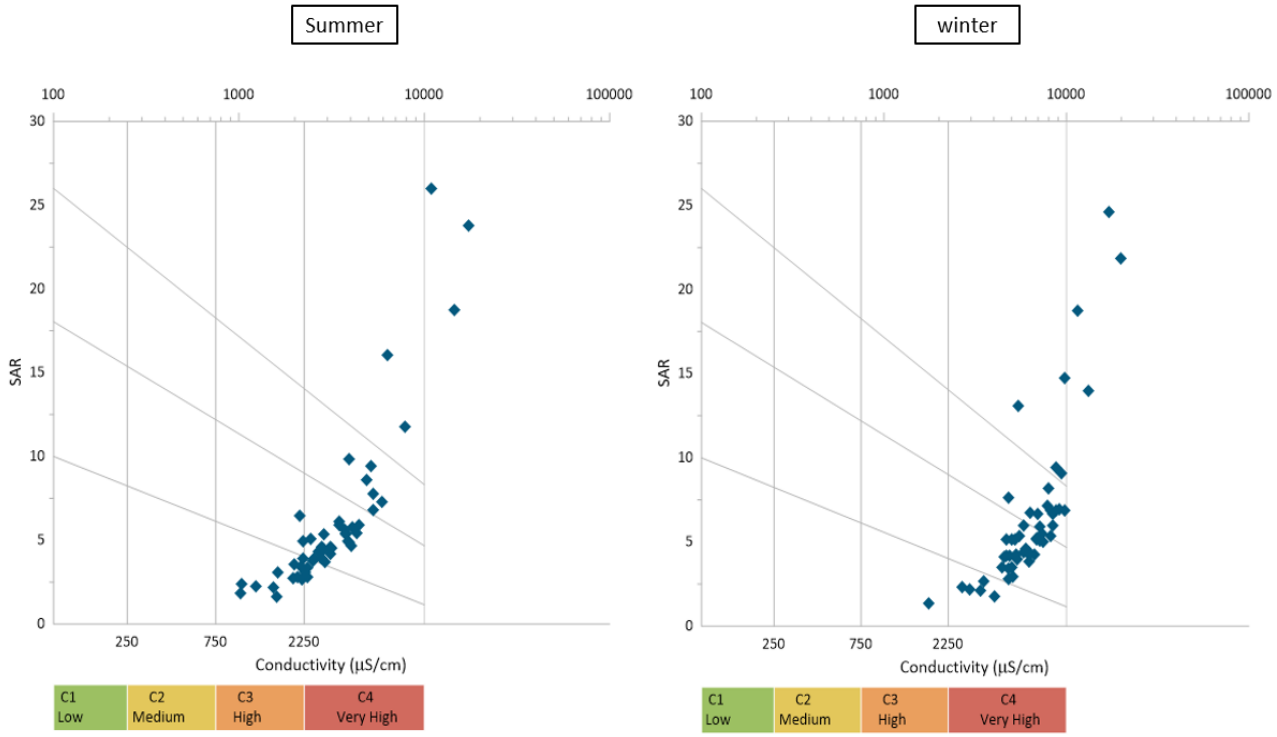


Figure 4.23. USSL diagram for classification of irrigation waters by four classes (low, medium, high and very high) based on SAR and EC (left summer, right winter).

Groundwater Soluble Sodium Percentage (SSP) or Sodium Percent (Na%)

Soils with reserves of Ca^{2+} in the semi-soluble mineral form are able to resist the damaging effects of Na^{+} on soil structure. Thus, even with a high value of SSP, the presence of gypsum in soil may prevent structural deterioration and thereby enable the use of doubtful water for irrigation (Ogunfowokan *et al.*, 2013). Since most soils in Qatar contain gypsum (FAO, 2008), irrigation water with a high SSP might not present a problem (Table 4.22).

Table 4.22. Classification of groundwater quality for the investigated sites based on Na% (summer n=53 and winter n=57).

Value Range[1] (meq L^{-1})	Water classification	Number of samples		Percentage (%)	
		Summer	Winter	Summer	Winter
<20	Excellent	1	1	2%	1.8%
20–40	Good	31	31	66%	54.2%
40–60	Permissible	17	21	31.5%	37%
60–80	Doubtful	5	4	9%	7%
>80	Unsuitable	0	0	0%	0%

1. Soluble Sodium Percentage (SSP) value range(Wilcox, 1955)

Groundwater Permeability Index (PI)

Qatar groundwater is characterized by high salt concentrations because of marine intrusion (Al Mamoon *et al.*, 2015), over-extraction of groundwater compared to recharge (Baalousha, 2016b) and

the breakdown of limestone and dolomite in underground geological structures (Duggan *et al.*, 2014). Groundwater quality has been impacted by these causes, resulting in the majority of the wells sampled in the current study to be in Class-II (Table 4.23).

Table 4.23. Classification of groundwater quality for the investigated sites based on PI (summer n=53 and winter n=57).

Value Range[1] (meq L^{-1})	Water classification	Number of samples		Percentage (%)	
		Summer	Winter	Summer	Winter
>75	Good for irrigation	1	0	1.8%	0%
25–75	Suitable for irrigation	52	55	96.4%	96.5%
<25	Unsuitable for irrigation	1	2	1.8%	3.5%

1. Permeability Index value range (Wills *et al.*, 1996; Batarseh *et al.*, 2021; Eldaw *et al.*, 2021)

Groundwater Potential Salinity (PS)

Qatar suffers the effect of sea intrusion which contaminates fresh groundwater reservoirs. Thus, it is predicted that PS values for all the samples were likely to be 'Injurious to unsatisfactory' (Table 4.24), with groundwater samples near the coast having the highest value. Chloride is required by plants in very small amounts, but excessive concentrations are harmful to sensitive crops (Dennis W. *et al.*, 2019). When spray irrigation is used, excessive chloride concentrations, from sea salt, cause additional difficulties (Delgado *et al.*, 2010; Ismail *et al.*, 2021).

Table 4.24. Classification of groundwater quality for the investigated sites based on PS (summer n=53 and winter n=57).

Value Range[1] (meq L^{-1})	Water classification	Number of samples		Percentage (%)	
		Summer	Winter	Summer	Winter
< 3.0	Excellent to good	0	0	0%	0%
3.0–5.0	Good to injurious	0	1	0%	1.8%
> 5.0	Injurious to unsatisfactory	54	56	100%	98.2%

1. Potential salinity value range (Delgado *et al.*, 2010; Ravikumar *et al.*, 2011; Ismail *et al.*, 2021)

Groundwater Chloride concentration

Again, because saltwater intrusion is a major issue in Qatar's fresh groundwater reservoir, the chloride concentrations for most samples were expected to fall under the 'Can cause Severe problems' class (Table 4.25).

Table 4.25. Classification of groundwater quality for the investigated sites (summer n=53 and winter n=57) based on Chloride (meq L^{-1})

Value Range (meq L^{-1})	Water classification	Number of samples		Percentage (%)	
		Summer	Winter	Summer	Winter
Below 2.03	Generally safe for all plants	0	0	0%	0%
2.03–4.06	Sensitive plants show injury	0	2	0%	3.5%
4.07–10.15	Moderately tolerant plants show injury	8	15	15%	26.5%
Above 10.15	Can cause Severe problems	46	40	85%	70%

1. Chloride value range (Dennis W. *et al.*, 2019)

Groundwater Irrigation Water Quality Index (IWQI)

The majority of wells (61% sampled in summer and 65% in winter) fell in the high water use restrictions class in which it is recommended to implement frequent irrigation to prevent salt accumulation in the soil if the EC is more than 2000 µS cm^{-1} (Table 4.26). Since the sampled wells had an average conductivity of 4149 µS cm^{-1} summer and 6470 µS cm^{-1}, those recommendations could be applied to the Qatar farms. However, the recommendation of using more water for irrigation may increase the seawater intrusion, hence degrading the IWQI even more. Thus, the best recommendation in the Qatar context may be using high salinity tolerant plants to be more efficient with groundwater usage.

Table 4.26. Classification of groundwater quality for the investigated sites (summer (S) n=53 and winter (W) n=57) based on IWQI, with recommendation for the water type usage for both soil and plants

IWQI meq L^{-1}	Water use restrictions[1]	# of wells		Percentage		Recommendations[2]	
		S	W	S	W	Soil	Plant
85 ≤ 100	No restriction needed	0	0	0	0	Appropriate for use for most soil types with different permeability with low chances of salinity and sodicity problems. With the recommendation for soil leaching irrigation practice	Low toxicity risk for most plants
70 ≤ 85	Low	0	0	0	0	Not recommend for soil with high clay content 2:1, as it may cause soil sodicity. Irrigation is appropriate for soil with moderate permeability and light texture	Salt sensitive plants should be avoided
55 ≤ 70	Moderate	9	8	17%	14%	Irrigation is appropriate for soil with moderate and high permeability, with salts leaching practices	Irrigation for plants with moderate tolerance to salinity
40 ≤ 55	High	33	37	61%	65%	Irrigation may be appropriate for soil with high permeability. If the water have values of EC above 2000 µS cm^{-1} and SAR above 7 meq L^{-1} then frequent irrigation practices should be implemented	Irrigation for plants with moderate to high tolerance to salinity, with Constant monitoring. Exemption applied for water with low Na^+ and Cl^- values.
0 ≤ 40	Severe	12	12	22%	21%	For the most of soil types this water should be avoided. However, if gypsum is present or applied then water with high SAR could be used. While water with high salts content frequent irrigation practices should be implemented to prevent salts accumulation in the soil	Irrigation for plant with high salt tolerance only. Exemption applied for water with low Na^+ and Cl^- values.

1. IWQI categorizes (Muniz *et al.*, 2020; Batarseh *et al.*, 2021; Eldaw *et al.*, 2021)
2. Soil and plants irrigation recommendations (Muniz *et al.*, 2020; Ismail *et al.*, 2021)

Moreover, 17% of wells sampled in summer and 14% in winter fell under the ‘moderate water use’ restriction where it is recommended to grow plants with moderate tolerance to salinity and implement salt leaching practices. It was observed that the zones classed as ‘moderate’ decreased away from the coast and in the recharge zones of Qatar. In fact, some wells fell in the ‘severe water use restriction’ class, with the recommendation of growing plants with high salt tolerance only. Those wells, were seen be near the coast, highlighting the issue of marine intrusion. The IWQI severe class recommends the use of gypsum if the SAR values were high, which is the case in the natural soil of Qatar (FAO, 2008)

In conclusion, the lagoons samples were shown better water quality classification compared to groundwater, but similar salinity and sodicity problems were seen in both water sources

4.3.5 General soil quality

This section discusses and compares the quality of soil irrigated with water from groundwater and soil lying adjacent to lagoons. Many previous studies have explored the influence of long term irrigation with TWW on soil, often using multivariate statistical tests to examine the impact of TWW on soil chemical composition (Rusan *et al.*, 2007; Balkhair *et al.*, 2016; Abd-Elwahed, 2018). In this research PCA, HCA and GLM were used to investigate the difference between soil on irrigated farms and soil surrounding lagoons. General soil quality is discussed then a range of statistical analysis tools were used to examine the relationship between the characteristics of soil on farms and their proximity to lagoons. Moreover, SAR and EC were used to characterise soil salinity and sodicity. Lastly, soil quality indices were used to classify soil types based on their intended usage.

4.3.5.1 Soil multivariate statistical water analysis

A multivariate statistical analysis was used to investigate the interaction between the farms and lagoons' soil variables. A few tested variables were excluded from this study, because they were not detected in most samples or were detected at negligible concentrations lower than LOD, including: total nitrogen content (TN) and concentrations of B, Be, Se, Ag, Cd, Cs, and Tl.

Soil normality test

Soil data normality tests for both farms and lagoons (Table 4.27) show that 17 out of 28 were not normal ($p<0.05$) using the Kolmogorov-Smirnov test and 23 out of 28 were not normal with the Shapiro-Wilk Test ($p<0.05$). Thus, non-parametric tests or data transformations were recommended.

Table 4.27. Tests of normality (Kolmogorov-Smirnov and Shapiro-Wilk) for all the farm and lagoon soil variables; if the significant level (Sig.) of the test is greater than 0.05, the data is normal.

	Kolmogorov-Smirnov[a]			Shapiro-Wilk				Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.		Statistic	df	Sig.	Statistic	df	Sig.
General Variables							V	0.144	57	0.005	0.903	57	0
Carbon %	0.167	57	0	0.73	57	0	Cr	0.101	57	0.2	0.97	57	0.169
EC	0.182	57	0	0.869	57	0	Mn	0.107	57	0.158	0.951	57	0.021
pH	0.065	57	0.2	0.982	57	0.534	Fe	0.142	57	0.006	0.895	57	0
Anions and Cations Variables							Co	0.152	57	0.002	0.897	57	0
I	0.146	57	0.004	0.741	57	0	Ni	0.147	57	0.003	0.896	57	0
Na^+	0.122	57	0.035	0.951	57	0.021	Cu	0.12	57	0.041	0.897	57	0
Mg^{2+}	0.059	57	0.2	0.976	57	0.309	Zn	0.216	57	0	0.787	57	0
P	0.215	57	0	0.635	57	0	As	0.178	57	0	0.821	57	0
S	0.213	57	0	0.832	57	0	Rb	0.089	57	0.2	0.952	57	0.024
K^+	0.092	57	0.2	0.973	57	0.232	Sr	0.195	57	0	0.895	57	0
Ca^{2+}	0.096	57	0.2	0.931	57	0.003	Mo	0.417	57	0	0.281	57	0
Metal and metalloid variables							Ba	0.148	57	0.003	0.886	57	0
Ti	0.112	57	0.071	0.98	57	0.446	Pb	0.092	57	0.2	0.957	57	0.043
Li	0.143	57	0.005	0.885	57	0	U	0.114	57	0.064	0.929	57	0.002
Al	0.105	57	0.179	0.949	57	0.018							

Soil Principal Component analysis (PCA)

PCA was used to show the difference between the correlation of the variables between soils from farms and lagoons. Because the data set was not normally distributed, the KMO Bartlett's Test was used first with a value of (0.759; Table 4.8). This number is acceptable and does not necessitate corrective action.

Table 4.28. Farms and lagoon soil data: KMO and Bartlett's Test results.

KMO and Bartlett's Test		
KMO measure of sampling adequacy.		.759
Bartlett's Test of Sphericity	Approx. Chi-Square	2081.699
	df	378
	Sig.	.000

For Farms, 5 PCs were needed to explain 74% of the data variation, while lagoons needed 4 PCs to explain 82% of the variation (Table 4.29; Fig 4.24).

Table 4.29. Farms and Lagoon soil principal components; PC1 to PC5 had cumulative eigenvalues of more than 80%.

	Farm					Lagoon			
	PC1	**PC2**	**PC3**	**PC4**	**PC5**	**PC1**	**PC2**	**PC3**	**PC4**
Cumulative %	37	52	62	69	74	36	59	73	82
General variables									
C%	-0.172	**0.744**	-0.103	-0.336	0.254	0.009	**0.954**	-0.079	-0.127
EC	-0.177	-0.017	0.328	**0.8**	-0.08	-0.491	0.123	**0.533**	0.565
pH	0.052	-0.183	-0.224	0.036	-0.159	-0.386	0.006	**0.778**	0.262
Anionic and cationic variables									
Ca^{2+}	0.059	0.164	**0.728**	-0.265	0.396	-0.355	**0.681**	**0.557**	-0.194
I	0.032	0.175	0.078	-0.13	0.028	**0.634**	0.244	0.3	-0.564
K^{+}	**0.65**	-0.37	-0.135	0.159	-0.411	**0.531**	-0.802	-0.101	0.055
Mg^{2+}	0.352	0.273	0.023	0.132	**0.7**	-0.007	**0.649**	-0.589	-0.005
Na^{+}	-0.263	-0.109	0.049	**0.852**	0.11	-0.059	-0.417	0.476	**0.731**
P	-0.252	**0.871**	-0.07	-0.062	-0.016	**0.63**	-0.409	0.203	-0.303
S	-0.084	-0.022	**0.82**	0.289	-0.051	-0.639	0.344	0.349	0.093
Metal and metalloid variables									
Al	**0.924**	-0.209	-0.121	-0.023	-0.003	**0.66**	-0.709	-0.214	0.046
As	**0.842**	-0.074	0.155	-0.224	-0.288	**0.745**	0.297	0.574	0.045
Ba	-0.064	-0.148	-0.006	0.083	-0.15	0.193	0.194	-0.805	0.112
Co	**0.967**	0.015	0.031	-0.149	0.01	**0.919**	0.205	0.229	-0.065
Cr	**0.775**	-0.049	0.049	-0.125	**0.548**	**0.809**	-0.038	0.217	-0.067
Cu	**0.627**	0.441	-0.004	0.078	-0.019	**0.706**	**0.581**	-0.319	0.164
Fe	**0.981**	-0.006	0.031	-0.134	0.031	**0.781**	0.021	0.067	0.187
Li	**0.96**	-0.007	0.038	0.03	0.006	**0.818**	0.047	0.115	0.293
Mn	**0.904**	0.146	-0.001	-0.147	0.272	**0.836**	-0.086	-0.045	0.053
Mo	0.211	0.033	0.235	-0.226	-0.284	0.314	**0.691**	-0.066	**0.521**
Ni	**0.871**	0.06	-0.112	-0.125	0.242	**0.703**	0.349	0.266	0.004
Pb	0.49	0.034	0.486	0.214	0.13	**0.721**	0.285	-0.265	0.494
Rb	**0.852**	-0.234	-0.229	0.12	-0.102	**0.671**	-0.714	-0.063	-0.015
Sr	-0.032	0.134	**0.868**	0.177	-0.139	**0.5**	**0.506**	0.316	-0.331
Ti	**0.831**	-0.033	0.102	-0.14	0.374	**0.768**	-0.434	0.008	0.08
U	0.058	**0.724**	0.291	-0.091	0.049	**0.726**	0.281	0.404	0.032
V	**0.953**	0.008	0.169	-0.135	-0.018	**0.578**	0.401	0.173	-0.132
Zn	0.123	**0.811**	0.169	0.157	0.051	0.236	**0.584**	-0.635	0.256

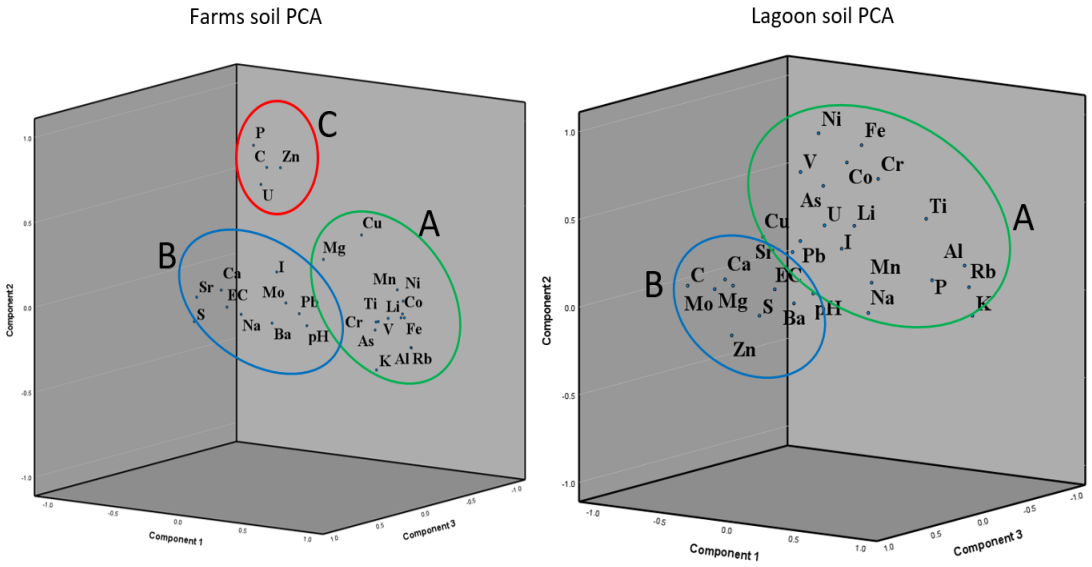


Figure 4.24. Farms and lagoons PCA 3D plot for the soils variables (farms: left, lagoons: right). Varibles clustered in the same group showen by three circules labled A,B and C. PCA was used with the Varimax rotation method and Kaiser Normalization.

Soil hierarchical cluster analysis (HCA)

The HCA analysis of farm and lagoon soils illustrated that each type produced two clades containing the same variables in each clade (Fig 4.25), with the exception of P, U, I and Sr which were in clade B for farms and clade A for lagoon soils. Clade A for farms and lagoons contained Fe, Co, V, Li, Ni, As, Ti, Mn, Cr, Al, Rb and K^+ and clade B comprised EC, Na^+, S, Ca^{2+}, Mo, Ba, C, Zn, pH, Cu, Pb and Mg^{2+}.

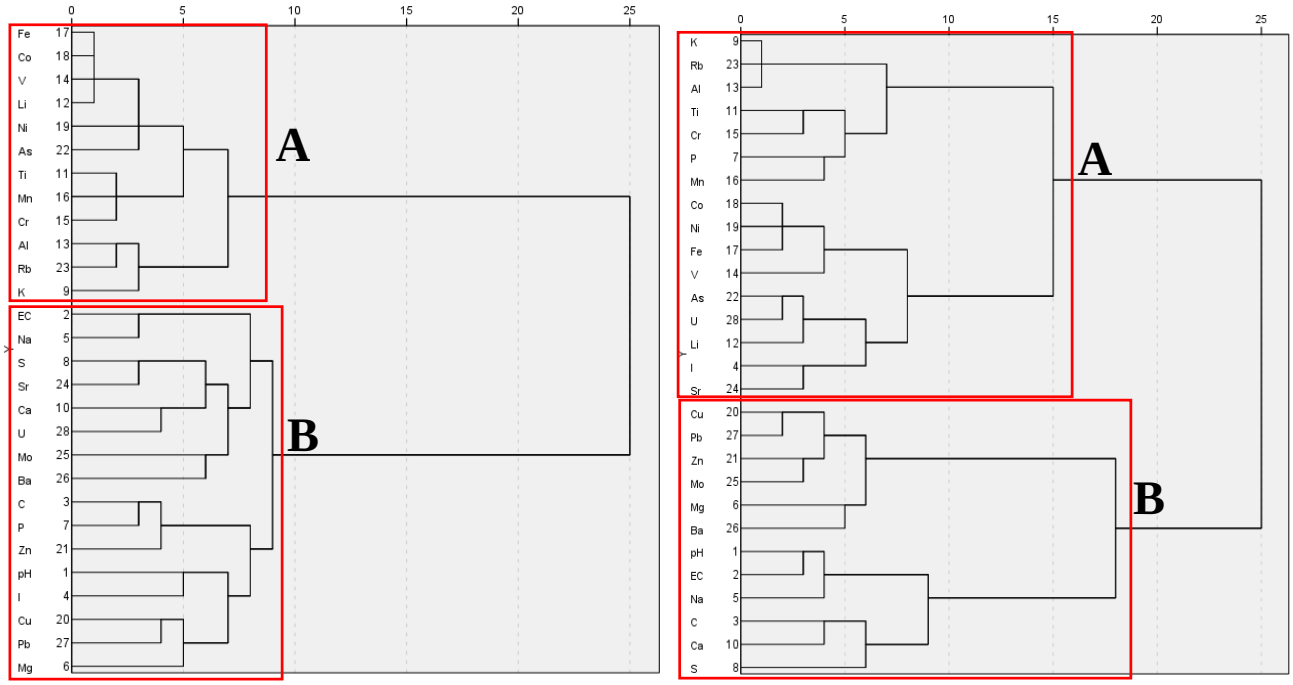


Figure 4.25. Farm and lagoon soil Dendrogram, produced by HCA using Ward linkage, with Euclidean distance and Z score transformation; Varibles clustered in the same group showen by two squares labled A and B. (Farms: left, Lagoons: right).

Soil Generalized Linear model

GLMs were used to test the spatial variance of the soil data. The soil variables were assigned as a dependent variable and the sample source as a fixed factor (Table 4.30). The distance of the farms from the nearest lagoon was the second fixed factor (Table 4.31). GLM analysis showed that 16 variables were significantly different when comparing farms to lagoons (Table 4.30). By contrast, only two variables were significantly different for the lagoon's proximity to the farms' soil samples.

Table 4.30. Results of GLM showing the soil variables that were significantly different between farm and lagoon soil (p<0.05) highlighted in grey.

Dependent Variable	Mean Square	F	Sig.	Dependent Variable	Mean Square	F	Sig.
General Variables				**Ba**	16792.567	5.746	0.02
				Co	11.277	5.576	0.021
C%	27.449	4.93	0.03	**Cr**	9.996	0.107	0.744
EC	886.418	2.317	0.133	**Cu**	141.478	8.818	0.004
pH	0.966	5.68	0.02	**Fe**	40072866	3.704	0.059
Anions and Cations Variables				**Li**	65.454	10.179	0.002
Ca	2.114254631	21.227	0	**Mn**	44169.864	7.563	0.008
I	273010133	7.864	0.007	**Mo**	2.415	0.622	0.433
K	80082056	31.202	0	**Ni**	327.967	3.651	0.061
Mg^{2+}	369455448	7.998	0.006	**Pb**	21.862	10.711	0.002
Na^{+}	1333049.6	0.365	0.548	**Rb**	571.273	21.514	0
P	3574213.6	3.048	0.086	**Sr**	65066.545	0.43	0.514
S	90599659	1.02	0.316	**Ti**	31945.146	4.362	0.041
Metal and metalloid variables				**U**	2.568	22.758	0
Al	364098835	13.024	0.001	**V**	293.719	2.685	0.106
As	1.129	0.936	0.337	**Zn**	938.6	0.441	0.509

Table 4.31. Results of GLM showing the soil chemical variables that were significantly correlated between farm variables to the distance of the closest lagoon (p<0.05) highlighted in grey.

Dependent Variable	Mean Square	F	Sig.	Dependent Variable	Mean Square	F	Sig.
General Variables				**Ba**	1312.12	0.54	0.83
				Co	2.36	2.40	0.34
C%	5.88	21.92	0.04	**Cr**	102.37	1.25	0.54
EC	268.05	2.70	0.31	**Cu**	18.80	7.95	0.12
P	1378541.52	22.62	0.40	**Fe**	12523516.00	2.77	0.30
pH	0.14	0.55	0.83	**Li**	7.37	1.72	0.44
S	91741739.82	0.53	0.84	**Mn**	6704.33	2.71	0.31
Anions and Cations Variables				**Mo**	4.73	151.03	0.01
Ca	522231774.20	0.74	0.73	**Ni**	102.05	1.49	0.48
I	41040884.82	3.69	0.24	**Pb**	2.15	1.50	0.48
K	2147036.36	2.75	0.30	**Rb**	24.29	1.80	0.42
Mg	31691363.98	1.39	0.51	**Sr**	146040.50	7.64	0.12
Na	2588274.31	4.32	0.21	**Ti**	8195.13	1.36	0.52
Metal and metalloid variables				**U**	0.13	2.91	0.29
Al	27696390.00	2.16	0.37	**V**	125.99	2.02	0.39
As	1.33	4.61	0.19	**Zn**	686.29	7.15	0.13

4.3.5.2 Farm and lagoon soil quality analysis

Many studies have analysed the long term influence of using both WW and TWW on soil quality. Some studies showed a noticeable increase in heavy metal concentrations as a negative side effect, but at the same time increased macronutrients such as N, P and K which benefit plant growth and thereby limit the need for fertilizers (Abd-Elwahed, 2018; Mng'ong'o *et al.*, 2021). The main

objective of this section was to understand the influence of lagoon water on the soil quality in relation to irrigation with groundwater suspected to be polluted with lagoon water. Thus, the characteristics of soils from farms and lagoons were analysed in this section.

Table 4.32 presents, in summary, the characteristics of soils from both the lagoons and farms, with the number of soil samples showing values outside the recommended soil quality standards of the European Union (EU) and FAO/WHO. Furthermore, for comparison, the average values of the measured soil characteristics in this study were compared with data from a geochemistry study of Qatari farms undertaken in 2015 (Shomar, 2015). The overall objective was to understand the influence of groundwater and lagoon water irrigation on soil characteristics.

Table 4.32. Summary of the farm (n=53) and lagoon (n=10) soils' variables (mean, minimum, maximum and standard deviation), with the number of farms and lagoons soil violating EU and WHO (highlighted in grey).

	Mean		min		max		SD		EU[1]			FAO/WHO[2]			Qatar soil 2015[3]
	F	L	F	L	F	L	F	L	STD	violations F	violations L	STD	violations F	violations L	
General quality variables (mg kg^{-1}), except EC in µs cm^{-1} and pH no unit															
C%	6	8	1	4	20	11	2	2	-	-	-	-	-	-	5.7
EC	23	33	2	3	79	102	16	32	-	-	-	-	-	-	-
pH	7.9	8	7	7.5	9	9	0.4	0.6	-	-	-	-	-	-	-
P	1140	489	75	94	6390	1850	1150	524	-	-	-	-	-	-	-
S	10500	7260	559	1040	33000	21000	9740	7320	-	-	-	-	-	-	10000
Anions and cations variables (mg kg^{-1})															
Ca^{2+}	123000	173000	31300	98200	165000	269000	23000	60700	-	-	-	-	-	-	143518
I	7640	1950	315	322	40300	6600	6310	2200	-	-	-	-	-	-	-
K^{+}	7230	4140	2840	1430	10600	8149	1447	2300	-	-	-	-	-	-	6889
Mg^{2+}	1590	22500	3040	8600	36000	43200	5600	11500	-	-	-	-	-	-	20148
Na^{+}	5920	5520	3040	844	10900	9800	1580	3200	-	-	-	-	-	-	8627
Metal and metalloid variables (mg kg^{-1})															
Al	21200	14600	9890	7040	36900	23400	5210	5720	-	-	-	-	-	-	5923
As	3	2	1	1	7	4	1	1	-	-	-	-	-	-	1.38
Ba	217	262	122	137	380	491	37	109	-	-	-	-	-	-	53
Cd	0	0	0	0	0	0	0	0	3	0	0	0.3	0	0	0.39
Co	3	2	1	1	8	3	1	0.6	-	-	-	-	-	-	1.59
Cr	33	32	8	21	70	41	10	7	100	0	0	100	0	0	12.84
Cu	9	5	3	3	26	9	4	2	100	0	0	100	0	0	4.42
Fe	8570	6390	2930	3990	20000	8860	3490	1660	-	-	-	-	-	-	3798
Li	8	5	4	3	18	7	3	1	-	-	-	-	-	-	
Mn	240	167	70	89	503	224	81	42	-	-	-	-	-	-	104
Mo	1	0.6	0.4	0.3	13	1	2	0.2	-	-	-	-	-	-	0.4
Ni	24	17	4	10	68	24	10	5	50	2	0	50	2	0	10.2
Pb	5	4	3	2	10	6	1.5	1.3	100	0	0	100	0	0	2.67
Rb	22	14	11	6	41	26	5	6	-	-	-	-	-	-	
Sr	907	995	415	398	2170	1660	375	457	-	-	-	-	-	-	638
Ti	316	254	98	165	539	357	90	53	-	-	-	-	-	-	
U	1	0.7	0.4	0.4	3	1	0.4	0.2	-	-	-	-	-	-	0.68
V	30	24	11	16	66	32	11	5	-	-	-	-	-	-	12.65
Zn	47	57	13	9	147	347	26	103	300	0	0	-	-	-	15.9

1. European Parliament and of the Council as regards maximum levels for certain undesirable substances in soil (European Commission, 2018a, 2018b)
2. FAO/WHO join standard for soil for agriculture (FAO/WHO food standards Program, 2007)
3. Soil profile from a study done in Qatar (Shomar, 2015) to compare with this study's results

General soil quality

GLM analysis (Table 4.30) shows the alkalinities of farm and lagoon soils were significantly different: lagoon soils showed a higher pH value (mean 8.23) than farm soils (mean 7.89). Arid regions often have predominantly alkaline soils, which is caused by minimal rainfall restricting leaching in dry environments so that soil acidification is minimized. Low rainfall causes the soil to retain sufficient non-acid Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+} to prevent the accumulation of acid cations. This alkaline arid condition is also seen in Saudi Arabia (Table 4.31) where the pH average is (8-8.9). The noticeably high lagoon soil pH may reflect the high pH in lagoon water seen in section 4.3.2.

Major anions and cations

In both lagoon and farm soils, alkali and alkali-earth cations dominated the soil characteristics: $Ca^{2+} > Mg^{2+} > Na^{+} > K^{+}$. These cations are non-hydrolyzing and do not produce acid (H^{+}) which explains the alkalinity of the soil. Moreover, the observed correlation of Na^{+}, Ca^{2+}, Mg^{2+} with EC, S, Mo and C in both farms and lagoons indicates the mineralogy of the local soil; the soil in Qatar is reported to contain gypsum and dolomite (Ca^{2+}, Mg^{2+} and S), with high levels of Mo and with soil salinity influences (EC and Na^{+})

GLM analysis (Table 4.30) showed a significant difference between the lagoon and farm soil Ca^{2+}, I, K^{+} and Mg^{2+}, with all those variables higher in lagoons; this could indicate that continuous agriculture in farms has depleted those constituents. Moreover, it is reported that several farms across the country have imported soil from Asian countries to use as a more suitable substrate for agriculture (Shomar, 2015), which could have changed the soil characteristics in the farms.

Metal and metalloid variables

The only parameter violating both European Union (EU) and FAO/WHO maximum allowable levels in the soil were Ni (two out of 52) in farm soil samples; there were no instances of Ni violation in lagoon soils. The concentration of Ni was double that of the 2015 study. The PCA (Fig 4.24) analysis indicated that Ni was correlated with other heavy metals, and in the HCA (Fig 4.25) Ni was correlated with As in farms soils, suggesting a common origin for both which might be a consequence of reduction processes in the groundwater used for irrigation.

Metal concentrations were significantly greater in farm soils (Al, Co, Cu, Mn, Pb, Rb, Ti and U), except Ba, which was higher in lagoon soil. Moreover, those variables were correlated to each other in both PCA and HCA, except for Cu and Pb; this may indicate that Al, Co, Mn, Rb, Ti and U share the same source as other redox-active metals (Fe, Ni and As). Also, those variables were noticeably higher than their average values in the 2015 study. All of those heavy metals have been shown in

previous studies to significantly increase in farm soils after the application of manures (Deng *et al.*, 2020; Li *et al.*, 2020; Cai *et al.*, 2021). Thus, the higher values in Qatari farms could be from the practice of using animal manure as fertilizer (Kalra *et al.*, 2011; FAO *et al.*, 2016). However, those metals have the same correlation and high values in lagoon soils, which do not receive manure or imported soil. Therefore, the TWW impact on the groundwater used for irrigation could be the source of those metals in the farm soil. The GLM analysis did not show the influence of lagoon water proximity on the soil, as was seen in the water section, and it was not possible to determine lagoon water's influence on the heavy metals in the soil. Lithium was also found to be significantly higher in farm soils, which could due to the high level of Li in groundwater shown in section 4.3.2.3

4.3.5.3 Saline-sodic soil analysis

In terms of salinity classification, the soils can be divided into four types: normal, saline, saline-sodic, and sodic soils (Zaman *et al.*, 2018). To determine the type of lagoon and groundwater soil, values of the SAR were calculated using the same equation used for water in meq L^{-1}. Soil classified as saline have EC values greater than 4 dS m^{-1} but a SAR less than 13 meq L^{-1} in the saturation extract (Zaman *et al.*, 2018). From Figure 4.26, it is seen that the majority of the farm and lagoon soils collectively (50 out of 53 farms and 2 out of 10 lagoons) must be considered saline. As a result, Ca^{2+} and Mg^{2+}, rather than Na^{+}, dominate the exchange complex of saline soils. Saline soils are also defined as having a pH <8.5, which is the case for this research; soils had a mean pH of 7.89 for farms and 8.23 for lagoons. Plant growth on saline soils is not often limited by poor infiltration, aggregate stability or aeration, like in sodic soils, because the divalent cations prevent the soil colloidal component from dispersing (Hashem *et al.*, 2021). The evaporation of water leaves a white salt crust on the soil surface in many circumstances, which explains the term "white alkali" that was previously used to describe saline soils (Hashem *et al.*, 2021).

The remaining soils (three farms and two lagoons) were classified as ‘normal’ soil regarding salinity and sodicity. The majority of the farm and lagoon soil samples classified as saline soil is an important revelation since policymakers in the interviews have stated that the lagoon water is better than groundwater in terms of causing soil salinity; this research clearly shows that soil salinity is found in both environments.

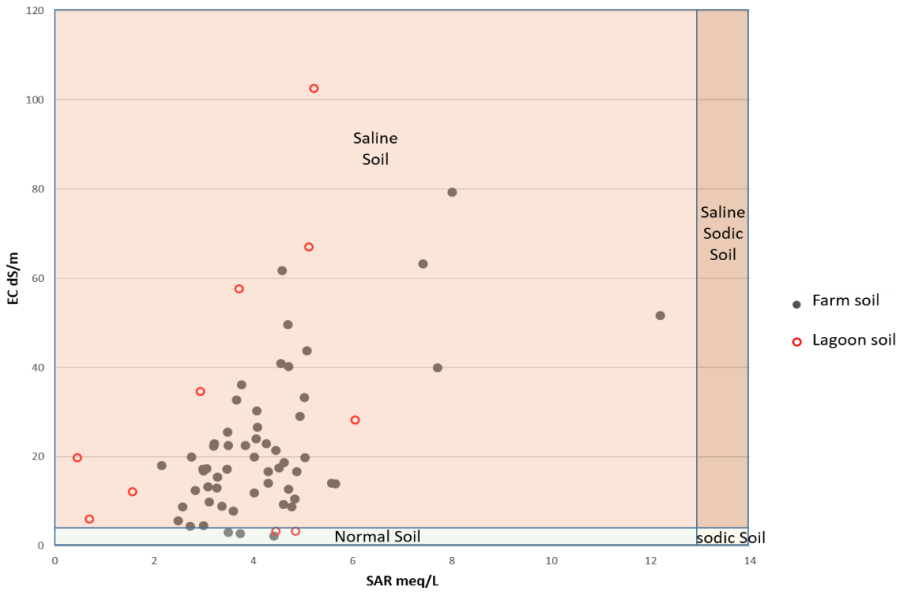


Figure 4.26. Diagram showing the relationship between soil electrical conductivity and SAR; delineated zones illustrate the soil classification of normal, saline, saline-sodic, and sodic soils.

4.3.5.4 Soil quality index

Soils irrigated with groundwater and lagoon water were both used for a range of agricultural purposes. All of the agricultural land irrigated with TWW is used to grow fodder for livestock; land irrigated with groundwater is utilised for fodder all year long and growing fruit and vegetables mostly in winter. The different sources of water will also have a different impact on the Soil Quality Index (SQI). The SQI is a decision-making tool that aids in the identification of the most long-term soil management strategies (Andrews *et al.*, 2002; Biswas *et al.*, 2017). There is no single way of measuring SQI, since each soil type, land use, irrigation water and soil management strategy is different. Thus, the chosen process of SQI should reflect the unique soil system and the specific soil standards of the area (Abd-Elwahed, 2018; Karaca *et al.*, 2021). SQI here was used as a quantifying tool to estimate the difference between soil irrigated with groundwater and soil irrigated with TWW. Table 4.33 illustrates that the majority of farms' soils were of high and very high quality, while the lagoon soils varied between very high and low. Again, this information should be communicated to policymakers, to notify them about the lagoons' effects on soil quality.

Table 4.33. Soil classification based on SQI, with the percentage of the lagoon (n=10) and farm (n=53) soil in each classification.

SQI Value Range[1]	Soil classification	Number of samples		Percentage (%)	
		Farms	Lagoon	Farms	Lagoon
≥0.85	Grade I (Very high)	45	7	85%	70%
≥0.7	Grade II (high)	8	1	15%	10%
≥0.55	Grade III (moderate)	0	1	0%	10%
0.55 – 0.4	Grade V (low)	0	1	0%	10%
<0.4	Grade VI (very Low)	0	0	0%	0%

1. (Andrews *et al.*, 2002; Biswas *et al.*, 2017; Jahany *et al.*, 2020)

4.3.6 General plant quality

This section covers the plant quality grown in both groundwater-irrigated farms and lagoon soils. Previous research has investigated the impact of long-term TWW irrigation on plants, with multivariate statistical tests and comparisons of BCF values (Zhang *et al.*, 2010; Balkhair *et al.*, 2016; Mng'ong'o *et al.*, 2021). In this section, PCA, HCA, and GLM were used to investigate the differences between farm plants and lagoon-exposed plants, beginning with general plant quality and moving on to the different statistical analysis tools used to illustrate the correlation and relationship between farm plants variables and proximity to the lagoons.

4.3.6.1 Plant multivariate statistical water analysis

The relationship between farm and lagoon soil factors was investigated using multivariate statistical analyses. A few of the examined variables were eliminated from this investigation because they were not discovered in most samples or were detected at low concentrations. These included: Be, As, Ag, Cd, Cs, U and Tl.

Plant normality test

Table 4.34 shows that 2 out of 28 data were not normal ($p>0.05$) according to the Kolmogorov-Smirnov test and Shapiro-Wilk test 24 out of 26 was not normal ($p<0.05$) for farms and lagoons plants samples. Thus, the assumptions should always not normal.

Table 4.34. Tests of normality (Kolmogorov-Smirnov and Shapiro-Wilk) for all the farm and lagoon soil variables; if the significant level (Sig.) value of the test is greater than 0.05, the data is deemed normal.

	Kolmogorov-Smirnov[a]			Shapiro-Wilk				Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.		Statistic	df	Sig.	Statistic	df	Sig.
Anions and Cations Variables							**Cu**	0.197	57	0	0.673	57	0
B	0.199	57	0	0.801	57	0	**Fe**	0.276	57	0	0.503	57	0
Ca^{2+}	0.175	57	0	0.813	57	0	**Li**	0.319	57	0	0.362	57	0
I	0.162	57	0.001	0.8	57	0	**Mn**	0.169	57	0	0.854	57	0
K^{+}	0.087	57	.200	0.974	57	0.254	**Mo**	0.16	57	0.001	0.89	57	0
Mg^{2+}	0.155	57	0.002	0.904	57	0	**Ni**	0.128	57	0.022	0.852	57	0
Na^{+}	0.257	57	0	0.605	57	0	**Pb**	0.174	57	0	0.764	57	0
P	0.119	57	0.043	0.936	57	0.005	**Rb**	0.11	57	0.084	0.929	57	0.2
S	0.166	57	0	0.8	57	0	**Se**	0.187	57	0	0.82	57	0
Metal and metalloid variables							**Si**	0.152	57	0.002	0.921	57	0.001
Al	0.247	57	0	0.581	57	0	**Sr**	0.145	57	0.004	0.89	57	0
Ba	0.189	57	0	0.793	57	0	**Ti**	0.237	57	0	0.568	57	0
Co	0.27	57	0	0.577	57	0	**V**	0.226	57	0	0.592	57	0
Cr	0.186	57	0	0.66	57	0	**Zn**	0.132	57	0.015	0.947	57	0.015

Plant Principal Component Analysis (PCA)

To provide a better picture of the farms and lagoons' plant characteristics, a PCA was utilized to demonstrate the differences in correlations between farm and lagoon plants. The KMO Bartlett's Test was employed initially. Table 4.35 shows that 0.754 is the KMO value which is acceptable.

Table 4.35. Farm and lagoon plant data KMO and Bartlett's test results.

KMO and Bartlett's Test		
KMO measure of sampling adequacy.		.754
Bartlett's Test of Sphericity	**Approx. Chi-Square**	1609.828
	df	325
	Sig.	.000

For the farms, six PCs were needed to explain 80% of the data variations, with three groups (Table 4.36): group A containing Ba, Co, Al, V, Cr, Fe, B, Ti, Ni, I and Si; group B comprising K, Na, P, Rb, Mo, Cu, Zn, Li, Se; group C including Sr, S, Ca^{2+}, Mg^{2+} and Mn. Lagoon PCA analysis required five PCs to explain 88% of the variation, with three groups: Group A contained Ti, Ni, Pb, Co, Cr, Fe, Al, Ba and V; Group B comprised Na, Li, K, P, I, Rb, Zn, Mo, Cu, Si, and Mn; group C included Mg^{2+}, S, Sr, and Ca^{2+} (Fig 4.27).

Table 4.36. Farm and lagoon plants principle components showing a correlation between the chemical variables; PC1 to PC6 had cumulative eigenvalues of more than 80%.

	Groundwater						Lagoon				
PCs	**PC1**	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**	**PC1**	**PC2**	**PC3**	**PC4**	**PC5**
Cumulative %	36	52	59	66	72	80	37	55	70	82	88
Anionic and cationic variables											
B	0.489	-0.068	-0.233	0.192	-0.215	**0.555**	-0.173	0.03	-0.009	0.065	**0.949**
Ca	0.433	**0.831**	0.146	0.042	-0.061	0.036	0.436	**0.843**	0.222	-0.066	-0.196
I	0.256	-0.156	-0.273	**0.616**	-0.151	0.333	0.333	-0.056	-0.015	0.135	**0.851**
K	-0.042	0.418	**0.727**	0.126	-0.141	-0.114	-0.444	-0.082	**0.709**	-0.406	-0.289
Mg^{2+}	0.172	**0.771**	0.133	0.44	0.109	0.015	0.024	**0.974**	-0.086	0.048	-0.023
Na^{+}	0.015	0.187	0.251	**0.824**	0.091	-0.111	0.033	0.456	0.005	**0.81**	0.003
P	-0.131	0.058	**0.816**	-0.145	0.207	-0.016	-0.499	-0.222	0.327	-0.67	-0.247
S	0.265	**0.855**	0.077	0.105	0.085	-0.036	0.17	**0.958**	-0.104	0.158	-0.014
Metal and metalloid variables											
Al	**0.946**	0.215	0.057	0.099	0.039	0.064	**0.984**	0.113	-0.003	0.037	-0.031
Ba	**0.769**	0.343	0.012	0.164	0.132	-0.171	**0.905**	0.135	-0.171	-0.147	-0.081
Co	**0.863**	0.255	-0.021	-0.014	-0.13	0.092	**0.699**	-0.026	0.107	-0.05	0.213
Cr	**0.949**	0.111	-0.109	0.111	0.128	0.043	**0.965**	0.16	-0.005	-0.009	0.199
Cu	0.105	0.008	**0.571**	0.095	-0.048	0.079	0.267	-0.153	**0.863**	-0.126	-0.051
Fe	**0.95**	0.197	0.032	0.05	0.014	0.091	**0.957**	0.139	0.012	0.006	0.13
Li	0.149	0.103	0.022	0.087	0.119	**0.598**	-0.103	0.176	**0.879**	0.333	0.2
Mn	**0.519**	**0.604**	0.036	0.035	0.288	0.218	0.486	-0.401	-0.045	-0.366	0.379
Mo	-0.074	-0.039	0.458	-0.307	-0.417	0.314	-0.221	-0.249	0.1	**0.912**	0.006
Ni	**0.837**	0.071	0.022	-0.044	0.047	0.295	**0.822**	0.347	0.306	0.038	-0.019
Pb	**0.832**	0.284	-0.012	0.164	0.132	0.075	**0.802**	0.209	-0.002	0.055	0.546
Rb	-0.005	0.053	**0.729**	0.399	-0.247	-0.374	-0.288	-0.077	**0.521**	-0.457	-0.557
Se	0.159	0.29	0.076	**0.61**	-0.122	0.26	0.225	0.33	**0.581**	0.218	-0.609
Si	0.109	-0.096	-0.336	-0.132	**0.793**	-0.014	-0.292	-0.437	-0.498	-0.297	0.104
Sr	0.256	**0.904**	0.076	-0.025	-0.111	0.086	0.219	**0.961**	0.089	-0.088	0.008
Ti	0.486	-0.074	-0.406	0.004	0.237	-0.402	**0.729**	0.497	-0.208	-0.064	0.281
V	**0.949**	0.211	-0.015	0.092	0.057	0.092	**0.969**	0.065	-0.011	0.053	-0.159
Zn	0.167	0.226	0.464	0.008	**0.713**	0.172	-0.243	-0.194	0.419	0.591	0.579

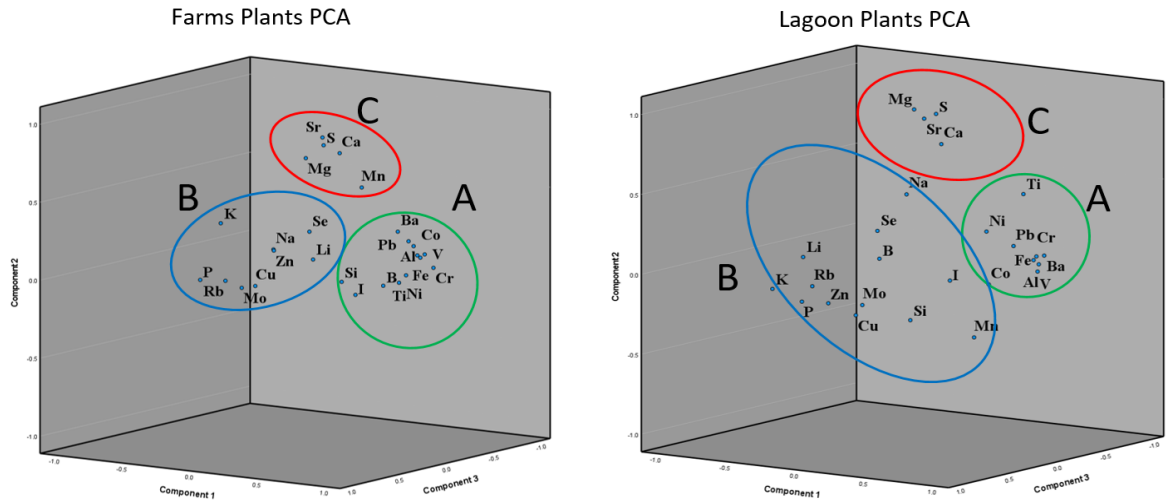


Figure 4.27. Farm and lagoon PCA 3D plot for the plants variables (farms: left, lagoons: right). Varibles clustered in the same group showen by three circules labled A,B and C. PCA was used with the Varimax rotation method and Kaiser Normalization.

Plant Hierarchical Cluster Analysis.

HCA analysis of farm and lagoon plants yielded three clades each (Fig 4.28) with the clades mostly having the same variables in both cases except that Fe was in clade A for farms but clade C for lagoons and Mn was in clade B for farms but in clade C for lagoons.

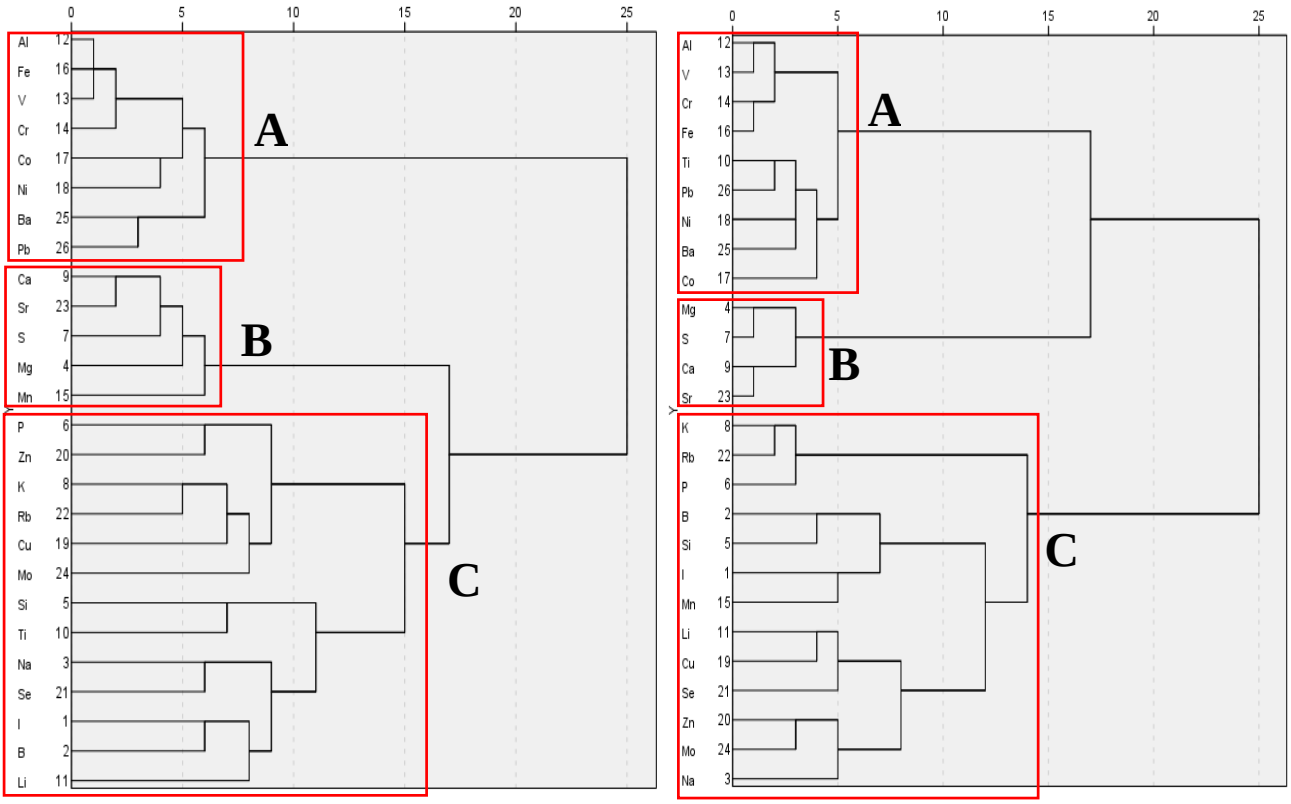


Figure 4.28. Farm and lagoon plants Dendrogram, produced by HCA using Ward linkage, with Euclidean distance and Z score standardization transformation. Varibles clustered in the same group showen by three squares labled A,B and C. (Farms: left, Lagoon: right)

Plant Generalized Linear model

The spatial variance in the plants' samples was tested using GLM. To begin, the plants' variables were assigned as a dependent variables, and the farms and lagoon were assigned as a fixed factor (Table 4.37). The distance between farms and the nearest lagoon was the second fixed factor (Table 4.38). Tables 4.37 show that Na^+, S, K, Sr, Ba, Pb were significantly different between farms and lagoons plants ($p<0.05$).

Table 4.37. Results of GLM showing the plant variables that have significant differences between farm and lagoon plants ($p<0.05$) highlighted in grey

Dependent Variable	Mean Square	F	Sig.	Dependent Variable	Mean Square	F	Sig.
Anionic and cationic variables				**Cu**	33.055	0.966	0.329
B	2.352	0.002	0.966	**Fe**	8653.617	0.075	0.786
Ca^{2+}	82863465	0.492	0.485	**Li**	67.729	1.424	0.237
I	1.011	2.09	0.153	**Mn**	4953.315	3.519	0.065
K^+	1.6468659	13.474	0	**Mo**	9.079	1.192	0.279
Mg^{2+}	53280500	2.889	0.094	**Ni**	3.887	3.197	0.078
Na^+	213296214	4.304	0.042	**Pb**	0.22	4.033	0.049
P	13199865	4.968	0.029	**Rb**	0.014	0.001	0.973
S	390654618	7.57	0.008	**Se**	6.671	2.349	0.13
Metal and metalloid variables				**Si**	43512.46	0.715	0.401
Al	17232.437	0.246	0.622	**Sr**	190628.26	4.132	0.046
Ba	175.385	9.319	0.003	**Ti**	4.769	0.084	0.773
Co	0.452	5.947	0.017	**V**	0.997	1.146	0.288
Cr	0.756	1.001	0.321	**Zn**	469.116	1.404	0.24

Table 4.38. Results of GLM showing the plant chemical variables that have significant correlation between farm variables to the distance to the closest lagoon ($p<0.05$) highlighted in grey

Dependent Variable	Mean Square	F	Sig.	Dependent Variable	Mean Square	F	Sig.
Anions and cations variables				**Cu**	19.94	2.93	0.288
B	1021.60	1.64	0.453	**Fe**	142163.97	39.25	0.025
Ca^{2+}	184544395.05	3.06	0.277	**Li**	60.77	8.01	0.117
I	0.53	15.21	0.064	**Mn**	1262.97	0.73	0.737
K^+	135876364.82	5.54	0.165	**Mo**	5.64	3.11	0.274
Mg^{2+}	7638813.22	0.46	0.875	**Ni**	1.22	38.92	0.025
Na^+	47500620.42	2.45	0.333	**Pb**	0.05	0.95	0.645
P	3161771.56	2.36	0.343	**Rb**	11.29	0.57	0.816
S	22832120.89	0.69	0.754	**Se**	2.83	0.16	0.996
Metal and metalloid variables				**Si**	61993.74	2.50	0.327
Al	82215.08	73.13	0.014	**Sr**	53321.85	1.49	0.484
Ba	16.70	6.36	0.145	**Ti**	71.89	47.22	0.021
Co	0.06	200.87	0.005	**V**	0.94	189.89	0.005
Cr	0.85	96.33	0.010	**Zn**	359.64	1.69	0.442

4.3.6.2 Farms and Lagoon plant quality analysis

Several studies were found that looked at the long-term impact of using both WW and TWW on plant quality. Some studies showed a significant increase in heavy metal concentration, as a negative side effect, but, simultaneously, an increase in uptake of beneficial macronutrients such as N, P, and K producing improved plant growth without the use of fertilizers (Rusan *et al.*, 2007; Hashem *et al.*, 2021). The purpose of this section is to comprehend the impact of lagoon water on soil quality in relation to irrigation with groundwater potentially polluted by lagoon water. The farms plant

samples consisted of a mixture of crops, including parsley, lettuce, vegetable leaves and fodder while the lagoon plants included fodder crops and reeds growing naturally around the lagoons. Thus, the EU and FAO/WHO animal fodder standards were used for comparison, since the edible crops standards require all the samples to be from the edible part of the crops (Table 4.39).

Major anions and cations

In the farm plants the major cation was K^+ then Ca^{2+} followed by Na^+ and Mg^{2+}; by contrast, the sequence was $Ca^{2+}>K^+>Mg^{2+}$ for lagoon plants. This could be due to gypsum in the soil for lagoon plants, where studies have shown that soil gypsum increases both Ca^{2+} and K^+ in the plants (Favaretto et al., 2008). Also, the fertilizers and exported soil applied to farm plants may have decreased the influence of gypsum on the farms crops. The dominant anions for both farm and lagoon plants followed the sequence S > P > I, which reflects the plant requirements for Sulfur (Favaretto *et al.*, 2008).

Table 4.39. Summary of the farms (n=53) and lagoons (n=10) measured plant variables (mean, minimum, maximum and standard deviation), with the number of farms (F) and lagoons (L) plants violating the EU standards for products intended for animal feed (highlighted in grey).

	Mean		Min		Max		SD		EU [1]			FAO/WHO[2]		
	F	L	F	L	F	L	F	L	STD	# of violations F	# of violations L	STD	# of violations F	# of violations L
Anions and cations variables (mg kg^{-1})														
B	50	49	7	14	172	220	32	61	-	-	-	-	-	-
Ca^{2+}	22600	19300	6600	7000	73200	45800	13400	12700	-	-	-	-	-	-
I	1	1	0	0	4	3	0.7	0.7	-	-	-	-	-	-
K^+	30200	16700	6540	7800	59200	41800	11500	9620	-	-	-	-	-	-
Mg^{2+}	5430	7780	1600	1550	12800	26400	2830	9220	-	-	-	-	-	-
Na^+	5780	10500	307	890	37400	28300	6810	9200	-	-	-	-	-	-
P	3870	2670	820	1650	10300	4540	1760	1030	-	-	-	-	-	-
S	7760	14300	2430	2700	24500	44600	4820	15300	-	-	-	-	-	-
Metal and metalloid variables (mg kg^{-1})														
Al	218	258	27	38	1715	650	281	208	-	-	-	-	-	-
As	0	0	0	0	0	0	0	0	2	0	0	0.1	0	0
Ba	6	10	1	2	24	21	4	6	-	-	-	-	-	-
Co	0	0.5	0	0	1.5	1	0.2	0.4	-	-	-	-	-	-
Cr	1	1	0	0	6	2	0.9	0.8	1	5	4	2.3	2	3
Cu	8	7	2	4	30	10	4	2	15	4	1	73	0	0
Fe	300	326	81	103	2361	621	369	197	-	-	-	-	-	-
Li	4	1	0	0	56	3	8	0.7	-	-	-	-	-	-
Mn	63	86	17	44	179	222	35	50	-	-	-	-	-	-
Mo	4	3	1	0	10	15	2	4	5[3]	13	1	-	-	-
Ni	2	2	0	1	6	5	1	1	0.5	53	10	66	0	0
Pb	0	0	0	0	1	1	0.2	0.3	10	0	0	0.3	14	5
Rb	6	6	0	2	18	15	3	4	-	-	-	-	-	-
Se	2	1	0	0	8	2	2	0.7	5[3]	4	0	-	-	-
Si	439	495	104	192	1020	995	246	263	-	-	-	-	-	-
Sr	399	245	53	99	1130	600	229	160	-	-	-	-	-	-
Ti	8	7	2	4	55	11	8	2	-	-	-	-	-	-
V	1	1	0	0	6	3	1	1	-	-	-	-	-	-
Zn	45	36	16	19	108	62	19	13	50	17	1	60	12	1

1. EU maximum levels for certain undesirable substances in animal feed (European Commission, 2018a)
2. Codex committee on fresh fruits and vegetables (FAO/WHO food standards Program, 2007)
3. The upper “safe” limit for levels of Molybdenum and Selenium for animal forage consumption

Metal and metalloid variables

Table 4.37 shows that plant heavy metal concentrations violated EU and FAO/WHO standards in terms of Cr, Cu, Mo, Ni, Rb and Zn for both farm and lagoon plants. It is seen from the plant PCA analysis (Fig 4.28) that Cr and Ni were correlated in the same group with Ti, Pb, Co, Fe, Al, Ba in both lagoon and farm plots, indicating that they may have the same source. This could reflect the lagoon water influence on the groundwater since Al, Co, Fe, Cr, Ni and Ti, values in the farm plants were shown to be significantly influenced by farm proximity to the closest lagoon in the GLM analysis (Table 4.37). Moreover, those variables were shown to increase in crops subject to long term irrigation with TWW, even when the soil variables were not affected (Rusan *et al.*, 2007; Mng'ong'o *et al.*, 2021).

The trace elements Cu, Mo, Rb and Zn correlated with Na, Li, K, P in both farm and lagoon plants (Fig 4.27) indicating the source could be from the local environment and K and P rich fertilizers since none of those elements was shown to be correlated with lagoon proximity according to GLM analysis.

In addition, an HCA Dendrogram (Fig 4.28) illustrated a close correlation between Al, Fe, and V metals. The correlation of those three variables has been shown by previous studies to be signs of soil dust deposition, that influenced both farm and lagoon plants (Weiss *et al.*, 2002; Motta *et al.*, 2020); dust storms are very common in Qatar.

4.3.7 Water, soil and plant relationships

To summarize, the same chemical variables were measured in water, soil and plants, from farms using groundwater and TWW for irrigation and from lagoons. A generalized linear model showed that heavy metals in groundwater and plants were significantly influenced by the wells proximity to the closest lagoon, but this was not seen with farm soils. In this section, the transfer of elements from water to soil and plants was examined, using BCF (Table 4.40) and GLM (Table 4.41) to show the influence of lagoons and TWW on the groundwater, soil and plants.

BCF analysis in Table 4.40 suggested bioconcentration of I, K^+, Na^+, P, S, Cu, Mo, Zn. The concentration of K^+ and P are essential for plant health, which suggests a positive impact of using TWW on plants (Abd-Elwahed, 2018; Mng'ong'o *et al.*, 2021). Moreover, Mo, Cu and Zn were shown to have the highest bioconcentration rate in studies related to long term irrigation with TWW compared to other heavy metals (Vymazal et al., 2009; Avci et al., 2013).

Table 4.40. Bioconcentration factors for all the chemical variables measured in plant and soil from farms and lagoons, the values highlighted in grey were greater than one and indicate plant accumulation

Variables	Farms	Lagoons
Anionic and cationic variables		
Ca^{2+}	0.19	0.13
I	0.86	1.2
K^+	4.26	4.46
Mg^{2+}	0.41	0.38
Na^+	0.98	3.67
P	5.48	9.37
S	2.17	3.18
Metal and metalloid variables		
Al	0.01	0.02
Ba	0.03	0.04
Co	0.07	0.22
Cr	0.03	0.04
Cu	1.01	1.46
Fe	0.04	0.05
Li	0.61	0.28
Mn	0.28	0.54
Mo	5.75	4.07
Ni	0.09	0.16
Pb	0.05	0.12
Rb	0.26	0.42
Sr	0.49	0.32
Ti	0.03	0.03
V	0.03	0.05
Zn	1.16	1.72

However, the BCF values did not show a significant difference between lagoon and groundwater data, the variables had similar BCF values, except for P which was higher in lagoons.

While BCF illustrated the transfer of certain elements from soil to plants, the influence of water used for irrigation was also shown using GLM. Regression models have been used in many studies to

understand the influence of irrigation with contaminated water on the chemical variables in soil and plants (Khan *et al.*, 2008; Kumar, Singh, *et al.*, 2019; Kumar, Thakur, *et al.*, 2019; Eid *et al.*, 2021).

The main objective of this study was to highlight the impact of the lagoon on the groundwater aquifers. A direct comparison between water data with soil and plant could not be done because (i) the measured units for chemical variables in water (mg L^{-1}) were different from that of soil and plant (mg kg^{-1}) and (ii) this study measured the total, rather than 'available' concentrations of chemical variables in soils.

Thus, to illustrate the lagoon proximity influence on the groundwater and subsequently on the groundwater irrigated soil and plants, GLM was employed using the calculated BCF data. The dependent variables were the BCF value for each farm site, and the fixed factor was the farms' proximity to the closest lagoon. GLM resulted that none of the BCF values was influenced by farm proximity to the lagoons, indicating the bioconcentration seen in Table 4.40 is not influenced by lagoon impact on groundwater aquifers.

In terms of lagoon impact on groundwater, soil data showed that Mo was influenced by lagoon proximity, while plant data suggested that Al, Co, Fe, Cr, Ni and Ti were influenced by lagoon proximity. However, when BCF data was analysed none of the variables was shown to be influenced. This suggests the need for utilization of other indicators, such as faecal bacteria or pharmaceutical products, to understand the lagoon impact on the exposed soil and plants in farms close to the lagoons, or soil and plants irrigated with lagoon water. This impact on soil and plant is important to investigate since the main use for both groundwater and lagoon water is for agriculture purposes.

The concentration of heavy metals in plants varies with environmental conditions (Meng *et al.*, 2016; Sharma *et al.*, 2021), and since fodder is the main plant used with TWW irrigation in Qatar, it is particularly important to instigate a study of heavy metal uptake by fodder as well as transfer to grazing animals.

4.4 Conclusions

In conclusion, the hydrochemical characteristics of Qatar's lagoons have not been studied or reported previously and, currently, there is no official monitoring of lagoons. In particular, the influence of lagoon infiltration into groundwater has never been investigated. Thus, this research addressed this knowledge gap, by characterising water, soil and plants exposed to the influence of both lagoons and nearby groundwater wells.

Lagoon water violated the Qatari TWW reuse standards in terms of pH, TDS, TN, SO_4^{2-}, Mn, and Zn, whereas groundwater violated the WHO, Qatar drinking and irrigation standards in terms of pH, TDS, TOC, B, Ca^{2+}, Cl^-, Mg^{2+}, Na^+, SO_4^{2-}, As, Fe, Se, Sr, Tl, and U. Moreover, the expected salinization in Qatar was successfully shown with piper diagrams and Gibbs plots as the major process controlling lagoon and groundwater chemistry. Chadha diagrams showed lagoons with different water sources had different water processes, and ion exchange is the dominant water type in lagoons, while reverse ion exchange were dominant processes controlling groundwater chemistry.

Lagoon water infiltrating the groundwater aquifers and influencing the water chemistry was seen using both GLM and IDW maps. Concentrations of Fe, As, I, and NO_3 in groundwater, in both summer and winter, were influenced by the lagoons' locations, with different lagoons influencing different aspects of the groundwater chemistry, this illustrated the possible lagoon water infiltration to groundwater

The suitability of both lagoon water and groundwater for their intended uses was explored using different water indices. Using WQI the majority of groundwater wells were judged unsuitable as a source of potable water. Moreover, the water indices calculated (SAR, SSP, Na%, PI, PS, Chloride, and IWQI) showed that lagoon and groundwater samples varied substantially in quality, ranging from ‘good’ to ‘bad’ quality; the major issues arising were high potential salinity and sodicity in the irrigated soil. However, lagoons were shown to have more issues with sodicity, while groundwater issues were mostly salinity. This goes against policymakers believes lagoon water is of high quality for irrigation than groundwater.

In terms of lagoon and farm soils, only Ni concentration violated the EU and FAO/WHO standards; the farm and lagoon soils showed similar trends and correlations indicated by PCA and HCA analysis. Both farm and lagoon soils were shown to be ‘saline’, with farm soils classed as ‘high quality’ using the SQI approach, and lagoon soils ranging from ‘high’ to ‘low’ quality, indicating that irrigating soil with groundwater is to be preferred - contrary to the current views of policymakers.

Farm and lagoon plants violated EU and FAO/WHO fodder standards in terms of Cr, Cu, Mn, Mo, Ni, Pb, Se and Zn concentrations, with those variables showing similar trends in farms and lagoons, possibly suggesting a common source. Moreover, BCF values showed bio-accumulation of different macronutrients and metals (I, K^+, Na^+, P, S, Cu, Mo, Zn) from the soil to plants, which was in alignment with other studies exploring the long term influence of TWW on plant composition.

In conclusion, the multivariate statistical analyses chosen for this study were able to show the relationships between measured variables in water, soil, and plants. A marked influence of lagoon water on the underlying groundwater was seen, which answer this research overall question ‘Does the lagoon water infiltrate the groundwater reservoirs? Does it change its chemical characteristics?’ . on the other hand the question of ‘Does lagoon water impact soil and plant irrigated with lagoon water?’could not be answered with this method, and another approach is needed to better illustrate it.

5.1 Introduction

Globally the environmental issues of WW, TWW and lagoons affecting groundwater reservoir bacterial communities have been reported in many studies. Most reported research results on groundwater contamination concern untreated WW and sewage seeping into groundwater (McKeon *et al.*, 1995; Morris, 2009; Castro *et al.*, 2015; Bamigboye *et al.*, 2020), with relatively few about secondary-treated or tertiary TWW (Okoh *et al.*, 2007; Popovic *et al.*, 2015; Zaouri *et al.*, 2020; Ofori *et al.*, 2021).

Moreover, literature discussing bacterial contamination of groundwater almost always measures basic chemical conditions such as pH, EC, TN and PO_4^{3-}. However, a comprehensive study that covers the detailed chemical and bacterial impact of lagoons on groundwater is uncommon. Thus, this research included a bacterial survey alongside hydrogeochemical analysis and social study.

Most studies exploring groundwater contamination from WW determine the total coliforms, faecal coliforms, and *E.coli* bacteria using selective media (Schuettpelz, 1969; Cameron *et al.*, 2003; Kaseva, 2004; Al-Farawati *et al.*, 2008; Sanders *et al.*, 2013; Talat *et al.*, 2019). This is because groundwater globally is mostly used for drinking purposes. Thus, legislative standards use total coliforms, faecal coliforms, and *E.coli* bacteria to control groundwater pollution (WHO, 2006; Herschy, 2012; U.S. EPA, 2017). However, previous research has highlighted the importance of monitoring not only coliform bacteria (CB) but also the 'Antibacterial Resistance' bacterial contamination of groundwater near WW or TWW sources. This was observed to be significantly higher in urban settlements and when the groundwater is adjacent to septic tanks and WW treatment plants (McKeon *et al.*, 1995; Andrade, Kelly, *et al.*, 2020; Zaouri *et al.*, 2020) indicating the importance of extending the study beyond simply using CB and E.coli only as indicators of bacterial contamination.

Research regarding microorganism identification in water in the environment has used several methods including ribotyping using 16S rRNA (Sorensen *et al.*, 2015; Suzuki *et al.*, 2018; Chen *et al.*, 2021) and 'Matrix-assisted laser desorption/ionisation time-of-flight mass spectrometry' (MALDI-TOF MS) (Sala-Comorera *et al.*, 2016; Suzuki *et al.*, 2018; Ashfaq *et al.*, 2019; Tang *et al.*, 2021). MALDI-TOF-MS is an instrumental technology for rapidly generating protein profiles from biological samples and has been widely used for bacteria identification and in clinical proteomics for disease-related biomarker development using Proteomic profiling and biomarker identification (Cobo *et al.*, 2016; Tang *et al.*, 2021). It has been recently used for studies of bacterial contamination

in the environment for its accurate and rapid results in terms of bacterial flora identification in WW and groundwater (Rivas *et al.*, 2017; Ae, 2019; Ashfaq *et al.*, 2022a). Studies have shown that the MALDI-TOF-MS identification success rate is approximately 96% , suggesting that it can be used as a tool to rapidly and effectively classify coliforms in water (Suzuki *et al.*, 2018).

MALDI-TOF MS has been used in previous studies in Qatar to (i) isolate and identify bacteria found in oil-polluted sites and (ii) identify high salinity resistant bacteria (Al-Kaabi *et al.*, 2018; Ashfaq *et al.*, 2019, 2022b; Abdel Samad *et al.*, 2020a, 2020b). However, a study of the bacterial community in both groundwater and lagoons has not yet been undertaken in Qatar.

In conclusion, most studies of the hazards arising from the use of TWW for irrigation, or the impact of lagoons on groundwater, present a geochemical survey and focus on the transfer of potentially toxic metals and organic contaminants to crops (Wuana *et al.*, 2011; Almuktar *et al.*, 2018; Rasiq *et al.*, 2018; Canal *et al.*, 2021; Hashem *et al.*, 2021; Ofori *et al.*, 2021). However, bacterial studies of the impact of lagoons on groundwater were rare and were reported separately from the more common chemical studies. Thus, this research attempts to combine a hydrogeochemical survey and a geo-bacterial survey of the lagoons to assess their impact on groundwater in Qatar. The hypothesis is that Qatar groundwater is contaminated by bacterial sources from adjacent lagoon water infiltration. To explore such a hypothesis, the following studies were performed:

- determine and quantify bacterial communities in lagoons and the groundwater of surrounding areas;
- determine CB in both lagoons and the groundwater sources;
- determine whether the bacterial species found in wells are the same as in surrounding lagoons;
- determine the influence of the wells' proximity to neighbouring lagoons on the bacterial counts in the groundwater.

This chapter will be based on two sets of data. First, data identifying and quantifying the different bacterial species in both lagoons and the adjacent groundwater. Secondly, the bacterial strains will be classified based on their lactose fermenting and pathogenic ability. This classification method was chosen since bacteria of intestinal origin fall within this category of bacteria, having an effect on the environment and human health. PCA analysis was used to identify the correlation between the strains of CB and the groundwater of the surrounding area.

The information established in this chapter, accompanied by hydrogeochemical analysis, will further illustrate the influence of lagoons on the adjacent groundwater quality.

5.2 Methodology

The sampling methodology and instruments for the chemical and statistical analysis used in this chapter were discussed in the methodology presented in Chapter 2. However, the methodology which is specific to this chapter will be discussed in this section.

For the microbiological part of this research, two types of data were collected. Quantitative data comprised the number/concentration of faecal bacterial colonies found in each of the lagoon and groundwater samples. Qualitative data was derived using a MALDI-TOF MS to identify bacterial species. For both sets of data, the collection process starts with plating samples on selective media for the isolation of faecal bacteria and E.coli. After counting the number of colonies in each plate, the colony is isolated for MALDI-TOF-MS analysis (Figure 5.1)

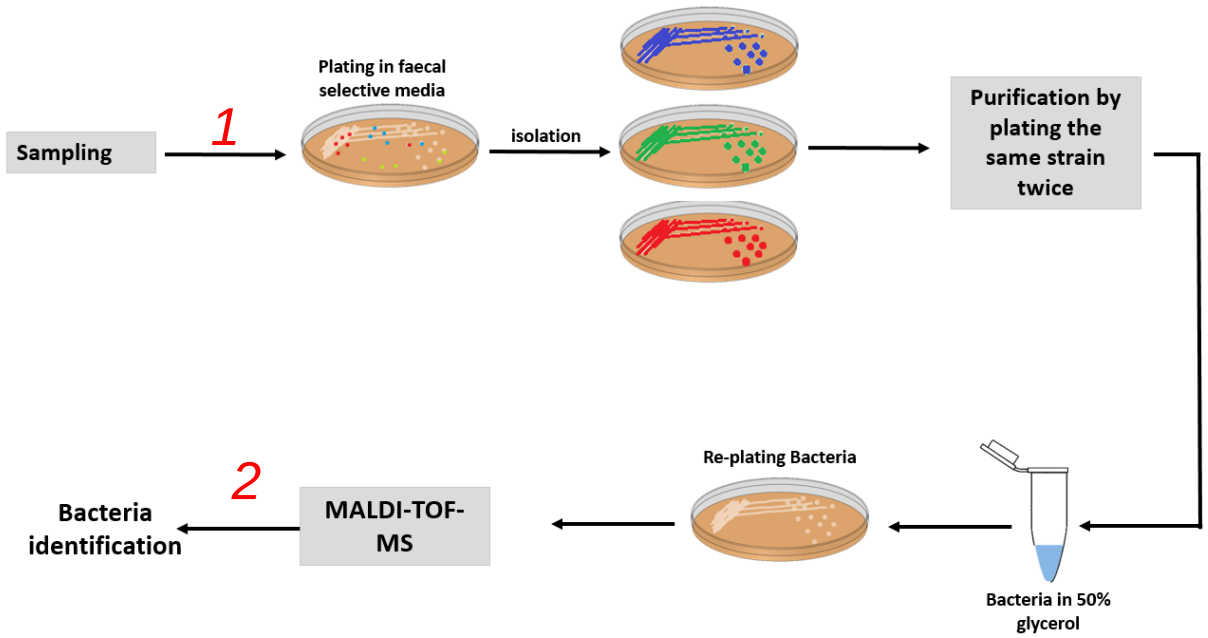


Figure 5.1. Summary of bacterial data collection methodology for: (1) Quantitative data of Colony Forming Units (CFU); (2) Qualitative method of bacterial speciation using MALDI-TOF-MS.

5.2.1 Sample collection

Microbial samples were collected in sterilized tubes and analysed on the same day at Qatar university labs to avoid bacterial degradation in the storage conditions. In addition, separate water samples were taken and stored to be transported and chemically analysed in the university of Nottingham labs. For the microbial survey, the sampling trip (winter 2020) was done separately from the hydrogeochemical survey (winter 2019), since the collaboration for the microbial survey was finally approved in late 2019. The map in figure 5.2 shows the sampling locations for lagoon and

groundwater. What is worth mentioning, the sample locations were noticeably less than the hydrogeochemistry section because of time and resources as well as Covid restrictions faced by the researcher.

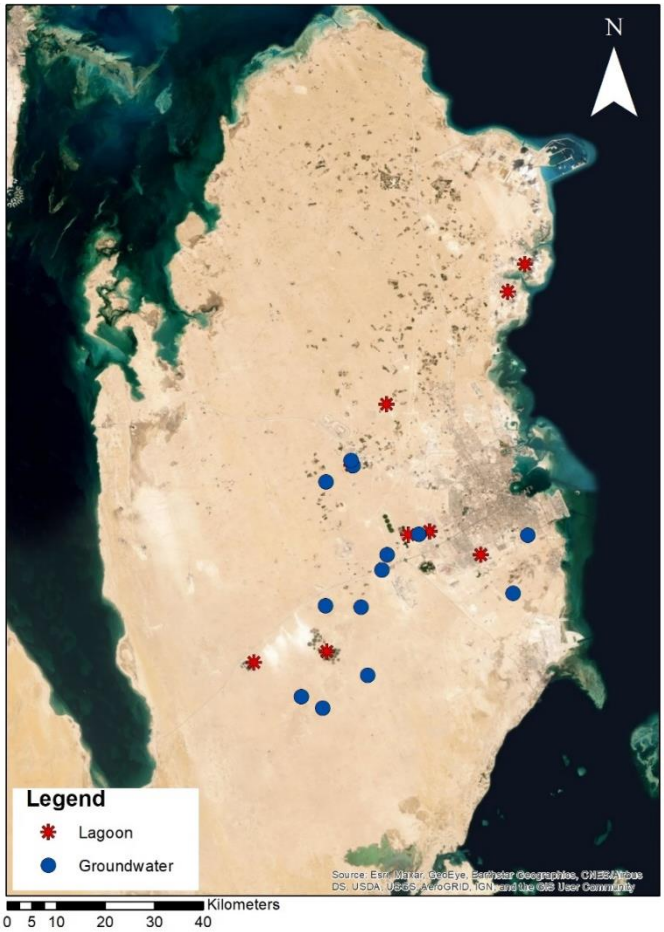


Figure 5.2. Map of Qatar with sampling locations for the microbial survey section. Red symbols show the location of all the lagoons; blue symbols indicate wells that were sampled.

5.2.2 Media and materials preparations

MacConkey selective media is a differential medium for the isolation of coliforms and intestinal pathogens in water. The typical formula (all quantities in g L^{-1}) is: peptone 20.0, lactose 10.0, bile salts 5.0, sodium chloride 5.0, neutral red 0.075, agar 12.0, pH 7.4 ± 0.2 (Thermofisher). The media was prepared by dissolving 52 g of MacConkey powder in 1 litre of distilled water the mixture was brought to a boil to dissolve all constituents completely. The resulting solution was sterilised by autoclaving at 121°C for 15 minutes, then poured into petri dishes, cooled and allowed to solidify while closing the dish to avoid contamination.

Eosin Methylene Blue Agar (EMB) is a selective medium for the isolation *E. coli* bacteria. The typical formula (all quantities in g L^{-1}) is: peptone 10.0, lactose 10.0, dipotassium hydrogen phosphate 2.0, eosin Y 0.4, methylene blue 0.065, agar 15.0, and pH 6.8 ± 0.2 (Thermofisher). The

medium was prepared by dissolving 37.4 g of EMB powder in 1 litre of distilled water and bringing to a boil to dissolve constituents completely. The solution was sterilised by autoclaving at 121°C for 15 minutes, poured into petri dishes, allowed to cool and solidify while closing the dish to avoid contamination. Other media and materials, such as distilled water, glycerol, metallic loops and 0.45 µm filter paper were autoclaved and stored in a sterilised hood.

5.2.3 Sample plating

Unlike the chemical analysis, the samples for microbiological analysis were processed on the same day of the sample collection to avoid bacterial degradation. Two types of agar were used: MacConkey and Eosin Methylene Blue Agar (EMB); both are gram-negative selective bacteria to target faecal bacteria growth in the samples. At first 1000 µl of the sample was poured onto the agar plate. Culture dishes were wrapped with laboratory sealing film (plastic or paraffin) and stored upside down (agar side up) to minimize contamination, avoid water condensation on the agar surface and keep both the culture and agar properly hydrated.

5.2.4 Colony Forming Units (CFU): dilution and concentration

To acquire quantitative data on the amount of faecal and E.coli bacteria in each sample a counting process was needed to determine the number of CFU. Counting was done to determine the number of viable bacterial cells found in a unit volume per sample (CFU ml^{-1}). Each colony in the agar plate is linked to a bacterial cell in the sample. Some counting rules were followed for best practice:

- The best possible number of colonies should be between 20-200, less than that should be filtered, more than that should be diluted;
- plates with more than 200 CFUs were serial diluted, the dilution with the best results (20-200 CFUs) was used;
- plates with less than 20 CFUs or no colonies were filtered to concentrate the sample;
- if, after the filtration, no colonies were present then the sample was reported as ‘clean’, without viable colonies;
- plates with colonies merged with no clear boundaries were also serially diluted.

After preliminary plating of the samples, some samples showed overgrowth on the agar plate. Thus, the sample was diluted to 1:10 or 1:100. The equation used to calculate the correct CFU value for each sample was:

$$\text{Count (CFU ml}^{-1}) = \frac{N}{D\ V} \qquad 5.1$$

Where;

N: Average number of colonies from duplicated plates

D: Dilution factor, or concentration factor

V: volume plated (ml)

For those samples that did not produce any colonies a 45 µm filter (Thermofisher) with a vacuum pump was used to concentrate 10 ml of sample, then the filter was incubated on an agar plate for 24 hours for colonies to be produced.

$$\text{Count (CFU ml}^{-1}) = \frac{N}{V} \qquad 5.2$$

Where

N: Average number of colonies from duplicated plates

V: volume plated (ml)

Ultimately, all the results were reported in the same unit of CFU per ml.

5.2.5 Purification and storage

A single colony was picked from an actively growing culture using a sterile, straight wire. The wire with the bacteria was then streaked on a new clean agar plate with the same selective media. The streaking was started in the outer age of the agar plate then moved in a zigzag pattern to the centre. Then a second streak was undertaken to almost half of the plate, then a third and final streak with a few lines to cover the remainder of the petri dish. After incubating the first streaking plates of a single colony, and the second streaking, the process was repeated on a third new plate to purify the bacterial colony.

After the bacterial strain purification with two ‘streakings’, a single log-phase colony from the second streak (less than 48 hours old) was picked with a sterilized loop and placed in an Eppendorf tube with a glycerol mixture. To prepare glycerol stocks, the glycerol was first autoclaved and then allowed to cool. The appropriate volume of glycerol was added to a suspension of log-phase bacteria and vortexed to dissociate the cells and ensure an even mixing of the bacteria with the glycerol. Finally, all the isolated bacteria were labelled and stored in a -70^{o}C freezer.

5.2.6 MALDI-TOF-MS

Bacterial isolates from the freezer were subcultured on LB agar (Thermo Fisher Scientific, UK) and incubated for 24–48 h at 37°C. Samples were then sent, on the same day, to Sidra labs for identification using a Bruker MALDI Biotyper System (Microflex LT, Bruker) according to the manufacturer’s instructions. From every fresh isolate plate an individual colony was picked out using a sterile wooden or plastic stick and placed on spots on a standard MALDI target plate; this is called ‘direct’ smear application. After smearing all bacterial colonies on the plates they were left for

approximately 5 min at room temperature (25 °C) then overlaid with 1–2 µL of HCCA matrix (saturated solution of α-cyano-4-hydroxycinnamic acid in 50% acetonitrile, 2.5% trifluoroacetic acid) which was added on the top of each bacterial spot no later than 10 min after drying the samples. The spots were then air-dried again at room temperature making sure the plate was completely dry before loading the plate into the MALDI-TOF-MS instrument.

The matrix is added to prevent bacterial decomposition and absorb energy from the laser applied by the instrument, allowing the laser light to transfer to heat. This heat is then absorbed by the colony to form numerous single charged ions which go into the 'time of flight' component where lighter ions travel faster and were detected earlier, than heavy charged ions thus producing the mass spectrum. The mass spectrum forms a graph of mass-to-charge (m/z) plotted against signal intensity, representing protein fingerprints for each colony. This mass profile is used as a fingerprint which can be compared to a well-established organism's mass spectrum database. When the analysed colony's mass spectrum matches another organism's fingerprint in the database, then the bacteria is identified.

Each bacterial colony was represented twice on the MALDI plate and each was run three times. Thus, a total of six spectra for each bacterium were obtained. For bacterial typing, the mass spectra were recorded from 0 to 30,000 Da. The software used to obtain the final data was MALDI Biotyper Real-time Classification (MBT-RTC) which compares spectral peaks from unknown samples with reference peaks in a database. The profile matched in the system was graded on a scale of 0 to 3 on a log scale. According to the manufacturer's instructions the result produced scores of: 1.7–3.000 indicating a highly likely species-level identification which means that the results are highly reliable; 2.00–2.299 indicating a genus identification reliable for genus level only; 1.70– 0in which case the analysis should be repeated because the results are not reliable.

The Bruker Bacterial Test Standard (BTS) was used for the calibration of the instrument which is an automatic calibration procedure using Escherichia coli DH5α, spiked with two additional proteins to enable calibration over a mass range of 4–17 kDa. E. coli mass spectra include a peak at 10299.09 Da. This is a characteristic peak for E. coli DH5α, and its presence indicates proper sample preparation, instrument tuning and calibration, and instrument operation. Negative controls were used by running a blank spot with only the matrix added to ensure the plate used is clean.

Pre-processing

MALDI-TOF-MS output data is divided into two sets. First, is the bacterial species identification list. The second is the protein profile list extracted from each bacterial species which is a list of proteins recorded from 0 to 30,000 Da. Both of those datasets were handled using different analyses.

Data validation

Data validation was conducted mainly by replicating the plating of samples. Moreover, some samples were randomly selected to be re-run in MALDI-TOF-MS to check the reproducibility of the instrument and the different analysis steps.

5.2.7 Coliform bacteria identification

Coliforms are rod-shaped Gram-negative bacteria that do not form spores. They are either motile or non-motile and capable of fermenting lactose (Herschy, 2012). Coliform bacteria are considered bio-indicators of (i) the safety of drinking water and tap water and (ii) general contamination of groundwater and surface water from WW or sewage (Talat *et al.*, 2019; Lyons *et al.*, 2021). Because other microorganisms overgrew the CB of interest in media, precise selection methods were used to target coliforms (Quiñónez-Díaz *et al.*, 2001; Lyons *et al.*, 2021). Growth on two selective and differential media was used to evaluate the presence of contamination by faecal coliforms. When using MacConkey and EMB agar solid media, the morphology of the developed colonies is used to determine the Gram-negative and lactose fermenting bacteria. In MacConkey, only Gram-negative bacteria grow, and lactose fermentation is distinguished by the formation of a pink colour surrounding the colonies, while EMB colonies will produce a flat dark colour, or green metallic sheen (Winn, 2006). After selection and purification of the bacterial colonies, the corresponding strains were identified using MALDI-TOF-MS. Then, the strain protein profile was used to classify it as coliform or non-coliform bacterium.

5.2.8 Bacterial flora heatmaps

Heatmaps are false colour images in which cells in the matrix with high relative values are coloured differently from those with low relative values. They are a widely used tool for visualizing microbiome data to show differences in the bacterial community abundance between settings for evaluations and comparisons (Santos *et al.*, 2018; Xu *et al.*, 2020; Lyons *et al.*, 2021). Heatmaps can be as simple as two-sided colour blocks with lists, or they might include information about hierarchical clustering and/or values of other covariates of interest (Lyons *et al.*, 2021). In this research OriginPro software was used to construct a 2D heatmap matrix that illustrates bacterial log-transformed abundance and distribution in both lagoon and groundwater samples at the strain level (OriginLab Corporation, 2021).

5.3 Results and discussion

5.3.1 Bacterial identification and distribution in both lagoons and groundwater

Bacterial species isolated from both lagoons and groundwater were discussed in this section. A total of 153 morphologically different colonies were isolated and purified, then subsequently identified using MALDI-TOF-MS. A summary of the number of bacterial colonies identified and not identified are showed in Table 5.1 alongside the chemical variables of the sampled water.

Table 5.1. Summary of the lagoons (n=9) and groundwater (n=13) 'identified' and 'not identified' bacterial strains using MALDI-TOF-MS with the measured variables (mean, minimum, maximum and standard deviation).

		Groundwater				Lagoon			
		mean	**min**	**max**	**SD**	**mean**	**min**	**max**	**SD**
Coliform bacteria									
Identified	**CFU ml^{-1}**	33	3	110	37	830	42	3240	983
Not Identified		5	0	28	8	74	0	230	93
score		2	2	3	0.1	2	2	3	0.2
General water quality variables									
EC	**µs cm^{-1}**	6970	3700	17000	3270	5820	1200	18000	5180
pH		7	7	7	0	8	6	9	1
Temp	**°C**	27	23	31	2	22	20	26	2
TDS	**ppm**	4000	2000	8000	2000	3000	1000	9000	3000
IC		39	30	51	6	24	10	47	12
TN	**mg L^{-1}**	7	2	16	4	11	1	58	18
TOC		11	8	14	2	15	8	32	7
Anionic and cationic variables									
Cl^-		687	208	1190	296	1920	167	8720	2790
NO_3^-		13	0	28	7	2	0	9	3
PO_4^{3-}		0	0	0	0	0	0	2	1
SO_4^{2-}		588	437	784	102	374	95	909	301
B		1	0	2	0	1	0	4	1
Na^+	**mg L^{-1}**	538	150	806	213	1650	108	7650	2500
Mg^{2+}		155	77	255	51	156	4	431	175
S		675	495	921	125	520	23	1510	513
K^+		53	12	74	20	82	15	332	101
Ca^{2+}		668	572	822	62	444	46	1380	414
Metal and metalloid variables									
Al		1	0	6	2	3	0	8	2
As		2	0	9	2	2	0	6	2
Ba		14	7	17	3	38	15	142	38
Cr		2	0	6	2	3	0	27	8
Cu		2	0	7	2	1	0	8	2
Fe		29	1	359	95	6	0	27	8
Li		77	43	128	22	52	4	132	53
Mn	**µg L^{-1}**	1	0	8	2	95	1	778	242
Mo		26	11	67	16	12	1	38	11
Ni		3	1	10	2	3	1	7	2
Rb		9	4	17	3	32	6	150	43
Se		7	1	16	5	4	0	27	8
Sr		14700	12900	16800	1150	8360	259	21800	7380
U		12	3	32	8	4	0	22	7
V		28	0	56	15	11	0	25	7
Zn		58	2	284	98	9	3	14	3

The MALDI-TOF-MS identification performances were 91% for the lagoon and 86% for the groundwater. This performance is in alignment with other studies that used MALDI-TOF-MS for the

identification of environmental bacteria, with a performance always of around 90% (Ae, 2019; Imai *et al.*, 2020; Tang *et al.*, 2021; Ashfaq *et al.*, 2022a).

All the identified bacterial strains had MALDI-TOF scores of ≥1.7, with the majority having MALDI-TOF scores of ≥2.0 for both lagoon and groundwater bacteria (details of scores for each bacterial strain were documented in appendix E). Thus, the bacterial strains were identified at the genus level (≥1.7) and the species level (≥2.0). All the unidentified bacterial strains were plotted again for fresh colonies and rerun with MALDI-TOF-MS, and they produced the same results of not being identified with scores of ≥1.7. Four of them were in the *Pseudomonas genus*, three were in the *Enterobacter genus*, and the remaining 14 colonies showed no peaks for identification.

Furthermore, to be able to link the results of the hydrogeochemical survey with those of the bacterial survey, the chemical results obtained after the field survey in winter 2020 were statistically compared to the previous survey (winter 2019), by performing GLM analysis to show if the measured variables changed within one year. Table 5.2 shows that most of the variables did not significantly change, with the exceptions of EC, TDS and PO_4^{3-}. EC and TDS could be due to different amounts of rainfall recharge in the winter season and, for PO_4^{3-}, because of different TWW effluent characteristics in the lagoon.

Table 5.2. Results of GLM showing the lagoon and groundwater variables with significant differences (p<0.05) between winter 2019 and winter 2020.

Dependent Variable	Mean Square	F	Sig.	Dependent Variable	Mean Square	F	Sig.
General water quality variables				SO_4^{2-}	82473.882	8.194	0.098
EC	332577518	47.201	0.044	**Metal and metalloid variables**			
IC	28.414	0.303	0.587	**Al**	60.238	1.04	0.318
pH	0.06	1.057	0.314	**As**	0.398	0.071	0.792
TDS	115056654	30.402	0.036	**Ba**	1.638	0.113	0.74
Temp	9.36	1.012	0.325	**Cr**	0.335	0.058	0.811
TN	39.64	3.32	0.081	**Cu**	13.255	7.38	0.438
TOC	436.527	226.925	0.411	**Fe**	3168.539	0.168	0.686
Anionic and cationic variables				**Li**	2186.197	2.007	0.169
B	0.042	0.204	0.655	**Mn**	13.348	1.236	0.277
Ca^{2+}	88674.294	16.224	0.178	**Mo**	68.568	0.13	0.722
Cl^-	597310.087	0.987	0.33	**Ni**	0.285	0.033	0.857
K^+	2.947	0.005	0.946	**Rb**	76.426	1.513	0.231
Mg^{2+}	211.398	0.063	0.804	**Se**	71.068	4.536	0.237
Na^+	401566.177	1.454	0.24	**Sr**	15670790	3.364	0.079
NO_3^-	262.166	6.294	0.559	**U**	1.313	0.019	0.892
PO_4^{3-}	1.056	. 075	0.047	**V**	44.737	0.16	0.693
S	40246.439	2.456	0.13	**Zn**	16834.355	3.195	0.087

5.3.2 Bacterial relative abundance

The scientific classification and the relationships between the identified bacterial species were discussed in this section. Also, Heatmaps were used to show the relative abundance of the identified bacterial strains in both the lagoon and groundwater samples.

Bacterial strains classification

After analysing the 153 morphologically different colonies, 35 different bacterial species were identified both in the lagoon and groundwater. The bacterial phylum, class, order, family and genus name are shown in Table 5.3. Because of the use of the selective media, all identified strains were Gram-negative, indicating the success of the selection method.

Table 5.3 shows that 15 out of 32 identified bacterial species were found both in lagoon and groundwater samples, 11 bacterial species were found only in lagoons and six bacterial species were found only in groundwater.

Table 5.3. Bacteria strains identified using MALDI-TOF-MS in both lagoon and groundwater samples with the bacterial phylum, class, order, family, and genus name. Underscore denotes bacteria found in groundwater only; bold denotes bacteria found in lagoon only; the rest were found in both lagoons and groundwater.

Phylum	Class	Order	Family	Genus	Bacteria Strain
Proteo bacteria	Gammaproteo bacteria	Moraxellales	Moraxellaceae	Acinetobacter	***Acinetobacter baumannii***
					Acinetobacter dijkshoorniae
					Acinetobacter haemolyticus
					Acinetobacter Junii
					Acinetobacter venetianus
		Aeromonadales	Aeromonadaceae	Aeromonas	*Aeromonas caviae*
					Aeromonas hydrophila
					Aeromonas jandaei
					Aeromonas veronii
		Enterobacterales	Enterobacteriaceae	Citrobacter	***Citrobacter braakii***
				Enterobacter	*Enterobacter asburiae*
					Enterobacter cloacae
					Enterobacter kobei
				Escherichia	*Escherichia coli*
				Leclercia	***Leclercia adecarboxylata***
				Klebsiella	*Klebsiella pneumoniae*
			Yersiniaceae	Serratia	*Serratia marcescens*
			Erwiniaceae	Pantoea	***Pantoea dispersa***
		Pseudomonadales	Pseudomonadaceae	Pseudomonas	*Pseudomonas aeruginosa*
					Pseudomonas alcaliphila
					Pseudomonas composti
					Pseudomonas fulva
					Pseudomonas mendocina
					Pseudomonas oleovorans
					Pseudomonas pseudoalcaligenes
					Pseudomonas putida
					Pseudomonas stutzeri
		Alteromonadales	Shewanellaceae	Shewanella	*Shewanella putrefaciens*
		Xanthomonadales	Xanthomonadaceae	Stenotrophomonas	*Stenotrophomonas maltophilia*
		Vibrionales	Vibrionaceae	Vibrio	***Vibrio albensis***
	Betaproteo bacteria	Burkholderiales	Alcaligenaceae	Alcaligenes	***Alcaligens faecalis***
Bacteroidetes	Flavobacteriia	Flavobacteriales	Weeksellaceae	Wautersiella	*Wautersiella falsenii*

Additionally, all the bacterial species were found to belong to the Proteobacteria phylum with only one species from Bacteroidetes phylum. Moreover, 34 out of 35 bacterial species were Gammaproteobacteria (Table 5.3). Previous studies have reported that bacteria from the Gammaproteobacteria phylum have the highest relative abundance in soil and water exposed to WW (Santos *et al.*, 2018; Ofori *et al.*, 2021).

Within the Gammaproteobacteria phylum, four main genera were found, including *Pseudomonas*, *Acinetobacter*, *Aeromonas* and *Enterobacter*; the percentage of the identified bacteria for each genus were 37%, 15%, 12% and 10% respectively. The other genus had one or two bacterial species in them constituting 26% of the identified bacterial strains. Those main genera were always reported to be found together in WW, TWW and contaminated groundwater (McLain *et al.*, 2014; Al-Jassim *et al.*, 2015; Martin *et al.*, 2018; Rodríguez *et al.*, 2020).

Pseudomonas

Pseudomonas was the most common species found in the current study (10 out of 35 samples). Many studies related to WW bacterial communities showed that *Pseudomonas* is also the most abundant strain identified in such environments (Sala-Comorera *et al.*, 2016; Jumat *et al.*, 2018; Ae, 2019). Moreover, a study by Grehs et al. showed that *Pseudomonas* increases with time in stored TWW (Grehs *et al.*, 2019). Moreover, bacteria belonging to the *Pseudomonas* genus can be found in soil and water, as well as on the surfaces of plants and animals. *Pseudomonas* bacteria as plant pathogens were the most common (Ridl *et al.*, 2018), although some strains were also harmful to humans (Lalucat *et al.*, 2006; Bentzmann *et al.*, 2011; Moloney *et al.*, 2020).

Acinetobacter

Acinetobacter species were the second most common bacterial genus identified in this study. This bacterial group can survive for long periods in the environment, and bacterial counts may even increase after WW treatment and the heavy disinfectant stage (Guerrero *et al.*, 2010). Studies have shown that *Acinetobacter* species increased in areas with heavy antibiotic use, and in WW, and persisted long enough to reach receiving watersheds and groundwater (Al-Ahmad *et al.*, 1994; Zhang *et al.*, 2009; Carvalheira *et al.*, 2021). Moreover, some *Acinetobacter* species are opportunistic human pathogens so this genus constitutes the third leading cause of nosocomial pneumonia in hospitals (Guerrero *et al.*, 2010; Vijayakumar *et al.*, 2019; Carvalheira *et al.*, 2021).

Aeromonas

Most species of *Aeromonas* are pathogenic to humans transferred from water or from handling diseased fish with those strains (Popovic *et al.*, 2015; Solaiman *et al.*, 2021). All the reported

Aeromonas species found in this research were previously reported in freshwater and WW, and have been mostly found to be antibiotic-resistant in cases of infection of both humans and fish (Chen *et al.*, 2019, 2021). *A. hydrophila* and *A. veronii* are the most common *Aeromonas* species. *Aeromonas* has also been shown to increase in occurrence in stored TWW compared to freshly produced TWW (Grehs *et al.*, 2019).

Enterobacter

Several *Enterobacter* species can be found in the gastrointestinal tracts of mammals, while others can be found on human skin and in water, food, soil and human sewage (Regli *et al.*, 2015; Annappah *et al.*, 2022). Like the other identified genera, *Enterobacter* species were also reported to be common in WW and were part of the bacterial community contaminating groundwater (Calheiros *et al.*, 2017; Pires *et al.*, 2017; Mbanga *et al.*, 2021)

Including *Enterobacter*, Enterobacterales also has other genera that were highly abundant in WW and contaminated groundwater, including: *Citrobacter*, *Escherichia*, *Leclercia*, *Klebsiella*, *Serratia* and *Pantoea* (Castro *et al.*, 2015; Santos *et al.*, 2018; Rodríguez *et al.*, 2020). One of those genera contains CB *Escherichia coli (E.coli)* and *Klebsiella pneumonia* (K. *pneumonia);* both are important indicators of WW contamination with bacteria (Paczosa *et al.*, 2016; Destiani, 2019; Bamigboye *et al.*, 2020; Ozyurek *et al.*, 2021)

Others

The rest of the genera were *Shewanella*, *Stenotrophomonas*, *Vibrio*, *Alcaligenes*, and *Wautersiella*. They are from different classes and even phyla (Table 5.3) and are represented collectively by only five strains.

Bacterial species relative abundance

Bacterial species in lagoons, and the corresponding adjacent groundwater, were not homogeneously distributed. To visually illustrate that, heatmaps were used. Heatmaps produced for both lagoons (Fig 5.3) and groundwater (Fig 5.4) show the lagoons have a high diversity in bacterial species in terms of quantity and type. The lagoon heatmap log scale was between 1 and 930 CFU ml^{-1}, while the groundwater log scale spanned 1 to 70 CFU ml^{-1}. Wastewater usually have higher numbers of Gram-negative bacterial strains than groundwater as reported in previous studies (Gallert *et al.*, 2005; Malik *et al.*, 2011; Xu *et al.*, 2020; Kaszab *et al.*, 2021); this trend was also seen in the current research.

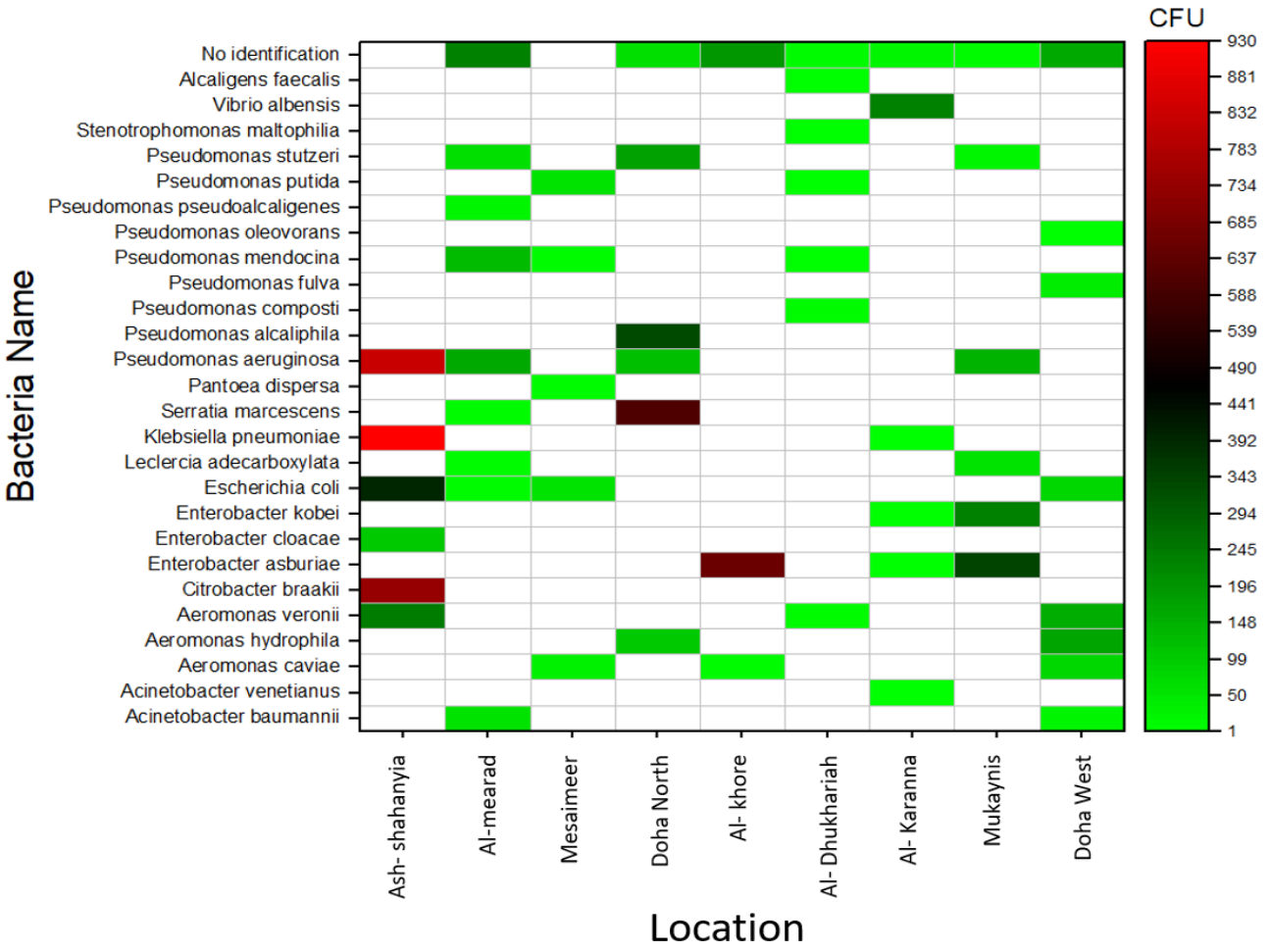


Figure 5.3. Heatmap depicting the relative abundance of bacterial populations (CFU ml^{-1}) in lagoon water at the species level.

Al-Mearad and Doha west Lagoon showed the highest number of bacterial species abundance and also a higher abundance of unidentified bacteria. Doha west treatment plant is the main treatment plant for the cities around the capital Doha. The effluent produced was reported to be 100% recycled with destinations including: (i) Doha City which uses 42% of the treated water for irrigation of green areas; (ii) farms which use 55% of the water for irrigation in the desert areas; (iii) aquifers which were replenished by injecting the remaining 3% (DWTP, 2010). These recycling practices should be reconsidered, and the tertiary treatment used in treatment plants should be reviewed, to enhance bacterial removal from the effluent reused.

The Al-Mearad lagoon is situated in the residential city of Mearad, in a government-protected area (MDPS, 2019). This lagoon was said to have surface water from network leakage and rainfall events. Therefore, the water is dumped into the lagoon without any treatment. The Al-Mearad lagoon has been the subject of complaints in the local newspapers (Al-shareq, 2015; Suliman, 2016) for being a source of mosquitoes and unpleasant odours and has also been mentioned during this study's survey

of public perception. The water sources are recommended to be reviewed and it is suggested that treatment should be implemented.

AL-Khore Lagoon was shown to have the least number of bacterial species. In fact, this lagoon is situated on the low-lying ground adjacent to the coast, where seawater has mixed with the lagoon water (information from treatment plant manager). This lagoon also showed the highest EC value of 18030 µs cm^{-1}, and this is a range typical of groundwater highly affected by marine intrusion (PSA, 2018).

The well with the highest relative bacterial abundance is Well 13, which is located in the industrial area of Doha, where the anthropological activities are concentrated. The other wells exhibited more or less the same relative abundance with *P. aeruginosa, A. hydrophila and A. Junii* as the most abundant bacterial species.

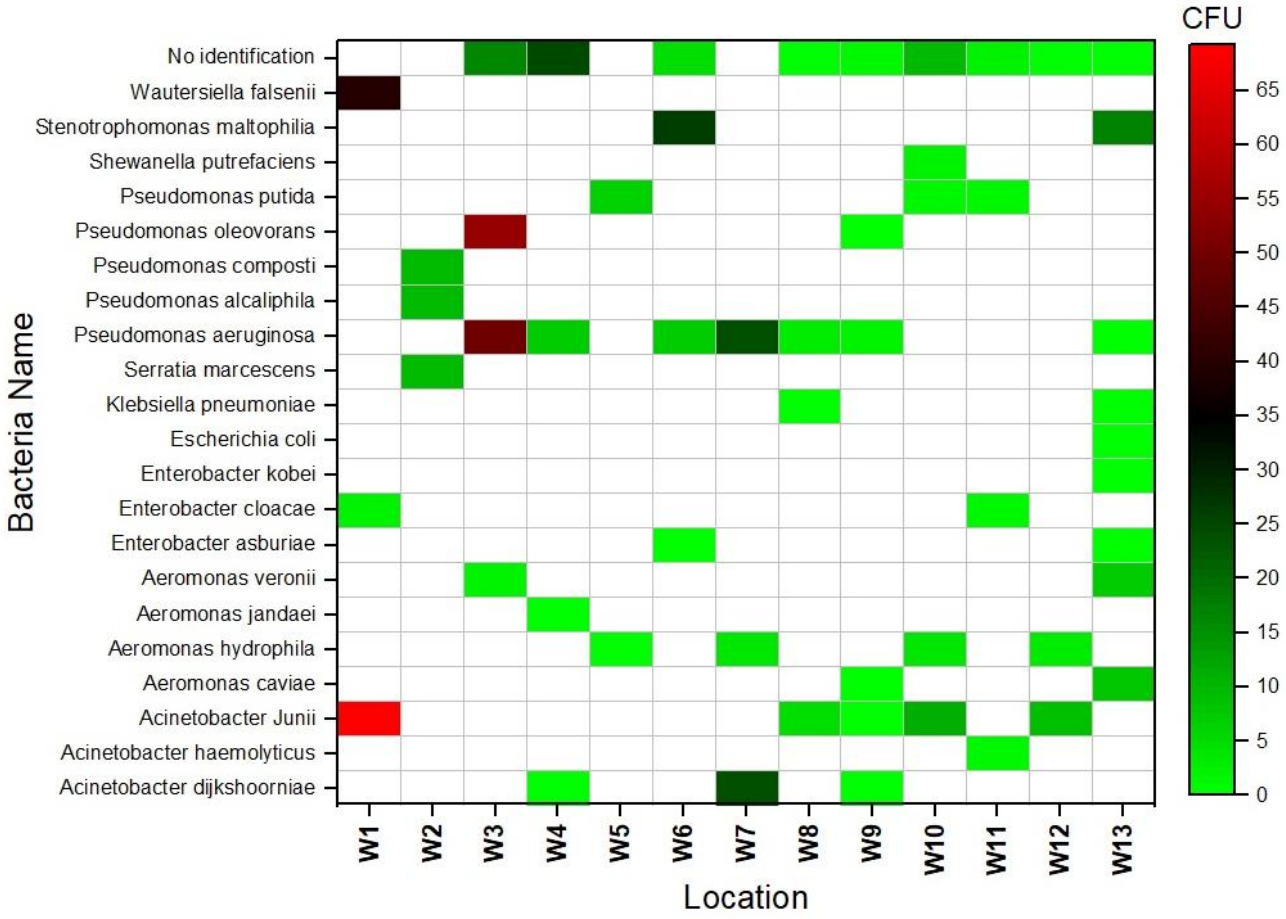


Figure 5.4. Heatmap depicting the relative abundance of bacterial populations (CFU ml^{-1}) in groundwater at the species level.

By comparing the relative bacteria abundances of the lagoons with those of the groundwater, it can be seen that *Acinetobacter* species found in the lagoons (*A. baumannii* and *A. venetianus*) are

different from the *Acinetobacter* in groundwater (*A. dijkshoorniae*, *A. haemolyticus* and *A. Junii*), with no common bacteria in this genus. Moreover, four species of *Pseudomonas* were found in lagoons but not in groundwater (*P. fulva*, *P. mendocina*, *P. pseudoalcaligenes*, and *P. stutzeri*). On the other hand, the species *P. aeruginosa* was found to have the highest abundance in both lagoons and groundwater samples.

5.3.3 Lagoons and groundwater bacterial species multivariate statistical analysis

Previous studies have used multivariate statistical analysis to explore the relationship between chemical pollutants with bacterial contamination in the TWW and groundwater (O *et al.*, 2006; Mouser *et al.*, 2010; Korbel *et al.*, 2022). This section will illustrate the relationship between the chemical characteristics of the water with the bacterial profile of the lagoon and groundwater.

First, a normality test was done to understand which statistical test types should be used. The results of the normality tests were similar to those reported in Chapter 4, where Table 5.4 shows that 22 of the 32 samples were not normally distributed ($p<0.05$) by the Kolmogorov-Smirnov test and 28 of the 32 samples were not normal ($p<0.05$) by the Shapiro-Wilk test. Thus, the assumptions should not be normal.

Table 5.4. Tests of normality (Kolmogorov-Smirnov and Shapiro-Wilk) for all the lagoon and groundwater bacterial and chemical variables; if the significance level (Sig.) of the test is greater than 0.05, the data is normal; if it is below 0.05, the data significantly deviate from a normal distribution.

	Kolmogorov-Smirnov			Shapiro-Wilk				Kolmogorov-Smirnov			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.		Statistic	df	Sig.	Statistic	df	Sig.
Bacterial profile	0.335	22	0	0.496	22	0	**S**	0.146	22	0.2	0.939	22	0.188
							SO_4^{2-}	0.169	22	0.104	0.921	22	0.079
General water quality variables							**Metal and metalloid variables**						
pH	0.224	22	0.006	0.837	22	0.002	**Al**	0.297	22	0	0.719	22	0
Temp	0.081	22	0.2	0.961	22	0.503	**As**	0.323	22	0	0.734	22	0
EC	0.178	22	0.067	0.853	22	0.004	**Ba**	0.378	22	0	0.453	22	0
TDS	0.183	22	0.052	0.858	22	0.005	**Cr**	0.33	22	0	0.465	22	0
TOC	0.24	22	0.002	0.7	22	0	**Cu**	0.252	22	0.001	0.757	22	0
IC	0.109	22	0.2	0.955	22	0.398	**Fe**	0.47	22	0	0.262	22	0
TN	0.316	22	0	0.558	22	0	**Li**	0.114	22	0.2	0.942	22	0.216
Anionic and cationic variables							**Mn**	0.48	22	0	0.252	22	0
B	0.129	22	0.2	0.89	22	0.019	**Mo**	0.223	22	0.006	0.849	22	0.003
Ca^{2+}	0.206	22	0.016	0.877	22	0.011	**Ni**	0.201	22	0.021	0.782	22	0
Cl^-	0.365	22	0	0.501	22	0	**Rb**	0.387	22	0	0.412	22	0
K^+	0.329	22	0	0.625	22	0	**Se**	0.198	22	0.024	0.79	22	0
Mg^{2+}	0.174	22	0.08	0.899	22	0.029	**Sr**	0.239	22	0.002	0.872	22	0.008
Na^+	0.406	22	0	0.481	22	0	**U**	0.155	22	0.183	0.888	22	0.017
NO_3^-	0.184	22	0.05	0.906	22	0.04	**V**	0.149	22	0.2	0.942	22	0.217
PO_4^{3-}	0.539	22	0	0.221	22	0	**Zn**	0.454	22	0	0.481	22	0

Moreover, to be able to conduct a dimensional reduction PCA, a KMO and Bartlett's Test were performed and the results in Table 5.5 indicate the suitability of the PCA analysis for this data set.

Table 5.5. Lagoon water data: KMO and Bartlett's test results

KMO and Bartlett's Test		
KMO measure of sampling adequacy.		.652
Bartlett's Test of Sphericity	**Approx. Chi-Square**	12506.95
	df	725
	Sig.	.006

Lagoon bacterial profiles PCA analysis

PCA has been used in previous studies to explore the relationship between the bacteria of interest and the chemical characteristics of the contaminated water (O *et al.*, 2006; Mouser *et al.*, 2010; Korbel *et al.*, 2022). PCA was carried out to identify the relationship between the lagoon bacterial profiles and the chemical variables of the water. PCA analysis is shown in Table 5.6 and Figure 5.5. The analysis produced 5 PCs that explain 83% of the variations. Results from the PCA analysis showed that the bacterial species in the lagoons were divided into two groups according to their correlation with the water chemical and physical variables.

Table 5.6. Lagoon bacterial profiles PCA 3D plot for the bacterial strains and the water chemical variables.

Component	**PC1**	**PC2**	**PC3**	**PC4**	**PC5**		**PC1**	**PC2**	**PC3**	**PC4**	**PC5**
Cumulative %	35.2	53.5	66.6	76.1	83.8	**TDS**	.038	-.356	.202	-.320	**.523**
A. baumannii	-0.09	-0.068	**0.919**	-0.097	0.058	**TOC**	**.805**	.488	.015	-.107	-.261
A. caviae	-0.255	-0.177	-0.122	-0.16	0.201	**IC**	-.015	**.756**	.449	-.192	.282
A. faecalis	0.001	-0.107	-0.075	**0.981**	0.085	**TN**	**.905**	.340	-.164	-.174	.016
A. hydrophila	0.378	-0.061	-0.11	-0.127	0.051	**Anions and cations variables**					
A. venetianus	-0.176	-0.211	-0.151	-0.114	-0.907	**B**	**0.873**	-0.214	0.272	0.267	-0.182
A. veronii	-0.235	**0.836**	-0.125	-0.009	0.027	**Ca^{2+}**	**0.879**	-0.176	0.367	0.068	0.102
C. braakii	-0.149	**0.978**	-0.103	-0.037	-0.019	**Cl^{-}**	**0.926**	-0.007	-0.027	0.364	0.042
E. asburiae	-0.25	-0.293	-0.315	-0.349	**0.554**	**K^{+}**	**0.934**	-0.091	0.011	0.333	-0.019
E. cloacae	-0.149	**0.978**	-0.103	-0.037	-0.019	**Mg^{2+}**	**0.698**	-0.147	0.489	0.478	0.097
E. coli	-0.203	**0.962**	-0.098	-0.066	0.005	**Na^{+}**	**0.913**	-0.077	-0.033	0.389	0.034
E. kobei	-0.165	-0.163	-0.179	-0.16	0.175	**NO_3^{-}**	-0.335	-0.299	-0.308	-0.325	0.47
K. pneumoniae	-0.15	**0.977**	-0.104	-0.037	-0.026	**PO_4^{3-}**	-0.149	**0.978**	-0.103	-0.037	-0.019
L. adecarboxylata	-0.166	-0.168	0.021	-0.173	0.194	**S**	**0.801**	-0.176	0.484	0.245	0.073
P. aeruginosa	-0.038	**0.975**	0.041	-0.1	0.015	**SO_4^{2-}**	**0.65**	-0.046	0.665	0.186	0.095
P. alcaliphila	**0.983**	0.007	-0.121	-0.134	-0.02	**Metals variables**					
P. composti	0.001	-0.107	-0.075	**0.981**	0.085	**Al**	0.319	**0.902**	-0.168	0.121	0.031
P. dispersa	-0.128	-0.169	-0.067	-0.115	0.079	**As**	**0.588**	-0.295	0.224	-0.029	-0.68
P. fulva	-0.174	-0.072	-0.048	-0.06	0.069	**Ba**	**0.97**	-0.06	-0.038	-0.058	-0.22
P. mendocina	-0.03	-0.065	**0.987**	-0.049	0.043	**Cr**	**0.985**	0.008	-0.126	-0.112	-0.015
P. oleovorans	-0.174	-0.072	-0.048	-0.06	0.069	**Cu**	**0.98**	-0.029	-0.139	-0.118	0.03
P. pseudoalcaligenes	-0.013	-0.038	**0.987**	-0.074	0.029	**Fe**	0.048	**0.964**	0.015	-0.176	0.116
P. putida	-0.128	-0.178	-0.073	-0.045	0.086	**Li**	**0.681**	-0.167	0.465	**0.515**	0.091
P. stutzeri	**0.959**	-0.024	0.188	-0.175	0.01	**Mn**	0.053	-0.027	**0.985**	-0.084	0.03
S. maltophilia	0.001	-0.107	-0.075	**0.981**	0.085	**Mo**	**0.889**	-0.191	0.355	0.047	0.041
S. marcescens	**0.984**	0.006	-0.105	-0.135	-0.02	**Ni**	**0.939**	-0.145	0.169	0.069	0.157
V. albensis	-0.176	-0.211	-0.151	-0.114	-0.907	**Rb**	**0.975**	0	-0.168	0.049	-0.099
No identification	-.043	-.257	**.573**	-.303	.358	**Se**	**0.992**	-0.027	-0.1	-0.053	-0.008
General water quality variables						**Mo**	**.889**	-.191	.355	.047	0.064
pH	-.206	-.041	.072	.207	**.937**	**U**	0.156	-0.103	**0.961**	-0.081	0.066
Temp	-.232	.416	**.692**	.251	-.100	**V**	0.301	-0.463	-0.116	**0.696**	-0.108
EC	-.011	-.356	.207	-.315	**.524**	**Zn**	**0.617**	0.009	0.227	0.022	**0.583**

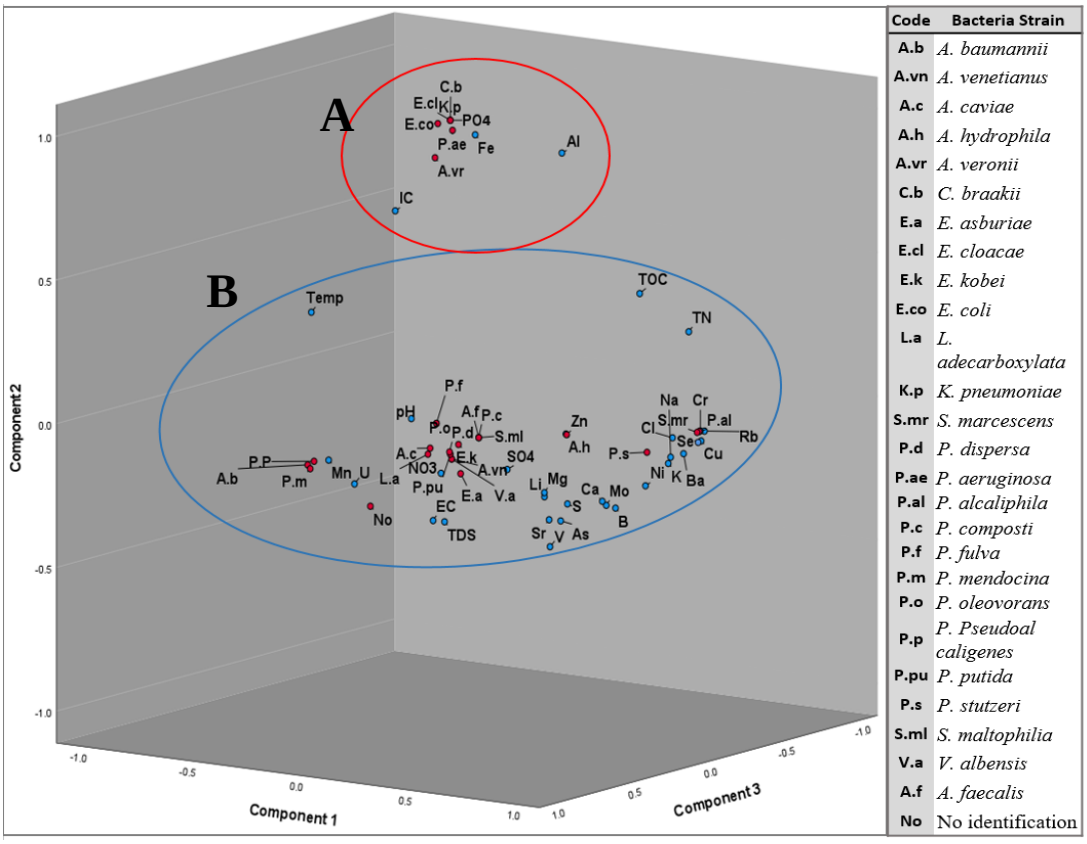


Figure 5.5. Lagoon bacterial profiles PCA 3D plot for the bacterial strains (red dots) and the water chemistry (blue dots); Varibles clustered in the same group showen by two circules labled A and B. PCA was used with Varimax Rotation Method and Kaiser Normalization.

Group A contained *E. cloacae*, *E. coli*, *C. braakii*, *A. veronii*, *P. aeruginosa* and *K. pneumoniae*. This group was correlated with Fe, PO_4^{3-}, IC, and Al. Group B consisted of all the other bacteria species (A. baumannii, A. haemolyticus, A. Junii, A. venetianus, A. caviae, A. hydrophila, E. asburiae, E. kobei, L. adecarboxylata, S. marcescens, P. dispersa, P. alcaliphila, P. composti, P. fulva, P. mendocina, P. oleovorans, P. pseudoalcaligenes, P. putida, P. stutzeri, S. maltophilia, V. albensis and A. faecalis), with the chemical variables: TOC, TN, Cr, Rb, Cu, Na^+, Cl^-, K^+, Ni, Mo, B, Ca^{2+}, S, Mg^{2+}, Li, Sr, V, As, SO_4^{2-}, EC, TDS, NO_3^-, pH, U, Mn and Temp.

Profiles of PCA analysis of groundwater bacterial proteins

To examine the association between the bacteria profiles from groundwater and the chemical variables, PCA was used. Table 5.7 and Figure 5.6 show the results of the PCA analysis. The analysis yielded five PCs accounting for 77% of the variance. As found for the lagoon PCA results, the PCA for the groundwater was divided into two groups. In the first group, only *K. pneumoniae* correlated with the majority of water/rock interaction variables (Mg^{2+}, SO_4^{2-}, Sr, Ca^{2+} and Se). The second group consisted of all the other bacteria species and chemical variables.

Table 5.7. Groundwater proteins profiles PCA 3D plot for the bacterial strains, the water chemical variables and the groundwater distance to the closest lagoon in km.

Component	PC1	PC2	PC3	PC4	PC5	PC6
Cumulative %	24.4	40	55	64	71	77.6
Distance to Lagoon	**-0.539**	-0.087	-0.263	0.221	-0.002	-0.539
A. caviae	**-0.442**	0.035	**0.982**	-0.025	0.004	0.04
A. dijkshoorniae	-0.05	0.004	-0.097	-0.057	**0.976**	0.011
A. haemolyticus	-0.057	0.157	-0.08	0.052	-0.009	-0.069
A. hydrophila	**-0.427**	-0.06	-0.145	0.477	**0.625**	-0.122
A. jandaei	-0.315	-0.165	-0.103	-0.307	-0.035	-0.178
A. Junii	**0.972**	-0.055	-0.069	0.07	-0.075	-0.095
A. veronii	-0.272	-0.022	**0.96**	-0.054	-0.065	0.002
E. asburiae	**-0.465**	-0.08	0.007	-0.029	-0.111	0.975
E. cloacae	-0.357	0.157	-0.08	0.052	-0.009	-0.069
E. coli	**-0.436**	0.033	**0.993**	-0.024	0.013	0.04
E. kobei	-0.236	0.033	**0.993**	-0.024	0.013	0.04
K. pneumoniae	-0.038	**0.899**	-0.104	-0.052	-0.13	-0.082
P. aeruginosa	**-0.461**	-0.145	-0.094	-0.163	0.19	0
P. alcaliphila	-0.282	-0.171	-0.06	-0.064	-0.059	-0.066
P. composti	-0.272	-0.171	-0.06	-0.064	-0.059	-0.066
P. oleovorans	-0.117	-0.167	-0.024	-0.095	-0.24	-0.113
P. putida	-0.256	-0.299	-0.107	-0.323	-0.146	-0.264
S. maltophilia	-0.273	-0.054	**0.468**	-0.036	-0.09	**0.863**
S. marcescens	**-0.472**	-0.171	-0.06	-0.064	-0.059	-0.066
S. putrefaciens	-0.252	0.079	-0.067	0.056	-0.079	-0.071
W. falsenii	**0.984**	-0.102	-0.043	-0.054	-0.048	-0.06
No identification	-0.206	-0.198	-0.13	-0.301	-0.221	-0.1
General water quality variables						
pH	-0.269	-0.096	0.654	-0.083	-0.321	0.099
Temp	**0.508**	0.056	-0.135	0.247	**0.599**	0.428
EC	0.066	0.17	-0.207	**0.949**	0.008	-0.034
TDS	0.061	0.167	-0.212	**0.951**	-0.006	-0.039
TOC	0.32	0.03	0.542	0.29	0.083	0.152

	PC1	PC2	PC3	PC4	PC5	PC6
IC	-0.28	**0.536**	0.054	0.043	**0.583**	-0.242
TN	-0.373	0.051	0.42	**0.786**	0.004	-0.062
Anionic and cationic variables						
B	0.17	**0.504**	0.158	**0.68**	0.293	0.208
Ca^{2+}	-0.387	**0.803**	0.087	0.071	0.006	-0.313
Cl^{-}	0.328	**0.699**	-0.241	0.385	-0.051	0.183
K^{+}	0.419	0.406	0.124	**0.52**	0.355	0.429
Mg^{2+}	0.073	**0.804**	0.064	0.43	0.212	0.09
Na^{+}	0.471	**0.572**	-0.178	0.44	0.013	0.257
NO_3^{-}	**-0.58**	0.331	0.087	**0.766**	0.045	0.055
S	-0.002	**0.79**	0.164	0.442	0.215	0.085
SO_4^{2-}	-0.09	**0.771**	0.245	0.454	0.23	0.062
Metal and metalloid variables						
Al	0.077	0.018	**0.967**	0.051	-0.06	0.186
As	**0.936**	-0.066	-0.118	-0.106	-0.216	-0.145
Ba	0.191	**-0.672**	0.122	0.144	**-0.597**	0.21
Cr	-0.349	0.053	-0.155	-0.253	-0.416	-0.252
Cu	-0.335	-0.244	0.28	0	0.016	-0.072
Fe	**0.984**	-0.1	-0.039	-0.054	-0.048	-0.058
Li	-0.031	**0.817**	-0.188	0.119	0.047	-0.133
Mn	**0.972**	-0.108	-0.043	-0.088	-0.056	0.1
Mo	0.007	-0.079	-0.089	0.16	**0.522**	0.774
Ni	-0.122	-0.082	-0.118	0.002	**0.811**	0.132
Rb	0.702	0.282	0.255	0.4	0.031	0.41
Se	-0.288	**0.634**	0.419	-0.036	-0.012	**0.538**
Sr	-0.213	**0.647**	-0.032	0.132	-0.252	0.048
U	-0.258	0.452	0.069	0.157	**0.764**	0.038
V	**-0.587**	0.07	-0.173	-0.285	-0.371	-0.47
Zn	-0.159	-0.223	0.341	-0.294	-0.068	-0.14

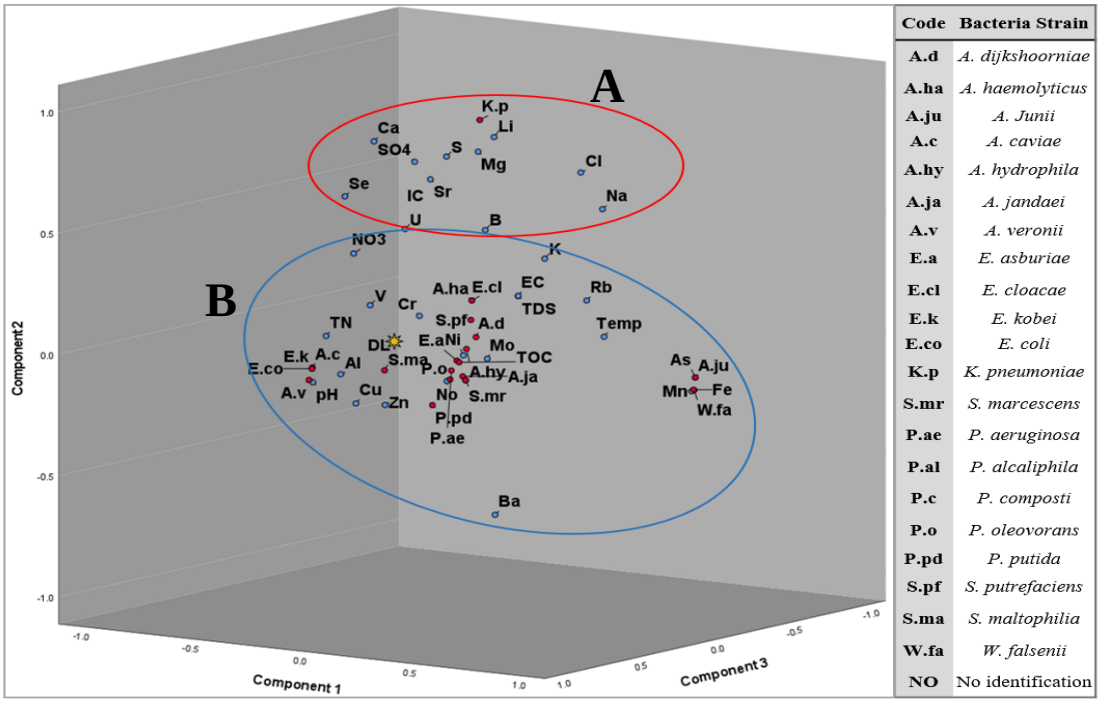


Figure 5.6. Groundwater proteins profiles PCA 3D plot for the bacterial strains (red dots), the water chemical variables (blue dots) and the groundwater distance to the closest lagoon in km (yellow star); Varibles clustered in the same group showen by two circules labled A and B. PCA was used with Varimax rotation method and Kaiser Normalization

Lagoon and groundwater correlation matrix analysis

To understand how the different bacterial strains were affected by the chemical variables, a spearman correlation matrix was produced between the strains found in both lagoon and groundwater and the water chemical and physical variables (Table 5.8).

Table 5.8. Lagoon and groundwater protein profiles spearman correlation matrix between bacterial strains and the water chemical variables.

	A. caviae	***A. hydrophila***	***A. veronii***	***E. asburiae***	***E. cloacae***	***E. kobei***	***E. coli***	***K. pneumoniae***	***S. marcescens***	***P. aeruginosa***	***P. alcaliphila***	***P. putida***	***S. maltophilia***
EC			-.378	.435									
IC												-.433	
pH	.387			.503									
TC					.437			.432		.454		-.494	
TDS			-.386	.433									
Temp	-.429	-.434											
TN		.420							.907		.907		
TOC					.420		.382	.422	.797	.533	.794		
B			-.368						.704		.698		
Ca^{2+}			-.506	-.409	-.397		-.447	-.401	.609		.606		
Cl-									.867		.865		
K^{+}									.855		.853		
Mg^{2+}									.514		.506		
Na^{+}									.855		.854		
NO_3^{-}													
PO_4^{3-}			.834		1.00		.975	1.00		.962			
S			-.466	-.399	-.365		-.415	-.369	.570		.563		
SO_4^{2-}	-.402		-.437	-.492		-.363							
Al			.660		.682		.675	.683		.701			
As									.383		.379		
Ba		.468							.954		.952		
Cr		.416							.938		.939		
Cu									.649		.655		
Fe													
Li	-.403		-.445	-.388			-.417	-0.347					
Mn													
Mo			-.366										.540
Ni									.426		.425		
Rb		.465							.965		.965		
Se									.679		.680		.407
Sr	-.411		-.579	-.470	-.450		-.516	-.454	.375	-.392	.371		
U													
V										-.378			
Zn													

5.3.4 Bacterial and chemical profiling in the lagoon water

This section covers bacterial species found only in lagoon samples and not in groundwater. The bacterial species were divided based on lactose fermenting and pathogenic ability. Figure 5.7 shows the locations of the lagoon strains. Bacterial strains *C. braakii*, *L. adecarboxylata*, *P. dispersa*, *A. baumannii*, *A. venetianus*, *P. fulva*, *V. albensis*, *A. faecalis* and P. *pseudoalcaligenes* were isolated only from one lagoon each, while *P. mendocina* and *P. stutzeri* were found in two lagoons.



Figure 5.7. Qatar map with the distribution of bacterial species found only in lagoon water.

Lactose fermenting positive bacteria

Pathogenic bacteria

Citrobacter braakii

This species is considered to be an opportunistic coliform pathogen and has been isolated from hospital infections and UTIs, but only rarely has it been recorded in the literature as a pathogen (Kumar Trivedi *et al.*, 2015; Hirai *et al.*, 2016). This species was also reported to be isolated from WW and is widespread in nature; it is mainly found in human urine. *C. Braakii* was isolated and characterized when screening for bacteria degrading anionic surfactants such as sodium lauryl ether sulfate (Dhouib *et al.*, 2003). Lagoon PCA results (Fig. 5.5) show that this species was separated in a group with *E. cloacae*, *E. coli*, *A. veronii*, *P. aeruginosa* and *K. pneumoniae*, with all those bacteria reported as dominant bacterial species in WW (McKeon *et al.*, 1995; Castro *et al.*, 2015; Tesfaye *et al.*, 2019).

Non-pathogenic bacteria

Leclercia adecarboxylata

This is a rare opportunistic human pathogen that is phenotypically closely related to *E. coli*; mass spectrometry was used to distinguish between the two bacterial species. It has been reported in immunocompromised patients exposed to water environments contaminated with it (Keren *et al.*,

2014; Adapa *et al.*, 2019). It was studied for its applicability in WW for the degradation of ammonia as well as heavy metals removal abilities (Li *et al.*, 2021). With PCA analysis, this strain is correlated with the majority of the lagoon strains and the chemical variables (Fig 5.5), indicating a similar source.

Pantoea dispersa

This bacterium is found in the environment, associated with plants, soil and water, and rarely causes human infections. However, it is resistant to almost all the known antibacterial medicines. It has been reported that it is capable of phenol degradation and has resistance to arsenic. This bacterium is considered a coliform bacterium and so presents a risk, along with *E. coli*, when WW is used for crop irrigation (Gutierrez *et al.*, 2020). With PCA analysis, this strain is seen to correlate with the majority of the lagoon strains and the chemical variables (Fig 5.5), indicating a similar source.

Lactose fermenting negative bacteria.

Pathogen bacteria

Acinetobacter baumannii

This is an opportunistic pathogen with high numbers of cases reported among immunocompromised patients in hospitals, as well as military personnel having skin and soft tissue infection by this bacterium (Guerrero *et al.*, 2010; Howard *et al.*, 2012). Its presence is reported in WW and also studies showed that it survives in water and soil receiving TWW with this bacterium (Hrenovic *et al.*, 2016; Higgins *et al.*, 2018; Dekic *et al.*, 2020). It was correlated with Mn and U in the PCA analysis. This could be explained by the fact that it was found, in previous studies, to need Mn for it to thrive (Ghosh *et al.*, 2016; Green *et al.*, 2020).

Non-pathogenic bacteria

Acinetobacter venetianus

This species was found only in the Al-Karanna lagoon. A few studies on this bacterium have shown its ability to biodegrade diesel oil and tetradecane oil, since this bacterium was isolated from oil refining WW sludge (Viggor *et al.*, 2020; Liu *et al.*, 2021). The fact that this bacterium is known to exist in oil-contaminated zones and that the strain was correlated with the majority of the heavy metals (As, V, Cu, Cr, Co, Ni, Zn, As) suggests that the AL-Karanna lagoon receives industrial wastes as well as domestic waste, or was at some time receiving oil source contamination. During the social interviews, it was stated several times that this lagoon was used to dump untreated forms of sewage, but this has changed in the last three years. However, the existence of this bacterium suggests that the lagoon is still receiving oil contaminants.

Pseudomonas mendocina

This species was found in three lagoons. It is an aerobic denitrifying bacterium rarely causing disease in humans (Zhang *et al.*, 2019; W. Zhang *et al.*, 2021). This bacterium is used in wetlands and biochar-based reactors for WW treatment. It is correlated to Mn and U as shown in the PCA analysis (Fig 5.5), which is consistent with reports stating that this bacterium exists in reduction conditions (Zhang *et al.*, 2021).

Pseudomonas pseudoalcaligenes

This species is known to be of low virulence to humans, causing peritoneal dialysis-associated peritonitis. It is reported to be taxonomically positioned in the *P. aeruginosa* group as shown by 16S rRNA analysis. It is a strict aerobe and able to grow at 42°C and reduces nitrate to nitrite (Viggor *et al.*, 2020; Xie *et al.*, 2021). This strain is found in Al-Mearad lagoon, which receives only surface water, the fact that it is also correlated to Mn and U, indicates the influence of lagoon redox conditions.

Pseudomonas fulva

This bacterium was found only in Doha west lagoon. It is a very rare infectious human pathogen. It is reported to be mainly isolated from rice, petroleum fields, oil brine and the gills of a few types of mollusc (Cobo *et al.*, 2016). It has the ability for heterotrophic nitrification and aerobic denitrification. This strain has been isolated from WW in different studies, reporting the removal of different pollutants, including mercury (Döbler *et al.*, 2000; Liu *et al.*, 2014; Yang *et al.*, 2018; Deng *et al.*, 2021). This bacterium correlated with the majority of the heavy metals (As, V, Cu, Cr, Co, Ni, Zn, As), indicating that the lagoon could be subject to contamination with oil pollutants.

Pseudomonas stutzeri

This bacterium was found in three lagoons. It is a non-fluorescent denitrifying bacterium that has also been found in humans as an opportunistic, but rarely pathogenic, infection (Lalucat *et al.*, 2006). It was found related to other strains in the same genus such as *P. mendocina, P. alcaligenes, P. pseudoalcaligenes. P. stutzeri* is also distributed in WW. Many studies have discussed the efficiency of *P. stutzeri* for the treatment of WW with high ammonium concentrations. It is considered a hydrocarbon-degrading bacterium (Ohtsubo *et al.*, 2013; Zhao *et al.*, 2018; Gao *et al.*, 2020; Otsuka *et al.*, 2020; F. Yang *et al.*, 2021), and it has been reported in research related to Qatar environments that were polluted with oil (Al-Kaabi *et al.*, 2018). Moreover, this bacterium correlated with the majority of heavy metals, indicating oil pollution in the Al-Mearad, Doha North, and Mukayinas lagoons.

Alcalignes faecalis

This bacterium was reported to be isolated from groundwater contaminated with NO_3^- and U, where it exhibits heterotrophic nitrification and aerobic denitrification heavy metal resistance (Joo *et al.*, 2006, 2007; Abo-Amer *et al.*, 2015). Moreover, this bacterium proved to have the ability to degrade anionic surfactants (Fedeila *et al.*, 2018). It is also an indicator of heavy metal contamination since it correlated with the majority of metals as shown using the PCA analysis and as discussed in a literature review on its existence in heavy metal contaminated sites (Abo-Amer *et al.*, 2015).

Vibrio albensis

Vibrio cholerae biovar *albensis*, known as *Vibrio albensis*, is a fresh water bioluminescent bacterium. While this bacterium biochemically resembles the epidemic *V. cholera*, cases of this bacterial infection are uncommon (Araj *et al.*, 2019). Moreover, this bacterium is reported in fresh and marine water but not in WW or groundwater. However, it correlated with the majority of the WW bacteria, indicating its possible WW origin.

5.3.5 Bacterial and chemical profiling in the groundwater

This section covers bacterial species found only in groundwater samples and not in lagoons. *A. Junii* was found in five out of 13 wells, *A. dijkshoorniae* was found in three wells, while the others (*W. falsenii*, *S. putrefaciens* and *A. jandaei*) were found only in one well each (Fig. 5.8).



Figure 5.8. Qatar map with the distribution of bacterial species found only in groundwater.

Lactose fermenting positive bacteria

Pathogenic bacteria

There were no examples of lactose positive pathogenic bacteria found exclusively in groundwater but not in lagoons in Qatar.

Non-pathogenic bacteria

Aeromonas jandaei

This bacterium was reported in lettuce and crops irrigated with reclaimed water (Solaiman *et al.*, 2021). In the PCA analysis, it was shown to be correlated with the majority of the bacteria species and metals, as well as the groundwater distance to the lagoons (Fig 5.6).

Lactose fermenting negative bacteria

Pathogenic bacteria

Acinetobacter junii

This is a rare urinary tract infectious pathogen, commonly found in WW with high abundance, even after chlorination as a tertiary WW treatment (Jumat *et al.*, 2018). It is also an efficient heterotrophic nitrifying and aerobic denitrifying bacterium (Hrenovic *et al.*, 2011; Yang *et al.*, 2015; Jumat *et al.*, 2018). It was correlated with Mn and Fe, as shown with PCA analysis (Fig 5.6), indicating its existence in reducing groundwater conditions, and its origin from a common source of contamination, which could be lagoons, even though this bacterium was not found in all lagoons.

Acinetobacter haemolyticus

This is an important human pathogen with known resistance to antibiotics. It has been found in heavy metal contaminated soils and waters is reported to have the ability to remove heavy metals in WW by converting them to biomass (Zakaria *et al.*, 2007; Bai *et al.*, 2020; Alhashimi *et al.*, 2021). It correlated with the majority of the bacterial species and metals in the PCA analysis (Fig 5.6), as well as the groundwater distance to the lagoons, signifying that it could be from a WW source.

Non-pathogenic bacteria

Acinetobacter dijkshoorniae

This bacterium is reported to belong to the pathogenic *Acinetobacter* species that are isolated from drinking water and food (Almirall *et al.*, 2019; Carvalheira *et al.*, 2021). It was seen in three groundwater locations and it was connected with the majority of bacteria species, metals and the groundwater distance to the lagoons in the PCA analysis (Fig 5.6) demonstrating that it could originate from a WW source.

Shewanella putrefaciens

This bacterial species was found only in one well and correlated with the majority of bacteria species and chemical variables. It is was reported to be isolated from marine environments and anaerobic conditions, and has the ability to reduce both iron and manganese (Najem *et al.*, 2016; Poggenburg *et al.*, 2016). Human infection by this species is rare, and not conclusive, but most cases were related to exposure to seawater (Vignier *et al.*, 2013). This bacterium is not reported in WW.

Wautersiella falsenii

This bacterium was found only in one well. It is a very rare, antibiotic-resistant and nosocomial infectious bacterium. It has been reported in water bodies receiving TWW, also in drinking water treatment plants (Velden, de Jong, de Jong, R. . de Gier, *et al.*, 2012; Velden, de Jong, de Jong, R. de Gier, *et al.*, 2012; Yang *et al.*, 2016). It was correlated with Mn and Fe and *A. junii* (Fig 5.6). This bacterium species could be a sign of groundwater reducing condition.

5.3.6 Bacterial and chemical profiling in both lagoons and groundwater

The bacterial species identified in both lagoons and groundwater are discussed here; they were divided based on their lactose fermentation and pathogenic characteristics. Maps showing the distribution of each bacterial species in lagoons and groundwater were also included.

Lactose fermenting positive bacteria

Pathogenic Bacteria

Escherichia coli

E.coli was found in four lagoons and one well. This bacterium is the most important indicator of faecal contamination, where institutions regulating drinking and groundwater consider its existence to regulate and implement treatment plans (Sanders *et al.*, 2013; Sorensen *et al.*, 2015; Bamigboye *et al.*, 2020; Uddin *et al.*, 2021). In both lagoon and groundwater, it correlated with WW related variables (Al, TOC and PO_4^{3-}), and negatively with natural groundwater variables (Ca^{2+}, S, and Sr) (Table 5.8). This result shows that *E.coli* is from WW treatment effluent and not from the local sites.

E.coli was found in high relative abundance in the lagoons but less so in groundwater (Fig 5.9); this could be due to the fact that *E.coli* die off before reaching the groundwater, while other strains like *P. aeruginosa* are able to survive reaching the groundwater. This was shown in a study of 15 months of monitoring groundwater showed the death of *E.coli* due to adverse effects and the survival of *P. aeruginosa* (Grisey *et al.*, 2010). Another long term study also showed groundwater contamination

with *E.coli* happening in shallow groundwater, while P. aeruginosa infiltrated deeper into groundwater aquifers (Andrade, Hynds, *et al.*, 2020).

Aeromonas caviae

This strain was found in three lagoons and two wells (Fig 5.9). In the literature, this bacterium species dominates in sewage and WW-contaminated streams. A few studies have identified this bacterium as a possible indicator of pollution with WW (Popovic *et al.*, 2015). This bacterium correlated with *E.coli* and Al in groundwater PCA analysis, and correlated positively with pH and negatively with SO_4^{2-}, Li, and Sr in the correlation matrix (Table 5.8). This could indicate that this bacterium originates from WW infiltration to groundwater in a manner similar to that of *E.coli*.

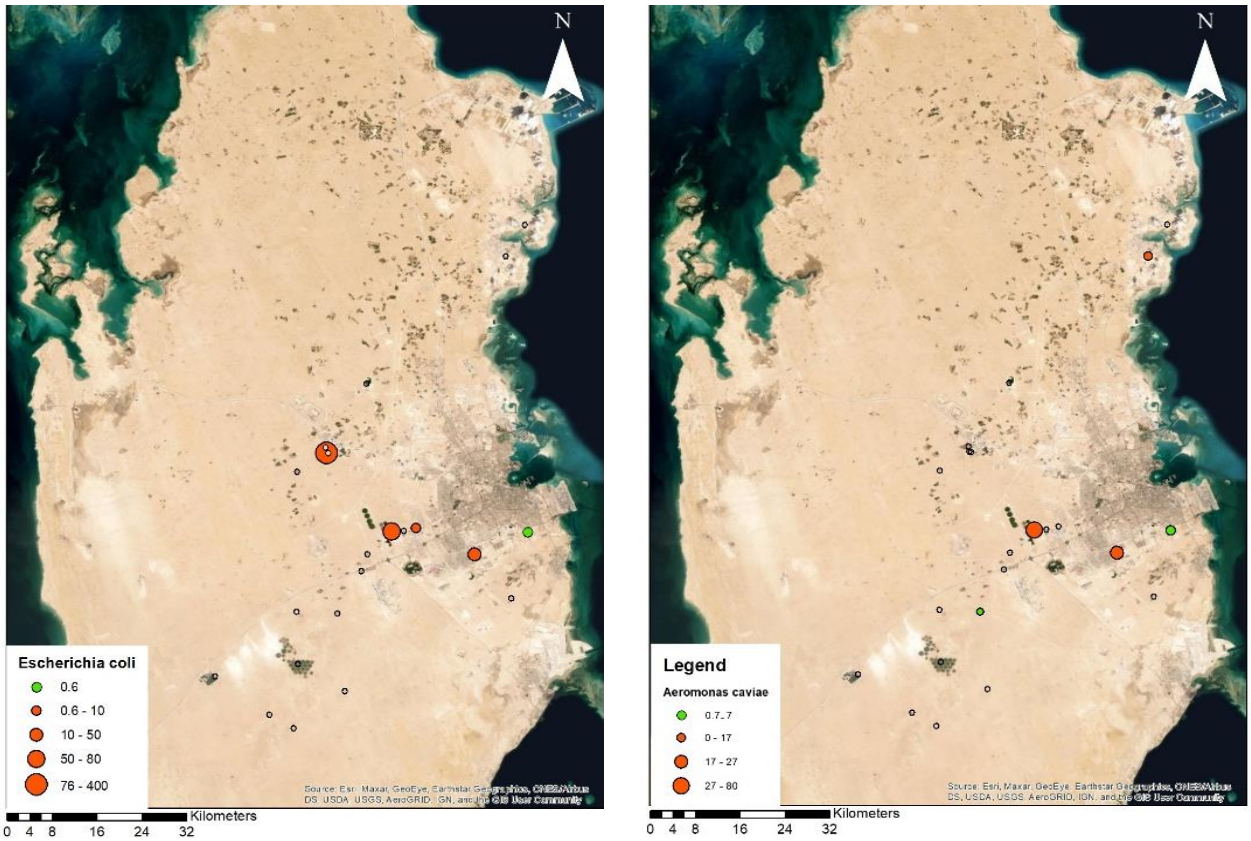


Figure 5.9. Qatar bacteria distribution map, *E. coli* on the left, *A. caviae* on the right (CFU ml^{-1}) lagoon (red) and groundwater (green)

Aeromonas hydrophila

This bacterium species was seen in two lagoons and three wells and was correlated with various metals (Fig 5.5 and 5.6); in the correlation matrix (Table 5.8) it correlated with TN, Ba, Cr, and Rb. It is known to be an opportunistic antibiotic-resistant pathogenic bacterium found in WW and TWW contaminating water surfaces (Popovic *et al.*, 2015; Chandrarathna *et al.*, 2018; Chen *et al.*, 2021).

Aeromonas veronii

This strain was found in two lagoons and one well. It is a freshwater bacterium that commonly causes sepsis and ulcer syndrome disease in fish, which has caused economic problems in farmed fish (Chandrarathna *et al.*, 2018). It is also reported to be an uncommon human pathogen but the concern is rising with increased water pollution with this organism (Ku *et al.*, 2017). It was found in both lagoons and groundwater (Fig 5.10) and it correlated with WW variables such as Al, TOC, PO_4^{3-} and negatively with groundwater variables such as EC, TDS, B, Mo, Ca^{2+}, S, Li, and Sr (Table 5.8). In both lagoons and groundwater PCA analysis (Fig 5.5 and 5.6), it correlated with *E. Cloacae*, a coliform, indicating its possible WW origin.

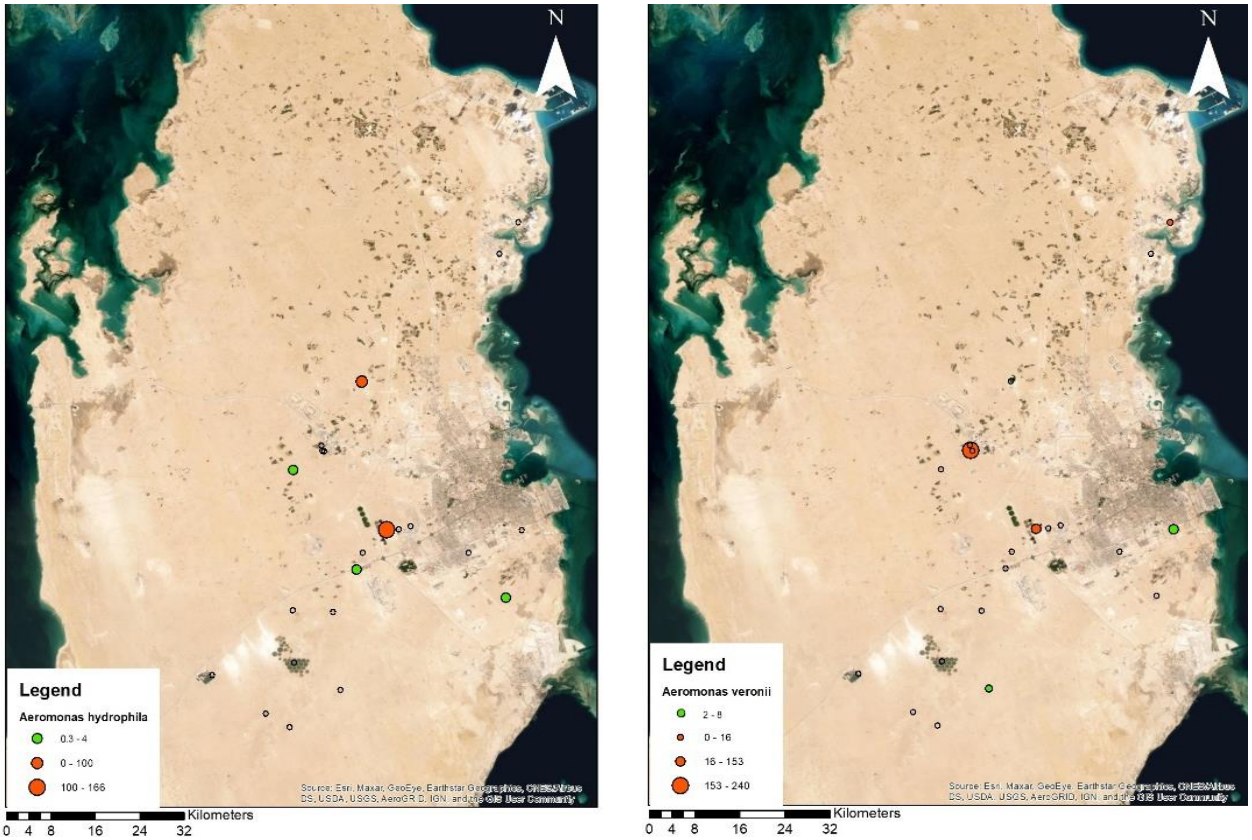


Figure 5.10. Qatar bacteria distribution map; *A. hydrophila* on the left, *A. veronii* on the right (CFU ml^{-1}) lagoon (red) and groundwater (green).

Klebsiella pneumonia

This bacterium is coliform and was found in two lagoons and three wells (Fig 5.11). *K. Pneumonias* is reported in urinary tract infections; bacteremias, and liver abscesses are also among the illnesses caused by it (Tesfaye *et al.*, 2019). Furthermore, it has become increasingly antibiotic-resistant, making infection with these species extremely difficult to cure (Paczosa *et al.*, 2016). Different strains of these bacteria have been isolated from WW and studied for their potential in

denitrification, petroleum, pesticides and surfactant degradation (Padhi *et al.*, 2013; Mustafa *et al.*, 2021). In both lagoons and groundwater, it correlated with WW-related variables (Al, TOC and PO_4^{3-}), and negatively with natural groundwater variables (Ca^{2+}, S, and Sr) (Table 5.8). In the lagoon PCA study (Fig 5.5), it correlated with other coliforms such as *E. cloacae*, *E.coli*, *C. braakii*, but in groundwater PCA (Fig 5.6), it did not correlate with the groundwater distance to the lagoon. Thus, in conclusion, even though this bacterium is coliform, it cannot be used to determine lagoon impact on the groundwater.

Serratia marcescens

This bacterium is considered coliform and was found in two lagoons and one well (Fig 5.11). It is reported as antibiotic-resistant and a rarely opportunistic pathogen (Khanna *et al.*, 2013). It is also reported to have the potential for anionic surfactants degradation and Mn removal (Fedeila *et al.*, 2018; Queiroz *et al.*, 2018). Looking at the correlation matrix (Table 5.8), this bacterium exhibits a substantial association with characteristics linked to both seawater intrusion and water/rock interaction in groundwater, leading to the conclusion that this is a bacterium found in both groundwater and seawater in Qatar.

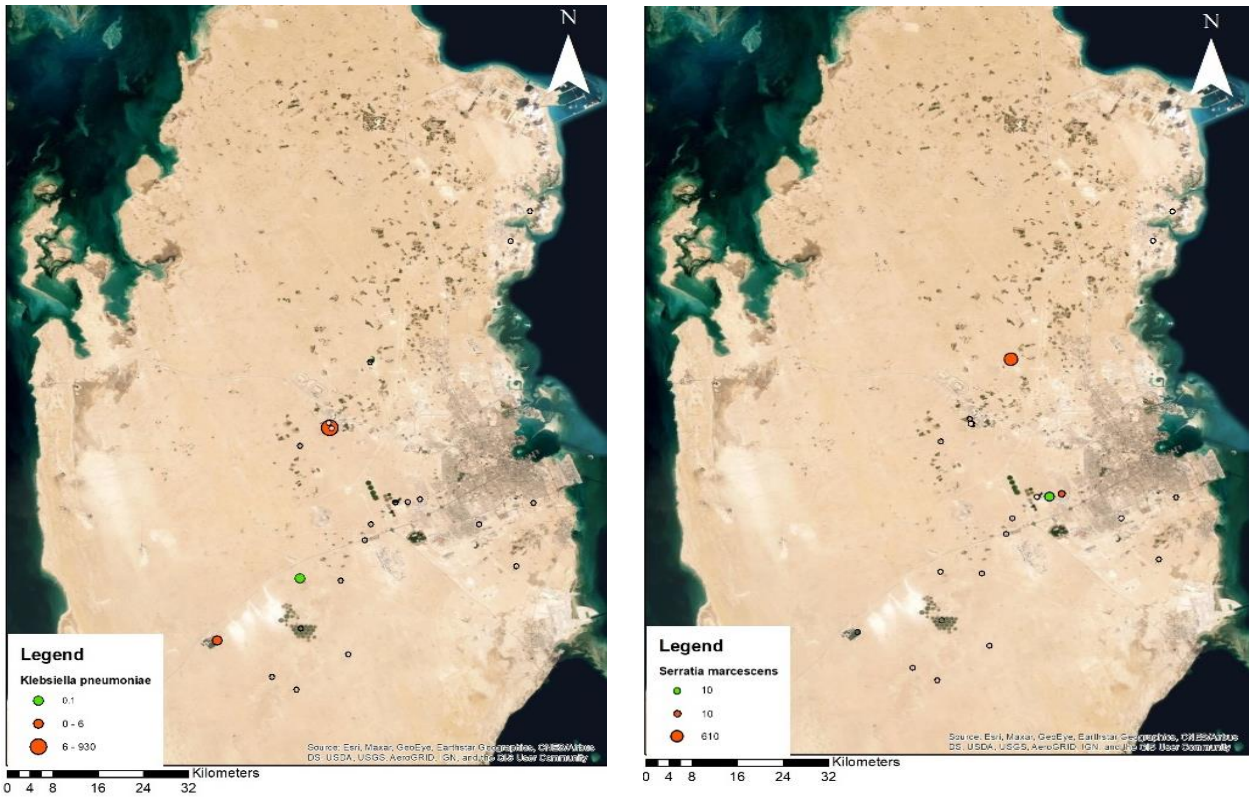


Figure 5.11. Qatar bacteria distribution map, *K. pneumoniae* on the left, *S. marcescens* on the right (CFU ml^{-1}) for lagoon (red) and groundwater (green).

Non-pathogenic bacteria

Enterobacter cloacae

Only one lagoon and one groundwater sample contained this bacterium (Fig 5.12). It is considered coliform with the ability to degrade anionic surfactants. It can be isolated from most WW, and is also a typical part of many people's gut flora; it rarely causes a major infection. (Regli *et al.*, 2015; Fedeila *et al.*, 2018). In both lagoons and groundwater, it was correlated with WW related variables (Al, TOC and PO_4^{3-}), and negatively with natural groundwater variables (Ca^{2+}, S, and Sr).

Enterobacter asburiae

This bacterium was isolated from three lagoons and two groundwater samples (Fig 5.12). This coliform is commonly found in soil, water, and sewage (Alvarez-Guzmán *et al.*, 2020). In the correlation matrix (Table 5.8), it was seen to correlate negatively to natural groundwater variables (Ca^{2+}, SO_4^{2-}, Li, Sr), indicating that it could be related to WW filtration.

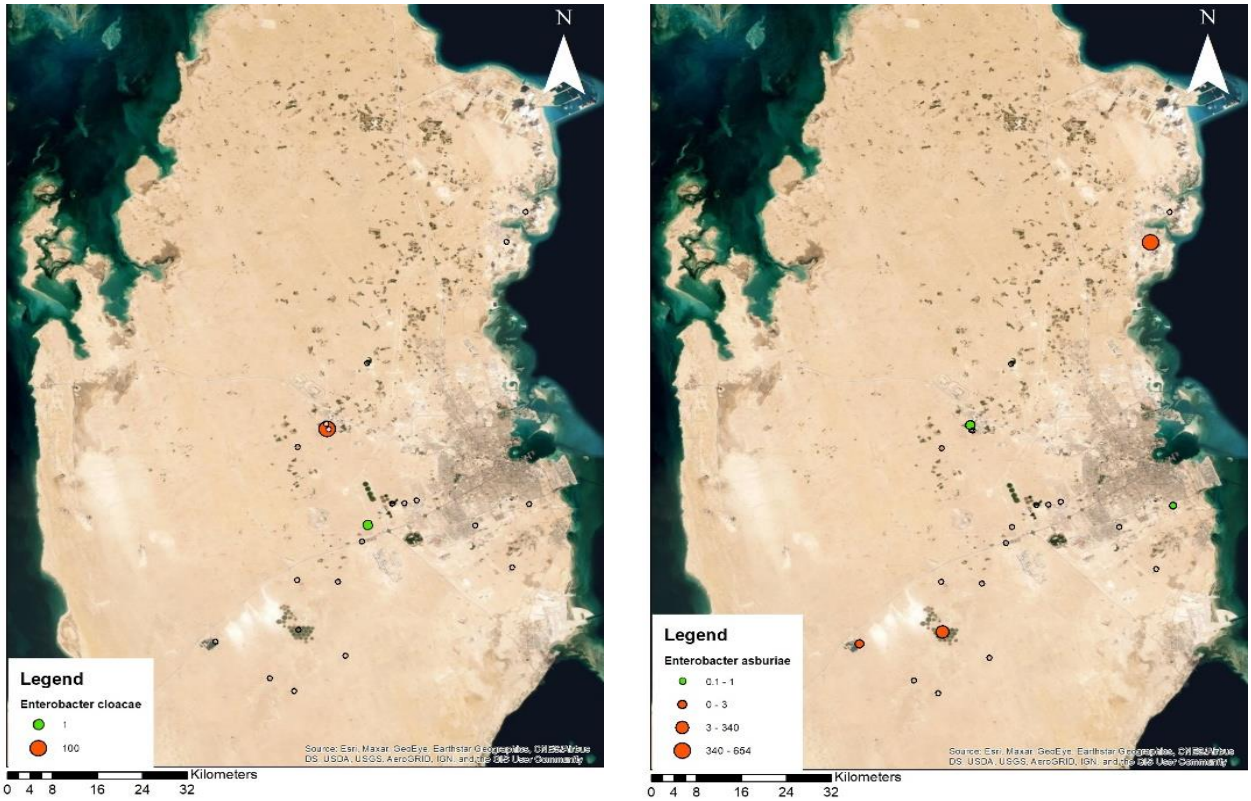


Figure 5.12. Qatar bacteria distribution map, *E. cloacae* on the left, *E. asburiae* on the right (CFU ml^{-1}) for lagoon (red) and groundwater (green).

Enterobacter kobei

This bacterium was found in two lagoons and one well (Fig 5.13). It is a coliform bacterium of the *E. cloacae* complex, previously isolated from WW (Zhu *et al.*, 2017; Suzuki *et al.*, 2018). However, it did not correlate with other Coliforms in the PCA plot.

Lactose fermenting negative bacteria

Pathogenic bacteria

Pseudomonas aeruginosa

This species is a hydrocarbon-degrading bacterium that has been reported as antibiotic-resistant and found in WW. It has been reported not only in WW but also in contaminated groundwater, lakes and even surface water. Studies have found the bacterium to be highly persistent in different water systems, including groundwater contaminated with WW (Al-Ansari *et al.*, 2021; Kaszab *et al.*, 2021; L. Yang *et al.*, 2021).

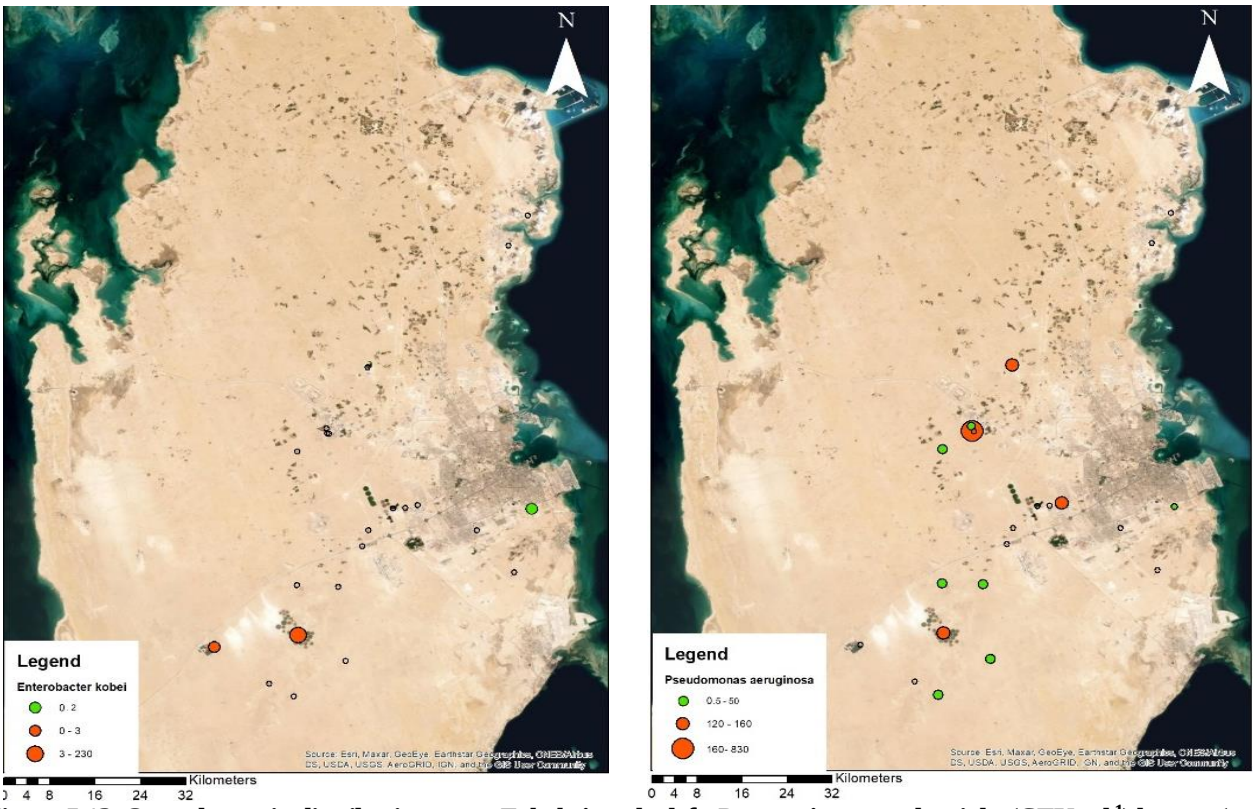


Figure 5.13. Qatar bacteria distribution map, *E. kobei* on the left, *P. aeruginosa* on the right (CFU ml^{-1}) lagoon (red) and groundwater (green)

Lately, *P. aeruginosa* has become a well-known human pathogen that is a hospital-acquired infection, causing respiratory and urinary tract infections in immunocompromised patients (Bentzmann *et al.*, 2011; Slekovec *et al.*, 2012). In Qatar, this bacterium was considered to have the most cases of infection in cystic fibrosis patients (Wahab *et al.*, 2004; Abdul Wahab *et al.*, 2005).

Studies have shown that this pathogen is found in WW and develops high resistance to antibiotics classifying it as a 'super bug' that finds its way into tap water. Moreover, a few studies were found that recommend that this bacterium should be monitored and regulated similarly to *E.coli* and faecal bacteria in drinking water (Slekovec *et al.*, 2012; Petit *et al.*, 2013; Al-Ansari *et al.*, 2021).

In both lagoon and groundwater correlation matrices (Table 5.8), this bacterium correlated positively with WW variables Al, TOC and PO_4^{3-}, and negatively with V and Sr. This points to the bacterium being associated with reducing conditions in the groundwater. Moreover, *P. aeruginosa* was found to be highly correlated with Al (Table 5.8). This could be explained that the fact that *P. aeruginosa* like most *Pseudomonas* is resistant to heavy metals. However, in a few specific studies, the ability of *P. aeruginosa* to grow in high Al concentration and to remove Al from WW into cell biomass was shown (Kurniawan *et al.*, 2018; Purwanti *et al.*, 2019).

Non-Pathogen Bacteria

Pseudomonas alcaliphila

This bacterium was found in one lagoon and one well (Fig 5.14). This is a seawater bacterium that was first isolated in Japan. It has the ability to reduce nitrate to nitrite, and degrade biphenyl and many congeners of polychlorinated biphenyls (W. Zhang *et al.*, 2014; Ridl *et al.*, 2018). However, its occurrence in WW or groundwater was never reported. With the correlation matrix (Table 5.8), it significantly correlated with variables related to both seawater intrusion and water/rock interaction in the groundwater, leading to the conclusion that, in Qatar, *P. alcaliphila* exists in groundwater and seawater.

Pseudomonas composti

Unlike other *Pseudomonas Sp.,* this bacterium has been reported in compost (Gibello *et al.*, 2011) but no other characteristics or studies involving this bacterium have been reported. In this study, no correlation was found using either PCA or correlation matrix.

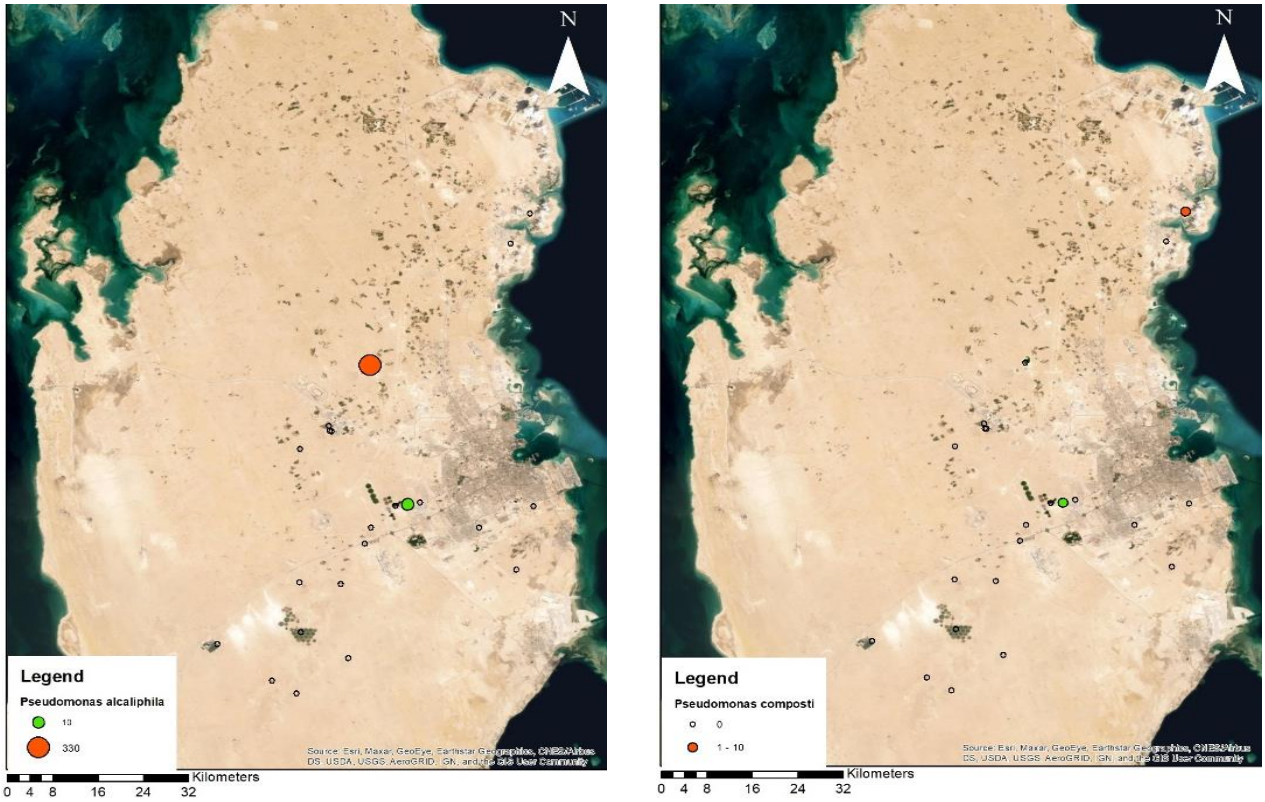


Figure 5.14. Qatar bacteria distribution map, *P. alcaliphila* on the left, *P. composti* on the right (CFU ml^{-1}) for lagoon (red) and groundwater (green)

Pseudomonas oleovorans

This bacterium was found in two lagoons and one well (Fig 5.15). This species is reported to be a common WW species, with few studies using it as a model to study the process of adding cultured microorganisms in treatment ponds during WW treatment, especially with phenol-containing WW. Studies have also shown the ability of *P. oleovorans* to degrade aromatic compounds such as phenols (Chen *et al*, 2013; Nandy *et al*, 2021). In this study, PCA for both groundwater and lagoons (Fig 5.5 and 5.6) show that the bacterium correlated in the middle of the plot and the correlation matrix showed no significant correlation. This could suggest that this bacterium is unconnected to WW filtration into Qatar's groundwater.

Pseudomonas putida

This bacterium was found in three wells and one lagoon (Fig 5.15). It is known as a low-virulent opportunistic human pathogen causing nosocomial infections in immunocompromised patients (Liu *et al.*, 2014). Also, it has exhibited arsenic reducing properties when it was isolated from arsenic-contaminated groundwater (Freikowski *et al.*, 2010; Chen *et al.*, 2013; Santos *et al.*, 2018). It was shown in both lagoon and groundwater PCA (Fig 5.5 and 5.6) that it correlates in the middle with all the other bacterial species and chemical variables but negatively correlated with pH and TDS using

the correlation matrix (Table 5.8), which could indicate that this bacterium cannot be associated with WW infiltration to the groundwater in Qatar.

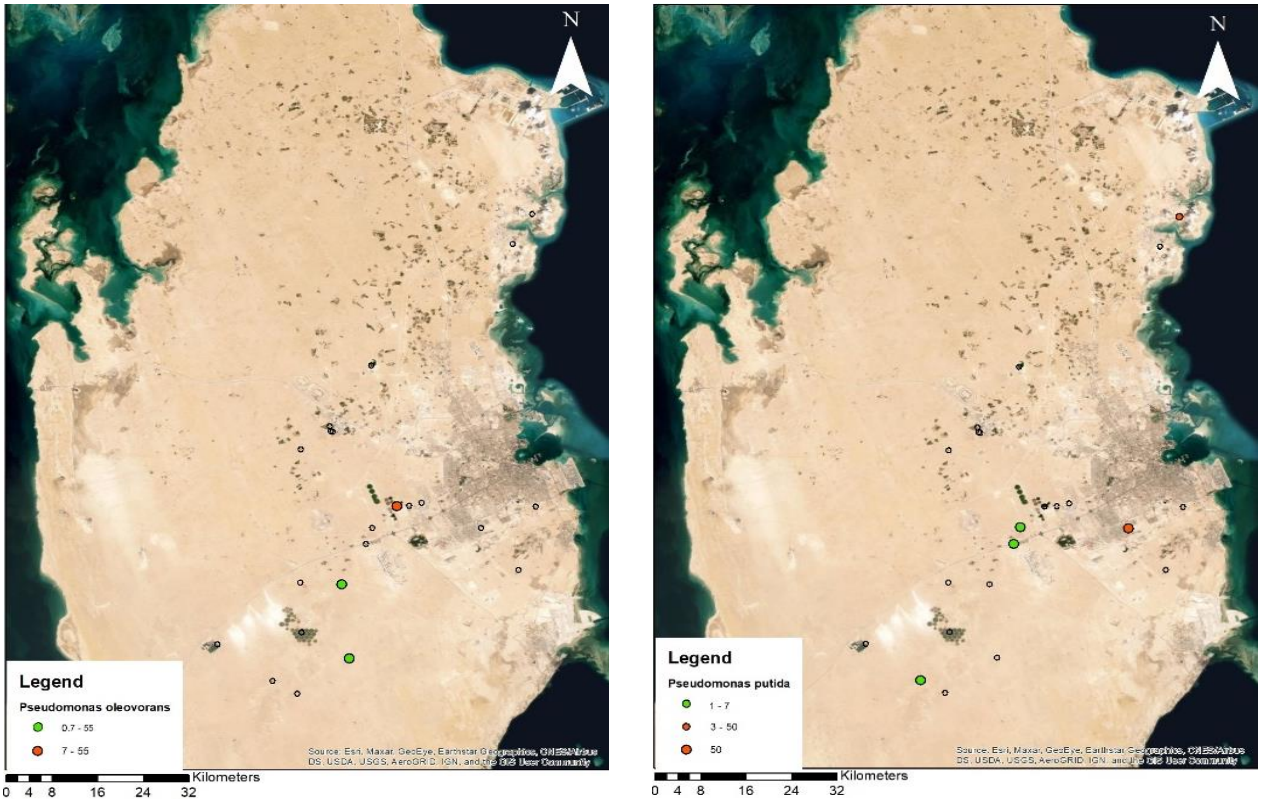


Figure 5.15. Qatar bacteria distribution map, P. oleovorans on the left, P. putida on the right (CFU ml^{-1}) lagoon (red) and groundwater (green).

Stenotrophomonas maltophilia

This bacterium was isolated from one lagoon and two wells (Fig 5.16). It was reported in alkaline, saline and heavy metal contaminated environments with the ability to fix nitrogen and some capacity for bioremediation of cadmium, aromatic hydrocarbon and phenol (Chen *et al.*, 2016; Bashandy *et al.*, 2020; Xiong *et al.*, 2020; Al-Dhabi *et al.*, 2021). In Qatar, this bacterium has been reported to cause lung infection in cystic fibrosis patients (Wahab *et al.*, 2004; Abdul Wahab *et al.*, 2005). In both lagoon and groundwater PCA (Fig 5.5 and 5.6), it correlates with the majority of the bacterial species and chemical variables. However, in the correlation matrix (Table 5.8) it correlates with variables known to be high locally (Mo and Sr) indicating that it could be a locally found bacterium in Qatar.

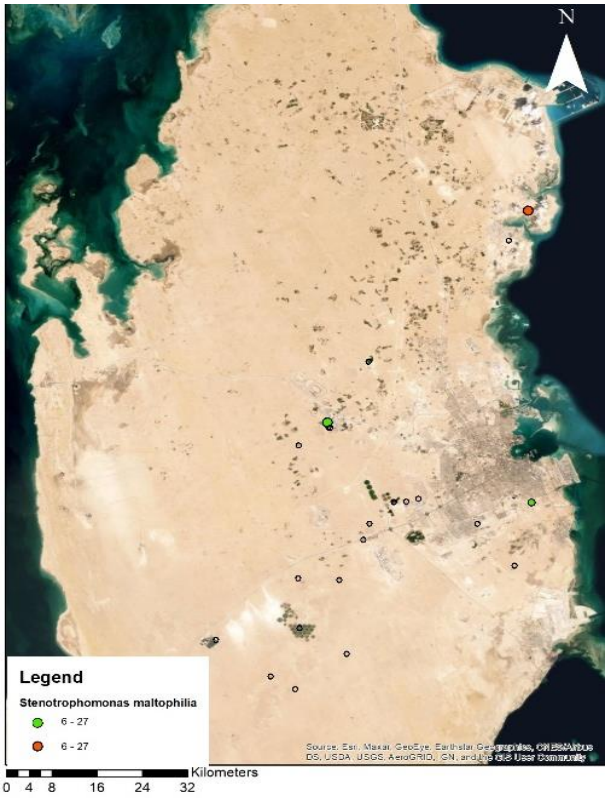


Figure 5.16. Qatar bacteria distribution map with *S. maltophilia* (CFU ml^{-1}) lagoon (red) and groundwater (green).

In summary, some of the identified bacterial species found in both lagoons and groundwater were shown to correlate with chemical variables related to TWW using PCA and correlation matrix analysis. Those bacterial species could therefore be attributed to TWW infiltration from the lagoon to the groundwater aquifer.

All the bacterial species identified in this research were classified in Table 5.9 by their lactose fermentation, pathogeny, whether they are coliform or not, and their TWW affiliation. Table 5.9 shows that the bacterial species found in both lagoons and groundwater that were affiliated with this study TWW variables were A. caviae, A. veronii, E. asburiae, E. cloacae, E. coli, K. pneumoniae and P. aeruginosa.

Table 5.9. Bacterial strain summary of lactose fermentation, pathogenic, CB group and bacteria affiliation to lagoons in this research. Underscore denotes bacteria found in groundwater only; bold denotes bacteria found in lagoon only; the rest were found in both lagoons and groundwater.

Bacteria Strain	Lactose fermenting	Pathogen	CB	TWW affiliation
Acinetobacter baumannii	negative	pathogen	No	aerobic
Acinetobacter dijkshoorniae	negative	non-pathogen	No	aerobic TWW
Acinetobacter haemolyticus	negative	pathogen	No	aerobic TWW
Acinetobacter Junii	negative	rare pathogen	No	aerobic TWW
Acinetobacter venetianus	negative	non-pathogen	No	aerobic Oil TWW
Aeromonas caviae	positive	pathogen	No	facultative anaerobic TWW
Aeromonas hydrophila	positive	pathogen	No	facultative anaerobic TWW
Aeromonas jandaei	positive	non-pathogen	No	facultative anaerobic TWW
Aeromonas veronii	positive	pathogen	No	facultative anaerobic TWW
Citrobacter braakii	positive	pathogen	yes	facultative anaerobic TWW
Enterobacter asburiae	positive	pathogen	yes	facultative anaerobic TWW
Enterobacter cloacae	positive	pathogen	yes	facultative anaerobic TWW
Enterobacter kobei	positive	pathogen	yes	facultative anaerobic
Escherichia coli	positive	pathogen	yes	facultative anaerobic TWW
Leclercia adecarboxylata	positive	rare pathogen	yes	facultative anaerobic TWW
Klebsiella pneumoniae	positive	pathogen	yes	facultative anaerobic TWW
Serratia marcescens	positive	rare pathogen	yes	facultative anaerobic fresh and seawater
Pantoea dispersa	positive	rare pathogen	yes	facultative anaerobic TWW
Pseudomonas aeruginosa	negative	pathogen	No	facultative anaerobic TWW
Pseudomonas alcaliphila	negative	non-pathogen	No	aerobic fresh and seawater
Pseudomonas composti	negative	non-pathogen	No	facultative anaerobic
Pseudomonas fulva	negative	rare pathogen	No	facultative anaerobic TWW
Pseudomonas mendocina	negative	rare pathogen	No	aerobic TWW
Pseudomonas oleovorans	negative	non-pathogen	No	facultative anaerobic
Pseudomonas pseudoalcaligenes	negative	non pathogen	No	aerobic TWW
Pseudomonas putida	negative	non-pathogen	No	facultative anaerobic
Pseudomonas stutzeri	negative	rare pathogen	No	facultative anaerobic TWW
Shewanella putrefaciens	negative	rare pathogen	No	anaerobic seawater
Stenotrophomonas maltophilia	negative	non-pathogen	No	aerobic fresh and seawater
Vibrio albensis	negative	non-pathogen	No	facultative anaerobic TWW
Alcaligens faecalis	negative	non-pathogen	No	aerobic
Wautersiella falsenii	negative	rare pathogen	No	aerobic

5.3.7 Coliform Bacteria identification and distribution in both lagoons and groundwater

This section will not cover all the bacteria species identified in both lagoons and groundwater, it will only elaborate on the CB distinguished by using a selective media, as well as compare the occurrence of CB to Qatar's national and international standards. Then, this section will discuss in detail: (i) the spatial abundance of CB; (ii) their distribution in both lagoons and groundwater; (iii) their relationship to the measured chemical variables.

Traditionally, coliforms are considered to be represented by 4 genera: *Escherichia*, *Klebsiella*, *Citrobacter*, and *Enterobacter*. It should be noted that not all coliforms are pathogens, but their existence is an indication of pathogenic bacteria sourced from human wastes. The bacteria that were

identified in this research by MALDI-TOF-MS and reported in previous literature as CB were: *C. braakii, E. asburiae, E. cloacae, E. kobei, E. coli, K. pneumonia, L. adecarboxylata, S. marcescens and P. dispersa.*

3.3.7.1 Coliform bacteria compared to national and international standards.

Coliform bacteria are unlikely to cause illness but their presence in drinking water indicates the presence of disease-causing pathogens in the water system. All the lagoons and groundwater CB count (CFU ml^{-1}) violated the Qatari and WHO standards for crop irrigation and the reuse of TWW for both crop and landscape irrigation (Table 5.10). This conclusion was drawn in a study done in 2009 for the groundwater artificial recharge using TWW in Qatar (Schlumberger water Services, 2009).

Table 5.10. Coliform bacteria in lagoons and groundwater, with the maximum allowable standards for Qatar quality criteria for treated WW and WHO.

Location	Coliform bacteria CFU ml^{-1}
Lagoon 1	2410
Lagoon 2	250
Lagoon 3	87
Lagoon 4	160
Lagoon 5	867
Lagoon 6	27
Lagoon 7	33
Lagoon 8	630
Lagoon 9	633
Well 1	0.1
Well 2	10
Well 3	18
Well 4	25
Well 5	0.3
Well 6	5
Well 7	4
Well 8	0.7
Well 9	2
Well 10	14
Well 11	3
Well 12	3
Well 13	17
Qatar Crop irrigation guidelines[1]	$2.2X10^{-2}$
Qatar landscaping Irrigation guidelines[2]	$23X10^{-2}$
WHO TWW Discharge standards[3]	10

1. Qatar quality criteria for treated WW used for irrigation, maximum allowable for food crops
2. Qatar quality criteria for treated WW used for irrigation, maximum allowable for landscaping
3. WHO maximum allowable standards for treated WW used for irrigation CB spatial abundance in relation to other water quality variables

3.3.7.2 Multivariate statistical analysis of coliform bacteria in lagoons and groundwater

In previous studies of the contamination of water bodies with CB, multivariate statistical analysis has been employed to associate CB with chemical variables to try and identify the WW or TWW source

(Carroll *et al.*, 2005; Olsen *et al.*, 2012) Thus, before discussing the relationship between CB and the chemical variables in the next section, this section will include a statistical analysis conducted on the CB in relation to: (i) each other; (ii) the chemicals variables of the lagoon and groundwater; (iii) the wells distance to the closest lagoon.

Lagoons coliform bacteria PCA and HCA analysis

PCA was used to investigate the relationship between the lagoons' CB counts and their chemical variables. The findings of the PCA analysis are shown in Figure 5.15 and Table 5.11 Four PCs emerged from the analysis accounting for 90% of the variance. Coliform counts were shown to correlate with PO_4^{3-}, Fe, Al and IC only.

Table 5.11. Lagoon principle components showing correlation between CB and chemical variables with PC1 to PC4 had a cumulative eigenvalues of more than 90%

Component	PC1	PC2	PC3	PC4		PC1	PC2	PC3	PC4
Cumulative %	6.5	70	82.2	90	**S**	0.782	-0.154	0.558	0.053
CB	-0.282	**0.911**	-0.239	0.145	**SO_4^{2-}**	0.608	-0.034	0.718	0.043
General water quality variables					**Metal and metalloid variables**				
EC	0.003	-0.117	0.179	0.151	**Al**	0.302	**0.877**	-0.177	0.061
IC	-0.069	**0.864**	0.397	0.181	**As**	**0.545**	-0.265	0.282	-0.701
pH	-0.139	0.035	0.051	**0.932**	**Ba**	**0.953**	-0.017	0.026	-0.292
TDS	0.052	-0.115	0.177	0.145	**Cr**	**0.978**	0.065	-0.072	-0.121
Temp	-0.283	0.452	**0.687**	-0.104	**Cu**	**0.979**	0.043	-0.086	-0.084
TN	**0.886**	0.393	-0.129	-0.098	**Fe**	-0.003	**0.976**	-0.026	-0.005
TOC	**0.758**	**0.531**	0.046	-0.351	**Li**	0.688	-0.163	**0.557**	0.175
Anionic and cationic variables					**Mn**	-0.019	0.068	**0.979**	-0.044
B	**0.864**	-0.198	0.362	-0.162	**Mo**	**0.867**	-0.125	0.419	-0.076
Ca^{2+}	**0.857**	-0.141	0.43	0.018	**Ni**	**0.936**	-0.08	0.235	0.037
Cl^-	**0.948**	-0.004	0.065	0.082	**Rb**	**0.98**	0.039	-0.097	-0.145
K^+	**0.951**	-0.082	0.105	0.015	**Se**	**0.99**	0.028	-0.039	-0.099
Mg^{2+}	**0.699**	-0.139	**0.578**	0.169	**Sr**	**0.73**	-0.198	**0.607**	0.02
Na^+	**0.94**	-0.077	0.063	0.089	**U**	0.084	-0.033	**0.961**	-0.035
NO_3^-	-0.276	-0.19	-0.331	0.478	**V**	0.352	-0.637	-0.026	0.117
PO_4^{3-}	-0.189	**0.932**	-0.148	-0.044	**Zn**	**0.638**	0.118	0.303	**0.568**

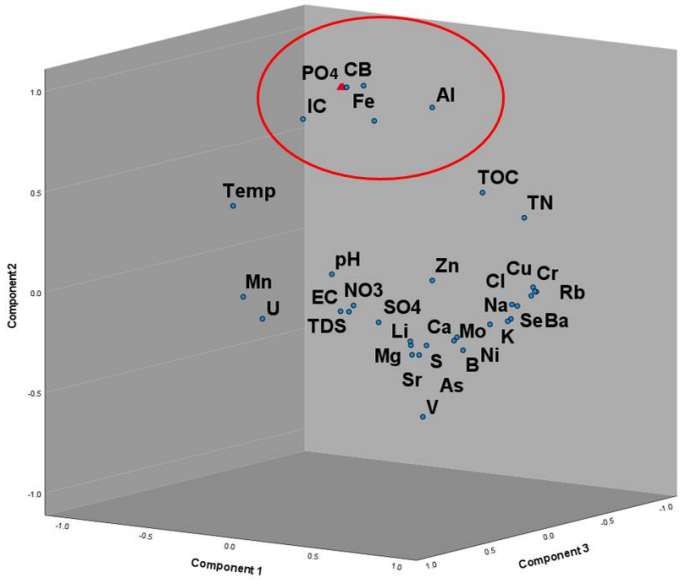


Figure 5.17. Lagoon water PCA 3D plot showing the correlation between CB and chemical variables, CB shown with a red triangle clustering in the group shown in red circule; Using PCA with Varimax rotation method and Kaiser Normalization

HCA analysis for the CB in the lagoon water produced three clades, with CB in a clade with EC, TDS, pH, NO_3^-, Zn, Mn, U, Temp, IC, PO_4^{3-}, Fe, and Al.

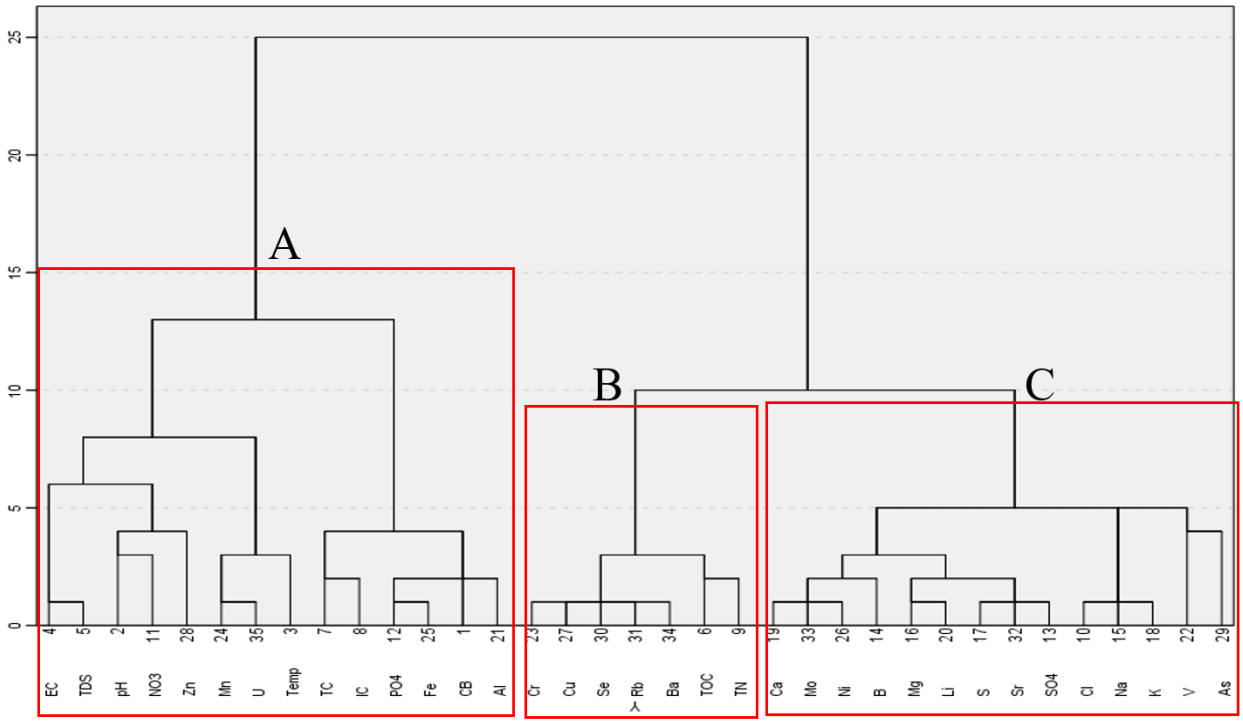


Figure 5.18. Lagoon water Dendrogram showing the correlation between CB and chemical variables, produced from HCA, using ward linkage, with Euclidean distance measurement with Z score standardization transformation. Varibles clustered in the same group showen by three squares labled A, B and C.

PCA and HCA analysis of groundwater coliform bacteria

PCA was conducted between CB, groundwater distance to nearest lagoon, and water chemical characteristics. PCA was used here to visually show (i) the influence of groundwater distance to the nearest lagoon on the concentration of CB in each lagoon and (ii) the chemical variables associated with the CB. In addition, the PC component table illustrates the level of correlation within each PC. Figure 5.17 and Table 5.12 show the results of the PCA analysis; the data revealed five PCs accounting for 85% of the variance. Coliform bacteria correlated with groundwater proximity to the closest lagoon and other chemical variables (pH, Al, TN, NO_3^-, EC, TDS, Cr, Cu, Ni, IC, U, Mo, Sr and V)

Table 5.12. Groundwater principal components showing the correlation between CB and chemical variables with groundwater distance to the nearest lagoon in km; PC1 to PC5 had cumulative eigenvalues of more than 85%

Component	PC1	PC2	PC3	PC4	PC5		PC1	PC2	PC3	PC4	PC5
Cumulative %	34.58	55.8	66.11	76.55	85.23	**S**	**0.641**	0.031	**0.464**	0.134	**0.514**
Distance to lagoon	0.132	**-0.52**	0.291	-0.451	-0.093	**SO_4^{2-}**	**0.65**	-0.063	**0.468**	0.115	0.472
CB	-0.22	**-0.557**	-0.244	-0.32	0.065	**Metal and metalloid variables**					
General water quality variables						**Al**	0.026	0.041	0.003	0.003	0.028
						As	-0.207	**0.935**	-0.068	-0.078	-0.048
EC	0.052	0.064	**0.959**	0.112	0.115	**Ba**	-0.835	0.142	0.125	-0.051	-0.254
IC	**0.954**	-0.153	0.104	0.016	0.086	**Cr**	-0.145	-0.377	-0.197	**-0.438**	0.021
pH	-0.348	-0.331	-0.143	-0.241	0.077	**Cu**	-0.167	-0.302	-0.039	-0.195	-0.069
TDS	0.036	0.052	**0.959**	0.103	0.112	**Fe**	-0.163	**0.951**	-0.047	0.082	-0.095
Temp	0.233	0.43	0.183	**0.781**	0.034	**K**	0.318	0.354	**0.469**	**0.629**	0.251
TN	0.171	-0.382	**0.793**	-0.076	-0.037	**Li**	**0.627**	0.059	0.205	-0.135	**0.602**
TOC	-0.013	0.203	0.216	0.203	-0.169	**Mn**	-0.214	**0.936**	-0.094	0.186	-0.03
Anionic and cationic variables						**Mo**	0.044	-0.159	0.049	**0.948**	-0.026
B	0.463	0.166	**0.672**	0.371	0.292	**Ni**	0.36	-0.175	-0.07	0.473	-0.192
Ca^{2+}	**0.623**	-0.299	0.138	-0.411	0.533	**Rb**	0	**0.61**	0.349	0.461	0.309
Cl^-	0.282	0.353	0.414	0.186	**0.634**	**Se**	0.27	-0.34	-0.085	0.28	**0.601**
K^+	0.318	0.354	0.469	**0.629**	0.251	**Sr**	0.186	-0.181	0.155	-0.202	**0.809**
Mg^{2+}	**0.624**	0.123	0.455	0.168	**0.543**	**U**	**0.862**	-0.23	0.149	0.371	0.043
Na^+	0.228	0.47	0.452	0.311	**0.516**	**V**	-0.027	**-0.46**	-0.195	**-0.736**	0.179
NO_3^-	0.259	**-0.573**	**0.77**	0.039	0.263	**Zn**	-0.176	-0.087	-0.317	-0.293	-0.1

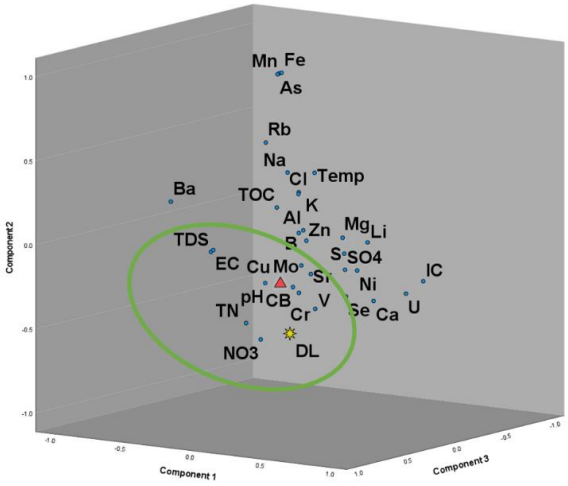


Figure 5.19. Groundwater PCA 3D plot showing the correlation between CB and chemical variables with groundwater distance to the nearest lagoon on km (DL). Coliform Bacteria shown with a red triangle, DL shown with a yellow star clustering in the same group shown in green circule; using PCA with Varimax rotation method and Kaiser Normalization.

Moreover, HCA analysis produced three main clades. Clade C has CB and groundwater proximity to the closest lagoon and other chemical variables (Mn, Fe, As, V, Cr, Cu, Zn, pH, Al, TOC, and Ba)

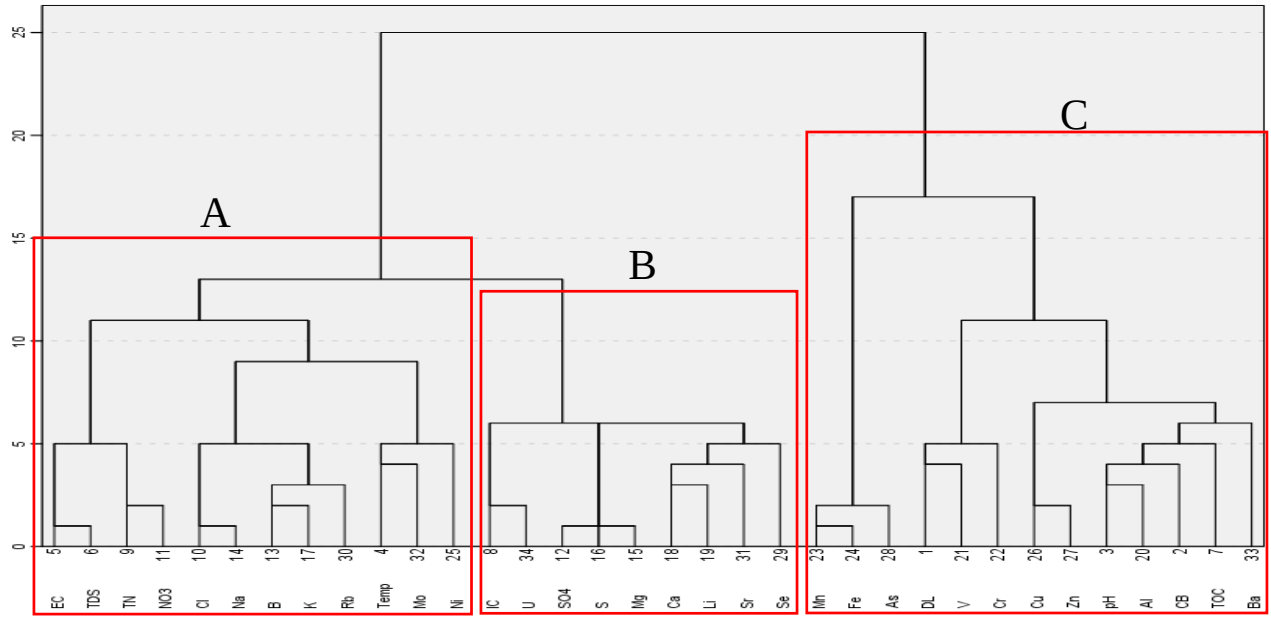


Figure 5.20. Groundwater Dendrogram showing the correlation between CB and chemical variables with groundwater distance to the nearest lagoon (km), produced from HCA, using Ward linkage, with Euclidean distance measurement with Z-score standardization transformation. Varibles clustered in the same group showen by three squares labled A, B and C.

3.3.7.3 Coliform bacteria relation to chemical variables in lagoons and groundwater

Lagoon and groundwater PCA results showed CB to be correlated to different chemical variables. In the lagoons PCA (Fig 5.15), CB was correlated to PO_4^{3-} and the redox-active metals of Fe, Al, whereas in the groundwater PCA (Fig 5.19), CB were correlated to most heavy metals, but not Fe.

Furthermore, the HCA analyses for both lagoon and groundwater CB were similar, with CB correlated in the same clade with the same chemical variables. Moreover, the chemical variables in both HCA plots were similar to the HCA analysis performed on the chemical variables in Chapter 4, where the analysis produced three main clades, showing (i) salinization, (ii) water/rock interaction, and (iii) anthropological contamination variables. Coliform bacteria were found in the anthropological contamination clade separated from the other two, where this clade included distance to the nearest lagoon, CB and chemical variables related to anthropological pollution (Fe, Mn, As, Cr, Cu, Zn, pH, Al, and TOC). This indicates that lagoons and groundwater CB have the same relationship with the water chemical variables.

5.3.8 Bacterial relationship between the lagoons and the surrounding groundwater

When analysing the bacterial flora in lagoons and groundwater, several bacteria spatial distributions were found to have a relationship with chemical variables originating from TWW and were correlated with the groundwater distance to the closest lagoon. Moreover, looking at the CB distribution in both lagoons and groundwater (Fig 5.21), it is seen that all the wells surrounding the lagoons had variable concentrations of coliforms. To further understand the influence of the lagoon location and proximity on groundwater CB abundance, a GLM analysis on the bacteria distribution and PCA analysis on the protein profile was used.

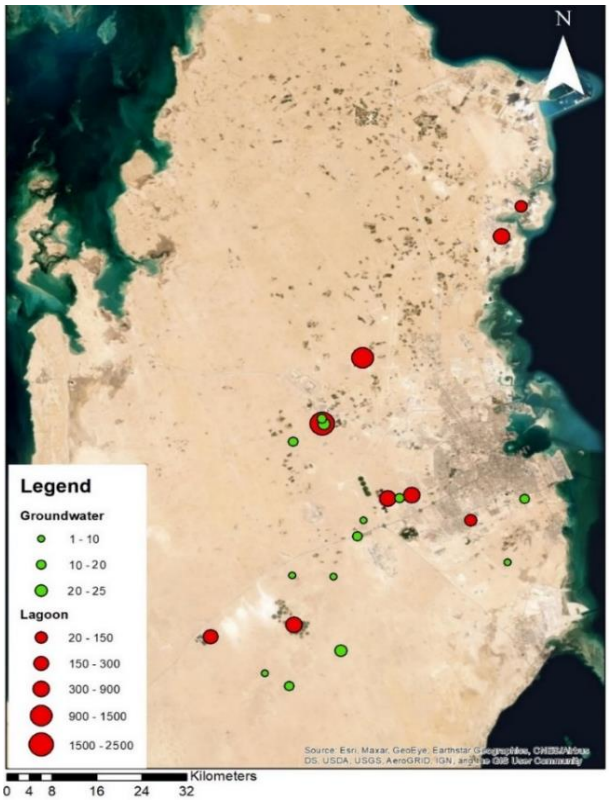


Figure 5.21. Qatar map with CB (CFU ml^{-1}) distribution for lagoon and groundwater.

Bacterial spatial distribution: GLM analysis

GLM analysis was used in Chapter 4 to understand the influence of lagoon proximity on the groundwater chemical variables. However, in that case, the assumption was that groundwater proximity to the nearest lagoon was a valid factor because all the lagoons had similar types of chemical variables. However, this logic cannot be applied to the bacterial data since the bacterial flora was heterogeneous, as shown in the heatmap, where most of the bacteria do not occur in both groundwater and lagoons.

On the other hand, there were two cases where GLM analysis was appropriate. First, is conducting GLM using CB as the dependent variable since it is positive in all lagoons and wells. Secondly, using *P. aeruginosa* as the dependent variable, as it was the most abundant bacterium in both lagoons and groundwater. The fixed factor for both was the groundwater distance to the closest lagoon in km. This, satisfied the GLM requirement and the assumption of using groundwater proximity to the lagoon.

GLM results (Table 5.13) between groundwater and lagoons bacterial and chemical analysis showed that CB were almost significantly influenced by groundwater location to the nearest lagoon ($p<0.061$ instead of $p<0.05$), while it was significantly influenced by Al concentration ($p<0.05$). This is seen with a correlation matrix (Table 5.8), where CB correlated with Al. Moreover, CB were not significantly influenced by both Fe and Mn, while both elements correlated with both CB and distance to the lagoon as shown by the PCA analysis. This could be due to Fe and Mn correlating with Al, which in turn correlates with CB. These results have not been reported before, but most research published around groundwater contamination from WW or landfill leachate always showed the CB correlation to redox-active variables such as Fe and Mn (O *et al.*, 2006; Mouser *et al.*, 2010; Korbel *et al.*, 2022). However, in Chapter 4 of this thesis, it was revealed that Al and redox-active variables were always correlated to each other in lagoons and groundwater, while the coliforms correlate only to Al and not the redox-active metals which may be due to the small sample size.

Table 5.13. GLM estimates CB as the response for the different factors (groundwater distance to the closest lagoon, Al and Fe) with normal Probability distribution and Identity Link function

Factor	F	df	Sig.
DL	3.368	20	0.061
Al	16.015	20	0.001
Fe	0.016	20	0.902

When analysing *P. aeruginosa* distribution with GLM (Table 5.14), unlike CB, *P. aeruginosa* is not affected by groundwater distance to the lagoon ($p>0.05$) but was impacted by Al ($p<0.05$). While Al could be from natural sources, it was shown in Chapter 4 of this thesis, that there were high concentrations in lagoon water and groundwater, and Al was significantly correlated to groundwater proximity to lagoons ($p<0.05$). Thus, *P. aeruginosa* could be originated from the lagoon water infiltration to the groundwater aquifers, but due to the small sample size, this could not be proven in this research. Moreover, during groundwater recharge, the surface water cause the weathering process of plagioclase and K–feldspar, increasing Al concentration in the groundwater (Tay, 2021;

Walter, J. *et al.*, 2017), this could be the cause for the bacterial correlation to Al seen in all the GLM results shown in Table 5.13, 5.14 and 5.15.

Table 5.14. GLM estimates CB as the response for the different factors (groundwater distance to the closest lagoon, Al and Fe) with normal Probability distribution and Identity Link function

Factor	F	df	Sig.
DL	1.593	20	0.221
Al	15.768	20	0.001
Fe	0.000	20	0.988

Examining all the bacterial correlations to the chemical variables of the lagoons and groundwater, it was seen that the five bacteria correlating to the known WW sourced chemical variables were *A. veronii, E. cloacae, E.coli, K. pneumoniae* and *P. aeruginosa*. Those bacteria have been reported in previous literature as bacterial biomarkers for WW pollution (McKeon *et al.*, 1995; O *et al.*, 2006; Padhi *et al.*, 2013; Chen *et al.*, 2019). Using GLM on the total number of only those five bacteria, as CFU ml^{-1}, instead of the total coliform numbers, showed a significant correlation with the groundwater distance to the closest lagoon (Table 5.15). This means that using bacteria known to grow in the media of interest could give a better indication than CB numbers when researching the TWW infiltration to the groundwater in Qatar.

Table 5.15. GLM estimates for five selected bacteria strains (*A. veronii, E. cloacae, E. coli, K. pneumoniae* and *P. aeruginosa*) as a response to the different factors (groundwater distance to the closest lagoon) with a normal probability distribution and identity link function

Factor	F	df	Sig.
DL	19.88	20	0.022
Al	15.768	20	0.001

Similar results had also been discussed in previous literature, exploring non-CB used as biomarkers for WW impact on groundwater aquifers. WHO guidelines for drinking water have highlighted the importance of monitoring non-CB alongside faecal bacteria and *E. coli* (Herschy, 2012).

Protein profile PCA analysis

Few studies have successfully linked environmental bacteria to the potential contamination source by using the protein profiles obtained from MALDI-TOF-MS analysis of the bacterial isolates and using these profiles as a fingerprint to link bacteria biomarkers to contamination sources (Siegrist *et al.*, 2007; Giebel *et al.*, 2008; Santos *et al.*, 2016). Thus, to visually illustrate the CB strain similarities, a PCA analysis was used by plotting the relationship between the bacterial protein profiles. This is

done to determine whether the different strains found from the same bacterium species were similar to each other, indicating the bacterial strains share the same contamination source.

After performing PCA, a 2D plot was produced (Fig 5.22). Since 98% of the variation was explained with the first two PCs, the PCs were all highly correlated (PC>0.700), so only the plot was analysed and the corresponding table is provided in the appendix (Appendix F).

The coliforms protein 2D profiles plots demonstrate that all *E. coli* strains were grouped together in one group, with *E. cloacae* closest to it. Also, *E. cloacae* correlated in one group with well 1 and Ash-Shahanyyia lagoon 1, where well 1 is located on a farm adjacent to the lagoon (0.2 km). Furthermore, *K. pneumoniae* strains correlated in one separate group, the furthest away from *E. coli*, indicating these strains were from the same environmental source, but not related to *E. coli*. L. adecarboxylata contain other strains correlating together, but the rest of the strains (*C .braakii, E. asburiae, E. kobei, S. marcescens* and *P.dispersa)* all formed one group in the middle correlating to each other including strains found in both groundwater and lagoons water, with the exception of one *E. asburiae* separate from any group on the top left. The lagoon and groundwater strains correlating in the middle indicate that the strains were from the same environmental source. Thus, there is evidence that CB in the groundwater were from lagoon water infiltrating the aquifer.

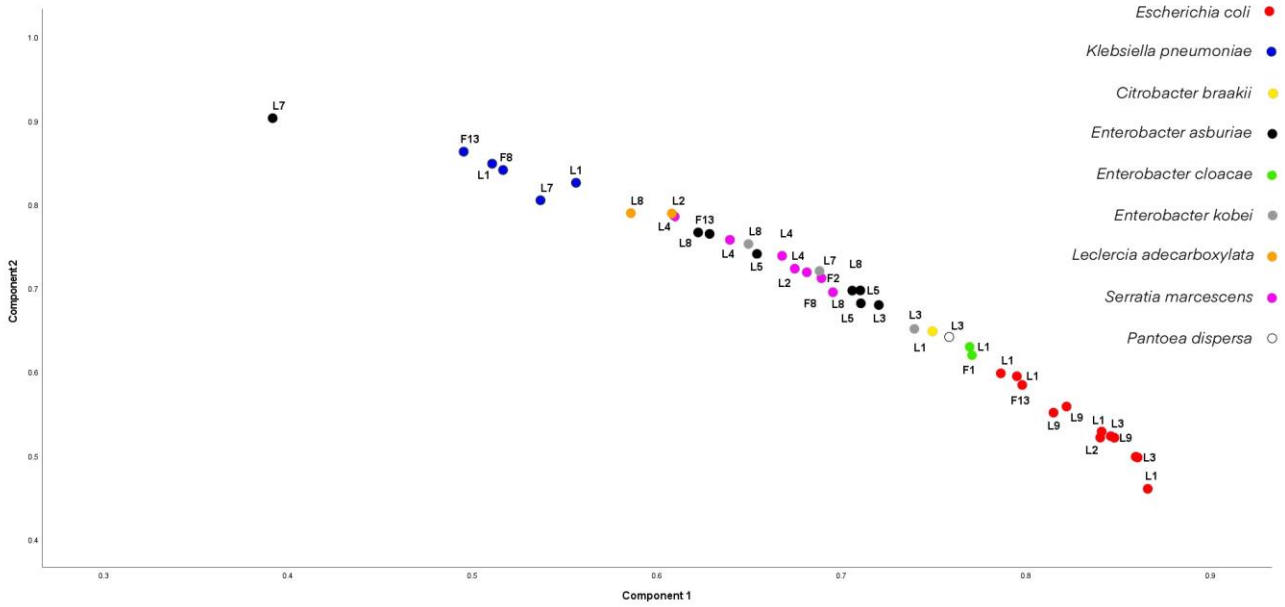


Figure 5.22. Coliform bacteria correlated bacteria PCA plot, showing bacterial strains in lagoons (L) and groundwater (F). MALDI-TOF-MS produced unique protein profiles acting as a fingerprint for each identified bacteria. The extracted protein profiles are used for this analysis representing each bacteria labelled with different colours; Bacteria of same strain and origin source clustered in the same group; PCA was used with the Varimax rotation method and Kaiser Normalization.

Another PCA analysis is shown in Fig 5.23, displaying the relationship between the bacterial strains derived from protein profiles to graphically illustrate the WW-linked bacterial association. After doing PCA, a 2D plot was generated. The first two PCs explained 97% of the variance, as found for the CB, where all the correlations were high (PCs>0.700) (Appendix F).

As found for the CB PCA, all the *E. coli* strains clustered in one separate group, with *E. cloacae* adjacent to it. However, *P. aeruginosa* strains were scattered along the PCA plot, correlating with all other strains for both groundwater and lagoons. *P. aeruginosa* strains from groundwater clustered together with *P. aeruginosa* strains from lagoons water, indicating they all have the same environmental source. *P. aeruginosa* correlation groups were combined with *K. pneumoniae* cluster groups, showing a high correlation between the two strains. This may be explained by previous literature that showed both bacteria share common biomarker proteins for drug resistance (Flores-Treviño *et al.*, 2019). Similar results were seen with *A. veronii* strains, since they did not cluster in one group, but clustered closely to all the other strains. As a consequence, only *E. coli* formed a separate cluster, while the others were correlating in the same manner.

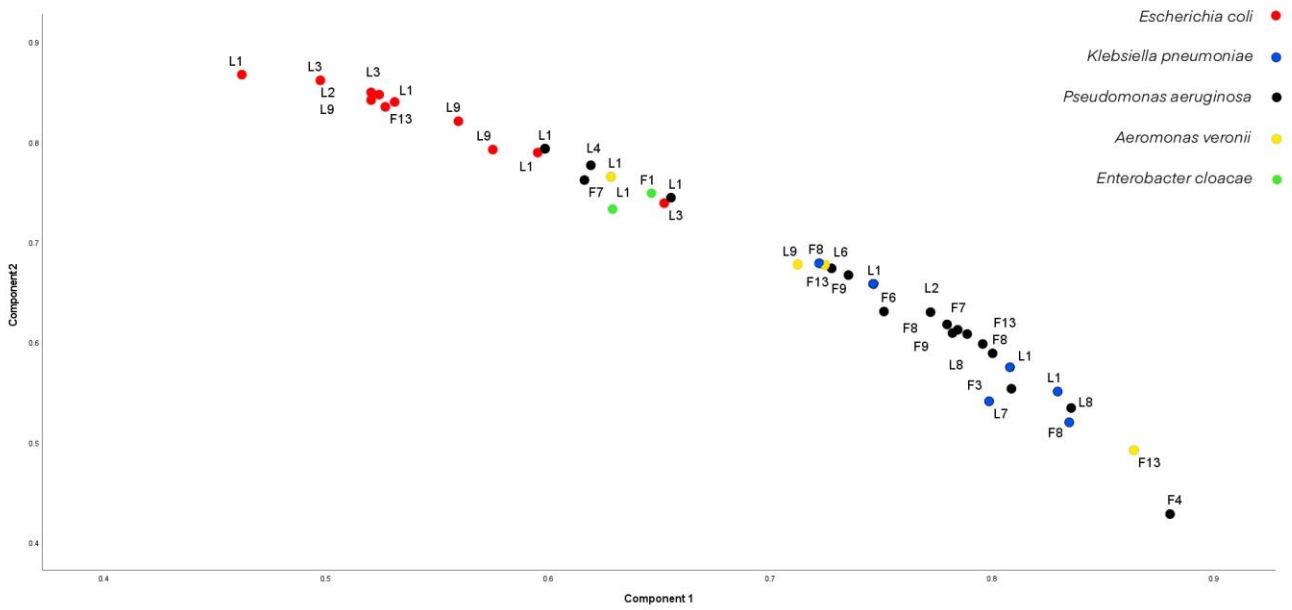


Figure 5.23. Treated wastewater correlated bacteria PCA plot, showing bacterial strains in lagoons (L) and groundwater (F). MALDI-TOF-MS produced unique protein profiles acting as a fingerprint for each identified bacteria. The extracted protein profiles are used for this analysis representing each bacteria labelled with different colours; Bacteria of same strain and origin source clustered in the same group; PCA was used with the Varimax rotation method and Kaiser Normalization.

Previous literature reports that used PCA of protein profiles have acknowledged the capacity of MALDI-TOF-MS to categorize strain isolates by their potential source, making it a tool for fingerprinting environmental isolates (Siegrist *et al.*, 2007; Giebel *et al.*, 2008; Santos *et al.*, 2016;

Alsayegh *et al.*, 2021). This leads to the conclusion that the bacterial strains found in groundwater that correlate to the strains found in lagoons, following PCA, probably originate from WW.

5.4 Conclusions

In Qatar, bacterial flora analysis in lagoons and groundwater has never been done, although MALDI-TOF-MS has been utilized to investigate bacterial strains in oil-contaminated areas and high-salinity areas in Qatar, it was used for the first time to investigate the microbial quality of the groundwater in Qatar as well as globally. MALDI-TOF-MS is a useful analytical technique for identifying Gram-negative bacteria in both lagoons and groundwater. Furthermore, 35 distinct bacterial strains with MALDI scores of ≥1.7 were discovered in both lagoons and groundwater, with the majority having values of ≥2.0, confirming species-level identification. Only one bacterial strain was found to be from the Bacteroidetes phylum, with the rest belonging to the Proteobacteria phylum. *Pseudomonas*, *Acinetobacter*, *Aeromonas*, and *Enterobacter* each had 37%, 15%, 12%, and 10% of the bacterial populations found, respectively. The number of Gram-negative bacterial strains in WW was higher than in groundwater.

Both lagoons and groundwater PCA of MALDI-TOF data formed two main groups, with CB correlating similarly to the chemical variables, and *Pseudomonas* species showing the same correlation behaviour. Coliform bacteria species identified in this research from protein profiles included *C. braakii, E. asburiae, E. cloacae, E. kobei, E. coli, K. pneumonia, L. adecarboxylata, S. marcescens,* and *P. dispersa.*

The groundwater and lagoons were above national and international standards for CB, which is in alignment with a previous study on groundwater in Qatar. Coliform bacteria were found to be correlated between lagoons and groundwater, indicating bacterial infiltration to the surrounding wells. Coliform bacteria were statistically correlated to chemical variables related to the TWW origin and groundwater locations to the lagoons.

While *E. coli* is used in most literature as a faecal indicator and WW contamination in groundwater, in this research it is found that *P. aeruginosa*, a hydrocarbon-degrading bacterium and a known human pathogen, was found in lagoons and wells adjacent to them. Therefore, this bacterium may be a more suitable indicator in the Qatar lagoon context.

In conclusion, protein profiles produced by MALDI-TOF-MS were successfully used to show that both CB and WW bacterial strain species were associated with each other, indicating lagoon water infiltration to the groundwater aquifers. Finally, data collected from this chapter when coupled with

the hydrogeochemical data should be used policymakers to review the current unlined lagoon practices and implement mitigation measurments when constructing lagoons to minimize lagoon water infiltration and protect the groundwater fromm furthure CB and WW bacterial contamination. Additionaly, more intensive studies of using other markers should be conducted to understand pollutant infiltration from lagoons to adjacent wells.

6.1 Introduction

There were four major parts to this research. The first part summarized the study area's current urban water system, the current management practices and the issues that have led to the lagoon distribution around Qatar. The second part is the perceptual study of public and policymaker's opinions on lagoons and lagoon management in Qatar. The third part is the Hydrogeochemical analysis of lagoons and the surrounding groundwater. The last part is microbial quantification and identification in the lagoons and the surrounding groundwater. All parts were done to give a comprehensive view of the current situation regarding lagoon management.

6.2 A perceptual study of lagoons and groundwater in Qatar

6.2.1 Summary

In this part of the study, it was shown there is a noticeable gap in the knowledge of both public and policymakers' perceptions regarding any component of the urban water cycle. No study was ever conducted regarding both public and policymakers' perceptions about lagoons in Qatar. Thus, this study is a baseline for future research on the social part of the urban water cycle.

6.2.2 Study Limitations

There were three major limitations faced when conducting this part of the research. The first one is the public survey method. While the questionnaires are fast and easy to distribute methods to reach the maximum number of participants, it has the limitation of providing less information compared to interviews for example. This limitation is faced with any questioner based study. However, the benefits of reaching more respondents would overcome it.

Another limitation faced with the survey method, is the survey distribution method of using an online survey and social media, while this method is useful to reach a full range of respondents in cost and time effective matters, it is also limited by not reaching people who do not use social media. Also, it could be limited to a certain group of people that uses the chosen social media platform.

Another limitation is the researcher unable to include the ministry responsible for groundwater in Qatar for the interview section, this led to ministry information about the real groundwater aquifers quality in Qatar being missing.

6.2.3 Recommendation for the perceptual study of lagoons and groundwater in Qatar

Public participation is crucial because members of the public were concerned about lagoons and the impact of the lagoons on their interests, and the ability to express their worries, opinions, and

preferences during the design process encourages people to communicate to better commission the lagoon designs. Moreover, public involvement will also increase their acceptability for TWW reuse and decrease the current pressure on the groundwater reservoirs. However, it is suggested before public involvement, public education about the current water challenges in Qatar should be done. Their knowledge about the consequences of the high consumption of both tap water and groundwater resulting problems could be the incentive for more sustainable water consumption practices, and the increasing willingness for TWW reuse.

Special attention to studying farmers' perception of the current groundwater quality and their willingness for future TWW reuse, as they are the key stakeholders in groundwater management and future reuse practices. This would release huge pressure on the groundwater aquifers and decrease the number of lagoons in the country.

For policymakers there is a need for the water management objectives to be stated clearly, a framework should be established, where each ministry's exact responsibility toward urban water management is established. Inter-ministries coordination and duties should be mandated, and a long-term strategy for accomplishing objectives should be developed. The strategy should be sufficiently comprehensive to address all areas of lagoon management specifically and the whole urban water cycle as well.

Moreover, understanding the difference between policymakers and public expectations related to the whole water cycle not only lagoons is highly recommended to be able to provide better services as well as mitigate future issues related to the urban water cycle.

6.2.4 Future work

- A study related to public perception and knowledge about current water consumption practices, since the major issue is the tremendous amount of municipal WW coming to the treatment plants, and the effluent produced, because of the high consumption rate in Qatar;
- Protecting the groundwater aquifers is everyone's responsibility. Thus, exploring public knowledge on the current groundwater quality in Qatar could provide recommendations on future protection policies, and it could be an educational opportunity as well;
- Exploring public willingness on using lagoons as leisure places for bird watching, green space cycling and walking. One of the lagoons in Qatar has been transformed to be open to the public, but the acceptability for it to be a leisure place was not explored;

– A study about policymakers' inter-communication regarding the whole urban water management, to formulate recommendations to enhance the communication for better policy setting and management.

6.3 Hydrogeochemical survey of lagoons and surrounding wells

6.3.1 Summary

A hydrogeochemical survey of the different types of lagoons has never been done in Qatar, making this research a possible baseline for future studies about lagoon management in Qatar. Local geography and hydrology conditions like salinization and gypsum dissolution were seen in the water disposed of in the lagoons and groundwater.

The lagoon was found to be infiltrating the groundwater and impacting its chemical characteristics, but no conclusive results were seen to illustrate the lagoon impacting groundwater farms soil and plants.

6.3.2 Study Limitations

Time and resources were the only limitations for this part of the study, where the results would be more accurate and reliable with more sampling points, not only around the lagoons but covering the whole aquifers in Qatar. Moreover, this study measured main water quality variables, major cations and anions, and metal variables. However, another source of pollution concern is pharmaceuticals and personal care by-products that are available in the lagoons and TWW that could infiltrate into groundwater. An advantage of measuring pharmaceuticals and personal care products is they could be exclusive in TWW. Thus, their existence in groundwater could be a conclusive marker for TWW infiltration levels in the Qatari groundwater aquifers.

6.3.3 Recommendation

The major recommendation here is to establish a long term program for constant monitoring of the lagoons and surrounding wells hydrogeochemical qualities. To be able to catch possible pollution at the point source, and better protection for the groundwater quality.

Another major recommendation is the direct injection of TWW into groundwater should be stopped since the damage done by this practice is not scientifically calculated and the long term consequences are unknown.

6.3.4 Future work for the HydroGeoChemical survey of lagoons and surrounding wells

- Exploring pharmaceuticals and personal care by-products in both lagoons and the surrounding groundwater aquifers;
- Studying the impact of the lagoons on the surrounding area air quality, considering public complaints regarding the smell surrounding the lagoons;
- Understanding pollution Bioconcentration and magnification in livestock meat and dairy fed with lagoon irrigated fodders;
- Understanding pollution Bioconcentration in fish and birds living in the lagoons;

6.4 Bacterial survey of lagoons and surrounding wells

6.4.1 Summary

MALDI-TOF-MS identified 35 bacterial species in both lagoon and groundwater. Within those species, nine were found to be coliform bacteria. The groundwater and lagoon have coliform bacteria levels above national and international guidelines. Coliform bacteria were found to be linked to lagoons' proximity to the groundwater wells. Lastly, P.aeruginosa, was found to be a better suitable indication in the Qatar lagoon context.

6.4.2 Study Limitations

The limitation for this part of the study is the sample size, which presented a need for microbial identification to be conducted in a bigger sample size for the groundwater in Qatar, with the focus not only on faecal bacteria but all the WW associated bacteria giving a more useful picture of the current microbial situation in the groundwater in Qatar

Only one season was explored in this research, which was the winter season after rainfall events. Thus, the same study should be done in summer when the microbial culture would not be influenced by rainfall infiltration, and to show temporal variation in the microbial distribution in lagoons and groundwater in Qatar

6.4.3 Recommendation

Recommendation for the chemical analysis is also applied here, where the long term microbial influence from the lagoon should be monitored and direct TWW injection to be stopped. Moreover, since this part of the research faced time and resource limitations which caused the small wells sampling number, it is recommended that an intensive study for the microbial identification and quantification in Qatar groundwater be done. Typical faecal coliform bacteria should not be the only

indicator for TWW infiltration to the groundwater, where this study showed that other bacteria were better to show lagoon infiltration such as P. aeruginosa

6.4.4 Future work for the bacterial survey of lagoons and surrounding wells

- This study was limited to 13 wells. Thus, more sampling points should be researched to have a better spatial variation image for the groundwater current microbial culture;
- Bacteria isolated from this study with oil and surfactant degrading ability could be further explored in studies related to bioremediation with contaminated water or soil in the unique hot arid Qatari conditions.

6.5 Overall Conclusion

In conclusion, this study has covered three different scientific areas related to the lagoon situation in Qatar in hope that Policymakers and managers in Qatar can benefit from these findings, which can be used to encourage the use of atypical waters in agriculture, such as reclaimed or recycled TWW, thereby conserving water, maintaining food security, and safeguarding public health. In addition, raising public knowledge of water reuse and evaluating the benefits of water use in agriculture were two important objectives.

Also, this research is to serve as a comprehensive baseline study for future research and policy setting for Qatar's urban water system in general and specifically for future lagoon related management practices.

Appendix A. Public perception on lagoons survey

Currently, Qatar has many lagoons in different places. This study is designed to investigate public perceptions of the lagoons and their impact on both the environment and public health. The results of this survey together with the data collected will be used to develop recommendations on lagoon management that will be communicated with the Qatar Ministries in the future. This study is organized by the University of Nottingham (UK) as part of a PhD thesis sponsored by Qatar University.



Figure 7.1. A picture of an example of a lagoon in Qatar, attached with the survey

After reading the statement, please sign this form if you are happy with the contents.

- I voluntarily agree to take part in this study.
- I authorize the investigator to disclose the results of my participation in the study but not my name.
- I understand that information about me recorded during the study will be kept in a secure database. If data is transferred to others it will be made anonymous. Data will be kept for 7 years after the results of this study have been published.
- I understand that I am free to withdraw from the study at any time, without having to give a reason for withdrawing.

Complaint procedure

If you wish to discuss the way in which the research is being conducted or have any concerns about the research then in the first instance please contact H.Al-Jabiry at [stxha12@exmail.nottingham.ac.uk]. If this does not resolve the matter to your satisfaction then please contact Liz Bailey at [plzeb@exmail.nottingham.ac.uk]; or contact the School's Research Ethics Officer, Dr Kate Millar (tel. 0115 951 6303, email Kate.Millar@nottingham.ac.uk).

- I consent
- I do not consent (if this option is chosen then the survey will automatically ends)

1. Age:
    a. 18-25
    b. 26-35
    c. 36-45
    d. 46-60
    e. 61 & above
    f. Prefer not to say

2. Education:
    a. Middle school
    b. High school
    c. Bachelor degree
    d. Postgraduate degree
    e. Prefer not to say

3. Nationality:
    a. Qatari
    b. GCC countries
    c. Middle east
    d. Other
    e. Prefer not to say

4. Before this survey, have you heard about lagoons before
    a. Yes
    b. No

5. When did you first hear about Lagoons
    a. In the past five years
    b. In the past 10 years
    c. Cannot recall

6. Based on your knowledge how many lagoons do we have in Qatar?
    a. 1 or 2
    b. around 5
    c. less than 10
    d. more than 10
    e. I don’t know

7. Are you aware of any lagoons in your city
    a. Yes, there is one in my city
    b. No, we do not have any lagoons in my city
    c. I don’t know, maybe there is a lagoon in my city

8. What do you think is the main water source in the lagoon? (you can choose more than one)
    a. Rainwater
    b. Groundwater
    c. Wastewater
    d. Treated wastewater
    e. Seawater
    f. I don’t know

9. Which ministry is responsible for the lagoons? (you can choose more than one)
    a. Ashghal
    b. Ministry of Municipality and Environment
    c. Kaharamma
    d. I don't know

10. To what extent do you agree with the following statements about lagoons:

1 = disagree, 2 = somewhat disagree, 3 = neither agree nor disagree, 4 = somewhat agree, 5 = agree, 6 = I do not know

1. lagoons are bad for public health
2. lagoons are a drowning hazard
3. lagoons attract dangerous animals
4. lagoons are a good place for fishing
5. lagoons are a good place for bird hunting
6. I would like to visit a lagoon
7. All lagoons are the same
8. I don't want to live next to a lagoon

11. How much do you agree with the following management option for Lagoons:

1 = disagree, 2 = somewhat disagree, 3 = neither agree nor disagree, 4 = somewhat agree, 5 = agree, 6 = I do not know

1. Lagoons should be fenced and locked
2. Lagoons should have security patrolling
3. The public should be informed about the lagoons near them
4. The public should be informed about the lagoon water source
5. More efficient treated wastewater reuse is needed
6. Treated wastewater should be used for fodder irrigation

12. If you have any questions about lagoons please write them below:

End of Survey

Appendix B. Policy Makers Interview Questions

School of Biosciences
Division of Agriculture and Environmental Science
Sutton Bonington Campus, Sutton Bonington
Loughborough, Leicestershire, LE12 5RD
www.nottingham.ac.uk/biosciences

Title of Project: Assessment of Groundwater aquifers impacts by the artificial lagoons and the reuse of wastewater

Name of Investigator: Hayat Al-Jabiry

Policy maker's Consent Form

Please sign this form if you are content with the contents.

- I voluntarily agree to take part in this study.
- I confirm that I have been given a full explanation by the above-named investigator and that I have read and understood the information sheet given to me.
- I have been given the opportunity to ask questions and discuss the study with the above-named investigator on all aspects of the study and have understood the advice and information given as a result.
- I authorise my anonymized data, such as my anonymized words, to be quoted in publications, reports and other research outputs
- I understand that information about me recorded during the study that can identify me, such as my name or where I work will not be shared beyond the study team and it will be kept in a secure database. If data is transferred to others it will be made anonymous. Data will be kept for 7 years after the results of this study have been published.
- Personal information collected about me that can identify me, such as my name or where I live, will not be shared beyond the study team
- I understand that I can ask for further instructions or explanations at any time.
- I understand that I am free to withdraw from the study at any time, without having to give a reason for withdrawing.

Name: ……

Signature: …… **Date:**…….

I confirm that I have fully explained the purpose of the study and what is involved to and I have given the above named a copy of this form together with the information sheet.

Investigators Signature: ……**Date**: ……

Complaint procedure

If you wish to discuss the way in which the research is being conducted or have any concerns about the research then in the first instance please contact H.Al-Jabiry at *[stxha12@exmail.nottingham.ac.uk]*. If this does not resolve the matter to your satisfaction then please contact Liz Bailey at *[plzeb@exmail.nottingham.ac.uk]*; or contact the School's Research Ethics Officer, Dr Kate Millar (tel. 0115 951 6303, email Kate.Millar@nottingham.ac.uk).

Policy Makers Interview Questions

Lagoons questions:

1. Can you tell me about your role in working in this institution?
2. Do you deal with lagoons as part of your job, yes or no? If yes how?
3. How many lagoons do you think are in Qatar?
4. What do you think is the water source for those lagoons?
    a. Same source for all?
5. Which ministries are currently responsible for lagoons?
6. For how long did we have lagoons in Qatar?
7. Do you think all lagoons are the same in terms of construction?
8. Do you think that lagoons have a positive or negative impact on the environment? (could you explain)
9. In your opinion what other treated wastewater reuse options do we have as an alternative for lagoons?

Aquifer questions

10. What do you think about the current quality of Qatar groundwater?
11. Do you have any concerns about the lagoon's impact on groundwater quality?
12. Do you have any recommendations to prevent lagoon water from impacting the aquifers?

Public questions

13. How do you think the public perceives lagoons?
14. Do you think the public are involved in decision making on matters regarding lagoons and treated wastewater reuse?
    a. Please explain…
15. Do you think it is a good idea to involve the public in decision making on matters regarding lagoons and treated wastewater reuse?
    a. Please explain…
16. Do you think it's a good idea to survey the public?
    a. Please explain…

Last question:

17. What are your concerns regarding future water management in Qatar?
18. If they have any comments, observations or criticisms regarding my research

End of Interview Questions

Appendix C. Hydrochemical Median, Range, Interquartile Range

Table 7.1. Summary of groundwater and lagoon median, range and interquartile range for both summer and winter.

	Groundwater Summer			Groundwater Winter			Lagoon Summer			Lagoon Winter		
	Median	Range	Interquartile	Median	Range	Interquartile	Median	Range	Interquartile	Median	Range	Interquartile
General water quality variables (mg L^{-1}), except EC in µs cm^{-1} and pH no unit												
EC	2999	18413	1989	6230	18240	3235	1460	12635	3057	2720	6330	3000
pH	7	1	0	7	2	0	NA	NA	NA	8	2	2
TDS	1919	11784	1273	3110	5	1	935	8086	1956	1555	3160	1430
Temp	30	14	2	26	13	5	NA	NA	NA	23	6	4
TN	6	17	6	4	22	6	6	19	7	78	24	18
TOC	7	20	3	3	5	1	4	16	10	9	95	5
Anionic and cationic variables (mg L^{-1})												
B	1	3	1	1	2	1	0	3	1	0	0	0
Ca^{2+}	469	533	160	545	639	213	112	806	365	193	692	141
Cl^{-}	653	6155	598	517	4796	654	161	4644	913	290	723	352
I	88	147	31	103	2	1	10	70	38	22	98	78
K	41	150	17	49	104	18	22	806	367	26	26	8
Mg^{2+}	123	382	64	133	299	80	25	367	76	36	121	52
Na^{+}	430	4354		508	2871	416	214	2155	474	273	500	244
NO_3	6	316	10	8	36	13	0	0	0	0	21	7
P	0			0	0	0	0	3	2	0	0	0
S	541	940	210	583	851	242	114	1366	430	177	702	174
SO_4^{2-}	503	1288	177	454	649	161	87	1708	491	134	600	140
Metal and metalloid variables (µg L^{-1})												
Ag	0	0	0	0	0	0	0	0	0	0	0	0
Al	1	6	1	1	90	1	6	22	9	3	8	5
As	1	5	1	1	10	1	1	3	2	1	3	1
Ba	13	32	7	16	90	7	16	42	15	24	54	15
Be	0	0	0	0	0	0		0	0	0	0	0
Cd	0	1	0	0	0	0	0	0	0	0	0	0
Co	0	0	0	0	0	0	0	0	0	0	0	0
Cr	1	17	3	2	20	4	0	0	0	0	0	0
Cs	0	3	1	0	4	1	0	1	0	0	0	0
Cu	1	103	1	1	4	1	1	2	1	0	0	0
Fe	2	799	5	2	606	6	16	28	8	6	36	15
Li	73	412	53	83	160	53	13	163	42	17	37	10
Mn	1	25	1	1	14	2	7	32	10	12	304	19
Mo	20	90	12	21	343	16	4	18	5	5	12	7
Ni	2	8	2	2	19	2	2	2	1	2	4	2
Pb	0	0	0	0	0	0	0	0	0	0	0	0
Rb	8	40	4	10	37	5	16	40	6	15	27	10
Se	6	973	6	6	32	4	0	0	0	0	0	0
Sr	12186	14253	2985	13231	17681	4463	2089	28255	9419	3454	13111	3531
Tl	0	1	0	0	1	0	0	0	0	0	0	0
U	11	38	9	12	32	9	0	11	3	1	5	2
V	25	45	20	28	59	19	4	8	6	5	12	5
Zn	3	57	10	3	701	4	22	526	18	5	27	9

Appendix D. Colony Forming Unit (CFU) results

Table 7.2. Microbial survey sampling site location and coordinates, with the bacteria colonies count (CFU ml^{-1}) in the different selective media, with the number of colonies identified and not identified by MALDI-TOF-MS.

	location name	X	Y	MC[1] 37° C	EMB[2]	MC 44°C[3]	Total CFU	Identified	Not Identified
				CFU ml^{-1}					
L1	Shahanyyia	51.22848	25.34546	720	2080	440	3240	3240	0
L2	Al-Mearad	51.37179	25.22413	510	40	130	680	450	230
L3	Mesaimeer	51.46591	25.18179	83	43	26	153	153	0
L4	Doha North Treatment Plant	51.29288	25.45626	480	920	0	1400	1340	60
L5	Al-khore	51.51573	25.66195	226	581	0	808	671	137
L6	Al-Dhukhariah	51.54672	25.71248	27	26	0	53	42	11.4
L7	Karanna	51.04959	24.98475	227	36	0	264	253	11
L8	Mukaynis	51.18276	25.00481	230	560	0	790	780	10
L9	Doha West Treatment Plant	51.33295	25.21828	621	90	40	751	543	207
W1	Shahanyyia	51.23123	25.3447	30	80	0	110	110	0
W2	Mearad	51.35216	25.21946	10	20	0	30	30	0
W3	Kharara	51.2579	24.9613	52	56	15	123	107	15
W4	Kharara	51.17537	24.90124	25	10	0	35	7	28
W5	Kharara	51.13652	24.92294	4	3	0	7	7	0
W6	Shahanyyia	51.22724	25.35363	38	0	0	38	34	4
W7	Rwdat Rashed	51.18148	25.31454	22	30	0	52	52	0
W8	Mukaynis	51.18046	25.0888	2	5	0	7	7	0
W9	Mukaynis	51.24618	25.08629	3	2	0	5	4	1
W10	Salwa	51.28428	25.15433	6	20	0	27	18	9
W11	Abu Nakhla	51.29407	25.18156	2	3	0	4	3	1
W12	Wakra	51.52505	25.11092	9	5	0	14	12	1.9
W13	Wakra	51.55212	25.21783	16	18	0	35	33	0.8

1. MacConkey media incubated at 37°C
2. EMB media incubated at 37°C
3. MacConkey media incubated at 44°C

Appendix E. Microbial protein profile results and scores

Figure 7.3. Microbial survey sampling site location bacterial strains identified by MALDI-TOF-MS, with the identification scores >1.70.

Lagoon 1		Lagoon 2		Lagoon 3		Lagoon 4	
strain name	score	strain name	score	strain name	score	strain name	score
A.veronii	2.21	*A.baumannii*	2.46	*A.caviae*	2.32	*A.hydrophila*	2.13
C.braakii	2.23	*E.coli*	2.33	*E.coli*	2.23	*P.aeruginosa*	2.53
E.cloacae	2.3	*L.adecarboxylata*	2.23	*E.coli*	2.21	*P.alcaliphila*	2.17
E.coli	2.3	*P.aeruginosa*	2.34	*E.coli*	2.31	*P.alcaliphila*	2.29
E.coli	2.02	*P.mendocina*	1.97	*P.dispersa*	2.44	*P.stutzeri*	2.08
E.coli	2.25	*P.pseudoalcaligenes*	2.23	*P.mendocina*	216	*P.stutzeri*	2.26
E.coli	2.47	*P.stutzeri*	2.26	*P.putida*	2.3	*P.stutzeri*	2.3
K.pneumoniae	2.11	*S.marcescens*	2.33	*P.putida*	2.3	*S.marcescens*	2.27
K.pneumoniae	2.36					*S.marcescens*	2.34
P.aeruginosa	2.59					*S.marcescens*	2.21
P.aeruginosa	2.34					*S.marcescens*	2.23

Continue Table 7.3.

Lagoon 5		Lagoon 6		Lagoon 7		Lagoon 8		Lagoon 9	
strain name	score	strain name	score	strain name	score	strain name	score	strain name	score
E.asburiae	2.23	*A.veronii*	2.3	*E.kobei*	2.25	*E.asburiae*	2.17	*A.baumanii*	2.38
E.asburiae	2.11	*A.faecalis*	2.16	*A.venetianus*	2.32	*E.asburiae*	2.32	*A.caviae*	2.28
A.caviae	2.39	*P.mendocina*	2.19	*E.asburiae*	2.32	*E.asburiae*	2.28	*A.hydrophila*	2.23
E.asburiae	2.27	*P.mendocina*	3.19	*K.pneumoniae*	2.3	*E.kobei*	2.07	*A.veronii*	2.24
		P.composti	2.16	*V.albensis*	1.95	*L.adecarboxylata*	2.4	*E.coli*	2.32
		P.putida	2.19			*P.aeruginosa*	2.47	*E.coli*	2.24
		S.maltophilia	2.04			*P.aeruginosa*	2.5	*E.coli*	2.21
						P.stutzeri	2.11	*P.fulva*	2.02
								P.oleovorans	1.73

Continue Table 7.3.

Well 1		Well 2		Well 3		Well 4		Well 5	
strain name	score	strain name	score	strain name	score	strain name	score	strain name	score
A.Junii	2.49	*P.alcaliphila*	1.92	*A.veronii*	2.02	*A.dijkshoorniae*	1.86	*A.hydrophila*	2.13
A.Junii	2.32	*P.composti*	1.87	*P.aeruginosa*	2.3	*A.jandaei*	2.11	*P.putida*	2.4
E.cloacae	2.13	*S.marcescens*	2.3	*P.oleovorans*	1.81	*P.aeruginosa*	2.49	*P.putida*	2.33
W.falsenii	2.23			*P.oleovorans*	1.78	*P.aeruginosa*	2.37		
						P.aeruginosa	2.45		

Continue Table 7.3.

Well 6		Well 7		Well 8		Well 9		Well 10	
strain name	score	strain name	score	strain name	score	strain name	score	strain name	score
E.asburiae	1.86	*A.Junii*	2.3	*A.dijkshoorniae*	2.2	*A.dijkshoorniae*	1.98	*A.haemolyticus*	2.39
P.aeruginosa	2.54	*A.Junii*	2.38	*A.Junii*	2.5	*A.dijkshoorniae*	2.02	*P.putida*	1.81
S.maltophilia	2.01	*A.Junii*	2.46	*A.caviae*	2.34	*A.dijkshoorniae*	1.93		
		K.pneumoniaee	2.1	*P.aeruginosa*	2.35	*A.hydrophila*	2.27		
		P.aeruginosa	2.36	*P.aeruginosa*	2.44	*P.aeruginosa*	2.41		
		P.aeruginosa	2.38	*P.oleovorans*	1.96	*P.aeruginosa*	2.42		

Continue Table 7.3.

Well 11		Well 12		Well 13	
strain name	score	strain name	score	strain name	score
A.Junii	2.42	*A.Junii*	2.32	*A.caviae*	2.18
A.hydrophila	2.22	*A.Junii*	2.28	*A.veronii*	2.22
P.putida	2.13	*A.Junii*	2.34	*E.asburiae*	2.17
P.putida	2.34	*A.hydrophila*	2.2	*E.kobei*	1.96
S.putrefaciens	1.82			*E.coli*	2.27
				K.pneumoniae	2.33
				P.aeruginosa	2.59
				P.aeruginosa	2.3
				S.maltophilia	2.02
				S.maltophilia	2.03

Appendix F. Microbial protein profile PCA principal components

Table 7.4. Coliform bacteria principle components showing bacteria strains in lagoons and groundwater correlate based on the extracted protein profiles with PC1 to PC6 had a cumulative eigenvalue of more than 98%.

Bacteria strain	PC1	PC2	Bacteria strain	PC1	PC2
Cumulative %	95%	98%	**L5 E.asburiae**	.720	.680
L1 E.cloacae	.769	.630	**L5 E.asburiae**	.654	.741
L1 E.coli	.786	.598	**L7 E.Kobei**	.688	.720
L1 E.asburiae	.771	.620	**L7 K.pneumoniae**	.537	.805
L1 E.coli	.866	.460	**L7 E.asburiae**	.392	.903
L1 K.pneumoniae	.795	.595	**L8 E.asburiae**	.710	.697
L1 E.coli	.841	.529	**L8 E.Kobei**	.650	.753
L1 K.pneumoniae	.556	.826	**L8 L.adecarboxylata**	.586	.789
L1 C.braakii	.758	.642	**L8 E.asburiae**	.706	.697
L2 E.coli	.840	.521	**L8 E.asburiae**	.628	.765
L2 L.adecarboxylata	.608	.789	**L9 E.coli**	.848	.521
L2 S.marcescens	.681	.719	**L9 E.coli**	.822	.558
L3 P.dispersa	.749	.648	**L9 E.coli**	.815	.551
L3 E.coli	.846	.523	**F1 E.cloacae**	.689	.712
L3 E.coli	.861	.498	**F2 E.asburiae**	.860	.499
L3 E.Kobei	.740	.651	**F6 S.marcescens**	.695	.695
L4 S.marcescens	.668	.738	**F8 K.pneumoniae**	.517	.841
L4 S.marcescens	.675	.723	**F8 S.marcescens**	.511	.848
L4 S.marcescens	.639	.757	**F13 K.pneumoniae**	.495	.863
L4 S.marcescens	.610	.785	**F13 E.coli**	.798	.584
L5 E.asburiae	.710	.682	**F13 E.asburiae**	.622	.766

Table 7.5. Wastewater correlated bacteria principle components showing bacteria strains in lagoons and groundwater correlate based on the extracted protein profiles with PC1 to PC6 had a cumulative eigenvalue of more than 97%.

Bacteria strain	PC1	PC2	Bacteria strain	PC1	PC2
Cumulative %	95%	97%	**L8 P.aeruginosa**	.836	.534
			L9 E.coli	.524	.847
L1 A.veronii	.808	.575	**L9 A.veronii**	.722	.679
L1 E.cloacae	.642	.758	**L9 E.coli**	.560	.820
L1 E.coli	.595	.789	**L9 E.coli**	.575	.792
L1 K.pneumoniae	.628	.765	**F1 E.cloacae**	.633	.796
L1 E.coli	.462	.867	**F3 P.aeruginosa**	.809	.553
L1 P.aeruginosa	.655	.744	**F4 P.aeruginosa**	.880	.428
L1 K.pneumoniae	.599	.793	**F6 P.aeruginosa**	.751	.630
L1 E.coli	.531	.840	**F7 P.aeruginosa**	.616	.762
L1 P.aeruginosa	.747	.658	**F7 P.aeruginosa**	.784	.612
L1 P.aeruginosa	.829	.551	**F8 P.aeruginosa**	.780	.618
L2 P.aeruginosa	.772	.630	**F8 K.pneumoniae**	.712	.678
L2 E.coli	.520	.842	**F8 P.aeruginosa**	.835	.520
L3 E.coli	.520	.849	**F9 P.aeruginosa**	.800	.589
L3 E.coli	.497	.861	**F9 P.aeruginosa**	.735	.667
L3 E.coli	.652	.739	**F13 A.veronii**	.860	.498
L4 P.aeruginosa	.619	.776	**F13 E.coli**	.527	.835
L6 A.veronii	.725	.677	**F13 A.veronii**	.864	.492
L7 P.aeruginosa	.799	.541	**F13 P.aeruginosa**	.728	.674
L8 P.aeruginosa	.796	.598	**F13 K.pneumoniae**	.789	.608

Reference

Abd-Elwahed, M. S. (2018) 'Influence of long-term wastewater irrigation on soil quality and its spatial distribution', *Annals of Agricultural Sciences*, 63(2), pp. 191–199.

Abdel-moneim, A. M. (2014) 'Histopathological and ultrastructural perturbations in tilapia liver as potential indicators of pollution in Lake Al-Asfar , Saudi Arabia', pp. 4387–4396.

Abdel-moneim, A. M., Al-kahtani, M. A. and Elmenshawy, O. M. (2012) 'Chemosphere Histopathological biomarkers in gills and liver of Oreochromis niloticus from polluted wetland environments , Saudi Arabia', *Chemosphere*, 88(8), pp. 1028–1035.

Abdel Samad, R. *et al.* (2020a) 'The use of principle component analysis and MALDI-TOF MS for the differentiation of mineral forming: Virgibacillus and Bacillus species isolated from sabkhas', *RSC Advances*, 10(25), pp. 14606–14616.

Abdel Samad, R. *et al.* (2020b) 'The use of principle component analysis and MALDI-TOF MS for the differentiation of mineral forming: Virgibacillus and Bacillus species isolated from sabkhas', *RSC Advances*, 10(25), pp. 14606–14616.

Abdelaziz, S. *et al.* (2020) 'Groundwater quality index based on PCA: Wadi El-Natrun, Egypt', *Journal of African Earth Sciences*, 172(August), p. 103964.

Abdelrahman, R. M., Khamis, S. E. and Rizk, Z. E. (2020) 'Public attitude toward expanding the reuse of treated wastewater in the United Arab Emirates', *Environment, Development and Sustainability*, 22(8), pp. 7887–7908.

Abdmouleh, Z., Gastli, A. and Ben-Brahim, L. (2018) 'Survey about public perception regarding smart grid, energy efficiency & renewable energies applications in Qatar', *Renewable and Sustainable Energy Reviews*, 82(July 2016), pp. 168–175.

Abdul Wahab, A., Janahi, I. A. and El Shafie, S. (2005) 'Stenotrophomonas maltophilla isolated from the sputum of the patient with cystic fibrosis mutation I1234V: First Qatari report', *Qatar Medical Journal*, 14(2), pp. 57–58.

AbdulRahim, H. F. *et al.* (2020) 'Willingness to participate in genome testing: a survey of public attitudes from Qatar', *Journal of Human Genetics*, 65(12), pp. 1067–1073.

Abed, R. M. M. *et al.* (2014) 'Diversity, distribution and hydrocarbon biodegradation capabilities of microbial communities in oil-contaminated cyanobacterial mats from a constructed wetland', *PLoS ONE*, 9(12), pp. 1–22.

Abed, R. M. M. *et al.* (2018) 'Bacterial communities in the rhizosphere of Phragmites australis from an oil-polluted wetland', *Archives of Agronomy and Soil Science*, 64(3), pp. 360–370.

Abo-Amer, A. E., El-Shanshoury, A. E. R. R. and Alzahrani, O. M. (2015) 'Isolation and Molecular Characterization of Heavy Metal-Resistant Alcaligenes faecalis from Sewage Wastewater and Synthesis of Silver Nanoparticles', *Geomicrobiology Journal*, 32(9), pp. 836–845..

AbuNada, H. (2021) 'The residents of Mebirek await the removal of the Abu Nakhla swamp', *Al Raya newspaper*, p. Accessed 16th.April.2021. Available at: https://www.raya.com/2021/02/01/سكان-مبيريك-ينتظرون-إزالة-مُستنقع-أبو/.

Adapa, S. *et al.* (2019) 'Peritonitis from Leclercia adecarboxylata: An emerging pathogen', *Clinical Case Reports*, 7(4), pp. 829–831.

Ae, B. (2019) 'Temporal variation of bacterial population and response to physical and chemical parameters along a petrochemical industry wastewater treatment plant', 91, pp. 1–18.

Ahmad, A. Y. *et al.* (2020) 'Hydrogeochemical characterization and quality evaluation of groundwater suitability for domestic and agricultural uses in the state of Qatar', *Groundwater for Sustainable Development*, 11(April), p. 100467.

Ahmed, S. (2011) 'أبو نخلة.. مدينة «غارقة» في النسيان.. وأشغال «غائبة» عن خدمة السكان', *Al Arab Newspaper*, 11 December. Available at: https://alarab.qa/article/11/12/2011/162853--أبو-نخلة-مدينة-غارقة-في-النسيان-وأشغال-غائبة-عن-خدمة-السكان.

Ahmed, S., Popov, V. and Trevedi, R. C. (2008) 'Constructed wetland as tertiary treatment for municipal wastewater', *Proceedings of Institution of Civil Engineers: Waste and Resource Management*, 161(2), pp. 77–84.

Akpan, V. E., Omole, D. O. and Bassey, D. E. (2020) 'Assessing the public perceptions of treated wastewater reuse: opportunities and implications for urban communities in developing countries', *Heliyon*, 6(10), p. e05246.

Akshitha, V., Balakrishna, K. and Udayashankar, H. N. (2021) 'Assessment of hydrogeochemical characteristics and saltwater intrusion in selected coastal aquifers of southwestern India', *Marine Pollution Bulletin*, 173(PA), p. 112989.

Al-Ahmad, M., Tichy, H. V. and Schon, G. (1994) 'Characterization of Acinetobacter type strains and isolates obtained from wastewater treatment plants by PCR fingerprinting', *Applied and Environmental Microbiology*, 60(11), pp. 4066–4071.

Al-Amro, A. M., El-Sheikh, M. A. and El-Sheikh, A. M. (2018) 'Vegetation analysis of some wetland habitats in central region of Saudi Arabia.', *Applied Ecology and Environmental Research*, 16(3), pp. 3255–3269. Available at: http://www.aloki.hu/pdf/1603_32553269.pdf.

Al-Ansari, M. M. *et al.* (2021) 'Effective removal of heavy metals from industrial effluent wastewater by a multi metal and drug resistant Pseudomonas aeruginosa strain RA-14 using integrated sequencing batch reactor', *Environmental Research*, 199(May), p. 111240.

Al-Dhabi, N. A. *et al.* (2021) 'Removal of nitrogen from wastewater of date processing industries using a Saudi Arabian mesophilic bacterium, Stenotrophomonas maltophilia Al-Dhabi-17 in sequencing batch reactor', *Chemosphere*, 268, p. 128636.

Al-Farawati, R. *et al.* (2008) 'Reclaimed Municipal Wastewater used for the Irrigation of Green Areas in Jeddah', *Journal of King Abdulaziz University, Marine Science*, 19, pp. 121–146.

Al-Farraj, A. S. *et al.* (2013) 'Evaluation of groundwater for arsenic contamination using hydrogeochemical properties and multivariate statistical methods in Saudi Arabia', *Journal of Chemistry*, 2013.

Al-Ghanim, K. (2017) 'Transitional Society and Participation of Women in the Public Sphere: A Survey of Qatar Society', 3(2), pp. 51–63.

Al-Jassim, N. *et al.* (2015) 'Removal of bacterial contaminants and antibiotic resistance genes by conventional wastewater treatment processes in Saudi Arabia: Is the treated wastewater safe to reuse for agricultural irrigation?', *Water Research*, 73, pp. 277–290.

Al-Kaabi, N. *et al.* (2018) 'A MALDI-TOF study of bio-remediation in highly weathered oil contaminated soils', *Journal of Petroleum Science and Engineering*, 168(May), pp. 569–576.

Al-Mamoon, A. *et al.* (2016) 'Comparison of two modelling approaches for a pilot catchment flood study in Qatar', *37th Hydrology and Water Resources Symposium 2016: Water, Infrastructure and the Environment, HWRS 2016*, 2016-Novem(November).

Al-Mohannadi, H. (2004) *water resources in the state of Qatar: toward holistic managment*. Doha: Qatar National printing press.

Al-Naimi, L. S. and Mgbeojedo, T. I. (2018) 'Hydrogeochemical Evaluation of Groundwater in Parts of Shamal, Northern Qatar', *Environmental Management and Sustainable Development*, 7(2), p. 181.

Al-obaid, S. *et al.* (2017) 'An overview of wetlands of Saudi Arabia : Values , threats , and perspectives', pp. 98–108.

Al-oqedi, M. (2015) 'مستنقعات; صرف صحي على طريق ابو سمرة الدولي', *Al Shareq Newspaper*, 20 January. Available at: https://al-sharq.com/article/20/01/2015/مستنقعات-صرف-صحي-على-طريق-ابو-سمرة-الدولي.

Al-oqedi, M. (2016) ‘مستنقع لمياه الصرف يهدد سكان السيلية بمخاطر صحية وبيئية’, *Al Shareq Newspaper*, 23 February. Available at: https://m.al-sharq.com/article/23/02/2016/مستنقع-لمياه-الصرف-يهدد-سكان-السيلية-بمخاطر-صحية-وبيئية.

Al-Rawahi, M. *et al.* (2014) ‘Constructing Wetlands in the Desert: An Example of Sustainable Produced Water Management in Oman ’.

Al-Saad, H. (2005) ‘Lithostratigraphy of the Middle Eocene Dammam Formation in Qatar, Arabian Gulf: Effects of sea-level fluctuations along a tidal environment’, *Journal of Asian Earth Sciences*, 25(5), pp. 781–789.

Al-shareq (2015) *إستياء من مستنقع مياه على مدخل سيلية المعراض*, *Al Shareq Newspaper*. Available at: https://al-sharq.com/article/31/08/2015/استياء-من-مستنقع-مياه-على-مدخل-سيلية-المعراض (Accessed: 20 February 2022).

Al-shareq (2019) ‘اكتمال مشروع استصلاح وإعادة تأهيل الأراضي في بحيرة الكرعانة’, *Al Shareq Newspaper*, 16 November. Available at: https://al-sharq.com/article/16/11/2019/اكتمال-مشروع-استصلاح-وإعادة-تأهيل-الأراضي-في-بحيرة-الكرعانة.

Al-Sheikh, H. and Fathi, A. A. (2010) ‘Ecological studies on Lake Al-Asfar (Al-Hassa, Saudi Arabia) with special references to the sediment.’, *Research Journal of Environmental Sciences*, 4(1), pp. 13–22.

Al-Shenaifi, M., Al-Shayaa, M. and Alharbi, M. (2015) ‘Perception and Attitudes of Farmers toward the Uses of Treated Sewage Water in Palm Trees Irrigation’, *Jordan Journal of Agricultural Sciences*, 11(3), pp. 693–704.

Al-thani, R. F. (2003) ‘The Coliform Bacteria in the Wastewater Ponds of Doha City , Qatar’, *Qatar Universiy scientific Journal*, 23, pp. 99–107.

Al-Yousef, M. (2003) ‘*mineralogy, geochemistry and origin of quaternary sabkhas in the qatar peninsula, arabian gulf*’. University of southampton archives.

Alhashimi, I. S. M., Abdul-Jabbar, R. A. and Issa, S. K. (2021) ‘The ability of Acinetobacter haemolyticus isolated from soil removes heavy elements (Cd, Pb, Zn, Ni)’, *Materials Today: Proceedings*.

Alhumoud, J. M. and Madzikanda, D. (2010) ‘Public Perceptions On Water Reuse Options: The Case Of Sulaibiya Wastewater Treatment Plant In Kuwait’, *International Business & Economics Research Journal (IBER)*, 9(1), pp. 141–158.

Ali, A. M. *et al.* (2017) ‘Chemosphere Occurrence of pharmaceuticals and personal care products in ef fl uent-dominated Saudi Arabian coastal waters of the Red Sea’, *Chemosphere*, 175, pp. 505–513.

Aljabiry, H. (2019) ‘field site communication’.

Almirall, M. *et al.* (2019) ‘Pathogenic Acinetobacter species including the novel Acinetobacter dijkshoorniae recovered from market meat in Peru’, *International Journal of Food Microbiology*, 305(June), p. 108248.

Almuktar, S. A. A. A. N., Abed, S. N. and Scholz, M. (2018) ‘Wetlands for wastewater treatment and subsequent recycling of treated effluent: a review’, *Environmental Science and Pollution Research*, 25(24), pp. 23595–23623.

Alsayegh, S. Y. *et al.* (2021) ‘Evaluation by MALDI-TOF MS and PCA of the diversity of biosurfactants and their producing bacteria, as adaption to weathered oil components’, *Biotechnology Reports*, 31(March), p. e00660.

Alvarez-Guzmán, C. L. *et al.* (2020) ‘Biohydrogen production from cheese whey powder by Enterobacter asburiae: Effect of operating conditions on hydrogen yield and chemometric study of the fermentative metabolites’, *Energy Reports*, 6, pp. 1170–1180.

Alves, A. *et al.* (2018) ‘Combining co-benefits and stakeholders perceptions into green infrastructure selection for flood risk reduction’, *Environments - MDPI*, 5(2), pp. 1–23.

Alyamani, M. S. and Hussein, M. T. (1995) ‘Hydrochemical study of groundwater in recharge area, Wadi Fatimah basin, Saudi Arabia’, *GeoJournal*, 37(1), pp. 81–89.

Andrade, L., Kelly, M., *et al.* (2020) ‘Groundwater resources as a global reservoir for antimicrobial-resistant bacteria’, *Water Research*, 170, p. 115360.

Andrade, L., Hynds, P. D., *et al.* (2020) 'Risk factor analysis of Escherichia coli and Pseudomonas aeruginosa occurrence in private domestic groundwater supplies in the Republic of', (November).

Andrews, S. S., Karlen, D. L. and Mitchell, J. P. (2002) 'A comparison of soil quality indexing methods for vegetable production systems in Northern California', *Agriculture, Ecosystems and Environment*, 90(1), pp. 25–45.

Anh, V. T. *et al.* (2007) 'Perceived health problems among users of wastewater for aquaculture in Southeast Asian cities', *Urban Water Journal*, 4(4), pp. 269–274.

Annappah, D. *et al.* (2022) 'Device-associated aortic valve endocarditis due to a complicated Enterobacter cloacae urinary tract infection', *IDCases*, 27, p. e01365.

Appelo, C. A. J. and Balkema, D. P. (1993) *Geochemistry, groundwater and pollution*. A.A. BALKEMA PUBLISHERS.

Araj, G. F. *et al.* (2019) 'Vibrio albensis: An unusual urinary tract infection in a healthy male', *Journal of Infection and Public Health*, 12(5), pp. 712–713.

Aravinthasamy, P. *et al.* (2020) 'Irrigation risk assessment of groundwater in a non-perennial river basin of South India: implication from irrigation water quality index (IWQI) and geographical information system (GIS) approaches', *Arabian Journal of Geosciences*, 13(21).

Arden, S. and Ma, X. (2018) 'Constructed wetlands for greywater recycle and reuse: A review', *Science of the Total Environment*, 630, pp. 587–599.

Arnon, S. *et al.* (2008) 'Transport of testosterone and estrogen from dairy-farm waste lagoons to groundwater', *Environmental Science and Technology*, 42(15), pp. 5521–5526.

Artiola, J., Pepper, I. L. and L, M. (2004) *Environmental Monitoring and Characterization*. Elsevier Acadmic Press.

Ashfaq, M. Y. *et al.* (2019) 'Isolation, identification and biodiversity of antiscalant degrading seawater bacteria using MALDI-TOF-MS and multivariate analysis', *Science of the Total Environment*, pp. 910–920.

Ashfaq, M. Y., Da, D. A. and Al-ghouti, M. A. (2022a) 'Application of MALDI-TOF MS for identification of environmental bacteria : A review', *Journal of Environmental Management*, 305(August 2021), p. 114359.

Ashfaq, M. Y., Da, D. A. and Al-ghouti, M. A. (2022b) 'Application of MALDI-TOF MS for identification of environmental bacteria : A review', *Journal of Environmental Management*, 305(August 2021), p. 114359.

Avci, H. and Deveci, T. (2013) 'Assessment of trace element concentrations in soil and plants from cropland irrigated with wastewater', *Ecotoxicology and Environmental Safety*, 98, pp. 283–291.

ávila, C. *et al.* (2013) 'Integrated treatment of combined sewer wastewater and stormwater in a hybrid constructed wetland system in southern Spain and its further reuse', *Ecological Engineering*, 50, pp. 13–20.

Ayaz, S. Ç. (2008) 'Post-treatment and reuse of tertiary treated wastewater by constructed wetlands', *Desalination*, 226(1–3), pp. 249–255.

Ayers, R. S. and Westcot, D. W. (1985) 'Water Quality for Agricultura FAO 29'.

Baalousha, H. M. (2016a) 'Development of a groundwater flow model for the highly parameterized Qatar aquifers', *Modeling Earth Systems and Environment*, 2(2), pp. 1–11.

Baalousha, H. M. (2016b) 'Groundwater vulnerability mapping of Qatar aquifers', *Journal of African Earth Sciences*, 124, pp. 75–93.

Baawain, M. S. *et al.* (2020) 'Public perceptions of reusing treated wastewater for urban and industrial applications: challenges and opportunities', *Environment, Development and Sustainability*, 22(3), pp. 1859–1871.

Baggett, S., Jeffrey, P. and Jefferson, B. (2006) 'Risk perception in participatory planning for water reuse', *Desalination*, 187(1–3), pp. 149–158.

Bai, L. *et al.* (2020) 'Comparative genomics analysis of Acinetobacter haemolyticus isolates from sputum

samples of respiratory patients', *Genomics*, 112(4), pp. 2784–2793.

Balkhair, K. S. and Ashraf, M. A. (2016) 'Field accumulation risks of heavy metals in soil and vegetable crop irrigated with sewage water in western region of Saudi Arabia', *Saudi Journal of Biological Sciences*, 23(1), pp. S32–S44.

Bamigboye, C. O. *et al.* (2020) 'An appraisal of the drinking water quality of groundwater sources in Ogbomoso, Oyo state, Nigeria', *Groundwater for Sustainable Development*, 11(May), p. 100453.

Banda, T. D. and Kumarasamy, M. (2020) 'Application of multivariate statistical analysis in the development of a surrogate water quality index (WQI) for South African watersheds', *Water (Switzerland)*, 12(6).

Baram, S. *et al.* (2014) 'Assessing the impact of dairy waste lagoons on groundwater quality using a spatial analysis of vadose zone and groundwater information in a coastal phreatic aquifer', *Journal of Environmental Management*, 132, pp. 135–144.

Barzegar, R., Asghari Moghaddam, A. and Kazemian, N. (2015) 'Assessment of heavy metals concentrations with emphasis on arsenic in the Tabriz plain aquifers, Iran', *Environmental Earth Sciences*, 74(1), pp. 297–313.

Bashandy, S. R., Abd-Alla, M. H. and Dawood, M. F. A. (2020) 'Alleviation of the toxicity of oily wastewater to canola plants by the N2-fixing, aromatic hydrocarbon biodegrading bacterium Stenotrophomonas maltophilia-SR1', *Applied Soil Ecology*, 154(April), p. 103654..

Batarseh, M. *et al.* (2021) 'Assessment of groundwater quality for irrigation in the arid regions using irrigation water quality index (IWQI) and GIS-Zoning maps: Case study from Abu Dhabi Emirate, UAE', *Groundwater for Sustainable Development*, 14, p. 100611.

Bauer, L. H. *et al.* (2021) 'Floating treatment wetland for nutrient removal and acute ecotoxicity improvement of untreated urban wastewater', *International Journal of Environmental Science and Technology*, (0123456789).

Bekele, E. *et al.* (2019) 'Inferring groundwater dynamics in a coastal aquifer near wastewater infiltration ponds and shallow wetlands (Kwinana, Western Australia) using combined hydrochemical, isotopic and statistical approaches', *Journal of Hydrology*, 568(November 2018), pp. 1055–1070.

Bentzmann, S. and Plésiat, P. (2011) 'The Pseudomonas aeruginosa opportunistic pathogen and human infections', *Environmental Microbiology*, 13(7), pp. 1655–1665.

Bickel, P. *et al.* (2007) *Linear and Generalized Linear Mixed Models and Their Applications*. Springer Science +Business Media, LLC.

Bikangaga, S. *et al.* (2007) 'Perceived benefits of littoral wetlands in Uganda: A focus on the Nabugabo wetlands', *Wetlands Ecology and Management*, 15(6), pp. 529–535.

Biswas, S. *et al.* (2017) 'Establishment of critical limits of indicators and indices of soil quality in rice-rice cropping systems under different soil orders', *Geoderma*, 292, pp. 34–48.

Bixio, D. *et al.* (2006) 'Wastewater reuse in Europe', *Desalination*, 187(1–3), pp. 89–101.

Breitholtz, M. *et al.* (2012) 'An evaluation of free water surface wetlands as tertiary sewage water treatment of micro-pollutants', *Ecotoxicology and Environmental Safety*, 78, pp. 63–71.

Brown, R. M. *et al.* (1970) 'A Water Quality Index Do we dare?', *Data and Instrumentation for Water Quality Management*, pp. 339–343.

Bryman, A. (2012) *Social Research Methods*. Fourth edi. Great Clarendon Street, Oxford OX2: Oxford University Press Inc., New York.

Cai, Z. *et al.* (2021) 'Striking a balance between N sources: Mitigating soil acidification and accumulation of phosphorous and heavy metals from manure', *Science of the Total Environment*, 754(12), p. 142189.

Calheiros, C. S. C. *et al.* (2017) 'Assessment of culturable bacterial endophytic communities colonizing Canna flaccida inhabiting a wastewater treatment constructed wetland', *Ecological Engineering*, 98, pp. 418–426.

Cameron, K. *et al.* (2003) 'Pollutant removal from municipal sewage lagoon effluents with a free-surface wetland', *Water Research*, 37(12), pp. 2803–2812.

Camus, D. R. D. *et al.* (2020) 'Perception-based Social Acceptability of Subsurface Flow Constructed Wetland Treated Dairy Farm Wastewater Reuse for Irrigation', *Internet Journal of Society for Social Managment Systems*, 12(2), pp. 155–166.

Canal, E. and Abd-elgawad, A. M. (2021) 'Hydrochemical Assessment of the Irrigation Water Quality of', pp. 1–18.

Candela, L. *et al.* (2007) 'Assessment of soil and groundwater impacts by treated urban wastewater reuse. A case study: Application in a golf course (Girona, Spain)', *Science of the Total Environment*, 374(1), pp. 26–35.

Carroll, S. and Goonetilleke, A. (2005) 'Assessment of high density of onsite wastewater treatment systems on a shallow groundwater coastal aquifer using PCA', *Environmetrics*, 16(3), pp. 257–274.

Carvalheira, A., Silva, J. and Teixeira, P. (2021) 'Acinetobacter spp. in food and drinking water – A review', *Food Microbiology*, 95(November 2020), p. 103675.

Castro, C. *et al.* (2015) 'Wastewater reuse in irrigation: A microbiological perspective on implications in soil fertility and human and environmental health', *Environment International*, 75, pp. 117–135.

Chadha D. (1999) 'Proposed new diagram for geochemical classification of natural waters and interpretation of chemical data', *Hydrogeology Journal*, 7, pp. 431–439.

Chandrarathna, H. P. S. U. *et al.* (2018) 'Outcome of co-infection with opportunistic and multidrug resistant Aeromonas hydrophila and A. veronii in zebrafish: Identification, characterization, pathogenicity and immune responses', *Fish and Shellfish Immunology*, 80(June), pp. 573–581.

Cheema, S. *et al.* (2017) 'Oral health behavior and factors associated with poor oral status in Qatar: results from a national health survey', *Journal of Public Health Dentistry*, 77(4), pp. 308–316.

Chen, D. Z. *et al.* (2013) 'Biodegradation of tetrahydrofuran by Pseudomonas oleovorans DT4 immobilized in calcium alginate beads impregnated with activated carbon fiber: Mass transfer effect and continuous treatment', *Bioresource Technology*, 139, pp. 87–93.

Chen, F. *et al.* (2019) 'Isolation, Identification and Characteristics of Aeromonas veronii From Diseased Crucian Carp (Carassius auratus gibelio)', *Frontiers in Microbiology*, 10(November), pp. 1–10.

Chen, H. *et al.* (2016) 'Removal of cadmium by bioflocculant produced by Stenotrophomonas maltophilia using phenol-containing wastewater', *Chemosphere*, 155, pp. 163–169.

Chen, J. S. *et al.* (2021) 'Prevalence, virulence-gene profiles, antimicrobial resistance, and genetic diversity of human pathogenic Aeromonas spp. from shellfish and aquatic environments', *Environmental Pollution*, 287(May), p. 117361.

Chen, T. Y. and Kao, C. M. (2006) 'Application of a constructed wetland for industrial wastewater treatment : A pilot-scale study', 64, pp. 497–502.

Chen, W. *et al.* (2015) 'Perceptions of different stakeholders on reclaimed water reuse: The case of Beijing, China', *Sustainability (Switzerland)*, 7(7), pp. 9696–9710.

Chen, X., Aravkin, A. Y. and Martin, R. D. (2018) 'Generalized Linear Model for Gamma Distributed Variables via Elastic Net Regularization', *arXiv:1804.07780*, (Tibshirani 1996), pp. 1–16. Available at: https://arxiv.org/abs/1804.07780.

Choi, J. and Harvey, J. W. (2000) 'Quantifying time-varying ground-water discharge and recharge in wetlands of the northern Florida Everglades', *Wetlands*, 20(3), pp. 500–511.

Cirelli, A. F. and Miretzky, P. (2004) 'Ionic relations: A tool for studying hydrogeochemical processes in Pampean shallow lakes (Buenos Aires, Argentina)', *Quaternary International*, 114(1), pp. 113–121.

Clare, S. *et al.* (2011) 'Where is the avoidance in the implementation of wetland law and policy?', *Wetlands Ecology and Management*, 19(2), pp. 165–182.

Claus, J. *et al.* (2016) *Numerical groundwater model of the dessication and dissipation of an unlined treated sewage effluent pond in Doha, Qatar, 5th International Geologica Belgica Meeting. Mother Earth*.

Cobo, F. *et al.* (2016) ' Posttraumatic Skin and Soft-Tissue Infection due to Pseudomonas fulva ', *Case Reports in Infectious Diseases*, 2016, pp. 1–2.

Cools, J. *et al.* (2013) 'Tools for wetland management: Lessons learnt from a comparative assessment', *Environmental Science and Policy*, 34, pp. 138–145.

Creswell, J. W. (1997) 'Qualitative inquiry and research design, Choosing among five traditions'. SAGE Publications, pp. 49–69.

Dalahmeh, S. S., Assayed, M. and Suleiman, W. T. (2009) 'Themes of stakeholder participation in greywater management in rural communities in Jordan', *Desalination*, 243(1–3), pp. 159–169.

Dar, S. A. *et al.* (2021) 'Identification of anthropogenic contribution to wetland degradation: Insights from the environmetric techniques', *Stochastic Environmental Research and Risk Assessment*, 0123456789.

Darwish, M. A. and Mohtar, R. (2013) 'Qatar water challenges', *Desalination and Water Treatment*, 51(1–3), pp. 75–86.

Davidian, M. (1989) 'Generalized linear models for nonnormal response', in *Applied Longitudianal Data Analysis*. North Carolina: North Carolina State University (NCSU) •, pp. 423–464.

Day, J. W. *et al.* (2019) 'Long-term assimilation wetlands in coastal Louisiana: Review of monitoring data and management', *Ecological Engineering*, 137(February 2018), pp. 7–20.

Dean, J. (2009) 'Choosing the Right Type of Rotation in PCA and EFA', 13(November), pp. 20–25.

Deh-Haghi, Z. *et al.* (2020) 'Farmers' acceptance and willingness to pay for using treated wastewater in crop irrigation: A survey in western Iran', *Agricultural Water Management*, 239(September 2019), p. 106262.

Dekic, S. *et al.* (2020) 'Survival of extensively- and pandrug-resistant isolates of Acinetobacter baumannii in soils', *Applied Soil Ecology*, 147(October 2019), p. 103396.

Delgado, C. *et al.* (2010) 'Quality of groundwater for irrigation in tropical karst environment: The case of Yucatán, Mexico', *Agricultural Water Management*, 97(10), pp. 1423–1433.

Demnati, F. *et al.* (2012) 'Socio-economic stakes and perceptions of wetland management in an arid region: A case study from Chott Merouane, Algeria', *Ambio*, 41(5), pp. 504–512.

Deng, W. *et al.* (2020) 'Heavy metals, antibiotics and nutrients affect the bacterial community and resistance genes in chicken manure composting and fertilized soil', *Journal of Environmental Management*, 257(November 2019), p. 109980.

Deng, X. *et al.* (2021) 'The intensified effect of nitrogen removal properties using Pseudomonas fulva K3 and MgBC for the weathered crust rare earth wastewater treatment', *Physicochemical Problems of Mineral Processing*, 57(3), pp. 69–84.

Dennis W., W. and Robert S., A. (2019) 'Irrigation Water Quality Criteria', *Irrigation With Reclaimed Municipal Wastewater–A Guidance Manual*, (0), pp. 3-1-3–37.

Dery, J. L. *et al.* (2019) 'Understanding grower perceptions and attitudes on the use of nontraditional water sources, including reclaimed or recycled water, in the semi-arid Southwest United States', *Environmental Research*, 170(July 2018), pp. 500–509.

Destiani, R. (2019) *ANTIBIOTIC RESISTANT BACTERIA AND GENES IN DRINKING WATER*. Imperial College London.

Dhouib, A. *et al.* (2003) 'Degradation of anionic surfactants by Citrobacter braakii', *Process Biochemistry*, 38(8), pp. 1245–1250.

Dill, H. G. and Henjes-Kunst, F. (2007) 'Strontium (87Sr/86Sr) and calcium isotope ratios (44Ca/40Ca-44Ca/42Ca) of the Miocene Dam Formation in Qatar: Tools for stratigraphic correlation and environment analysis', *GeoArabia*, 12(3), pp. 61–76.

Dixit, A., Siddaiah, N. S. and Joshi, P. (2021) 'Hydrogeochemical assessment of wetlands of Gurugram, Haryana, India: implications for natural processes and anthropogenic changes', *Arabian Journal of Geosciences*, 14(3).

Döbler, I. *et al.* (2000) 'Removal of mercury from chemical wastewater by microoganisms in techical scale', *Environmental Science and Technology*, 34(21), pp. 4628–4634.

Doneen, L. D. (1964) *Notes on Water Quality in Agriculture*. Department of Water Science and Engineering, University of California.

Duggan, J. *et al.* (2014) 'Testing Karst Hazard Predictions in Qatar', *Qatar Center for Coastal Research*.

DuPoldt, C. *et al.* (1996) 'A Handbook of Constructed Wetlands: General Considerations', *Ecological Engineering*, 1(1996), p. 53. Available at: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.169.7471&rep=rep1&type=pdf%0Awww.unhabitat.org.

DWTP (2010) *Doha West wastewater treatment reuse plant, Suez water degremont water handbook*. Available at: www.suezwaterhandbook.com.

Edo, C. *et al.* (2020) 'Science of the Total Environment Microplastics in sediments of arti fi cially recharged lagoons : Case study in a Biosphere Reserve', *Science of the Total Environment*, 729, p. 138824.

Edwards, A. C. (2010) 'Soil Sampling and Sample Preparation', *Trace Elements in Soils*.

Egbueri, J. C. (2020) 'Groundwater for Sustainable Development Groundwater quality assessment using pollution index of groundwater (PIG), ecological risk index (ERI) and hierarchical cluster analysis (HCA): A case study', *Groundwater for Sustainable Development*, 10(July 2019), p. 100292.

Eid, E. M. *et al.* (2021) 'Prediction models based on soil properties for evaluating the uptake of eight heavy metals by tomato plant (Lycopersicon esculentum Mill.) grown in agricultural soils amended with sewage sludge', *Journal of Environmental Chemical Engineering*, 9(5).

Eldaw, E. *et al.* (2021) 'Classification of groundwater suitability for irrigation purposes using a comprehensive approach based on the AHP and GIS techniques in North Kurdufan Province, Sudan', *Applied Water Science*, 11(7), pp. 1–19.

Electronic Code of Federal Regulations (2000) *GENERAL PRETREATMENT REGULATIONS FOR EXISTING AND NEW SOURCES OF POLLUTION*. Available at: https://www.ecfr.gov/cgi-bin/text-idx?SID=31c53392d516830fabdd7fbb029098a9&mc=true&node=pt40.31.403&rgn=div5#se40.31.403_15 (Accessed: 28 February 2021).

Elhag, E. A. *et al.* (2002) 'Meiofaunal Life of Man-Made Wastewater Ponds in Qatar', *Qatar Universiy scientific Journal*, 22, pp. 153–169.

Elobaid, E. A. (2000) 'Aquifer Investigations in North Qatar'. Available at: http://hdl.handle.net/10547/606074.

Elobaid, E. A. *et al.* (2019) 'Environmental Evaluation Risk Assessment and Management options of Abu Nakhla Treated Sewage Effluent TSE Unlined Pond Doha Qatar', in *Qatar Foundation Annual Research Conference Proceedings 2018:* doi: 10.5339/qfarc.2018.eepd470.

Elumalai, V. *et al.* (2020) 'Journal of African Earth Sciences Groundwater quality assessment and application of multivariate statistical analysis in Luvuvhu catchment , Limpopo , South Africa', *Journal of African Earth Sciences*, 171(August), p. 103967.

Emadi, K. El, Kerim, G. A. and Emadi, H. El (2014) *Public Works Authority Apply Sustainable Developments Concept with Sewerage Works, Qatar*. Doha.

Ernst, W. H. O. (1995) 'Sampling of plant material for chemical analysis', 9697(95).

European Commission (2018a) *Commission Implementing Regulation (EU) 2018/1039 of 23 July 2018, Official Journal of the European Union*.

European Commission (2018b) *COMMISSION REGULATION (EU) 2019/1869 of 7 November 2019*

amending and correcting Annex I to Directive 2002/32/EC of the European Parliament and of the Council as regards maximum levels for certain undesirable substances in animal feed, Official Journal of the European Union.

Fahmy, G. H. and Fathi, A. A. (2011) 'Limnological Studies on the Wetland Lake , Al-Asfar , with Special References to Heavy Metal Accumulation by Fish Gehan H . Fahmy and Adel A . Fathi Department of Biological Sciences , College of Science , King Faisal University , Al-Hassa , Saudi Arabia', 7(6), pp. 515–524.

FAO/WHO food standards Program (2007) *Joint FAO/WHO food standard programme codex Alimentarius Commission 13th session*.

FAO (2008) *CounFAO (2008) Country profile – Qatar. Available at: http://www.fao.org/3/ca0349en/CA0349EN.pdf.try profile – Qatar*.

FAO *et al.* (2016) 'Exploring of Deep Groundwater in the Southwest Aquifer of Qatar Exploring of Deep Groundwater in the Southwest Aquifer of Qatar', *Modeling Earth Systems and Environment*, 2(2), pp. 1–7.

Fathi, A. (2014) 'Water Quality and Phytoplankton Communities in Lake Al-Asfar , Al-Hassa , Saudi Arabia', (October).

Faulwetter, J. L. *et al.* (2013) 'Influence of Season and Plant Species on the Abundance and Diversity of Sulfate Reducing Bacteria and Ammonia Oxidizing Bacteria in Constructed Wetland Microcosms', *Microbial Ecology*, 65(1), pp. 111–127.

Favaretto, N. *et al.* (2008) 'Gypsum amendment and exchangeable calcium and magnesium effects on plant nutrition under conditions of intensive nutrient extraction', *Soil Science*, 173(2), pp. 108–118.

Fedeila, M. *et al.* (2018) 'Biodegradation of anionic surfactants by Alcaligenes faecalis, Enterobacter cloacae and Serratia marcescens strains isolated from industrial wastewater', *Ecotoxicology and Environmental Safety*, 163(August), pp. 629–635.

Feng, T. *et al.* (2017) 'Effect of inter-basin water transfer on water quality in an urban lake: A combined water quality index algorithm and biophysical modelling approach', *Ecological Indicators*, (1), pp. 0–1.

Filzmoser, C. R. P. (1999) 'Normal and lognormal data distribution in geochemistry : death of a myth . Consequences for the statistical treatment of geochemical and environmental data'.

Flores-Treviño, S. *et al.* (2019) 'Screening of biomarkers of drug resistance or virulence in ESCAPE pathogens by MALDI-TOF mass spectrometry', *Scientific Reports*, 9(1), pp. 1–10.

Freikowski, D., Winter, J. and Gallert, C. (2010) 'Hydrogen formation by an arsenate-reducing Pseudomonas putida, isolated from arsenic-contaminated groundwater in West Bengal, India', *Applied Microbiology and Biotechnology*, 88(6), pp. 1363–1371.

Fridrich, B. *et al.* (2014) 'Impact of wastewater from pig farm lagoons on the quality of local groundwater', *Agricultural Water Management*, 135, pp. 40–53.

Fromm, N. and Fromm, N. (2019) 'Why study Qatar and how? An introduction to the topic of this book', *Constructivist Niche Diplomacy*, pp. 1–17.

Gallert, C., Fund, K. and Winter, J. (2005) 'Antibiotic resistance of bacteria in raw and biologically treated sewage and in groundwater below leaking sewers', *Applied Microbiology and Biotechnology*, 69(1), pp. 106–112.

Gao, Jingqing *et al.* (2020) 'Ammonium removal characteristics of heterotrophic nitrifying bacterium Pseudomonas stutzeri GEP-01 with potential for treatment of ammonium-rich wastewater', *Bioprocess and Biosystems Engineering*, 43(6), pp. 959–969.

Garcia-Cuerva, L., Berglund, E. Z. and Binder, A. R. (2016) 'Public perceptions of water shortages, conservation behaviors, and support for water reuse in the U.S.', *Resources, Conservation and Recycling*, 113, pp. 106–115.

García, J. *et al.* (2003) 'Role of hydraulic retention time and granular medium in microbial removal in tertiary

treatment reed beds', *Water Research*, 37(11), pp. 2645–2653.

Gardezi, M. and Arbuckle, J. G. (2020) 'Techno-Optimism and Farmers' Attitudes Toward Climate Change Adaptation', *Environment and Behavior*, 52(1), pp. 82–105.

Ghazaryan, K. *et al.* (2020) 'Comparative hydrochemical assessment of groundwater quality from different aquifers for irrigation purposes using IWQI: A case-study from Masis province in Armenia', *Groundwater for Sustainable Development*, 11(July), p. 100459.

Ghosh, S. *et al.* (2016) 'Molecular identification of indigenous manganese solubilising bacterial biodiversity from manganese mining deposits', *Journal of Basic Microbiology*, 56(3), pp. 254–262.

Gibello, A. *et al.* (2011) 'Pseudomonas composti sp. nov., isolated from compost samples', *International Journal of Systematic and Evolutionary Microbiology*, 61(12), pp. 2962–2966.

Giebel, R. A., Fredenberg, W. and Sandrin, T. R. (2008) 'Characterization of environmental isolates of Enterococcus spp. by matrix-assisted laser desorption/ionization time-of-flight mass spectrometry', *Water Research*, 42(4–5), pp. 931–940. doi: 10.1016/j.watres.2007.09.005.

Goodwin, D. *et al.* (2019) 'Collaboration on risk management: The governance of a non-potable water reuse scheme in London', *Journal of Hydrology*, 573, pp. 1087–1095.

Green, E. R., Juttukonda, L. J. and Skaar, E. P. (2020) 'The Manganese-Responsive Transcriptional Regulator MumR Protects Acinetobacter baumannii from Oxidative Stress', *American Society for Microbiology*, 88(3), pp. 1–19.

Grehs, B. W. N. *et al.* (2019) 'Removal of microorganisms and antibiotic resistance genes from treated urban wastewater: A comparison between aluminium sulphate and tannin coagulants', *Water Research*, 166.

Grisey, E. *et al.* (2010) 'Survival of pathogenic and indicator organisms in groundwater and landfill leachate through coupling bacterial enumeration with tracer tests', *Desalination*, 261(1–2), pp. 162–168.

GSDP (2008) 'Qatar National vision 2030', *General Secretariat For Development Planning*, (July). Available at: www.planning.gov.qa.

GSDP (2009) *Qatar National Vision 2030: Advancing Sustainable Development. Qatar's Second Human Development Report.* Doha.

GSDP (2011) *Qatar National Development Stratagy 2011-2016*. Available at: www.psa.gov.qa.

Guerrero, D. M. *et al.* (2010) 'Acinetobacter baumannii-associated skin and soft tissue infections: Recognizing a broadening spectrum of disease', *Surgical Infections*, 11(1), pp. 49–57.

Gupta, I. C. and Gupta, S. K. (2003) *Use of Saline Water in Agriculture, 3rd Revised Ed.* Scientific Pblishers (India).

Gutierrez, R. M. and Montalla, V. (2020) 'Environmental and Microbiological Assessment of Small-Scale Vegetable Farming Systems Irrigated With Wastewater from Upper Balili River, La Trinidad Benguet, Philippines', in *International Conference on Sustainable Development of Water and Environment*. Environmental Science and Engineering book series (ESE), pp. 1–15.

Hafner, S. C., Harter, T. and Parikh, S. J. (2016) 'Evaluation of Monensin Transport to Shallow Groundwater after Irrigation with Dairy Lagoon Water', *Journal of Environmental Quality*, 45(2), pp. 480–487.

Hagen, B. *et al.* (2017) 'Longitudinal analysis of ecosystem services' socioeconomic benefits: Wastewater treatment projects in a desert city', *Ecosystem Services*, 23(July 2016), pp. 209–217.

Hamilton, A. *et al.* (2007) 'Wastewater Irrigation: The State of Play', *Vadose Zone Journal*, 6(4), pp. 823–840.

Hansen, D. J. and Horne, A. J. (2022) 'The Effect of Drying / Re-Flooding on Trace Metal , As and Se Environmental Concerns', *Metals in Biology*, 11(188).

Hashem, M. S. and Qi, X. Bin (2021) 'Treated wastewater irrigation-a review', *Water (Switzerland)*, 13(11), pp. 1–37.

Hayashi, M., Van Der Kamp, G. and Rudolph, D. L. (1998) 'Water and solute transfer between a prairie wetland and adjacent uplands, 2. Chloride cycle', *Journal of Hydrology*, 207(1–2), pp. 56–67.

Healy, M. and Cawley, A. M. (2002) 'Nutrient Processing Capacity of a Constructed Wetland in Western Ireland', *Journal of Environmental Quality*, 31(5), pp. 1739–1747.

Helsel, D. R. and Hirsch, R. (1992) *Statistical Methods in Water Resources*. Environmental Science and Pollution Research.

Hennessy, M. J. (2009) 'Understanding the blockages: Stakeholder perceptions of greywater reuse in Metro Vancouver', *ProQuest Dissertations and Theses*, pp. 1–177. Available at: http://ezproxy.library.ubc.ca/login?url=http://search.proquest.com/docview/205404754?accountid=14656%5Cnhttp://gw2jh3xr2c.search.serialssolutions.com/?ctx_ver=Z39.88-2004&ctx_enc=info:ofi/enc:UTF-8&rfr_id=info:sid/ProQ&rft_val_fmt=info:ofi/fmt:kev:mtx:dis.

Herath, G. (2004) 'Incorporating community objectives in improved wetland management: The use of the analytic hierarchy process', *Journal of Environmental Management*, 70(3), pp. 263–273.

Herschy, R. W. (2012) 'Water quality for drinking: WHO guidelines', *Encyclopedia of Earth Sciences Series*, pp. 876–883.

Hickey, A. *et al.* (2018) 'An assessment of the performance of municipal constructed wetlands in Ireland', *Journal of Environmental Management*, 210, pp. 263–272.

Higgins, P. G. *et al.* (2018) 'Characterization of Acinetobacter baumannii from water and sludge line of secondary wastewater treatment plant', *Water Research*, 140, pp. 261–267.

Hirai, J. *et al.* (2016) 'Bacteremia due to Citrobacter braakii: A case report and literature review', *Journal of Infection and Chemotherapy*, 22(12), pp. 819–821.

Hofste, R. W., Reig, P. and Schleifer, L. (2019) *17 Countries, Home to One-Quarter of the World's Population, Face Extremely High Water Stress, world resources institute*. Available at: https://www.wri.org (Accessed: 20 January 2021).

Horst D. Schulz, M. Z. (2000) *Marine Geochemistry*. Springer Berlin Heidelberg.

Horvat, K. P. and Smrekar, A. (2021) 'The wetland contract as a tool for successful wetland governance: a case study of Ljubljansko Barje Nature Park, Slovenia', *Sustainability (Switzerland)*, 13(1), pp. 1–17.

Hounslow, A. (1995) *Water Quality Data: Analysis and Interpretation*. Taylor & Francis Group.

Howard, A. *et al.* (2012) 'Acinetobacter baumannii An emerging opportunistic pathogen', *Virulence*, 3(3), p. 5.

Hrenovic, J. *et al.* (2011) 'Selective immobilization of Acinetobacter junii on the natural zeolitized tuff in municipal wastewater', *Colloids and Surfaces B: Biointerfaces*, 88(1), pp. 208–214.

Hrenovic, J. *et al.* (2016) 'Carbapenem-resistant isolates of Acinetobacter baumannii in a municipal wastewater treatment plant, Croatia, 2014', *Eurosurveillance*, 21(15), pp. 1–10.

Hsu, C. H. *et al.* (2010) 'Redox characteristics and zonation of arsenic-affected multi-layers aquifers in the Choushui River alluvial fan, Taiwan', *Journal of Hydrology*, 391(3–4), pp. 351–366.

Hu, J. *et al.* (2017) 'Assessment of the distribution, bioavailability and ecological risks of heavy metals in the lake water and surface sediments of the Caohai plateau wetland, China', *PLoS ONE*, 12(12), pp. 1–15.

Hu, J. *et al.* (2020) 'Influence of different land use types on hydrochemistry and heavy metals in surface water in the lakeshore zone of the Caohai wetland, China', *Environmental Pollution*, 267, p. 115454.

Huang, L. *et al.* (2020) 'Heavy metals distribution, sources, and ecological risk assessment in Huixian Wetland, South China', *Water (Switzerland)*, 12(2), pp. 1–14.

Hunter, R. G. *et al.* (2009) 'Impacts of secondarily treated municipal effluent on a freshwater forested wetland after 60 years of discharge', *Wetlands*, 29(1), pp. 363–371..

Hussein, A., Mahmoudi, A. El and Naeem, A. Al (2016) 'Assessment of the Heavy Metals in Al Asfar Lake,

Al-Hassa, Saudi Arabia', *Water environment research : a research publication of the Water Environment Federation*, 88(2), pp. 118–130.

Hussein, H. and Lambert, L. A. (2020) 'A Rentier state under blockade: Qatar's water-energy-food predicament from energy abundance and food insecurity to a silent water crisis', *Water (Switzerland)*, 12(4).

IBM SPSS Statistics (2020) *Kaiser-Meyer-Olkin measure for identity correlation matrix*. Available at: https://www.ibm.com/support/pages/kaiser-meyer-olkin-measure-identity-correlation-matrix (Accessed: 15 November 2021).

Ibrahim, E. and Alshaoui, A. (2015) *Qatar Population and water*. Available at: www.ppc.gov.qa.

Imai, M. *et al.* (2020) 'Validation of MALDI-TOF MS devices in reanalysis of unidentified pathogenic bacteria detected in blood cultures', *Fukushima Journal of Medical Science*, 66(2), pp. 103–112.

Ismail, E., Abdelhalim, A. and Heleika, M. A. (2021) 'Hydrochemical characteristics and quality assessment of groundwater aquifers northwest of Assiut district, Egypt', *Journal of African Earth Sciences*, 181(April), p. 104260..

Jafari, M. R. and Bernardeau, F. G. (2019) 'Deep Injection Wells for Flood Prevention and Groundwater Management', 13(5), pp. 336–350.

Jahany, M. and Rezapour, S. (2020) 'Assessment of the quality indices of soils irrigated with treated wastewater in a calcareous semi-arid environment', *Ecological Indicators*, 109(May 2019), p. 105800.

Jasim, S. Y. *et al.* (2016) 'Reuse of Treated Sewage Effluent (TSE) in Qatar', *Journal of Water Process Engineering*, 11, pp. 174–182.

Jenkins, L. D. (2021) 'Power, politics, and culture of marine conservation technology in fisheries', *Conservation Biology*, (October), pp. 1–10.

Johnston, R. *et al.* (2013) 'WETwin: A structured approach to evaluating wetland management options in data-poor contexts', *Environmental Science and Policy*, 34, pp. 3–17.

Joo, H. S., Hirai, M. and Shoda, M. (2006) 'Piggery wastewater treatment using Alcaligenes faecalis strain No. 4 with heterotrophic nitrification and aerobic denitrification', *Water Research*, 40(16), pp. 3029–3036.

Joo, H. S., Hirai, M. and Shoda, M. (2007) 'Improvement in ammonium removal efficiency in wastewater treatment by mixed culture of Alcaligenes faecalis no. 4 and L1', *Journal of Bioscience and Bioengineering*, 103(1), pp. 66–73.

Joshi, P., Siva, N. and Dixit, A. (2021) 'Urban wetlands of Delhi, India: water quality and pollution status', *Chemistry and Ecology*, 37(2), pp. 104–131.

Jumat, M. R. *et al.* (2018) 'An increase of abundance and transcriptional activity for Acinetobacter junii post wastewater treatment', *Water (Switzerland)*, 10(4).

Kacimov, A. R. *et al.* (2016) 'Modeling of transient water table response to managed aquifer recharge: A lagoon in Muscat, Oman', *Environmental Earth Sciences*, 75(4), pp. 1–13.

KAHRAMMA (2009) *Regulations of Internal Water Installations and Connection Works*. Doha.

Kalra, N. *et al.* (2011) *Recomended Research Priorities for teh Watar Foundation's Environment and Energy Research Institute*.

Kang, H. (2013) 'A Guide on the Use of Factor Analysis in the Assessment of Construct Validity', 43(5), pp. 587–594.

Kaplan, D. *et al.* (2011) 'Hydrological importance and water quality treatment potential of a small freshwater wetland in the humid tropics of Costa Rica', *Wetlands*, 31(6), pp. 1117–1130.

Karaca, S. *et al.* (2021) 'An assessment of pasture soils quality based on multi-indicator weighting approaches in semi-arid ecosystem', *Ecological Indicators*, 121(August 2020).

Kardousha, M. M. (2016) 'First record of some aquatic fauna collected from Qatari Inland waters with reference to Inland waters with reference to Arabian Peninsula', *International Journal of Current Research*,

8(06), pp. 32963–32969.

Kaseva, M. E. (2004) ‘Performance of a sub-surface flow constructed wetland in polishing pre-treated wastewater - A tropical case study’, *Water Research*, 38(3), pp. 681–687.

Kaszab, E. *et al.* (2021) ‘Groundwater, soil and compost, as possible sources of virulent and antibiotic-resistant Pseudomonas aeruginosa’, *International Journal of Environmental Health Research*, 31(7), pp. 848–860.

Kausch, M. E. *et al.* (2020) ‘Bacterial quality of groundwater downgradient of onsite wastewater disposal systems and the influence on eastern Long Island’s embayments’, *Marine Pollution Bulletin*, 150(November 2019), p. 110598.

Keppel Seghers (2015) ‘Keppel Seghers Doha North Sewage Treatment Works Doha North Sewage Treatment Works at a glance First of its kind Model project for the international One-stop service provider of water’.

Keren, Y. *et al.* (2014) ‘Is Leclercia adecarboxylata a new and unfamiliar marine pathogen?’, *Journal of Clinical Microbiology*, 52(5), pp. 1775–1776.

Kerr, S. C. *et al.* (2008) ‘Hydrologic and biogeochemical controls on trace element export from northern Wisconsin wetlands’, *Biogeochemistry*, 89(3), pp. 273–294.

Khan, S. *et al.* (2008) ‘Accumulation of polycyclic aromatic hydrocarbons and heavy metals in lettuce grown in the soils contaminated with long-term wastewater irrigation’, *Journal of Hazardous Materials*, 152(2), pp. 506–515.

Khan, S. J. and Gerrard, L. E. (2006) ‘Stakeholder communications for successful water reuse operations’, *Desalination*, 187(1–3), pp. 191–202.

Khanna, A., Khanna, M. and Aggarwal, A. (2013) ‘Serratia marcescens- a rare opportunistic nosocomial pathogen and measures to limit its spread in hospitalized patients’, *Journal of Clinical and Diagnostic Research*, 7(2), pp. 243–246.

Khanpae, M. *et al.* (2020) ‘Farmers’ attitude towards using treated wastewater for irrigation: The question of sustainability’, *Journal of Cleaner Production*, 243, p. 118541.

Kivaisi, A. K. (2001) ‘The potential for constructed wetlands for wastewater treatment and reuse in developing countries: A review’, *Ecological Engineering*, 16(4), pp. 545–560.

Knight, R. L. *et al.* (2003) ‘Strategies for effective mosquito control in constructed treatment wetlands’, 21, pp. 211–232.

Korbel, K. L., Greenfield, P. and Hose, G. C. (2022) ‘Agricultural practices linked to shifts in groundwater microbial structure and denitrifying bacteria’, *Science of the Total Environment*, 807..

Ku, Y. H. and Yu, W. L. (2017) ‘Extensive community-acquired pneumonia with hemophagocytic syndrome caused by Aeromonas veronii in an immunocompetent patient’, *Journal of Microbiology, Immunology and Infection*, 50(4), pp. 555–556.

Kuiper, N., Rowell, C. and Shomar, B. (2015) ‘High levels of molybdenum in Qatar’s groundwater and potential impacts’, *Journal of Geochemical Exploration*, 150, pp. 16–24.

Kumar, A. (2004) *Water Pollution*. A.P.H.Pulishing Corporation.

Kumar, M., Snow, D. D. and Honda, R. (2020) *Emerging Issues in the Water Environment during Anthropocene*. Springer International Publishing.

Kumar Trivedi, M. and Branton, A. (2015) ‘Phenotyping and 16S rDNA Analysis after Biofield Treatment on Citrobacter braakii: A Urinary Pathogen’, *Journal of Clinical & Medical Genomics*, 3(1), pp. 0–8.

Kumar, V., Singh, J. and Kumar, P. (2019) ‘Heavy metal uptake by water lettuce (Pistia stratiotes l.) from paper mill effluent (pme): Experimental and prediction modeling studies’, *Environmental Science and Pollution Research*, 26(14), pp. 14400–14413.

Kumar, V., Thakur, R. and Kumar, P. (2019) ‘Assessment of heavy metals uptake by cauliflower (Brassica oleracea var. botrytis) grown in integrated industrial effluent irrigated soils: A prediction modeling study’, *Scientia Horticulturae*, 257(January), p. 108682.

Kurniawan, S. B., Purwanti, I. F. and Titah, H. S. (2018) ‘The effect of pH and aluminium to bacteria isolated from aluminium recycling industry’, *Journal of Ecological Engineering*, 19(3), pp. 154–161.

Lachaal, F. and Gana, S. (2016) ‘Groundwater flow modeling for impact assessment of port dredging works on coastal hydrogeology in the area of Al-Wakrah (Qatar)’, *Modeling Earth Systems and Environment*, 2(4), pp. 1–15..

Lalucat, J. *et al.* (2006) ‘ Biology of Pseudomonas stutzeri ’, *Microbiology and Molecular Biology Reviews*, 70(2), pp. 510–547.

Landajo, A. *et al.* (2004) ‘Analysis of heavy metal distribution in superficial estuarine sediments (estuary of Bilbao, Basque Country) by open-focused microwave-assisted extraction and ICP-OES’, *Chemosphere*, 56(11), pp. 1033–1041.

Lemée, C. *et al.* (2018) ‘Personal Involvement in Greywater Reuse: A Study within a French Context’, *International Journal of Environmental & Science Education*, 13(5), pp. 457–465. Available at: http://www.ijese.com.

Leung, H. M. *et al.* (2017) ‘Monitoring and assessment of heavy metal contamination in a constructed wetland in Shaoguan (Guangdong Province, China): bioaccumulation of Pb, Zn, Cu and Cd in aquatic and terrestrial components’, *Environmental Science and Pollution Research*, 24(10), pp. 9079–9088.

Li, S. *et al.* (2020) ‘Evolution of heavy metals during thermal treatment of manure: A critical review and outlooks’, *Chemosphere*, 247, p. 125962.

Li, Y. *et al.* (2021) ‘Full evaluation of assimilatory and dissimilatory nitrate reduction in a new denitrifying bacterium Leclercia adecarboxylata strain AS3-1: Characterization and functional gene analysis’, *Environmental Technology and Innovation*, 23, p. 101731.

Liu, J. *et al.* (2021) ‘Enhanced degradation of different crude oils by defined engineered consortia of Acinetobacter venetianus RAG-1 mutants based on their alkane metabolism’, *Bioresource Technology*, 327(January).

Liu, Y. *et al.* (2014) ‘Identification and control of a Pseudomonas spp (P. fulva and P. putida) bloodstream infection outbreak in a teaching hospital in Beijing, China’, *International Journal of Infectious Diseases*, 23, pp. 105–108.

Di Luca, G. A. *et al.* (2011) ‘Metal retention and distribution in the sediment of a constructed wetland for industrial wastewater treatment’, *Ecological Engineering*, 37(9), pp. 1267–1275.

Lutowski, R. (2005) ‘Quality Requirements’, *Software Requirements*. doi: 10.1201/9781420031317.ch5.

Lyons, K. J. *et al.* (2021) ‘Surface Water Intrusion, Land Use Impacts, and Bacterial Community Composition in Shallow Groundwater Wells Supplying Potable Water in Sparsely Populated Areas of a Boreal Region’, *Microbiology Spectrum*, 9(3).

Mahmoudi, A. S. El, Massoud, M. A. and Hussein, A. H. A. (2011) ‘Studies of Al Asfar and Al Uyoun Evaporation Lakes Water Quality and the Potential of Its Reuse in Agriculture Activities , Al Hassa Area , KSA 22 , 000 farms . Nowadays this amount of water is increased due to the’, 22(3), pp. 67–85.

Malik, A. and Aleem, A. (2011) ‘Incidence of metal and antibiotic resistance in Pseudomonas spp. from the river water, agricultural soil irrigated with wastewater and groundwater’, *Environmental Monitoring and Assessment*, 178(1–4), pp. 293–308.

Al Mamoon, A. (2020) ‘Flood Risk Assessment and Protection Guidelines for Infrastructure Planning in Qatar’, (Cic), pp. 621–627.

Mamoon, A. Al and Rahman, A. (2017) ‘Rainfall in Qatar: Is it changing?’, *Natural Hazards*, 85(1), pp. 453–470.

Al Mamoon, A., Sylianteng, C. and Rahman, Ataur, Regan Benjamin, A. A. A. A. (2015) 'Flood Study in Qatar – Challenges and Opportunities Flood Study in Qatar – Challenges and Opportunities Abdullah Al Mamoon Benjamin Regan Carlos Sylianteng Ataur Rahman Abeer Ahmad Abd Alkader', (January 2016).

Manuel, P. M. (2003) 'Cultural perceptions of small urban wetlands: Cases from the Halifax Regional Municipality, Nova Scotia, Canada', *Wetlands*, 23(4), pp. 921–940.

Marsalek, J. *et al.* (2008) *Urban Water Cycle Processes and Interactions: Urban Water Series - UNESCO-IHP*. Taylor & Francis Group.

Martin, M. S. *et al.* (2018) 'Characterization of bacterial diversity in contaminated groundwater using matrix-assisted laser desorption/ionization time-of-flight mass spectrometry', *Science of the Total Environment*, 622–623, pp. 1562–1571.

Marvasti, F. (2001) *Nonuniform Sampling: Theory and Practice*. New York: Kluwer Acadmic/Plenum Publishers.

Massoud, M. A., Terkawi, M. and Nakkash, R. (2019) 'Water reuse as an incentive to promote sustainable agriculture in Lebanon: Stakeholders' perspectives', *Integrated Environmental Assessment and Management*, 15(3), pp. 412–421.

Maulan, S. (2006) *A Perceptual Study of Wetlands Implications for Wetland Restoration in the Urban Area in Malaysia (questions), ETDs: Virginia Tech Electronic Theses and Dissertations*. Virginia Polytechnic Institute and State University. Available at: https://vtechworks.lib.vt.edu/handle/10919/26966.

Mbanga, J. *et al.* (2021) 'Genomic analysis of antibiotic-resistant Enterobacter spp. from wastewater sources in South Africa: The first report of the mobilisable colistin resistance mcr-10 gene in Africa', *Ecological Genetics and Genomics*, 21(March), p. 100104.

McKeon, D. M., Calabrese, J. P. and Bissonnette, G. K. (1995) 'Antibiotic resistant gram-negative bacteria in rural groundwater supplies', *Water Research*, 29(8), pp. 1902–1908.

McLain, J. E. and Williams, C. F. (2014) 'Sustainability of water reclamation: Long-term recharge with reclaimed wastewater does not enhance antibiotic resistance in sediment bacteria', *Sustainability (Switzerland)*, 6(3), pp. 1313–1327.

MDPS (2017) *WATER STATISTICS In the state of Qatar 2015*, *Ministry of Development Planning and Statistics*. Available at: www.mdps.gov.qa.

MDPS (2019) *Qatar Second National Development Stratagy 2018-2022*. Available at: www.psa.gov.qa.

Medjani, F. *et al.* (2021) 'Groundwater physico-chemical properties and water quality changes in shallow aquifers in arid saline wetlands, Ouargla, Algeria', *Applied Water Science*, 11(5), pp. 1–9.

Mehmood, A. *et al.* (2019) 'Spatial distribution of heavy metals in crops in a wastewater irrigated zone and health risk assessment', *Environmental Research*, 168(June 2018), pp. 382–388.

Meireles, A. C. M. *et al.* (2010) 'A new proposal of the classification of irrigation water', *Revista Ciência Agronômica*, 41(3), pp. 349–357.

Mello, K. De *et al.* (2018) 'Impacts of tropical forest cover on water quality in agricultural watersheds in southeastern Brazil', in *Ecological Indicators*. Elsevier, pp. 1293–1301.

Mendes, L. R. D. *et al.* (2018) 'Phosphorus retention in surface-flow constructed wetlands targeting agricultural drainage water', *Ecological Engineering*, 120(May), pp. 94–103.

Meng, W. *et al.* (2016) 'Heavy metals in soil and plants after long-term sewage irrigation at Tianjin China: A case study assessment', *Agricultural Water Management*, 171, pp. 153–161.

Mesaieed Industrial City (2011) *MIC Environmental Guidelines and Protection Standards*. Doha.

Metcalfe, N. N. D. (2018) *MultiFunctional wetlands (Pollution Abatement abd Other Ecological SErvices from Natural and Constructed Wetlands)*. Edited by N. Nagabhatla. Springer International Publishing.

Michetti, M. *et al.* (2019) 'Interpreting farmers' perceptions of risks and benefits concerning waste water

reuse for irrigation: A case study in Emilia-Romagna (Italy)', *Water (Switzerland)*, 11(1).

Mng'ong'o, M. *et al.* (2021) 'Accumulation and bioconcentration of heavy metals in two phases from agricultural soil to plants in Usangu agroecosystem-Tanzania', *Heliyon*, 7(7), p. e07514.

Mohamad, I. *et al.* (2019) 'Application of MALDI Biotyper System for Rapid Identification of Bacteria Isolated from a Fresh Produce Market', *Current Microbiology*, 76(3), pp. 290–296.

Mohieldeen, Y. E. and Al-Marri, A. (2019) 'Using GIS to Quantify Change in the Groundwater Levels in Qatar Between 1980 & 2009', (December).

Mojid, M. A. *et al.* (2010) 'Farmers' perceptions and knowledge in using wastewater for irrigation at twelve peri-urban areas and two sugar mill areas in Bangladesh', *Agricultural Water Management*, 98(1), pp. 79–86.

Møller, K. A. *et al.* (2012) 'Economic, environmental and socio-cultural sustainability of three constructed wetlands in Thailand', *Environment and Urbanization*, 24(1), pp. 305–323.

Moloney, E. M. *et al.* (2020) 'Whole-genome sequencing identifies highly related Pseudomonas aeruginosa strains in multiple washbasin U-bends at several locations in one hospital: evidence for trafficking of potential pathogens via wastewater pipes', *Journal of Hospital Infection*, 104(4), pp. 484–491.

Morris, B. (2009) 'Pathogens and groundwater', *Unknown*, pp. 1–14. Available at: file:///R:/LITERATURE/Angela/Pathogens_and_groundwater_final version.pdf.

Motta, A. C. V. *et al.* (2020) 'Elemental composition of yerba mate (Ilex paraguariensis A.St.-Hil.) under low input systems of southern Brazil', *Science of the Total Environment*, 736.

Mouser, P. J. *et al.* (2010) 'Enhanced detection of groundwater contamination from a leaking waste disposal site by microbial community profiles', *Water Resources Research*, 46(12), pp. 1–12.

Mu'azu, N. D., Abubakar, I. R. and Blaisi, N. I. (2020) 'Public acceptability of treated wastewater reuse in Saudi Arabia: Implications for water management policy', *Science of the Total Environment*, 721.

Muniz, D. H. F. *et al.* (2020) 'Proposal of an irrigation water quality index (IWQI) for regional use in the Federal District, Brazil', *Environmental Monitoring and Assessment*, 192(9).

Muqeem, S. (2016) 'Development of an Environmental Health Risk and Socio- Economic Perception Framework to Critically Assess the Management of TWW Reuse Practice and Options in Kuwait', (January).

Mustafa, G. *et al.* (2021) 'Biodegradation and discoloration of disperse blue-284 textile dye by Klebsiella pneumoniae GM-04 bacterial isolate', *Journal of King Saud University - Science*, 33(4), p. 101442.

Nada, husaain A. (2019) 'مستنقع أبو نخلة بؤرة تلوث', *Al Raya Newspaper*, 29 June.

Naidoo, S. and Olaniran, A. O. (2013) 'Treated wastewater effluent as a source of microbial pollution of surface water resources', *International Journal of Environmental Research and Public Health*, 11(1), pp. 249–270.

Najem, T., Langley, S. and Fortin, D. (2016) 'A comparison of Fe(III) reduction rates between fresh and aged biogenic iron oxides (BIOS) by Shewanella putrefaciens CN32', *Chemical Geology*, 439, pp. 1–12.

Nandy, S. *et al.* (2021) 'Monitoring the growth, survival and phenol utilization of the fluorescent-tagged Pseudomonas oleovorans immobilized and free cells', *Bioresource Technology*, 338(May).

Narikkatan, A. and Reddy, A. G. S. (2021) 'Hierarchical Cluster Analysis as an Indicative of the Hydrogeochemical Evolution of Ground Water in a Shallow Aquifer System', 26(5).

Nathan, N. S., Saravanane, R. and Sundararajan, T. (2017) 'Spatial Variability of Ground Water Quality Using HCA , PCA and MANOVA at Lawspet , Puducherry in India', pp. 243–268.

Nivala, J. *et al.* (2018) 'The new German standard on constructed wetland systems for treatment of domestic and municipal wastewater', pp. 2414–2426.

O, A. A. *et al.* (2006) 'Relationships between Microbial Community Structure and Hydrochemistry in a Landfill Leachate-Polluted Aquifer Relationships between Microbial Community Structure and Hydrochemistry in a Landfill Leachate-Polluted Aquifer', *Waste management (New York, N.Y.)*, 5(1), pp.

435–56.

Ofori, S. *et al.* (2021) ‘Treated wastewater reuse for irrigation: Pros and cons’, *Science of the Total Environment*, 760.

Ogunfowokan, A. O., Obisanya, J. F. and Ogunkoya, O. O. (2013) ‘Salinity and sodium hazards of three streams of different agricultural land use systems in Ile-Ife, Nigeria’, *Applied Water Science*, 3(1), pp. 19–28.

Ogunlaja, A. *et al.* (2019) ‘Risk assessment and source identification of heavy metal contamination by multivariate and hazard index analyses of a pipeline vandalised area in Lagos State, Nigeria’, *Science of the Total Environment*, 651, pp. 2943–2952.

Ohtsubo, W. *et al.* (2013) ‘Bioaugmentation of a wastewater bioreactor system with the nitrous oxide-reducing denitrifier Pseudomonas stutzeri strain TR2’, *Journal of Bioscience and Bioengineering*, 115(1), pp. 37–42.

Okoh, A. I. *et al.* (2007) ‘Wastewater treatment plants as a source of microbial pathogens in receiving watersheds’, *African Journal of Biotechnology*, 6(25), pp. 2932–2944.

Olsen, R. L., Chappell, R. W. and Loftis, J. C. (2012) ‘Water quality sample collection, data treatment and results presentation for principal components analysis - literature review and Illinois River watershed case study’, *Water Research*, 46(9), pp. 3110–3122.

Opio, M. (2008) ‘an Institutional Analysis of the Management of Wetland Resources: a Comparative Study of Floahreppur Municipality in South Iceland and Oyam District in Uganda’, *Land Restoration Training Programme*, pp. 117–148.

OriginLab Corporation (2021) *https://www.originlab.com/*. Available at: https://www.originlab.com/index.aspx?go=Products/Origin (Accessed: 1 November 2021).

Otsuka, O. and Yamashita, M. (2020) ‘Selenium recovery from wastewater using the selenate-reducing bacterium Pseudomonas stutzeri NT-I’, *Hydrometallurgy*, 197(April), p. 105470.

Ozyurek, S. and Avcioglu, N. H. (2021) ‘Comparison of the petroleum removal efficiencies and plasmid profiles of clinical and environmental Klebsiella pneumoniae strains’, *International Journal of Environmental Science and Technology*, (0123456789).

Paczosa, M. K. and Mecsas, J. (2016) ‘Klebsiella pneumoniae: Going on the Offense with a Strong Defense’, *Microbiology and Molecular Biology Reviews*, 80(3), pp. 629–661.

Padhi, S. K. *et al.* (2013) ‘Characterisation of heterotrophic nitrifying and aerobic denitrifying Klebsiella pneumoniae CF-S9 strain for bioremediation of wastewater’, *International Biodeterioration and Biodegradation*, 78, pp. 67–73.

Palanivel, P. *et al.* (2021) ‘Assessment and evaluation of geochemical process in the groundwater of the coastal aquifers’, *Acta Ecologica Sinica*, (February).

Palta, M. M., Grimm, N. B. and Groffman, P. M. (2017) ‘“Accidental” urban wetlands: ecosystem functions in unexpected places’, *Frontiers in Ecology and the Environment*, 15(5), pp. 248–256.

Parde, D. *et al.* (2021) ‘A review of constructed wetland on type, treatment and technology of wastewater’, *Environmental Technology and Innovation*, 21, p. 101261.

Peacock, T. (1992) *The Preparation of Plant Material and Determination of Weight Percent Ash*.

Peprah, M., Acheampong, M. A. and DeVries, N. K. (2018) ‘Greywater Characteristics, Treatment Systems, Reuse Strategies and User Perception—a Review’, *Water, Air, and Soil Pollution*, 229(8).

Permanent Population Committee (2018) *Qatar Population statues report, Planning and statistics Authority*. Available at: www.psa.gov.qa.

Petit, S. M. C. *et al.* (2013) ‘Lagooning of wastewaters favors dissemination of clinically relevant Pseudomonas aeruginosa’, *Research in Microbiology*, 164(8), pp. 856–866.

Picó, Y. *et al.* (2020) ‘Science of the Total Environment Pharmaceuticals , pesticides , personal care products

and microplastics contamination assessment of Al-Hassa irrigation network (Saudi Arabia) and its shallow lakes', 701.

Pierce, L. and Shi, H. (2016) 'Evaluation of Veterinary Pharmaceuticals and Iodine for Use as a Groundwater Tracer in Hydrologic Investigation of Contamination Related to Dairy Cattle Operations', pp. 313–318.

Pires, J. F. *et al.* (2017) 'Diversity of microbiota found in coffee processing wastewater treatment plant', *World Journal of Microbiology and Biotechnology*, 33(12), pp. 1–12.

Poggenburg, C. *et al.* (2016) 'Microbial reduction of ferrihydrite-organic matter coprecipitates by Shewanella putrefaciens and Geobacter metallireducens in comparison to mediated electrochemical reduction', *Chemical Geology*, 447, pp. 133–147.

Popovic, N. *et al.* (2015) 'Detection and diversity of aeromonads from treated wastewater and fish inhabiting effluent and downstream waters', *Ecotoxicology and Environmental Safety*, 120, pp. 235–242.

Population & Housing Census (2020) *Main Results of the General Census of Population and Housing 2020 Report, Department of Statistics- Qatar*.

Princela, M. A. *et al.* (2021) 'Regional assessment of groundwater quality for drinking purpose', *Materials Today: Proceedings*, 45, pp. 2916–2920.

PSA (2018) *Water statistics in the State of Qatar 2017*. Available at: https://www.psa.gov.qa/en/statistics/Statistical Releases/Environmental/Water/2017/Water-Statistics-2017-EN.pdf.

PSA (2019) *Qatar water statistics Infographic 2019*. Available at: www.psa.gov.qa.

Purwanti, I. F., Kurniawan, S. B. and Imron, M. F. (2019) 'Potential of Pseudomonas aeruginosa isolated from aluminium-contaminated site in aluminium removal and recovery from wastewater', *Environmental Technology and Innovation*, 15, p. 100422.

QGDP (2016) *Qatar National Development Strategy 2011~2016*. Doha.

Queiroz, P. S. *et al.* (2018) 'Rich growth medium promotes an increased on Mn(II) removal and manganese oxide production by Serratia marcescens strains isolates from wastewater', *Biochemical Engineering Journal*, 140(September), pp. 148–156.

Quiñónez-Díaz, M. D. J. *et al.* (2001) 'Removal of pathogenic and indicator microorganisms by a constructed wetland receiving untreated domestic wastewater', *Journal of Environmental Science and Health - Part A Toxic/Hazardous Substances and Environmental Engineering*, 36(7), pp. 1311–1320.

Ramakrishnaiah, C. R., Sadashivaiah, C. and Ranganna, G. (2009) 'Assessment of Water Quality Index for the Groundwater in Tumkur Taluk, Karnataka State, India C.', 6(2), pp. 523–530.

Rana, V. and Maiti, S. K. (2018) 'Municipal wastewater treatment potential and metal accumulation strategies of Colocasia esculenta (L.) Schott and Typha latifolia L. in a constructed wetland', *Environmental Monitoring and Assessment*, 190(6).

Rasiq, K. T. *et al.* (2018) 'Polycyclic Aromatic Hydrocarbons (PAHs) in Surface Sediments of Two Polluted Lagoons in Saudi Arabia', 27(1), pp. 275–285.

Rattan, R. K. *et al.* (2005) 'Long-term impact of irrigation with sewage effluents on heavy metal content in soils, crops and groundwater - A case study', *Agriculture, Ecosystems and Environment*, 109(3–4), pp. 310–322.

Ravikumar, P. and Somashekar, R. K. (2017) 'Principal component analysis and hydrochemical facies characterization to evaluate groundwater quality in Varahi river basin, Karnataka state, India', *Applied Water Science*, 7(2), pp. 745–755.

Ravikumar, P., Somashekar, R. K. and Angami, M. (2011) 'Hydrochemistry and evaluation of groundwater suitability for irrigation and drinking purposes in the Markandeya River basin, Belgaum District, Karnataka State, India', *Environmental Monitoring and Assessment*, 173(1–4), pp. 459–487.

Rayner, J. *et al.* (2006) 'Correlation effects', in *Nonparametrics for Sensory Science: A More Informative*

Approach. First edit. Blackwell Publishing, pp. 101–125.

Regli, A. and Pagès, J. M. (2015) 'Enterobacter aerogenes and Enterobacter cloacae; Versatile bacterial pathogens confronting antibiotic treatment', *Frontiers in Microbiology*, 6(MAY), pp. 1–10.

Rezaei, A. *et al.* (2021) 'Assessing the hydrogeochemical processes through classical integration of groundwater parameters in the Birjand plain in eastern Iran', *Groundwater for Sustainable Development*, 15(September), p. 100684.

Rezapour, S. *et al.* (2021) 'Influence of treated wastewater irrigation on soil nutritional-chemical attributes using soil quality index', *Sustainability (Switzerland)*, 13(4), pp. 1–21.

Ricart, S. and Rico-Amorós, A. M. (2021) 'Constructed wetlands to face water scarcity and water pollution risks: Learning from farmers' perception in alicante, spain', *Water (Switzerland)*, 13(17).

Ridl, J. *et al.* (2018) 'Complete genome sequence of Pseudomonas alcaliphila JAB1 (=DSM 26533), a versatile degrader of organic pollutants', *Standards in Genomic Sciences*, 13(1), pp. 1–10.

Rivas, D. *et al.* (2017) 'Using MALDI-TOF MS imaging and LC-HRMS for the investigation of the degradation of polycaprolactone diol exposed to different wastewater treatments'.

Rivers, J. M. *et al.* (2019) 'The depositional history of near-surface Qatar aquifer rocks and its impact on matrix flow and storage properties', *Arabian Journal of Geosciences*, 12(12).

Rodríguez, E. A. *et al.* (2020) 'Multidrug resistance and diversity of resistance profiles in carbapenem-resistant Gram-negative bacilli throughout a wastewater treatment plant in Colombia', *Journal of Global Antimicrobial Resistance*, 22, pp. 358–366.

Romanelli, A., Massone, H. E. and Escalante, A. H. (2011) 'Stakeholder analysis and social-biophysical interdependencies for common pool resource management: La Brava Wetland (Argentina) as a case study', *Environmental Management*, 48(3), pp. 462–474.

Ruiz, A. M. *et al.* (2010) 'Patterns of development and abnormalities among tadpoles in a constructed wetland receiving treated wastewater', *Environmental Science and Technology*, 44(13), pp. 4862–4868.

Rusan, M. J., Hinnawi, S. and Rousan, L. (2007) 'Long term effect of wastewater irrigation of forage crops on soil and plant quality parameters', *Desalination*, 215(1–3), pp. 143–152. doi: 10.1016/j.desal.2006.10.032.

Russi, D. *et al.* (2012) *The Economics of Ecosystems and Biodiversity for Water and Wetlands: A final Consultation Draft., IEEP, London and Brussels; Ramsar Secretaria*.

Sadiq, A. M. and Nasir, S. J. (2002) 'Middle Pleistocene karst evolution in the state of Qatar, Arabian Gulf', *Journal of Cave and Karst Studies*, 64(2), pp. 132–139.

Sahu, P. and Sikdar, P. K. (2008) 'Hydrochemical framework of the aquifer in and around East Kolkata Wetlands, West Bengal, India', *Environmental Geology*, 55(4), pp. 823–835.

Sala-Comorera, L. *et al.* (2016) 'Use of matrix-assisted laser desorption/ionization–time of flight (MALDI–TOF) mass spectrometry for bacterial monitoring in routine analysis at a drinking water treatment plant', *International Journal of Hygiene and Environmental Health*, 219(7), pp. 577–584.

Saleh, A., Al-Ruwaih, F. and Shehata, M. (1999) 'Hydrogeochemical processes operating within the main aquifers of Kuwait', *Journal of Arid Environments*, 42(3), pp. 195–209.

Saliba, R. *et al.* (2018) 'Stakeholders' attitude towards the reuse of treated wastewater for irrigation in Mediterranean agriculture', *Agricultural Water Management*, 204(March), pp. 60–68.

Sanders, E. C., Yuan, Y. and Pitchford, A. (2013) 'Fecal coliform and E. coli concentrations in effluent-dominated streams of the upper santa cruz watershed', *Water (Switzerland)*, 5(1), pp. 243–261.

Santos, I. C. *et al.* (2018) 'Exploring the links between groundwater quality and bacterial communities near oil and gas extraction activities', *Science of the Total Environment*, 618, pp. 165–173.

Santos, I. C., Hildenbrand, Z. L. and Schug, K. A. (2016) 'Applications of MALDI-TOF MS in environmental microbiology', *Analyst*, 141(10), pp. 2827–2837.

Sarti, O. and Otal, E. (2021) ‘Groundwater for Sustainable Development Integrated assessment of groundwater quality beneath the rural area of R ’ mel , Northwest of Morocco’, 14(January).

Schlumberger water Services (2009) *Studying & developing the Natural & Artifcial Recharge pf the Groundwater Aquifer in the State of Qatar*.

Schmidt, H. C. R. *et al.* (2007) *Geochemical effects of induced streamwater and artificial recharge on the Equus Beds aquifer, southcentral Kansas*. Edited by U. S. G. S. S. I. Report. DIANE Publishing.

Scholz, M. (2016) ‘Constructed Wetlands’, in Miklas Scholz (ed.) *Wetlands for Water Pollution Control*. Elsevier, pp. 137–155.

Schuettpelz, D. H. (1969) ‘Fecal and total coliform tests in water quality evaluation’, *Department of Natural Resources*, (42), pp. 1–36. Available at: https://dnr.wi.gov/files/PDF/pubs/ss/SS0442.pdf.

Segura, D. *et al.* (2018) ‘Comparison of public perception in desert and rainy regions of chile regarding the reuse of treated sewage water’, *Water (Switzerland)*, 10(3).

Şener, Ş., Varol, S. and Şener, E. (2021) ‘Evaluation of sustainable groundwater utilization using index methods (WQI and IWQI), multivariate analysis, and GIS: the case of Akşehir District (Konya/Turkey)’, *Environmental Science and Pollution Research*, 28(35), pp. 47991–48010.

Setianto, A. and Triandini, T. (2013) ‘COMPARISON OF KRIGING AND INVERSE DISTANCE WEIGHTED (IDW) INTERPOLATION METHODS IN LINEAMENT EXTRACTION AND’, *Journal of Applied Geology*, 5(1), pp. 21–29.

Shamrukh, M. (2014a) ‘Exploring of Deep Groundwater in the Southwest Aquifer of Qatar Exploring of Deep Groundwater in the Southwest Aquifer of Qatar’, (April 2012).

Shamrukh, M. (2014b) ‘Exploring of Deep Groundwater in the Southwest Aquifer of Qatar Exploring of Deep Groundwater in the Southwest Aquifer of Qatar’, (April 2012).

Al shareq (2014) ‘2014 وقف مصب الكرعانة ومستنقع أبو نخلة نهاية’, *Al Shareq Newspaper*, 13 May. Available at: https://al-sharq.com/article/13/05/2014/2014-وقف-مصب-الكرعانة-ومستنقع-أبو-نخلة-نهاية.

Sharma, A. K. *et al.* (2016) ‘Water sensitive urban design: An investigation of current systems, implementation drivers, community perceptions and potential to supplement urban water services’, *Water (Switzerland)*, 8(7).

Sharma, P. *et al.* (2021) ‘Integrating phytoremediation into treatment of pulp and paper industry wastewater: Field observations of native plants for the detoxification of metals and their potential as part of a multidisciplinary strategy’, *Journal of Environmental Chemical Engineering*, 9(4), p. 105547.

Sharma, S. and Sujatha, D. (2016) ‘Characterization of the water chemistry, sediment 13C and 18O compositions of Kolleru Lake—a Ramsar wetland in Andhra Pradesh, India’, *Environmental Monitoring and Assessment*, 188(7).

Shewhart, W. and Wilks, S. (2001) *Generalized Linear Mixed Models (GLMMs).pdf*. John Wiley & Sons, Inc.

Shidi, M. *et al.* (2018) ‘The Impact of Back Produced Polymer on Surface Flow Constructed Wetland Water Treatment System in the Sultanate of Oman ’.

Shirkhorshidi, A. S., Aghabozorgi, S. and Wah, T. Y. (2015) ‘A Comparison Study on Similarity and Dissimilarity Measures in Clustering Continuous Data’, pp. 1–20.

Shomar, B. *et al.* (2013) ‘Natural and depleted uranium in the topsoil of Qatar: Is it something to worry about?’, *Applied Geochemistry*, 37, pp. 203–211.

Shomar, B. (2015) ‘Geochemistry of soil and groundwater in arid regions: Qatar as a case study’, *Groundwater for Sustainable Development*, 1(1–2), pp. 33–40.

Shomar, B., Darwish, M. and Rowell, C. (2014) ‘What does Integrated Water Resources Management from Local to Global Perspective Mean? Qatar as a Case Study, the Very Rich Country with No Water’, *Water Resources Management*, 28(10), pp. 2781–2791.

Shrivastava, A. and Gupta, V. (2011) 'Methods for the determination of limit of detection and limit of quantitation of the analytical methods', *Chronicles of Young Scientists*, 2(1), p. 21.

Siegrist, T. J. *et al.* (2007) 'Discrimination and characterization of environmental strains of Escherichia coli by matrix-assisted laser desorption/ionization time-of-flight mass spectrometry (MALDI-TOF-MS)', *Journal of Microbiological Methods*, 68(3), pp. 554–562.

Singh, K. (2021) 'Quantitative Social Research Methods', in *Multivariate Analysis*. SAGE Publications India Pvt Ltd, pp. 177–227.

Sirkin, R. M. (2011) *The Chi-Square Test In: Statistics for the Social Sciences*. Available at: http://dx.doi.org/10.4135/9781412985987.

Slekovec, C. *et al.* (2012) 'Tracking Down Antibiotic-Resistant Pseudomonas aeruginosa Isolates in a Wastewater Network', *PLoS ONE*, 7(12).

Sloey, T. M. *et al.* (2021) 'Critical Research Gaps for Understanding Environmental Impacts of Discharging Treated Municipal Wastewater into Assimilation Wetlands', *Wetlands*, 41(1), pp. 1–14.

Smedley, P. L. and Mike Edmunds, W. (2002) 'Redox patterns and trace-element behavior in the East Midlands Triassic Sandstone Aquifer, U.K.', *Ground Water*, pp. 44–58.

Smith, J. P. *et al.* (2008) 'Iodine-131: A potential short-lived, wastewater-specific particle tracer in an urbanized estuarine system', *Environmental Science and Technology*, 42(15), pp. 5435–5440.

Smith, S., Brazner, J. and Sherren, K. (2016) 'Farmer perceptions of wetlands and waterbodies: Using social metrics as an alternative to ecosystem service valuation', *Ecological Economics*, 126, pp. 58–69.

Solaiman, S. and Micallef, S. A. (2021) 'Aeromonas spp. diversity in U.S. mid-Atlantic surface and reclaimed water, seasonal dynamics, virulence gene patterns and attachment to lettuce', *Science of the Total Environment*, 779, p. 146472.

Sorensen, J. P. R. *et al.* (2015) 'Tracing enteric pathogen contamination in sub-Saharan African groundwater', *Science of the Total Environment*, 538, pp. 888–895.

Starkl, M. *et al.* (2015) 'Stakeholder views, financing and policy implications for reuse of wastewater for irrigation: A case from Hyderabad, India', *Water (Switzerland)*, 7(1), pp. 300–328.

Stefanakis, A. I. (2019) 'The Role of ConstructedWetlands as Green Infrastructure for Sustainable Urban Water Management', *Sustainability (Switzerland)*, 11(24).

Stefanakis, A. I. (2020) 'Constructed wetlands for sustainable wastewater treatment in hot and arid climates: Opportunities, challenges and case studies in the Middle East', *Water (Switzerland)*, 12(6).

Stefanakis, A. I., Al-hadrami, A. and Prigent, S. (2017) 'Treatment of produced water from oilfield in a large Constructed Wetland : 6 years of operation under desert conditions', (September), pp. 6–8.

Steyaert, P. *et al.* (2007) 'The role of knowledge and research in facilitating social learning among stakeholders in natural resources management in the French Atlantic coastal wetlands', *Environmental Science and Policy*, 10(6), pp. 537–550.

Streetly, M. J. and Kotoub, S. (1998) 'Determination of aquifer properties in northern Qatar for application to artificial recharge', *Quarterly Journal of Engineering Geology*, 31(3 Part 3), pp. 199–209.

Suchy, A. K. *et al.* (2020) 'High Potential Nitrate Removal by Urban Accidental Wetlands in a Desert City: Limitations and Spatiotemporal Patterns', *Ecosystems*, 23(6), pp. 1227–1242.

SUEZ (2021) *Doha West wastewater treatment plant (Qatar), degremont® water handbook*. Available at: www.suezwaterhandbook.com (Accessed: 20 January 2021).

Suliman, H. (2016) *من ينقذنا من حصار مستنقعات المياه؟*, *Al Arab Newspaper*. Available at: https://alarab.qa/article/26/07/2015/613838-من-ينقذنا-من-حصار-مستنقعات-المياه (Accessed: 20 February 2022).

Suzuki, Y. *et al.* (2018) 'Bacterial flora analysis of coliforms in sewage, river water, and ground water using MALDI-TOF mass spectrometry', *Journal of Environmental Science and Health - Part A Toxic/Hazardous*

Substances and Environmental Engineering, 53(2), pp. 160–173.

Sweileh, J. A. *et al.* (2002) 'Trace Metals in Wastewater Ponds in Qatar', *Qatar University Science Journal*, pp. 97–105.

Talat, R. A., Al-Assaf, A. Y. R. and Al-Saffawi, A. Y. T. (2019) 'Valuation of water quality for drinking and domestic purposes using WQI : Acase study for groundwater of Al-Gameaa and Al-Zeraee qaurters in Mosul city/Iraq', *Journal of Physics: Conference Series*, 1294(7).

Tan, M. *et al.* (2020) 'Study on heavy metal contamination in high water table coal mining subsidence ponds that use different resource reutilization methods', *Water (Switzerland)*, 12(12).

Tang, K. *et al.* (2021) 'MALDI-TOF MS platform combined with machine learning to establish a model for rapid identification of methicillin-resistant Staphylococcus aureus', *Journal of Microbiological Methods*, 180, p. 106109.

Tanty, H., Bekti, R. D. and Herlina, T. (2014) 'MANOVA Statistical Analysis of Inorganic Compounds in Groundwater Indonesia', 8(4), pp. 41–45.

Tay, C. K. (2021) 'Hydrogeochemical framework of groundwater within the Asutifi-North District of the Brong-Ahafo Region, Ghana', Applied Water Science, 11(4), pp. 1–16.

Tefera, A. K. *et al.* (2021a) 'Groundwater quality evaluation of the alluvial aquifers using GIS and water quality indices in the Upper Blue Nile Basin, Ethiopia', *Groundwater for Sustainable Development*, 14(June), p. 100636.

Tefera, A. K. *et al.* (2021b) 'Groundwater quality evaluation of the alluvial aquifers using GIS and water quality indices in the Upper Blue Nile Basin, Ethiopia', *Groundwater for Sustainable Development*, 14(June), p. 100636.

Tesfaye, H. *et al.* (2019) 'Antimicrobial susceptibility profile of selected Enterobacteriaceae in wastewater samples from health facilities, abattoir, downstream rivers and a WWTP in Addis Ababa, Ethiopia', *Antimicrobial Resistance and Infection Control*, 8(1), pp. 1–11.

Thapa, R., Gupta, S. and Kaur, H. (2020) 'Introducing an irrigation water quality index (IWQI) based on the case study of the Dwarka River basin, Birbhum, West Bengal, India', *Sustainable Water Resources Management*, 6(5), pp. 1–10.

Tohid, H. *et al.* (2017) 'Perceptions and attitudes to clinical research participation in Qatar', *Contemporary Clinical Trials Communications*, 8(October), pp. 241–247.

Tollenaere, J. De (2015) 'Modelling the influence of the Abu Nakhla pond on the phreatic aquifer in Qatar : present and future scenarios'.

Trobia, A. (2011) 'Cronbach s alpha', in Lavrakas, P. J. (ed.) *Encyclopedia of Survey Research Methods*. Thousand Oaks: Sage Publications, Inc, pp. 169–170. Available at: http://scholar.dkyobobook.co.kr/searchDetail.laf?barcode=4010027636216.

Tsui, C. K. M., Sundararaju, S. and Mana, A. (2020) 'crossm Draft Genome Sequence of an Extended-Spectrum', (April), pp. 18–20.

Turki, A. J. (2007) 'Metal Speciation (Cd , Cu , Pb and Zn) in Sediments from Al Shabab Lagoon , Jeddah , Saudi Arabia', *Journal of King Abdulaziz University*, 18, pp. 191–210.

U.S. EPA (2017) 'United States - Environmental Protection Agency. Water quality standards handbook: Chapter 3: Water quality criteria. EPA-823-B-17-001.', *EPA Office of Water, Office of Science and Technology, Washington, DC.*, pp. 1–26. Available at: https://www.epa.gov/sites/production/files/2014-10/documents/handbook-chapter3.pdf.

Uddin, M. G., Nash, S. and Olbert, A. I. (2021) 'A review of water quality index models and their use for assessing surface water quality', *Ecological Indicators*, 122, p. 107218.

UN-Water (2021) 'Summary Progress Update 2021 : SDG 6 — water and sanitation for all', p. 58. Available at: https://www.unwater.org/new-data-on-global-progress-towards-ensuring-water-and-sanitation-for-all-by-

2030/.

USEPA (2000a) ‘Manual Constructed Wetlands Treatment of Municipal Wastewaters’, *Office of Research and Development Cincinnati, Ohio*, 625(September).

USEPA (2000b) ‘Wastewater Technology Fact Sheet Wetlands: Subsurface Flow’, *Environmental Protection Agency*, pp. 1–7.

Uusheimo, S. *et al.* (2018) ‘High Nitrogen Removal in a Constructed Wetland Receiving Treated Wastewater in a Cold Climate’, *Environmental Science and Technology*, 52(22), pp. 13343–13350.

Varol, S., Şener, Ş. and Şener, E. (2021) ‘Assessment of groundwater quality and human health risk related to arsenic using index methods and GIS: A case of Şuhut Plain (Afyonkarahisar/Turkey)’, *Environmental Research*, 202(June), pp. 1–11.

Vázquez, M. A. *et al.* (2013) ‘Vertical flow constructed wetland treating high strength wastewater from swine slurry composting’, *Ecological Engineering*, 50, pp. 37–43.

Vecchioli, J. (1976) *Preliminary Evaluation of the Feasibility of Artificial Recharge in Northern Qatar*.

Vega, E., Lesikar, B. and Pillai, S. D. (2003) ‘Transport and survival of bacterial and viral tracers through submerged-flow constructed wetland and sand-filter system’, *Bioresource Technology*, 89(1), pp. 49–56.

Velden, L. ., de Jong, A., de Jong, H., de Gier, R. ., *et al.* (2012) ‘First report of a Wautersiella falsenii isolated from the urine of an infant with pyelonephritis’, *Diagnostic Microbiology and Infectious Disease*, 74(4), pp. 404–405.

Velden, L. ., de Jong, A., de Jong, H., de Gier, R., *et al.* (2012) ‘First report of a Wautersiella falsenii isolated from the urine of an infant with pyelonephritis’, *Diagnostic Microbiology and Infectious Disease*, 74(4), pp. 404–405.

Verhoeven, J. T. A. and Meuleman, A. F. M. (1999) ‘Wetlands for wastewater treatment : Opportunities and limitations’, 12, pp. 5–12.

Verlicchi, P. and Zambello, E. (2014) ‘How efficient are constructed wetlands in removing pharmaceuticals from untreated and treated urban wastewaters? A review’, *Science of the Total Environment*, 470–471, pp. 1281–1306.

Viggor, S. *et al.* (2020) ‘Microbial metabolic potential of phenol degradation in wastewater treatment plant of crude oil refinery: Analysis of metagenomes and characterization of isolates’, *Microorganisms*, 8(5).

Vignier, N. *et al.* (2013) ‘Human Infection with Shewanella putrefaciens and S. algae: Report of 16 Cases in Martinique and Review of the Literature’, *American Journal of Tropical Medicine and Hygiene*, 89(1), pp. 151–156.

Vijayakumar, S., Biswas, I. and Veeraraghavan, B. (2019) ‘Accurate identification of clinically important Acinetobacter spp.: An update’, *Future Science OA*, 5(7).

Vymazal, J. *et al.* (2009) ‘Trace elements in Phragmites australis growing in constructed wetlands for treatment of municipal wastewater’, *Ecological Engineering*, 35(2), pp. 303–309.

Wahab, A. A. *et al.* (2004) ‘Microbiological identification in cystic fibrosis patients with CFTR I1234V mutation’, *Journal of Tropical Pediatrics*, 50(4), pp. 229–233.

Walter, J. *et al.* (2017) ‘The influence of water/rock − water/clay interactions and mixing in the salinization processes of groundwater’, *Journal of Hydrology: Regional Studies*, 13(September), pp. 168–188.

Wang, J. *et al.* (2021) ‘A constructed wetland system with aquatic macrophytes for cleaning contaminated runoff/storm water from urban area in Florida’, *Journal of Environmental Management*, 280(November 2020), p. 111794.

Wastewater, A., Wastewater, D. and Drainage, C. M. (2000) ‘A handbook of constructed wetlands’, *Wetlands*, 1, p. 53.

Water, F. and Wetlands, S. (2000) ‘Wastewater Technology Fact Sheet Free Water Surface Wetlands’.

Wattage, P. and Mardle, S. (2005) ‘Stakeholder preferences towards conservation versus development for a wetland in Sri Lanka’, *Journal of Environmental Management*, 77(2), pp. 122–132.

Weaver, K. F. *et al.* (2018) ‘Pearson’s and Spearman’s Correlation’, in *An Introduction to Statistical Analysis in Research: With Applications in the Biological and Life Sciences*. First Edit. John Wiley & Sons, Inc., pp. 435–471.

Weiss, D. *et al.* (2002) ‘The geochemistry of major and selected trace elements in a forested peat bog, Kalimantan, SE Asia, and its implications for past atmospheric dust deposition’, *Geochimica et Cosmochimica Acta*, 66(13), pp. 2307–2323.

Weller, M. O. and Bossart, J. L. (2017) ‘Insect Community Diversity Tracks Degradation and Recovery of a Wastewater Assimilation Marsh in Southeast Louisiana’, *Wetlands*, 37(4), pp. 661–673.

WHO (2006) ‘Safe use of wastewater , excreta and greywater guidelines. Volume 2: wastewater use in agriculture’, *World Health*, II, p. 204. Available at: http://whqlibdoc.who.int/publications/2006/9241546832_eng.pdf.

Wilcox, L. V. (1955) ‘Classification and Use of Irrigation Waters. Department of Agriculture, United States’, 969(Circular No. 696), pp. 1–21. Available at: https://www.ars.usda.gov/arsuserfiles/20360500/pdf_pubs/P0192.pdf.

Wills, M. and Irvine, K. N. (1996) ‘Application of the National Sanitation Foundation Water Quality Index in the cazenovia Creek, MY, Pilot Watershed Management Project’, *Middle States Geographer*, pp. 95–104.

Winn, W. C. (2006) *Koneman’s Color Atlas and Textbook of Diagnostic Microbiology*. illustrate. Edited by E. W. Koneman. Lippincott Williams & Wilkins.

Wu, H. *et al.* (2020) ‘The efficiency and risk to groundwater of constructed wetland system for domestic sewage treatment - A case study in Xiantao, China’, *Journal of Cleaner Production*, 277, p. 123384.

Wuana, R. A. and Okieimen, F. E. (2011) ‘Heavy Metals in Contaminated Soils: A Review of Sources, Chemistry, Risks and Best Available Strategies for Remediation’, *ISRN Ecology*, 2011, pp. 1–20.

Wunsch, D. C. and Engineers, E. (2009) ‘Hierarchical clustering’, in *Clustering*. Institute of Electrical and Electronics Engineers, pp. 31–62.

Xia, C. *et al.* (2021) ‘Influence of saline intrusion on the wetland ecosystem revealed by isotopic and hydrochemical indicators in the Yellow River Delta, China’, *Ecological Indicators*, 133, p. 108422.

Xie, F., Thiri, M. and Wang, H. (2021) ‘Simultaneous heterotrophic nitrification and aerobic denitrification by a novel isolated Pseudomonas mendocina X49’, *Bioresource Technology*, 319(September 2020), p. 124198.

Xiong, W. *et al.* (2020) ‘Characterization of an efficient estrogen-degrading bacterium Stenotrophomonas maltophilia SJTH1 in saline-, alkaline-, heavy metal-contained environments or solid soil and identification of four 17β-estradiol-oxidizing dehydrogenases’, *Journal of Hazardous Materials*, 385(October 2019), p. 121616.

Xu, X. *et al.* (2020) ‘Comparative Study on Soil Microbial Diversity and Structure Under Wastewater and Groundwater Irrigation Conditions’, *Current Microbiology*, 77(12), pp. 3909–3918.

Xu, X. and Mills, G. L. (2018) ‘Do constructed wetlands remove metals or increase metal bioavailability?’, *Journal of Environmental Management*, 218, pp. 245–255.

Yadav, A. K. *et al.* (2018) ‘Constructed Wetland-Microbial Fuel Cell: An Emerging Integrated Technology for Potential Industrial Wastewater Treatment and Bio-Electricity Generation’, in Alexandros, S. (ed.) *Constructed Wetlands for Industrial Wastewater Treatment*. John Wiley & Sons, Ltd, pp. 493–510.

Yang, F. *et al.* (2016) ‘Propagation of New Delhi Metallo-β-lactamase Genes (blaNDM-1) from a Wastewater Treatment Plant to Its Receiving River’, *Environmental Science and Technology Letters*, 3(4), pp. 138–143.

Yang, F. *et al.* (2021) ‘Effects of biochar on biodegradation of sulfamethoxazole and chloramphenicol by Pseudomonas stutzeri and Shewanella putrefaciens: Microbial growth, fatty acids, and the expression quantity of genes’, *Journal of Hazardous Materials*, 406(September 2020), p. 124311.

Yang, J. *et al.* (2018) 'Characterization of a pyrethroid-degrading Pseudomonas fulva strain P31 and biochemical degradation pathway of D-phenothrin', *Frontiers in Microbiology*, 9(MAY), pp. 1–12.

Yang, L. *et al.* (2015) 'Nitrogen removal characteristics of a heterotrophic nitrifier Acinetobacter junii YB and its potential application for the treatment of high-strength nitrogenous wastewater', *Bioresource Technology*, 193, pp. 227–233.

Yang, L. *et al.* (2021) 'Nitrogen removal and aggregation characteristics of Pseudomonas aeruginosa YL and its application capacity for ammonium-rich wastewater treatment', *Journal of Water Process Engineering*, 43(July), p. 102260.

Yao, L. *et al.* (2021) 'Spatial-temporal analysis and background value determination of molybdenum concentration in basins with high molybdenum geochemical background - A case study of the upper Yi River basin', *Journal of Environmental Management*, 286(February).

Yin, X. *et al.* (2016) 'Effect of photosynthetically elevated pH on performance of surface flow-constructed wetland planted with Phragmites australis', *Environmental Science and Pollution Research*, 23(15), pp. 15524–15531.

Al Yousef, A. H., Abdalla, O. A. E. S. and Akbar, M. A. (2000) 'Progress Report for the National Report of the State of Qatar on the UNCCD implementation', (February), p. 15. Available at: http://www.unccd-prais.com/Uploads/GetReportPdf/fe77766c-d768-4c52-b419-a0fa014a4a8e.

Zaidi, F. K. *et al.* (2015) 'Reverse ion exchange as a major process controlling the groundwater chemistry in an arid environment: a case study from northwestern Saudi Arabia', *Environmental Monitoring and Assessment*, 187(10).

Zakaria, Z. A. *et al.* (2007) 'Hexavalent chromium reduction by Acinetobacter haemolyticus isolated from heavy-metal contaminated wastewater', *Journal of Hazardous Materials*, 146(1–2), pp. 30–38.

Zaman, M., Shahid, S. A. and Heng, L. (2018) *Guideline for Salinity Assessment, Mitigation and Adaptation Using Nuclear and Related Techniques*, *Guideline for Salinity Assessment, Mitigation and Adaptation Using Nuclear and Related Techniques*.

Zaouri, N. *et al.* (2020) 'Metagenomics-based evaluation of groundwater microbial profiles in response to treated wastewater discharge', *Environmental Research*, 180(October 2019), p. 108835.

Zhang, D. *et al.* (2014) 'Application of constructed wetlands for wastewater treatment in developing countries - A review of recent developments (2000-2013)', *Journal of Environmental Management*, 141, pp. 116–131.

Zhang, H. *et al.* (2010) 'Heavy metals in water, soils and plants in riparian wetlands in the Pearl River Estuary, South China', *Procedia Environmental Sciences*, 2(5), pp. 1344–1354.

Zhang, Q. *et al.* (2008) 'Major ion geochemistry of Nam Co lake and its sources, Tibetan Plateau', *Aquatic Geochemistry*, 14(4), pp. 321–336.

Zhang, Q. *et al.* (2021) 'Groundwater quality assessment using a new integrated-weight water quality index (IWQI) and driver analysis in the Jiaokou Irrigation District, China', *Ecotoxicology and Environmental Safety*, 212, p. 111992.

Zhang, W. *et al.* (2014) 'Effects of cathode potentials and nitrate concentrations on dissimilatory nitrate reductions by Pseudomonas alcaliphila in bioelectrochemical systems', *Journal of Environmental Sciences (China)*, 26(4), pp. 885–891.

Zhang, W. *et al.* (2019) 'Characterization of aerobic denitrifying bacterium pseudomonas mendocina strain GL6 and its potential application in wastewater treatment plant effluent', *International Journal of Environmental Research and Public Health*, 16(3).

Zhang, W. *et al.* (2021) 'Efficient nitrate removal by Pseudomonas mendocina GL6 immobilized on biochar', *Bioresource Technology*, 320(PA), p. 124324.

Zhang, Y. *et al.* (2009) 'Wastewater treatment contributes to selective increase of antibiotic resistance among Acinetobacter spp.', *Science of the Total Environment*, 407(12), pp. 3702–3706.

Zhao, B. *et al.* (2018) ‘Assessing the performance of a sequencing batch biofilm reactor bioaugmented with P. stutzeri strain XL-2 treating ammonium-rich wastewater’, *Bioresource Technology*, 270(September), pp. 70–79.

Zhu, B. *et al.* (2017) ‘High-quality genome sequence of human pathogen Enterobacter asburiae type strain 1497-78T’, *Journal of Global Antimicrobial Resistance*, 8, pp. 104–105.

Zhu, S. and Chen, H. (2014) ‘The fate and risk of selected pharmaceutical and personal care products in wastewater treatment plants and a pilot-scale multistage constructed wetland system’, *Environmental Science and Pollution Research*, 21(2), pp. 1466–1479.

Zhu, Z., Li, A. and Wang, H. (2018) ‘Public perception and acceptability of reclaimed water: The case of shandong province, china’, *Journal of Water Reuse and Desalination*, 8(3), pp. 308–330.

Zou, Y. *et al.* (2018) ‘Water use conflict between wetland and agriculture’, *Journal of Environmental Management*, 224(March), pp. 140–146.