Modification of the Canadian Water Quality Index : Case Study Assessment of Groundwater Quality in Mekong Delta, Vietnam

Dao Thi Bich, Van

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MODIFICATION OF THE CANADIAN WATER QUALITY INDEX – CASE STUDY ASSESSMENT OF GROUNDWATER QUALITY IN MEKONG DELTA, VIETNAM

Dissertation

Zur Erlangung des akademischen Grades Doktor-Ingenieur (Dr.-Ing.)

Dissertation von Van Dao Thi Bich, M.Sc, aus Vietnam

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1. Gutachter: Prof. Dipl. –Ing. Dr. nat.techn. Wilhelm Urban

2. Gutachter: Prof. Dr. habil. Subhendu Bikash Hazra

TECHNISCHE UNIVERSITÄT DARMSTADT

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Erklärung zur Dissertation

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MODIFICATION OF THE CANADIAN WATER QUALITY INDEX – CASE STUDY ASSESSMENT OF GROUNDWATER QUALITY IN MEKONG DELTA, VIETNAM

(Van Dao Thi Bich) Ort, Datum

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Kurzfassung

Das Wasserressourcenmanagement ist derzeit mit einer erheblichen Kluft zwischen den Interessen und Zielsetzungen von Politikern und Entscheidungsträgern verschiedenster Sektoren konfrontiert. Die Forschung hat gezeigt, dass Wasserqualitätsindizes zu nützlichen Instrumenten für die Bewertung und das Management der Wasserqualität von natürlichen Wasserressourcen geworden sind. Diese Studie zielt darauf ab, den Zustand der Grundwasserqualität des vietnamesischen Mekong-Deltas durch einen geeigneten Wasserqualitätsindex im Vergleich mit der europäischen Wasserrahmenrichtlinie und der nationalen vietnamesischen Regelung zu bewerten.

Aufbauend auf den bestehenden Arbeiten und Veröffentlichungen, muss der erforderliche Wasserqualitätsindex grundsätzlich für verschiedenene Auswahlen von Qualitätsparametern anwendbar sein (z.B. Vietnamesische Grundwasser Regulierung und Europäische Trinkwasserverordnung) und empfindlich gegenüber einzelnen besonders schlechten Qualitätsparametern sein. Basierend auf einer zusammenfassenden Literaturrecherche über Wassermanagement und Theorien zu Wasserqualitätsindizes wird der kanadische Wasserqualitätsindex (CCME WQI) als Argumentationsbasis gewählt, da er die erste der oben genannten Eigenschaften aufweist. Die Analyse der impliziten statistischen Daten, insbesondere die Einbeziehung der Anzahl von Qualitätsparametern mit mindestens einem fehlerhaften Test (Scope) sowie der Anzahl fehlerfafter Tests (Frequency) bei der Definition des CCME WQI zeigte, dass der CCME WQI auch ein Index für die Qualität der Kontrollmechanismen der Wasserqualität ist. Denn eine hohe Anzahl fehlerhafter Tests oder eine hohe Anzahl von Qualitätsparametern mit fehlerhaften Tests ist ein Zeichen dafür, dass Kontrollmechanismen nicht ausreichen. Dennoch gibt es Situationen, in denen die Wasserqualität als gut bewertet werden muss, während CCME WQI sie aufgrund einer Überbewertung statistischer Faktoren als schlecht qualifiziert. Daher wird in dieser Arbeit eine Modifikation des CCME WQI, genannt Modifizierter Kanadischer Wasserqualitätsindex (MCWQI), entwickelt und anhand der Fallstudie „Grundwasserqualität im Mekong Delta“ überprüft und die Ergebnisse anhand europäischer und vietnamesicher Regelungen verglichen. Die modifizierte Methodik beruht grundsätzlich auf dem CCME WQI, liefert aber in Situationen, in denen die statistischen Faktoren ein verzerrtes Bild der Situation liefern, realistischere Einschätzungen.

MCWQI wird als neues Instrument eingeführt, das nicht nur den Wasserakteuren und politischen Entscheidungsträgern, sondern auch den Gemeinden helfen kann und soll, die knappen Ressourcen effizienter und nachhaltiger zu bewirtschaften.

Schlüsselwörter: *Wasserqualitätsindex, Kanadischer Wasserqualitätsindex, CCME, Modifizierter Kanadischer Wasserqualitätsindex, MCWQI, Grundwasserqualität des Mekong-Deltas*

Abstract

In water resources management, there exists a significant disconnect between interests and goal stettings of stakeholders, policy-makers, and decision-makers. Researches have shown that water quality indices have become useful tools for water quality assessment and management. This study aims to determine the groundwater quality status of the Vietnamese Mekong Delta with a suitable water quality index regarding the European Water Framework Directive and the Vietnamese National Regulation.

Building on existing works, the needed Water Quality Index must have the following fundamental properties: independence of the particular set of quality parameters and sensitivity to individual failed parameters. Based on a review of the literature on water management and theories of water quality indices, the Canadian Water Quality Index (CCME WQI) is chosen as the basis of argumentation, because it has the first of the above properties. Analysis of the implicit statistical data, especially the inclusion of the number of quality parameters with one failed test (Scope) as well as the number of failed tests (Frequency) in the definition of CCME WQI, demonstrated that CCME WQI is also a quality index for the quality of water control: a high number of failed tests or a high number of quality parameters with failed tests indicate that water control is not sufficient. Nevertheless, there are situations where water must be regarded as good, while CCME WQI qualifies it as bad by its statistical factors. Therefore, this research presents a modification of CCME WQI, called Modified Canadian Water Quality Index (MCWQI), which widely has the same behavior as CCME WQI but is better in situations where the statistical factors furnish the wrong picture of the situation. The useability of MCWQI is verified by an application to the case study “Groundwater Quality in Mekong Delta”. The results concerning the Vietnamese groundwater regulation and the European drinking water regulation are compared.

MCWQI is defined as a new tool to help not only water stakeholders and policy-makers but also communities to target scant resources more effectively and sustainably.

Keywords: *Water quality index, Canadian Water Quality Index, Modified Canadian Water Quality Index, Groundwater Quality in Mekong Delta*

Graphical Abstract

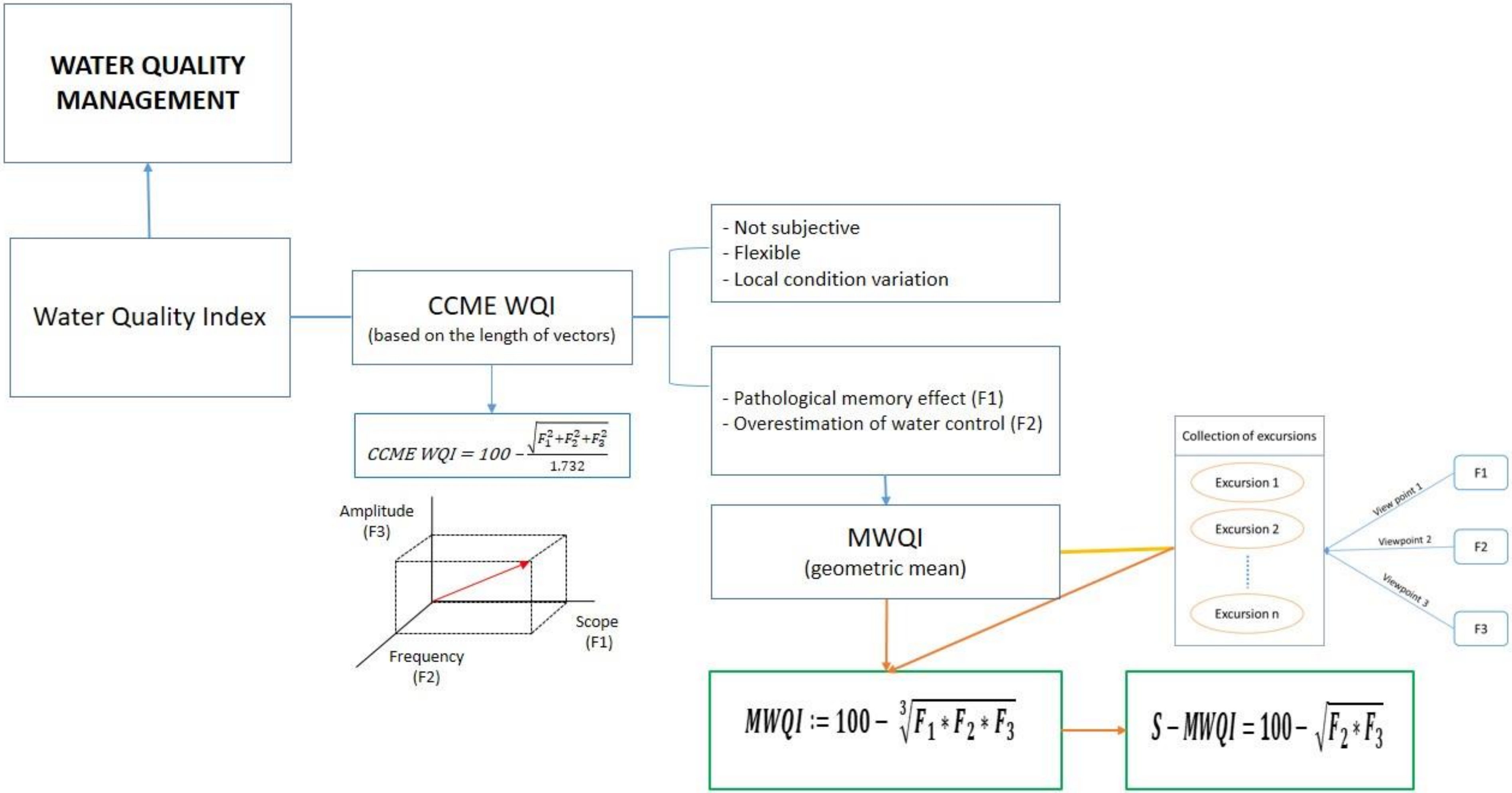

Figure 0.1: Graphical abstract

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List of Abbreviations

Al	Total Aluminum
As	Total Arsenic
BOD	Biochemical Oxygen Demand
CCME	Canadian Council of Ministers of the Environment
CCME WQI	Canadian Water Quality Index
Cd	Cadmium
Cl^-	Chloride
CN	Cyanide
COD	Chemical Oxygen Demand
Coli	Coliforms
Cr^{6+}	Chromium
Cu	Copper
DO	Dissolved Oxygen
DGMS	Division for Geological Mapping for the South of Vietnam
DS	Dissolved Solids
DWRPI	Division of Water Resources Planning and Investigation
E.coli	Escherilia Coli
EU	European Union
F^-	Fluoride
Fe	Total Iron
GIS	Geographic Information System
Hg	Mercury
Mn	Manganese
MONRE	Minister of Natural Resources and Environment
MCWQI	Modified Canadian Water Quality Index
N	Nitrogen

Na^+	Sodium
Ni	Nickel
NO_3^-	Nitrate
NO_2^-	Nitrite
Pb	Lead
S-CCME WQI	Canadian Water Quality Index for Single Parameter
Se	Selenium
S-MCWQI	Modified Canadian Water Quality Index for Single Parameter
SO_4^{2-}	Sulfate
T.Coli	Total Coliforms
TDS	Total Dissolved Solids
TH	Total Hardness
TSS	Total Suspended Solids
UNEP	United Nations Environmental Programme
WFD	Water Framework Directive
WHO	World Health Organization
VNR	Vietnam National Regulation
WQI	Water Quality Index
Zn	Zinc
CFU/100ml	Colony-forming units per 100 mililiter
g/l	Gram per liter
m	Meter
m^3	Cubic meter
mg/l	Milligrams per liter
m^3/day	Cubic meter per day
Mm^3/day	Million cubic meter per day
μS/cm	microsiemens per centimeter

Contents

1. Introduction

1.1. Motivation

Water is increasingly becoming a basic need of life and is regarded as an essential element for all human and living creatures on Earth. European Water Charter (Europe, 1968) argued that there is no life without water; the treasure is indispensable to all human activities. Water is considered a precious resource, which is essential not only to human health, food productivity, energy, transportation, and recreation but also to poverty eradication and other aspects of sustainable development. Naturally, with about 71% of the Earth (Earthhow, 2019), water is quantitively an abundant natural resource. Water is distributed in oceans, glaciers, groundwater, lakes, soil moisture, streams, wetlands, and swamps. Water possesses diverse forms and is found in a multitude of locations. However, while the amount of water that exists seems to be plentiful, the availability of the water suitable for human consumption is limited (NGWA, 2019). Water scarcity is recognized in two senses: increasing demands and deteriorating quality.

According to the World Water Council (Cosgrove et al., 2000), during the 20th century, the world population tripled while water for human consumption purposes multiplied sixfold. As reported, safe and affordable drinking water has been provided to 80% of the since 2015 more slowly growing world population (Rudnicka, 2020) and sanitation facilities to 50% (Cosgrove et al., 2000). The population growth has been slowed down by rising living standards, better education, and the improvement of social and economic conditions. However, the growth of population and urbanization, socioeconomic development, unsustainable water consumption practices, and climate change have placed immense stress on the quality and the number of water resources (Bhatti and Latif, 2011). Over the last century, water use globally has increased more than double the population growth rate. A part of the world population, one in six people (approximately 1.1 billion people), does not have access to safe water, and nearly 40% of the world population does not have access to improved sanitation (WHO and UNICEF, 2000). About two billion people are projected to live in countries that experience high water stress, while nearly four billion are experiencing severe water scarcity at least twice a year. Most rivers, especially in Africa, Asia, and Latin America, are increasingly polluted from domestic and industrial waste disposal, return flows from agriculture, which commonly uses chemical fertilizers and pesticides, in comparison to the 1990s. Water quality is also deteriorating as a result of sediments from human-induced erosion, increased salinity of groundwater bodies as a result of saltwater intrusion, oil-spillages from river traffic, etc. It raises the need to increase the use of non-conventional water resources (e.g., treated wastewater reuse, desalinated water, etc.) to reduce water resources pressure. Besides that, water resources should be carefully managed to ensure sustainability and equitable sharing among users.

Traditional approaches to assess water quality are based on experimentally comparing determined parameter values with existing guidelines. However, it does not readily give an overall view of the spatial and temporal trends in the water quality in a watershed (Debels et al., 2005). The classification, modeling, and interpretation of monitoring data are the most critical steps in the water quality assessment. The quality is difficult to evaluate from many samples, each containing concentrations for many parameters (Almeida et al., 2007). Numerous studies have investigated the role of the water quality index, i.e., providing factual information about the percentage of pollutants or purity of water by avoiding massive amounts of data to present the water quality.

As reported by Abbasi et al. (Abbasi and Abbasi, 2012), the concept of water quality index in its rudimentary form was first introduced around 170 years ago – in 1848 – in Germany, where the presence or absence of specific organisms in water was used as an indicator of the fitness of water resources. In 1965, Horton (Horton, 1965) developed the first Water Quality Index (WQI) intending to give a single value, which represents the water quality of a source by translating the list of contaminants and their concentrations present in a sample into a single value (Abbasi and Abbasi, 2012). It shows the amelioration of measures by the administration and is more an indicator of the success of an administration's focused work. The index users can compare different quality samples, at different times or various sites. The water quality index also helps the layperson judge the usability of water resources and assist in decision-making. Horton's model started a trend toward using a numerical scale to assess the water quality and has been widely used in many parts of the world, not only for surface water classification but also for other specific uses. The practical implementation of the idea of a water quality index is dominated by uncontrolled growth of the number of water quality indices, mainly because in different regions, different sets of water constituents are used to define their suitable water quality index. A large and growing amount of literature has investigated the development of WQIs for groundwater. Backman et al. present an index for evaluating and mapping the degree of groundwater contamination and test its applicability in Southwestern Finland and Central Slovakia (Backman et al., 1998). A simple WQI involving nine parameters is created by Soltan (Soltan, 1999) to indicate the quality of groundwater from ten artesian wells located near the Dakhla Oasis in the Egyptian Western. The work of S'tambuk-Giljanovic reports the creation of a WQI both for surface water and groundwater and the results of its application for water evaluation in Dalmatia, Croatia. Coulibaly and Rodriguez developed utility performance indicators by operational, infrastructure, and maintenance characteristics of utilities for explaining surface water and groundwater quality as the primary source of drinking water in Quebec, Canada. Stigter et al. (Stigter et al., 2006) used groundwater quality indices for evaluating the influence of agricultural activities on several critical parameters of groundwater chemistry and portability. Saeedi et al. (Saeedi et al., 2009) formulated a WQI using the principal component analysis of drinking water in a large area. The primary objective was to develop WQIs as a monitoring tool for groundwater quality of Qazvin plateau area, Qazvin province, Iran.

The strength of a water quality index as an *overall* quality indicator is weakened by insensitivity to *individual* quality parameters. The acceptability of water for some usage is defined by regulation, and therefore highly sensitive to individual parameters: water has acceptable quality only if *all* parameters fulfill the challenges of the regulations or standards. Generally, the limitations of WQI methods are subjectivity, ambiguity, and eclipsing. The involvement of expert judgment has been applied in the parameter selection, and the development of sub-indices or rating curves has been to avoid subjective assessment. This expert judgment can be individual interviews, interactive groups, and the Delphi method (Meyer and Booker, 2001). The aggregation equations have also been developed throughout the years using different approaches to minimize ambiguity and eclipsing.

Along with other WQI-methods, the Canadian Councils of Ministers of the Environment Water Quality Index (CCME WQI) is also in use. The CCME WQI model comprises three measures of variance from selected water quality objectives (Scope F_1, Frequency F_2, Amplitude F_3). These three measures of variation combine to produce a value between 0 and 100 that represents the overall water quality. The CCME WQI values are then transformed into rankings using an index categorization scheme that can be modified to reflect the expert opinion on uses. This WQI method had undertaken sensitivity analysis for all the steps in developing the water quality index. This water quality index involves investigating the final index value concerning the number of selected parameters, the number of data samples, index aggregation methods, and the water quality objectives (Sutadian et al., 2016). This method allows the flexibility to select parameters so that the index users can easily modify and adapt according to local conditions and issues. The inferential statistic is free of subjectivity and a tool for the quality of water control. However, this CCME WQI has some demerits, one of which is hypersensitivity to the number of quality parameters with at least one measured value out of regulation. If at the first measurement time point all quality parameters are out of a benchmark and the measurements at other time points fulfill the regulation, then CCME WQI < 43, ranking the water quality as poor, regardless whether the considered period is one year or many years, only because of the first bad sample. CCME WQI will never forget the first bad sample. This behavior is firstly revealed in this dissertation and denoted as a pathological memory effect. Considering all these issues, the main aim of this study is to understand how to generate a water quality index, whose factors affect the construction of an aggregation equation from a water technical viewpoint and a purely mathematical point of view. From this fundamental analysis, the study attempts to propose a new water quality index without the memory effect, based on the examination and modification of CCME WQI.

1.2. Objectives

With the background mentioned above, the overall objectives of this study are first to identify and analyze the different factors that characterize the water quality and describe the development of water quality indices, and secondly, to define quality parameters set suitable index method and to assess the water quality status. This study aims to enhance knowledge of the water quality index and evaluation of groundwater quality status in the Vietnamese Mekong Delta.

The specific objectives of this study include:

- Understand how the water quality parameters are identified and how the water quality indices are developed and calculated in general.
- Analyze the aggregation functions of WQIs to find their advantages and disadvantages.
- Select a water quality index method from the result of the analyzing process as the critical method for developing the new approach. In this research, it is the CCME WQI as an anticipated result.
- Analyze and modify the CCME WQI to the new water quality index method named Modified Canadian Water Quality Index (MCWQI).
- Incorporate the CCME WQI and the MCWQI into a support system using MS Access to link with other meta-base.
- Case study to apply the CCME WQI and the MCWQI to existing groundwater monitoring data of the Vietnamese Mekong Delta on the base of the Vietnamese Groundwater Regulation and the European Water Framework Directive.
- Compare and verify the results and their accuracy and application potential of MCWQI with the aid of the computer-based support system.

1.3. Research Questions

Based on the above research objectives, the following questions will guide the empirical work. These questions are subdivided into critical issues and sub-questions.

Key research questions are:

1. Why is water resources management critical?
2. Which method can be used to evaluate water quality?
3. What can be developed to assess the changes and state of groundwater?
4. What can be developed to simplify the generation of MCWQI?
5. How is groundwater quality in the Vietnamese Mekong Delta in both methods, namely, CCME WQI and MCWQI, in comparison?
6. What can be concluded from the study's results?

For each key question, more precise and detailed inquiries are formulated. These specific research questions guide the empirical research of the study.

1. Why is water resources management critical?

- What is water? Furthermore, how can water be considered a critical natural resource?
- How fragile and vulnerable are water resources?
- Which actions need to be taken to remedy the degradation of water resources?
- Which method can be used to support water quality management?

2. Which method can be used to evaluate water quality?

- What is the water quality index? How can WQI be generated?
- How is a WQI method developed?
- What are the limitations of the WQI method?

3. What can be developed to assess the changes and state of groundwater?

- What is the Canadian Water Quality Index? What is the problem with the CCME WQI method?
- What is the new method, which can solve the problem of CCME WQI? How does it look?
- What are the factors which affect MCWQI?
- Can the CCME WQI classification be used for MCWQI?

4. What can be developed to simplify the generation of MCWQI?

- Why is this computer-based platform needed to be constructed?
- How many steps are included in this platform?
- How can these steps be performed?

5. How is groundwater quality in the Vietnamese Mekong Delta according to both index methods, CCME WQI and MCWQI?

- How is groundwater management in Vietnam?
- Which water standards can be used for the groundwater quality evaluation?
- What can be seen from the WQI results generated using both index methods (CCME WQI and MCWQI)?

6. What can be concluded from the study results?

- How is the validation result of the MCWQI?
- What are the potential areas for further research on that topic?

1.4. Research Framework

For this study, a literature review and document analysis are performed, contributing to formulating appropriate research questions by understanding the water resources assessment and the water quality index development. Reviewing the literature also enables the researcher to interpret related theories and concepts, the Vietnamese Mekong Delta's background, and the research gaps of the relevant studies in the delta.

Besides state of scientific publications and document analysis, participatory research tools and critical analysis are used to explore the main factors influencing the generation and accuracy of water quality indices, especially CCME WQI. Then, the modification in the equation of CCME WQI and adaptation in the quality classification was carried out to propose the new groundwater quality index. Moreover, the support platform coded in Visual Basic and integrated with Microsoft Access is established to support and improve the index generation and optimize groundwater resource management.

The primary tasks involved in accomplishing the objectives and questions defined in Section 1.2 and 1.3. are presented in Figure 1.1, displaying the methodological framework followed in this research. As explained previously, the principal purpose of this framework is to provide concrete guidelines upon which research ideas could be developed and constructed in a more focused and efficient manner, which finally shall lead to improvements upon practical applications.

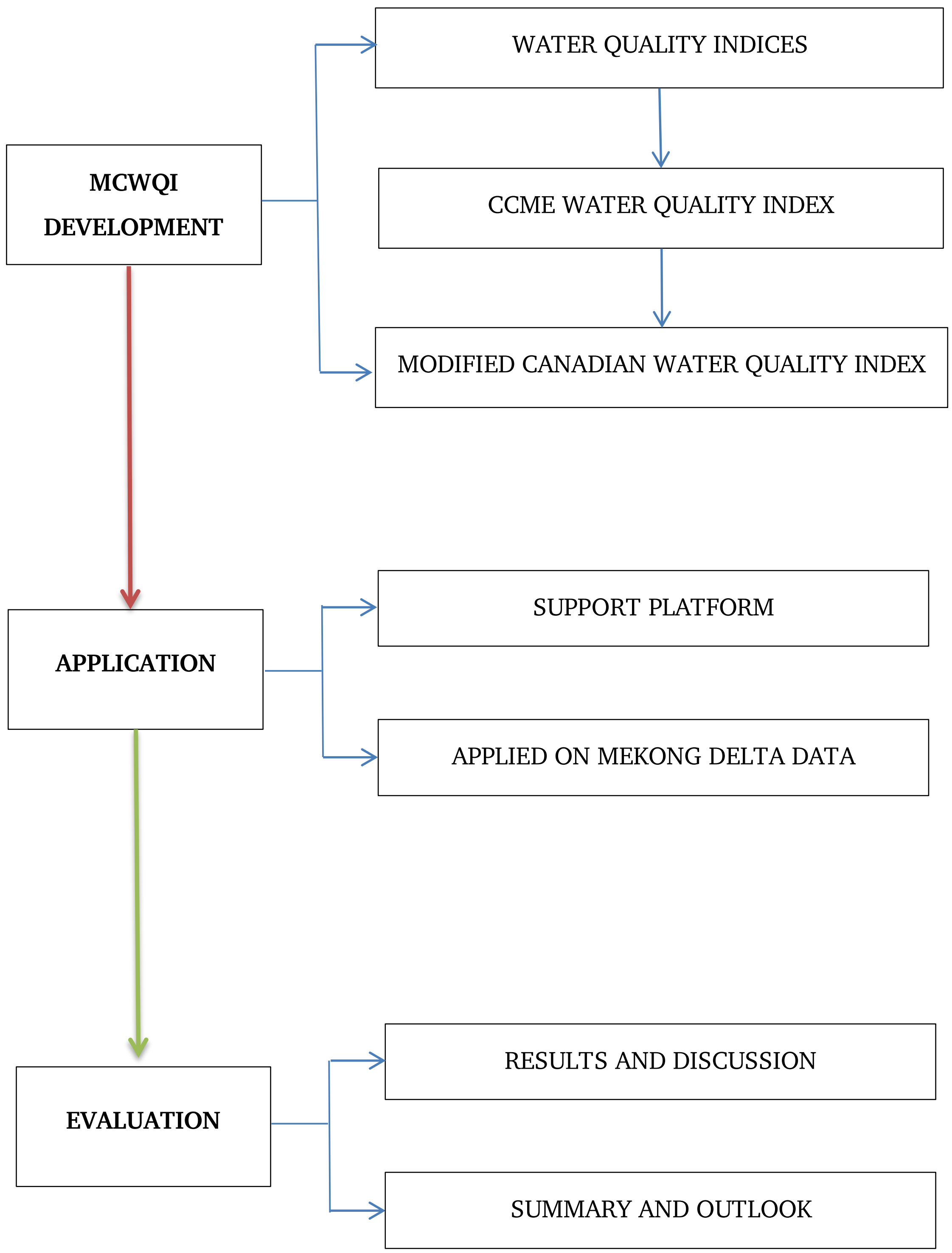

Figure 1.1: A schematic overview of the research process

1.5. Thesis Structure

The thesis is comprised of four different themes "Motivation and Concept," "Modified Canadian Water Quality Index Development", "Application", and "Summary and Outlook". These themes are expanded into six chapters. Figure 1.2 gives an overview of the approach and layout of the dissertation. The preceding sections have set the research objectives with a review of the literature on the concept of water quality assessment, water quality index, and groundwater quality index. Chapter 2 describes the definition, the development, and application of water quality index methods as given by the state of the art.

Chapter 3 is one of three main chapters, which presents the critical analysis of CCME WQI and the development of MCWQI as well as an adaption of MCWQI for the use by single parameters. Chapter 4 shows the development of the support platform supporting generating WQI in practice using different methods and standards. This chapter also introduces the characteristics of the Mekong Delta case study and the water legal frameworks that can be applied in the index generation. Chapter 5 shows the results of the groundwater quality index calculation and a discussion of the groundwater assessment.

Chapter 6 is the last chapter, which draws a summary of the previous sections and gives an outlook.

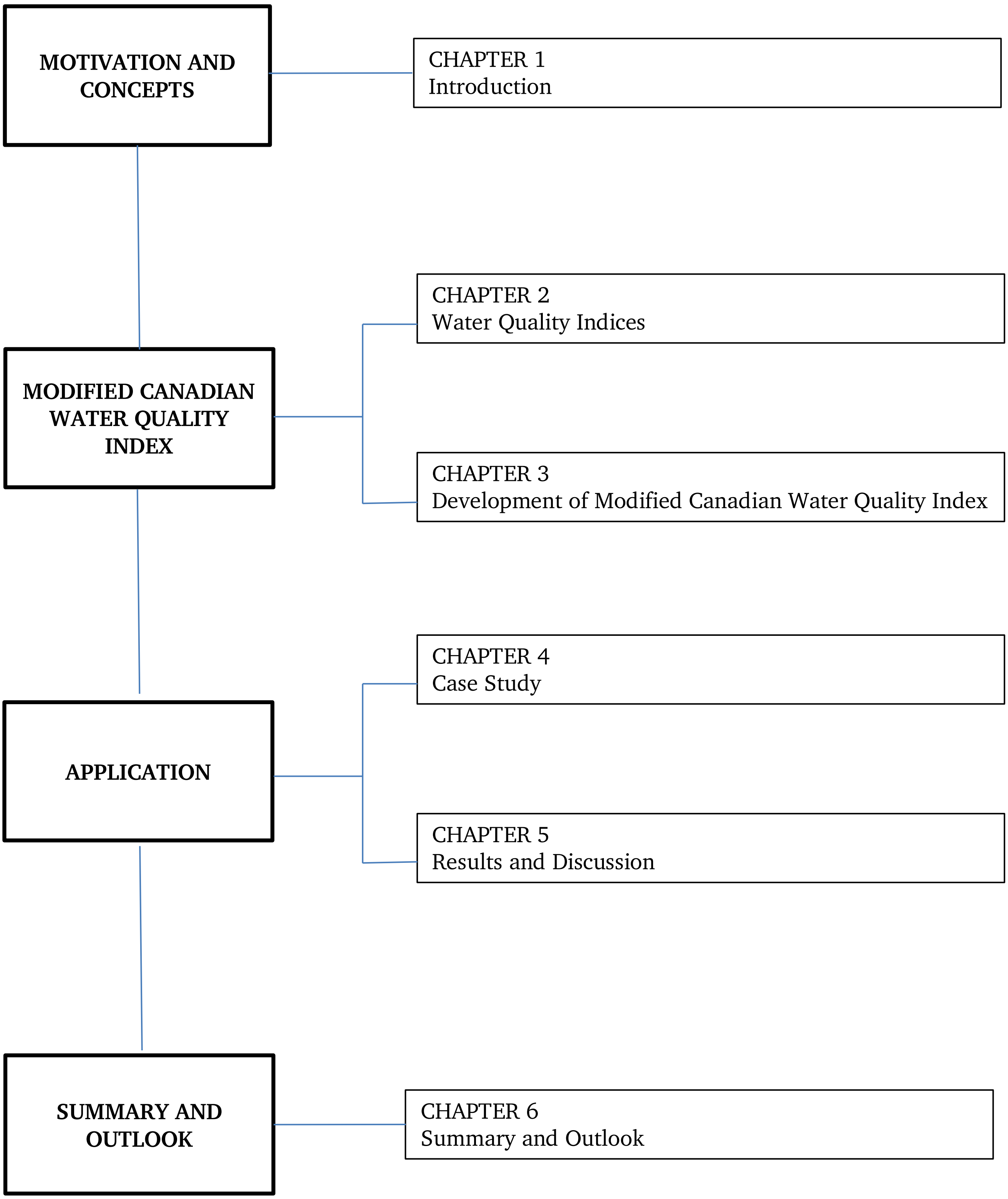

Figure 1.2: General outline of the dissertation

2. Water Quality Indices

2.1. Definition

In recent years, water quality has been of great concern as it is a critical environmental issue worldwide. The evaluation of water quality has become a priority for ensuring public health and safety. Many countries have begun to carry out water quality measurements and monitoring of imminent water shortages. A large amount of collected data complicates the interpretation immensely, necessitating the development of a water quality index to determine the quality of the water body.

There have been various definitions of water quality index. However, in a nutshell, the water quality index is considered a form of average derived by relating a set of parameters to a standard scale and combining them into a single number (Darapu and Chandra Sekhar, 2011). By the reproducible and straightforward, it can easily communicate to its intended audience (Brown et al., 1970), usually policy-makers and the general public (Abbasi and Abbasi, 2011). Even based on the subjective decision of a panel of experts, it is mathematically derived and, therefore, by an objective methodology, allows the assessment of water quality and permits meaningful spatial and temporal comparisons to be made. The water quality index provides a simple means to evaluate the water quality and the correlations between different water bodies' status, in different locations, and at different times. It allows the quantification of "good" and "bad" water quality, the summation of parameter effects, and an indication of river reaches, which have changed significantly in class and, if necessary, can be investigated in greater detail. The water quality index is applicable as a tool to predict potential harmful conditions (Ferreira et al., 2011).

The seed of water quality indices started in 1848 in Germany (Abbasi and Abbasi, 2012) with attempts to correlate the levels of water purity with specific biological organisms occurrence. Since then, many European countries have developed and applied systems to classify the quality of waters within their regions. These water classification systems usually are of two types:

- Those concerned with the present amount of pollution
- Those interested in living communities of macroscopic and microscopic organisms

In 1965 Horton (Horton, 1965) first introduced the indices, which use a numerical scale to represent gradation in water quality level and involved ten parameters including DO, pH, coliforms, EC, alkalinity, and Cl^-. Since the birth of WQI, it is believed that Horton's index has started the trend toward aggregating the various water quality data into an overall index. This idea was then implemented in the United Kingdom, followed closely by Europe's rest during the 1970s. One of the most important and utilized of these was the water quality index (NSF WQI) developed by Brown et al. (Brown et al., 1970) under the support of the National Sanitation Foundation (NSF). This index contains nine parameters in the USA, including DO, fecal coliform, pH, BOD_5, NO_3^-, PO_4^{3-}, temperature, turbidity, and TS (Brown et al., 1970, Abbasi and Abbasi, 2012). It was also found to be useful for classifying rivers in Africa and Asia ((Handa, 1981). Over the years, many types of research have been conducted to measure the water quality index for specific purposes with their rating schemes (Inhaber, 1975, Couillard and Lefebvre, 1985, Harkins, 1974). A remarkable contribution to water quality index development is a model proposed by the Canadian Council of Ministers of the Environment (CCME) (Khan et al., 2004) intending to create a means of communicating water quality issues to scientists, decision-makers, and stakeholders (CCME, 2014). Both index methods, the NSF WQI and CCME WQI have been used widely worldwide (Alexakis et al., 2016).

In the development history of water quality index, Wepener et al. (Wepener et al., 2006) reported the different past trends in the evolution of WQIs, each of which represents a distinct developmental phase in its history: the first trend is the emphasis on the development of a broad range of indices for specific uses. The general index was developed in the 1960s, in the 1970s, specific-use planning indices, and statistical approaches, and the 1980s, the development of trophic state indices. The second trend is the shift from an emphasis on freshwater systems to estuarine and marine systems mainly focus on water quality in lakes, waterways, and main rivers because surface water was considered as the most usable water resources. The third trend is using a single numerical value as a water quality index; some studies have transformed the expression with a combination of numerical or alphanumerical values (Wepener et al., 2006).

Regarding the publication of Tirkey (Tirkey et al., 2013), in general, water quality indices are categorized into four main groups:

- Public indices: these indices ignore the type of water uses within the analysis method and are used for the general quality of water resources description
- Specific consumption indices: the water classification is on the premise of the type of water uses and application as drinking, industrial and ecosystem preservation, etc.
- Designing or planning indices: this class acts as an instrument in planning water quality management projects and aiding decision making
- Statistical indices: these indices do not consider subjective opinions and are based on purely statistical methods.

The first three index-types are also called an expert opinion approach. Due to different weights and ratings given for the same variables by various panels of experts, it becomes a subjective approach and reduces the objectivity and comparability. This subjectivity will be discussed in more detail in Section 2.4. On the other hand, the statistical approaches are used for evaluating the data because of its relevance to the accepted assumption of water quality observation (Harkins, 1974). Using statistical approaches can reduce subjective assumptions and is also beneficial in identifying the significance of essential parameters in water quality assessment (Terrado et al., 2010).

Abbasi and Abbasi mentioned that the water quality indices as a convenient tool for examining trends, highlighting specific environmental conditions, and helping policy-makers evaluate regulatory programs (Abbasi and Abbasi, 2012). Ott (Ott et al., 1978) identified six primary uses of water quality indices as:

- Resource allocation: conveys complex water quality data in a simplified form to decision-makers
- Ranking of the location: indices may be applied to assist in comparing water quality at different locations or geographic areas, or even along the river's reach.
- Standard compliance: to some sites, indices help to determine the extent to which legislative standards and existing criteria are being satisfied or whether they have exceeded acceptable limits.
- Trend analysis: the WQI method is widely used in the rehabilitation of river reaches, as this method helps in studying the change in water quality over time.
- Public information: indices usually are accessible to raise awareness about water quality and the potential risk if this water is used for recreational activities such as bathing, fishing, or boating.
- Scientific research: index translates a large quantity of data to a single score, it is immensely valuable in scientific research, i.e., impacts of development activities on water quality.

The development and applications of the water quality index will be discussed in more detail in the following sub-chapters.

2.2. Development Steps

Previous studies have remarked that the Water Quality Index method is a physicochemical index method since it mainly uses physical and chemical parameters. It has been identified that there are four steps involved in the development of a water quality index, namely: parameter selection, sub-index development, assignment of weight for each parameter, and finally, index aggregation formulation. The general structure of a WQI is shown in Figure 2.1.

Abbasi Abbasi (Abbasi and Abbasi, 2012) demonstrated, as can be seen in Figure 2.1, a WQI is built by the aid of several water quality parameters with different units, which are transformed to a standard scale (usually 0 – 100) for better comparability. These values of the parameters converted to a standard range are called sub-indices. The sub-indices obtained are aggregated to form the final index value. As indicated in the figure, the aggregation process occurs principally in two sequential stages, generation of sub-indices and generation of the water quality index as a mathematical aggregation function. The final index will be applied to evaluate the water quality status.

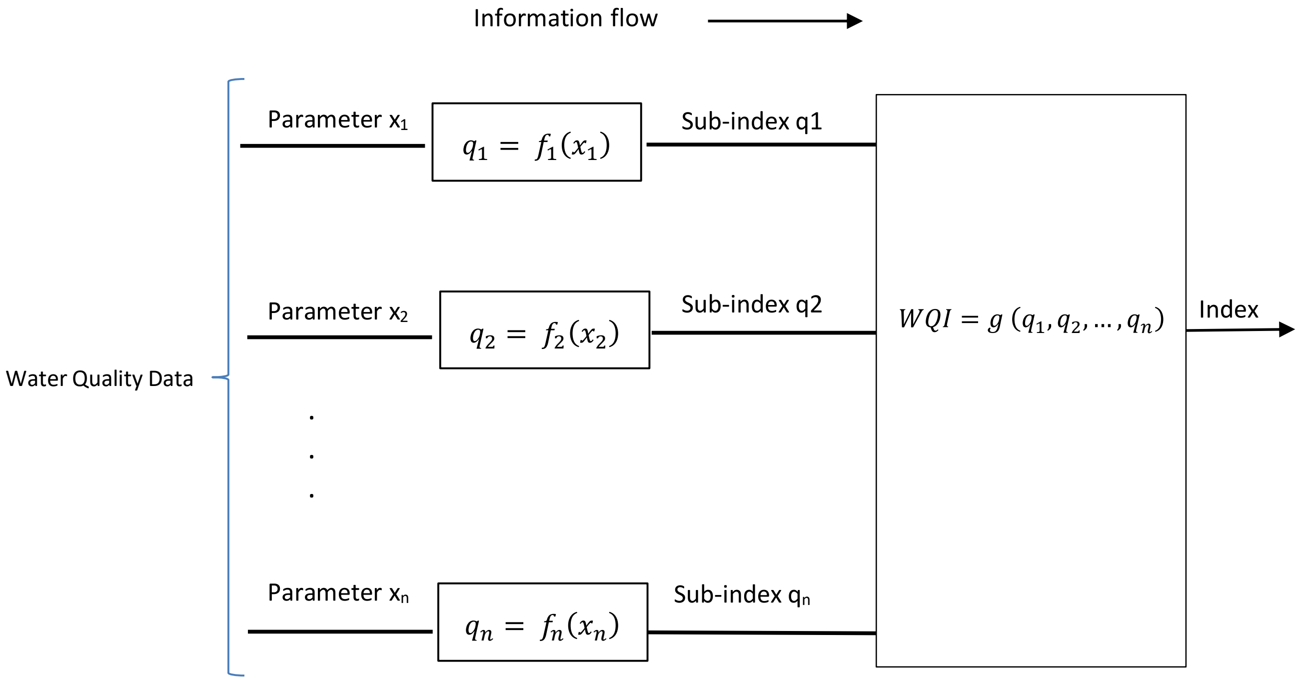

Figure 2.1: The index development process (Abbasi and Abbasi, 2012) modified by the author

2.2.1. Parameter Selection

Water quality is not merely defined by analysis results that specify the chemical composition of water samples or their physical or even biotic parameters. A water sample may have hundreds of constituents, including elements in neutral or ionic form (metals, non-metal, and metalloids); organics (pesticides, detergents, other organics of industrial or natural origin); anions such as CO^{2-}, HCO^{3-}, SO_4^{2-}, NO_3^-, NO_2^- (Wepener et al., 2006). Wepener mentioned that water might also have suspended solids, which constitute a range of chemicals or radioactive substances, color, and odor: or some elements concerning health hazards such as pathogenic bacteria, fungi, helminthic cysts (Wepener et al., 2006). An essential step in water quality monitoring is linking the analysis data to water quality classes by comparing the observed values of the parameters to standard values sets for different types of use. There are many types of water use, such as for drinking, irrigation, different types of industrial uses, etc., each one has its water quality requirements. It means that water quality has to be interpreted in the context of various potential uses, for each of which a full range of water suitability classes has been defined.

The core idea of the water quality index is choosing a set of parameters, which all together reflect the water quality for specific usages. Therefore, only the primary ones need to be selected. The exclusion of some parameters may, however, lead to the loss of valuable information. An additional concern has been the fact that the interrelationships between parameters are usually ignored (Lohani and Todino, 1984).

Depending on the perceptions of different experts and users, the parameter selection process may be fraught with uncertainty and subjectivity. Dunnette (Dunnette, 1979) contributed that the parameters of concern to water quality should be selected from those who have significant impacts on the water while Horton (Horton, 1965) used a subjective method based on a committee-debate process for parameter selection, as in the study of Dinius (Dinius, 1987). The research of Brown (Brown et al., 1970) used the Delphi opinion assessment process to reduce the subjectivity of parameter selection. The Delphi technique formed the basis of numerous subsequent indices. Following the idea of the Delphi method, Landwehr and Deininger (Landwehr et al., 1974) stated that this method correlated with that of the experts, and the basis of this WQI method would require the recalculation of the index whenever new data became available. However, in 1984 the study of Lohani and Todino stated that other authors had suggested that the range of parameters by a panel of experts still incorporates subjective opinion or a method of rank order observation for parameter selection (Lohani and Todino, 1984). Since the study of Lohan and Todino, other index methods have applied principal component analysis to improve the geographical identification of the problem areas and be more appropriate to water quality standards (Lohani and Todino, 1984).

In this research, water quality parameters are chosen based on the available water quality standards or regulations, which are already verified by water authorities and experts and monitored in practice.

2.2.2. Sub-indices Development

A large and growing body of literature in water quality monitoring has been developed. Therefore, more parameters are taken into account and added to the monitoring list. Various water quality parameters are expressed in different units, as well as different regions or nations have their own groups. Different settings that occur in different ranges are reproduced in different groups and have different behavior in terms of a concentration-impact relationship (Abbasi and Abbasi, 2012). Sub-indices are developed so that for different settings, each parameter is selected once for the index. The units and the range of concentrations (from highly acceptable to highly unacceptable) are all transformed into a single scale.

Sub-index functions mathematically transform different units and dimensions of water quality parameters to a standard scale. There are several different methods of parameter transformation. The sub-index equations are developed based on group parameters' desirable and acceptable limits, depending on the particular purposes.

The rating curves are selected as the best way in which individual parameter concentrations can be transformed to the same scale. These curves are developed using published water quality standards and guidelines relating to specific water uses (Walski and Parker, 1974) or environment standards (House, 1989). Most indices rate conditions concerning some measurements. A parameter links concentration to that parameter's desired value or standard (Melloul and Collin, 1998, Stambuk-Giljanovic, 1999).

2.2.3. Assignment of Weight for Each Parameter

The parameter weighting aims to assign relative importance to each parameter and elucidate interrelations between different parameters. Allocated weights usually add up to 1, with the essential parameter having the highest rating (Couillard and Lefebvre, 1986). The weights may be determined based on a parameter's relative importance, accepted standards (Inhaber, 1975), the Delphi technique or a statistical method such as principal component analysis (Lohani and Todino, 1984), discriminate analysis, regression analysis (Joung et al., 1979) or a combination of these. Out of all these, the Delphi technique is probably the most frequently used.

The applicability of weightings, which are assigned to parameters, should be continually assessed (Richardson, 1997). Continued research and acquisition of new information might inevitably alter information on which weights are based. Inhaber (Inhaber, 1976) stated, "A weighting system needs to take into account the varying emphasis between parameters, but also reflect non-linearity in a pollutant-effect relationship, and importance of thresholds and peaks as against averages" (Richardson, 1997).

Dojlido et al. (Dojlido et al., 1994) suggested that it is better not to weigh parameters. The parameter weightings may lead to improper evaluation due to different parameters having varying importance in different systems. Weighting eliminates the possibility of comparison between different systems since a particular parameter's importance differs from system to system (Dojlido et al., 1994). Weighing parameters also indicate that there is prior knowledge of that parameter's influence in the system and its interaction with other parameters. That is the way the relative importance of one parameter over another is known (Wepener et al., 1992). The study of Bolton et al. suggested that the weighting of parameters is not essential. However, Inhaber (Inhaber, 1976) argues that even though there is no consensus on which one is the best method to use, "not doing so may be regarded as an addiction of responsibility" (Richardson, 1997).

2.2.4. Aggregation of Functions

Many different formulae have been used to aggregate parameters (Couillard and Lefebvre, 1985). The collection process serves to consolidate all parameter'squality scores obtained from rating curves into a single number. Table 2.1 contains a list of the frequently used formula.

Table 2.1: Frequently used aggregation formula edited from (Wepener et al., 2006)

Methods	**Formula**	**Reference**
Arithmetic unweighted sum	$WQI = \frac{1}{n}\sum_{i=1}^{n} q_i$	(Couillard and Lefebvre, 1985, Landwehr and Deininger, 1976)
Arithmetic weighted sum	$WQI = \sum_{i=1}^{n} q_i\, w_i$	(Couillard and Lefebvre, 1985, Landwehr and Deininger, 1976, House and Ellis, 1980)
Modified Arithmetic mean	$WQI = \frac{1}{100}\left(\frac{1}{n}\sum_{i=1}^{n} q_i w_i\right)^2$	(Richardson, 1997)
An unweighted geometric mean or unweighted product or unweighted multiplicative index	$WQI = \left(\prod_{1=1}^{n} q_i\right)^{1/n}$	(Couillard and Lefebvre, 1985, Landwehr and Deininger, 1976, House and Ellis, 1980, Bhargava, 1983)
A weighted geometric mean or weighted product or weighted multiplicative index	$WQI = \prod_{i=1}^{n} {q_i}^{w_i}$	(Couillard and Lefebvre, 1985, Landwehr and Deininger, 1976, House and Ellis, 1980, Smith, 1990)
Solway modified unweighted sum	$WQI = \frac{1}{100}\left(\frac{1}{n}\sum_{i=1}^{n} q_i\right)^2$	(Couillard and Lefebvre, 1985, House and Ellis, 1980, Wepener et al., 1992)
Solway modified weighted sum	$WQI = \frac{1}{100}\left(\sum_{i=1}^{n} q_i\, w_i\right)^2$	(Couillard and Lefebvre, 1985, House and Ellis, 1980)
Harmonic square mean	$WQI = \sqrt{\frac{n}{\sum_{i=1}^{n}\frac{1}{q_i^2}}}$	(Dojlido et al., 1994, Richardson, 1997)
Minimum operator	$WQI = \min(q_1, q_2, .., q_n)$	(Couillard and Lefebvre, 1985, House and Ellis, 1980, Smith, 1990)
Maximum operator	$WQI = \max(q_1, q_2, .., q_n)$	(Couillard and Lefebvre, 1985, House and Ellis, 1980)
WQI: Water quality index, q: sub-index, i: parameter, w: weight, n: number of parameters Note that $\sum w_i = 1$		

Brown et al. (Brown et al., 1970) and Dinius (Dinius, 1987) used weighted arithmetic mean to aggregate parameters. This method, as well as the modified arithmetic mean, lacks sensitivity, in that a single lousy parameter does not allow sufficient lowering of the index. It is generally agreed that a weighted product is better than a weighted sum (Couillard and Lefebvre, 1985). Brown and Landwehr mentioned two additional methods: the weighted multiplicative and the unweighted multiplicative (geometric mean) (Brown et al., 1970).

Walski and Parker (Walski and Parker, 1974) found the geometric mean to be a good alternative. Joung (Joung et al., 1979) and Landwehr (Landwehr et al., 1974) suggested that this form is an unbiased and viable method. Gray (Gray, 1996) found that the geometric mean was not adequate since if one or more of the values scored zero that WQI becomes zero while Walski et. al (Walski and Parker, 1974) see this as an advantage. However, this geometric mean may lead to an underestimation of the final value (Richardson, 1997). On the other hand, the weighted multiplicative index, despite being responsive to low water quality scores, consistently overestimates water quality, the only exception being when concentrations are more than accepted limits (Richardson, 1997). It is contrary to Couillard and Lefebreve suggestion that it serves to eliminate such overestimation (Couillard and Lefebvre, 1985). Richardson (Richardson, 1997) suggested that this was due to its nonlinearity, especially when weights are small. However, Landwehr describes this form as excellent in describing water quality trends and distinguishing between different field situations.

Dojlido et al. (Dojlido et al., 1994) suggested using the square root of the harmonic mean because it gave a high statistical value to those parameters with the least favorable value. It also eliminates the weighting of parameters, which is advantageous.

Smith (Smith, 1990) defines the use of the minimum operator since it avoids eclipsing and does not exhibit ambiguity. This aggregation's usefulness is questionable because of the lack of information it conveys and its basis on the most inferior quality parameter (Couillard and Lefebvre, 1986). This method of aggregation is probably standard in combination with another way of aggregation, as seen in Wepener (Wepener et al., 1992).

The Solway Weighted and Unweighted Sums have been remarked to be sensitive and without bias to water quality parameters throughout their range and have been said to provide the best results for the generation of water quality index (Richardson, 1997).

2.3. Applications

The water quality indices have been developed by individuals, agencies, or organizations and applied in some countries and regions such as the United States, Canada, European countries, Malaysia, India, and Vietnam.

- United States: Water quality index is developed for each county; most countries around the world follow the method of the National Sanitation Foundation (NSF).
- Canada: Canada follows the approach of the Canadian Council of Ministers of the Environment.
- Europen countries: European countries mainly adapt the water quality indices method of NSF (United States).
- Malaysia and India: the water quality indices method has been developed based on the NSF technique and has been localized to adapt to the intended purposes.
- Vietnam: In Vietnam, the WQI approach has been developed by the Ministry of Natural Resources and Environment (MONRE), as described in Decision No. 879/QD-TCMT. This approach created

the guidelines on surface water quality for the protection and management of surface water resources.

The classification of water quality indices attracts many differing opinions, depending on the authors, and the intended uses. In this research, the WQIs are divided into four categories as inspired by Ott (Ott et al., 1978): general, specific, planning, and statistical.

- General WQIs is on the assumption that water quality is a general attribute of surface waters, irrespective of the use to which the water is put.
- Specific use WQIs are developed concerning a particular use of the water body, e.g., irrigation, outdoor bathing, drinking, etc.
- Planning WQIs are those generated for management purposes for decision making. They are custom-designed to assist the user in making specific decisions and in solving particular problems.
- Statistical approaches are mainly based on either factor analysis or parametric multivariate transforms.

A summary of WQIs (see Appendix 1), along with value ranges and interpretations, is shown in the appendix, which has been updated from the previous researches (Couillard and Lefebvre, 1985, Wepener et al., 2006). The following are the most well-known and commonly used WQIs in water management all over the world.

2.3.1. National Sanitation Foundation Water Quality Index (NSF WQI)

In 1970, the National Sanitation Foundation developed the water quality index NSF WQI as a standard method to compare the water quality of different water bodies (Brown et al., 1970). One hundred forty-two experts were involved in selecting nine of thirty-three quality parameters to be included in an index (Abbasi and Abbasi, 2012). They chose the following set of parameters: DO, fecal coliform, pH, BOD_5, temperature change (from 1 mile upstream), total P, NO_3^-, turbidity, TS.

The next step in WQI generation was rescaling the measuring units to one scale ranging from 0 (worst) to 100 (best) from the raw data. They obtained the resulting curves of rescaling to nine sub-indices by averaging the answers of various experts.

The following step was the mathematical aggregation of an overall WQI. The used formula is a weighted arithmetic average.

$$WQI = \sum_{i=1}^{n} q_i \, w_i$$

Where

- q_i =sub-index for i^{th} water quality parameter, $0 \le q_i \le 100$

- w_i = weight associated with i^th water quality parameter and $\sum w_i = 1$
- n = total number of water quality parameters

The last step was the classification of the water quality by WQI-range, as shown in Table 2.2.

Table 2.2: The WQI classification of NSF WQI (Brown and others, 1970)

Water Quality Index	Classification
91 - 100	Excellent
71 - 90	Good
51 - 70	Medium
26 - 50	Bad
0 - 25	Very bad

The research of Brown (Brown et al., 1970) proposed the use of a geometrical average instead of NSFWQI. According to Abbasi and Abbasi (Abbasi and Abbasi, 2012), using the index, it was found that arithmetic or additive formulation of a WQI lacked sensitivity in terms of the effect of a single bad parameter value on the water quality. Brown proposed a weighted geometrical mean:

$$WQI = \prod_{i=1}^{n} q_i^{w_i}$$

The problems of sensitivity will be analyzed in detail in a later section. This subsection aims to show that different types of weighted averages are used for WQI generation.

2.3.2. Oregon Water Quality Index (OWQI)

This section follows Tyagi's research outcomes (Tyagi et al., 2018) and Sutadian's (Sutadian et al., 2016). The OWQI has been used to evaluate the general water quality of Oregon's stream and other geographic regions. This WQI combines eight water quality parameters into one single number. They are temperature, dissolved oxygen (DO), biochemical oxygen demand (BOD), pH, ammonia and nitrate nitrogen, total phosphorus, total solids, fecal coliforms.

The index does not use a weighting of parameters. The concept of harmonic averaging is the base for the mathematical expression of this WQI method.

$$OWQI = \sqrt{\frac{n}{\sum_{i=1}^{n} \frac{1}{q_i^2}}}$$

Where

- n = total number of sub-indices
- q_i = sub-index of the i^th parameter

The rating scale of this WQI is given in Table 2.3.

Table 2.3: Water quality classification of OWQI (Tyagi et al., 2018)

Water Quality Index	Classification
90-100	Excellent
85-89	Good
80-84	Fair
60-79	Poor
0-59	Very poor

The Brown (Brown, 2018) report provides a summary of water quality and trends across Oregon for the years 2008-2017 by Oregon Water Quality Index. The OWQI is also used outside of Oregon. The research of Al-Shujairi (Al-Shujairi, 2013) is an application of OWQI to evaluate the water quality of Tigris and Euphrates Rivers in Iraq by OWQI.

2.3.3. Weighted Arithmetic Water Quality Index Method

According to Tyagi (Tyagi et al., 2013) and Sutadian (Sutadian et al., 2016), this index is not a water quality index but a water pollution index. It means WQI = 0 is the best value. Note that WQI > 100 is possible. Weights are directly computed from the measured values of the parameters, and no experts are needed for this proceeding:

$$WQI = \sum q_i * \frac{W_i}{\sum W_j}$$

The quality rating scale (q_i) for each parameter is calculated by using the expression:

$$q_i = 100 * \frac{V_i - V_0}{S_i - V_0}$$

Where:

- V_i is the estimated concentration of the i^{th} parameter in the analyzed water,
- V_o is the ideal value of this parameter, in pure water
- $V_o = 0$ (except pH =7.0 and DO = 14.6 mg/l)
- S_i is the recommended standard value of the i^{th} parameter.

The unit weight (W_i) for each water quality parameter is calculated by using the following formula:

$$W_i = \frac{1}{S_i} K$$

Where, K = proportionality constant and calculated by using the following equation:

$$K = \frac{1}{\sum \frac{1}{S_i}}$$

The rating of water quality according to this WQI is given in Table 2.4

Table 2.4: Water quality classification and grade (Tyagi et al., 2013)

Water Quality Index	Classification	Grade
0-25	Excellent	A
26-50	Good	B
51-75	Poor	C
76-100	Very poor	D
Above 100	Unsuitable for drinking	E

Remarks:

The use of the term WQI is misleading. It is far more accurate to call it a Water Pollution Index, where WQI = 0 means the best water quality. Growing pollution results in an increasing index. $V_i > S_i$ therefore, qi > 100 is possible. The sub-indices q_i are not restricted to the range 0 – 100. Consequently, it is possible that WQI > 100. Batabyal and Chakraborty classify the computed WQI values into the following five categories, as shown in Table 2.5.

Table 2.5: Water quality classification (Batabyal and Chakraborty, 2015)

Water Quality Index	Classification
0-50	Excellent
50-100	Good
101-200	Poor
201-300	Very poor
> 300	Unsuitable for drinking

The weighting uses a summation $\sum_j \frac{1}{S_j}$. It restricts the applicability to parameters with the same measuring units, here concentrations (mg/l). It is exciting that one tries to avoid experts' consensus as much as possible. The term $\frac{1}{S_i}$ has the unit l/mg. It is the volume of water needed to dilute 1mg of the constituent such that the concentration of the constituent in the water is just the maximal allowed concentration. This idea is the same as used for the definition of a greywater footprint in a more global setting.

2.3.4. Vietnamese Surface Water Quality Index

The Vietnamese Water Quality index is a so-called two-tier quality index. Regarding the publication of Pham (Pham et al., 2011), the water quality index is a combination of arithmetic and geometrical averages.

This WQI utilizes in a total of twenty-seven closely monitored parameters, eight of which are the base water quality parameters, which are responsible for water quality comparison and water pollution identification. They are SS, turbidity, DO, COD, BOD_5, orthophosphate-phosphorus, ammonium-nitrogen, T. Coli.

The other nineteen parameters are not monitored as frequently as those mentioned eight above. They provide additional information on factors that may not be relevant in all water bodies, especially on toxic pollutants. These parameters represent the second tier for individual needs. These parameters are water temperature, pH, conductivity, TDS, Cl-, fecal coliform, NO_3-N, NO_2-N, total P, oil and grease, heavy metals: Fe, Pb, Cd, Hg, Zn, Cu, Ni, Cr, and pesticides.

However, this study considers only the primary water quality parameters. The mathematical aggregation function uses three groups of primary parameters and uses arithmetic averages of each group:

- Organic and nutrients group with five substances and sub-indices $q_{i,1}$: DO, BOD_5, COD, NH_4^+-N, PO_4^3-P.
- Particular group with two substances and sub-indices $q_{j,2}$: SS, turbidity.
- Bacteria group containing only one substance and sub-index $q_{k,3}$: T. coli.

$$WQI_B = \left(\left(\frac{1}{5}\sum_{i=1}^{5} q_{i,1}\right) * \left(\frac{1}{2}\sum_{j=1}^{2} q_{j,2}\right) * \left(\frac{1}{1}\sum_{k=1}^{1} q_{k,3}\right)\right)^{\frac{1}{3}}$$

WQI_B is the basic Vietnamese Water Quality Index. Finally, it is a geometrical mean of the arithmetic means of the three groups of basic parameters. Each sub-index has a value greater than or equal 1. The rating scale of this WQI is shown in Table 2.6.

Table 2.6: The WQI classifications (Pham et al., 2011)

Class	Index score	Interpretation
1	71-100	Indicates water of high quality suitable for all high value uses at low cost
2	51-70	Indicates water of reasonable quality suitable for high value uses at moderate cost
3	31-50	Indicates polluted water with generally moderate value uses and high treatment cost
4	10-30	Indicates badly polluted waters of low economic value requiring a significant investment in treatment facilities if they are to be upgraded

Remarks:

- The linear approximation of this WQI computed as

$$WQI_B \approx \sum_{i=1}^{5} q_{i,1} * \frac{1}{15} + \sum_{j=1}^{2} q_{j,2} * \frac{1}{6} + \sum_{k=1}^{1} q_{k,3} * \frac{1}{3}$$

- The research of Pham (Pham et al., 2011) presented in Table 2.7 is an application example for the Red River.

Table 2.7: Application example for the Red River (Pham et al., 2011)

Parameter	**Measured value**	**Sub-index score***
DO	5.03 mg/l	65.74
BOD_5	7.58 mg/l	70.60
COD	9.88 mg/l	100
PO_4^{3}-P	0.095 mg/l	100
NH_4^{+}-N	0.047 mg/l	100
SS	17 mg/l	100
Turbidity	16.9 NTU	80.11
T.Coli	550 CFU/100ml	100
pH	7.9	100 (c-value=100/100=1)
Temperatur	28.5°C	100 (c-value =100/100=1)
Cd	0.008 mg/l	70 (c-value =70/100=0.7)
Pb	0.059 mg/l	49.02 (c-value =49/100=0.49)
Fe	1.22 mg/l	64.00 (c-value =64/100=0.64)

*The sub-index scores are calculated by Pham (Pham et al., 2011) based on their rating curves for sub-indices. Their rating curves are piece-wise linear functions, relating to each measured value a unique sub-index value.

$$\frac{1}{5}\sum_{i=1}^{5} q_{i,1} = \frac{(65.74 + 70 + 100 + 100 + 100)}{5} = \mathbf{87.27}$$

$$\frac{1}{2}\sum_{j=1}^{2} q_{j,2} = \frac{(80.11 + 100)}{2} = \mathbf{90.05}$$

$$\frac{1}{1}\sum_{k=1}^{1} q_{k,3} = \mathbf{100}$$

$$WQI_B = \left(\left(\frac{1}{5}\sum_{i=1}^{5} q_{i,1}\right) * \left(\frac{1}{2}\sum_{j=1}^{2} q_{j,2}\right) * \left(\frac{1}{1}\sum_{k=1}^{1} q_{k,3}\right)\right)^{\frac{1}{3}} = \sqrt[3]{87.27 * 90.05 * 100} = \mathbf{92.28}$$

The linear approximation yields:

$$WQI_B \approx \sum_{i=1}^{5} q_{i,1} * \frac{1}{15} + \sum_{j=1}^{2} q_{j,2} * \frac{1}{6} + \sum_{k=1}^{1} q_{k,3} * \frac{1}{3} = 29.09 + 30.02 + 33.34 = 92.45$$

It can be seen that the linear approximation is a simple arithmetic average, and the result is just in line. As long as all three components are not near 0, the linear approximation can be used equivalently to

WQI_B. The example of Red River shows that different aggregation functions do not necessarily have different results. Differences are apparent when one group of the basic WQI tends to 0. Then WQI_B also tends to 0, but the linear approximation, as arithmetic weighted average does not.

2.3.5. Canadian Water Quality Index (CCME WQI)

As reported by Rocchini and Swain (Rocchini and Swain, 1995), the British Columbia Ministry of Environment, Lands, and Parks developed an index, the British Columbia Water Quality Index (BCWQI), which has been adopted for use by some provinces, including Manitoba. BCWQI is a water pollution index: the lower the value, the better the water quality. In this index, water quality parameters are measured, and their violation is determined through comparison with a predefined limit. It provides the possibility to make a classification based on all existing measurement parameters. The following equation is used to calculate the final index value:

$$BCWQI = \left[\frac{\sqrt{F_1^2 + F_2^2 + (F_3/3)^2}}{1.453}\right]$$

where the number 1.453 was selected in order to normalize the index number on a scale from 0 to 100. These factors F_1, F_2, and F_3, are the same as for CCME WQI, as explained below.

This BCWQI does not indicate the water quality trend until it deviates from the standard limit, and due to usage of the maximum percentage of deviation, it cannot determine the number of withdrawals above the maximum limit of standard (Nazaratul Ashifa Abdullah et al., 2008).

Later in 1997, the Canadian Council of Ministers of the Environment modified the British Colombia WQI to create a Canadian Water Quality Index, which could be applied by many water agencies in various countries with slight modifications. The CCME WQI was developed as a tool to assess and report water quality information to management institutions and the public (CCME, 2014). This method allows the flexibility to select parameters so that the index users can easily modify and adapt it according to local conditions and issues. As first, CCME WQI has been developed to evaluate surface water for the protection of aquatic life by specific guidelines. Later, several studies have applied this for various purposes, e.g., evaluate drinking water quality (Khan et al., 2004, Hurley et al., 2012) or water quality in metal mines (de Rosemond et al., 2009).

CCME WQI provides a straightforward mathematical framework for aggregating the final index value without sub-index generation, weights establishing, and conventional index aggregation. As mentioned by CCME, the CCME WQI is based on three significant factors (scope, frequency, and amplitude) to produce a single unitless number that represents overall water quality relative to the benchmark chosen (CCME, 2014). The result is represented as a single unitless number ranging from 0-100, where 100 indicates that the parameters were similar to the selected benchmark or below the benchmark (Tirkey et al., 2013). In brief, the equation is calculated using the three factors as follows:

F_1 (***Scope***) represents the number of parameters whose objectives are not met ("*failed parameters*"), relative to the total number of parameters measured:

$$F_1 = \left(\frac{Number\ of\ failed\ parameter}{Total\ number\ of\ parameter}\right) * 100 \tag{2.1}$$

F_2 (***Frequency***) represents the frequency by which the objectives are not met ("*failed tests*"):

$$F_2 = \left(\frac{Number\ of\ failed\ tests}{Total\ number\ of\ tests}\right) * 100 \tag{2.2}$$

F_3 (***Amplitude***) represents the amount by which the objectives are not met. The factor F_3 is calculated in three steps.

The relative deviation that an individual concentration is higher than (or less than, when the objective is a minimum) the objective is denominated an *excursion* and is expressed as follows in (CCME, 2001):

When the test value must not exceed the objective:

$$excursion_i = \left(\frac{FailedTestValue_i}{Objective_j}\right) - 1 \tag{2.3}$$

For the cases in which the test value must not fall below the objective:

$$excursion_i = \left(\frac{Objective_j}{FailedTestValue_i}\right) - 1 \tag{2.4}$$

The index i enumerates the *excursion*, respectively, the corresponding *failed test* values. The quality parameters may have lower and upper objectives, for example, pH. Therefore, the objectives have their enumeration by j in the above definition.

The normalized sum of the *excursions*, *nse*, is the aggregate amount by which individual tests are out of compliance. It is calculated by summing the *excursions* of individual tests from their objectives and dividing by the total number of tests (both those meeting objectives and those not meeting objectives).

$$nse = \frac{\sum_{i=1}^{n} excursion_i}{Total\ number\ of\ tests} \tag{2.5}$$

F_3 is then calculated by an asymptotic function that scales the normalized sum of the *excursions* from objectives (*nse*) to yield a number in the range [0,100].

$$F_3 = \left(\frac{nse}{0.01 * nse + 0.01}\right) = \frac{nse}{nse + 1} * 100 \quad (2.6)$$

F_3 is monotonically increasing concerning *nse*.

Once the factors are obtained, the index itself can be calculated by

$$CCME\ WQI = 100 - \sqrt{\frac{F_1^2 + F_2^2 + F_3^2}{3}} \quad (2.7)$$

In another way

$$CCME\ WQI = 100 - \frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732} \quad (2.8)$$

The constant, 1.732 is a scaling factor ($\sqrt{3}$) to ensure the index varies between 0 and 100. The index can be used both for following changes at one site over time and for comparisons among sites (Khan et al., 2004). The application of CCME WQI is given later in Section 3.1.2.

The WQI values are between 0 and 100, and the range 0 - 100 is divided into five quality classes:

Table 2.8: Water quality classification of CCME WQI (CCME, 2011)

Ranges	Classification	Explanation
95 -100	Excellent	Water quality is protected with a virtual absence of threat or impairment, conditions very close to the natural or pristine level
80 - 94	Good	Water quality is protected with only a minor degree of threat or impairment; conditions rarely depart from natural or desirable levels
65 - 79	Fair	Water quality is usually protected but occasionally threatened or impaired; conditions sometimes depart from natural or desirable levels
45 - 64	Marginal	Water quality is frequently threatened or impaired; conditions often depart from natural or desirable levels
0-44	Poor	Water is almost always threatened or impaired; conditions usually depart from natural or desirable levels

2.4. Structural analysis

2.4.1. Different Technical Definitions of Quality Classes

There exist principally two ways of defining quality classes.

Table 2.9: Water classification, type 1

Class	WQI ranges	Usage
3	90-100	Drinking
2	46-89	Irrigation
1	0-45	Not useable

The quality classes have lower and upper bounds inclusive. This definition is acceptable as long as WQI-values are integer values (0, 1, 2, 3, 4,…, n). Because WQI-values are presented as fractions, the non-integer values between two adjacent quality classes are uncounted. For example, an index value of 45.7 lies between the above-defined “not usable” and “irrigation.” In these cases, the values are always rounded down, so 45.7 would be treated as 45 and mean that the water is “not useable.”

From a mathematical point of view, half-open intervals could be used instead of the above classification method.

Table 2.10: Water classification, type 2

Class	WQI ranges	Usage
3	[90,100]	Drinking
2	[46,90)	Irrigation
1	[0,46)	Not useable

The half-open interval [0, 46), means that the WQI-value 0 is in the quality class and 46 is not in this quality class. This research uses water quality classification by type 1 because the case of half-open intervals can be reduced to the first method: the highest integer value in each half-open interval is treated as the upper bound of the concerned quality class, and the quality classes are rewritten in the form of type 1.

2.4.2. Subjectivity, Rigidity, and Compensation

Subjectivity

As mentioned in Section 2.1, water quality indices could be broadly classified into “objective” and “subjective” indices. Objective indices are those that do not make use of any subjective inference (e.g., based on the expert opinion questionnaire, etc.). These are often called as the statistical indices. On the other hand, subjective indices need two relevant specifications, namely weights (i.e., values according to the importance of the water quality parameters) and sub-indices. These specifications are entirely subjective and are drawn out of questionnaire analysis, inquiring the opinion of experts. Unlike the objective indices, however, the subjective indices have some casual basis for representing the multivariate (i.e., consisting of more than one water quality parameter) data. The advantage of an objective index is its impartiality.

The possible danger in applying an index is that it may be misused or valuable information may be lost or hidden due to the aggregation of data. The main area of concern is “subjectivity” related to the selection of parameters and parameter weightings, which raises several important questions, whether parameters should be weighted at all and how to get the most effective method of aggregation without unnecessary loss of information or, on the other hand, without too much complexity to be effective. Expert judgment has been applied to reduce the uncertainty and inaccuracy in some steps of the water quality index development. Expert judgment can be incorporated in selecting parameters through three approaches, namely individual interviews, interactive groups, and the Delphi method (Meyer and Booker, 2001). Of the three approaches, the Delphi method is the one that has been widely used for the selection of parameters (Juwana et al., 2010) and the development of sub-index functions or rating curves (Sutadian et al., 2016).

Rigidity

A WQI suffers from rigidity when it is impossible to accurately add quality parameters to address specific water quality concerns without experts' opinions. Hence, expert opinions are always needed. Abbasi argued that rigidity is related to the number of sub-indices in the artificial reduction of the index value when new sub-indices are added in an aggregation model. The research of Swamee also mentioned that product-type operators and nonlinear summation-type operators generally exhibit this behavior. Most of the aggregation methods do not have any provision to add a parameter into its pre-identified set of water quality constituents (Swamee and Tyagi, 2000). This decrease exacerbates the ambiguity in indices, which are already suffering from this problem and reintroduces the issue of ambiguity in indices, which were free from this problem (Swamee and Tyagi, 2000, Swamee Prabhata and Tyagi, 2007). The problem of ambiguity (water quality underestimated by WQI) and eclipsing (water quality overestimated by WQI) is discussed in Section 2.4.4.

Compensation

Good compensation

A water quality index is intentionally an overall index, and its index value furnishes a general picture of water quality. As a consensus of the effects of different quality constituents (sub-indices), it should not be biased towards extremes (i.e., highest or lowest sub-index value). Generally, a WQI aggregation method is regarded as having excellent compensation when it satisfies the following constraint:

For all sub-indices $q_1, \cdots, q_n$: $min(q_1, \cdots, q_n) \le WQI(q_1, \cdots, q_n) \le max(q_1, \cdots, q_n)$

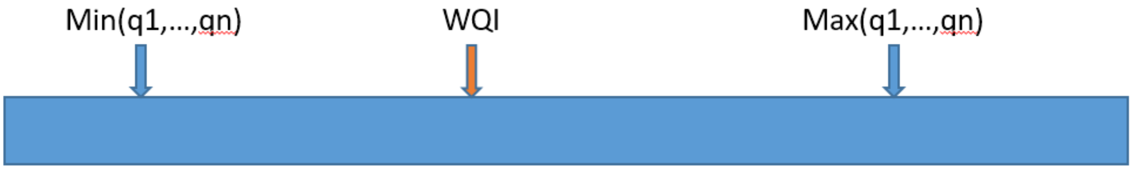

Figure 2.2: Explanation of compensation

Weak compensation

This notion is introduced for the first time in this research. A WQI has weak compensation when for all sub-indices q it holds:

$$WQI(q, \cdots, q) = q$$

Indeed this is good compensation for the case where all sub-indices are equal because

$$q = min(q, \cdots, q) \leq WQI(q, \cdots, q) \leq max(q, \cdots, q) = q$$

Implies

$$WQI(q, \cdots, q) = q$$

The good compensation for arbitrary combinations of sub-indices is not challenged, but only for the situation where all indices are equal. This property of a WQI will be used in a later section.

2.4.3. Conflict of Desired Properties of a Water Quality Index

The analysis raises an important question: which properties should a WQI function have? In literature, Swamee (Swamee and Tyagi, 2000) complained about the insensitivity to individual parameters of a WQI. In their publication, they challenge

$$WQI(100, \cdots, 100, q, 100, \cdots, 100) = q \qquad \text{(Sensitivity to an individual parameter)}$$

On the other hand, a WQI should be the consensus of all sub-indices. Referring to the property of "good compensation" presented in the research of Abbasi (Abbasi and Abbasi, 2012), only weak compensation is challenged here:

$$q = WQI(q, \cdots, q) \qquad \text{(Weak compensation)}$$

Moreover, monotonicity is challenged

$$\text{If } q_1 \leq Q_1, \cdots, q_n \leq Q_n \text{ then } WQI(q_1, \cdots, q_n) \leq WQI(Q_1, \cdots, Q_n) \quad \text{(Monotonicity)}$$

The only mathematical function with these properties is the minimum function.

$$WQI(q_1, \cdots, q_n) = \min(q_1, \cdots, q_n),$$

which is highly insensitive to the global aspect of a WQI.

In the short proof: For more straightforward writing suppose $q_1 = \min(q_1, \cdots, q_n)$

$$\begin{aligned}
q_1 = &\ \min(q_1, \cdots, q_n), && \text{by assumption} \\
&= WQI(q_1, \cdots, q_1), && \text{by weak compensation} \\
&\leq WQI(q_1, \cdots, q_n), && \text{by monotonicity} \\
&\leq WQI(q_1, 100, \cdots, 100), && \text{by monotonicity} \\
&= q_1, && \text{by sensitivity to individual parameters}
\end{aligned}$$

Hence, all terms in the series of inequalities must be equal. In combination, the above properties are too strong. Better is simply to challenge the following properties for a WQI:

- Monotonie
- The WQI-value is a value in the quality class of the water sample

The last challenge preposes the knowledge of the quality class of a water sample independent of the evaluation of WQI-values. Indeed, the sub-indices q_1, q_n of a water sample as one-to-one mappings of the measured values allow a water quality classification of a water sample without relation to any water quality index.

2.4.4. Limitations of Conventional Water Quality Indices

Water quality indices, as closed mathematical expressions, may have outliers contradicting the experience of water administrators. This conflict of evaluation of water quality a priori by sub-indices or corresponding measured values, and a posteriori on the base of the WQI values is crucial. The WQI values must respect the a priori water quality classification, based on the measured values. If not, the WQI value furnishes a wrong quality class, causing discussions of water experts about ambiguity, eclipsing, and insensitivity to individual parameters.

This subsection begins with an example where the quality classification by WQI is not correct. Assuming that ten quality parameters $p_1,\ldots,p_{10}$ correspond to sub-indices q_1, q_{10} in the range 0 – 100, the arithmetic mean of $q_1,\ldots, q_{10}$ is used here to demonstrate a possible WQI aggregation function:

$$WQI(q_1, \cdots, q_{10}) = \frac{1}{10} \sum q_i$$

The idea of a WQI is to account for all quality parameters to get an index value. Therefore, a water quality index may fail if the water is "bad" because only one individual parameter exceeds limitations. It is just an inherent flaw of a WQI generation. As a quality classification, we use exemplarily the classification of Table 2.9. The example is as follows:

Suppose $q_1 = 0, q_2 = 100, \ldots, q_{10} = 100$

with $q_1 = 0$ as the sub-index of chloride with a concentration of 10g/L, which is bad, and water quality must be classified as not useable.

The WQI calculation is:

$$WQI(0,100,\ldots,100) = \frac{1}{100} * (0 + 100 + \cdots + 100) = 90$$

The WQI range 90 classifies the water as drinking water. This ranking is not acceptable.

In the literature, the above behavior of a water quality index is defined as eclipsing.

Considering $q_1 = 60, \ldots, q_{10} = 60$, all sub-indices have the same value.

$$WQI(60,60,\cdots,60) = 60$$

The result of the calculation is confusing because water with WQI=90 is not useable, and water with WQI=60 is useable for irrigation.

Water with a lower WQI value may have a higher quality class than water with higher WQI value.

This result is nowhere stated in the literature and presented here for the first time. The fact that a lower WQI may furnish a better water quality is new and surprising. In practical application, sub-indices do not change in the above way such that a trend tracking over a period by a conventional WQI is meaningful. However, the application of a WQI for trend tracking in academia is not reliable. It means, before presenting a trend by WQI, it is necessary to control whether the change of sub-indices over time allows the trend tracking. In the same way, a comparison of the water quality of different water resources may produce the wrong result.

Before an exact approach to WQI generation could be established, the behavior of a WQI defined as a geometric mean will be examined. A geometric mean has a higher sensitivity to one individual bad parameter than the arithmetic mean.

$$WQI(0,100,\cdots,100) = \sqrt[10]{0 * 100 * \cdots * 100} = 0$$

Water is not useable because one sub-index has value 0, and the WQI-value of 0 gives the right quality classification as “not useable water” in this example.

However, water quality may improve over time. A geometrical mean does not distinguish between $WQI(0,20,\cdots,20)$ and $WQI(0,100,\cdots,100)$. Both terms furnish the index value 0. Therefore, water improvement cannot be seen. In practice, on the scale from 0 to 100, there is no significant difference between an index value of 0 and an index value of 1. Therefore, the index value 0 is often not used, and the index value one is used as the lowest sub-index such that the improvements over time are visible. However, with one as the lowest index value, there is the same problem for a geometrical mean as for arithmetic mean:

$$WQI(1,100,\cdots,100) = \sqrt[10]{1 * 100 * \cdots * 100} = 63.095$$

This result by geometrical mean classifies the water as "usable for irrigation" instead of "not usable" (according to Table 2.9).

A geometrical mean has better behavior in this situation than the arithmetic mean. Nevertheless, using highly salted water for irrigation would result in an ecological catastrophe and is not acceptable.

Furthermore $WQI(60, \cdots, 60) = \sqrt[10]{60 * \cdots * 60} = 60$. Even in the case of a geometrical mean as WQI function, water with a lower WQI value has better quality than water with a higher WQI.

Ambiguity and Eclipsing

Over the past decade, most water quality index research has emphasized the use of different formulae for aggregation. This process, which serves to consolidate all different quality scores obtained from rating curves into a single number, is the most crucial step in WQI design. Several studies have revealed that this simplification process has the potential for distortion of information. Wepener (Wepener et al., 2006) points out that the two common types of data loss are overestimation by WQI (eclipsing), underestimation by WQI (ambiguity).

Generally, aggregation functions, either additive or multiplicative forms, suffered from both eclipsing and ambiguous effects (Smith, 1990, Ott et al., 1978, Bolton et al., 1978, Cude, 2001, Liou et al., 2004). Couillard and Lefebrve noted that ambiguity occurs when an index's value exceeds a limit value where none of the individual quality scores do, especially for non-standardized indices (Couillard and Lefebvre, 1985). Simultaneously, eclipsing occurs when an overall index score is acceptable, but one or more of the parameters exceed acceptable limits. It can be easily seen when the weighted sum for aggregation is used (Couillard and Lefebvre, 1985). Certainly, Abbasi and Abbasi (Abbasi and Abbasi, 2012) explain that eclipsing occurs when the WQI ranks the water as acceptable, but the lowest sub-index ranks it as unacceptable; ambiguity occurs when each parameter is acceptable, but WQI ranks the water as unacceptable.

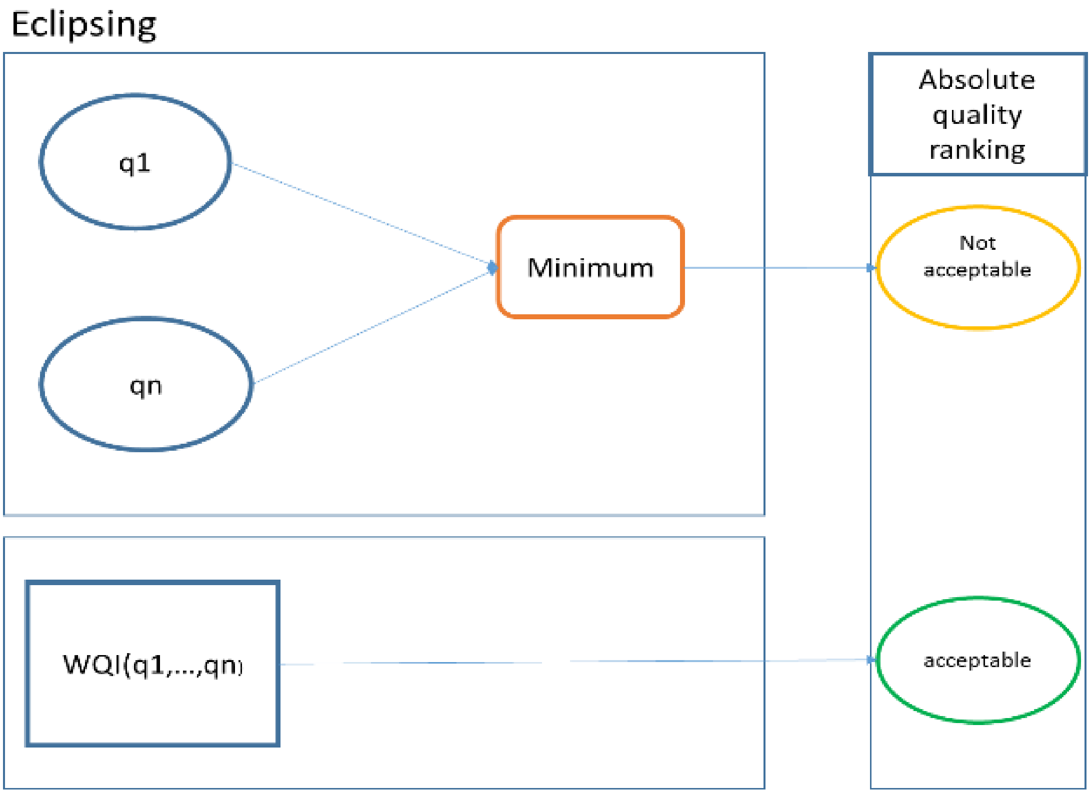

Figure 2.3: Clarification model of eclipsing

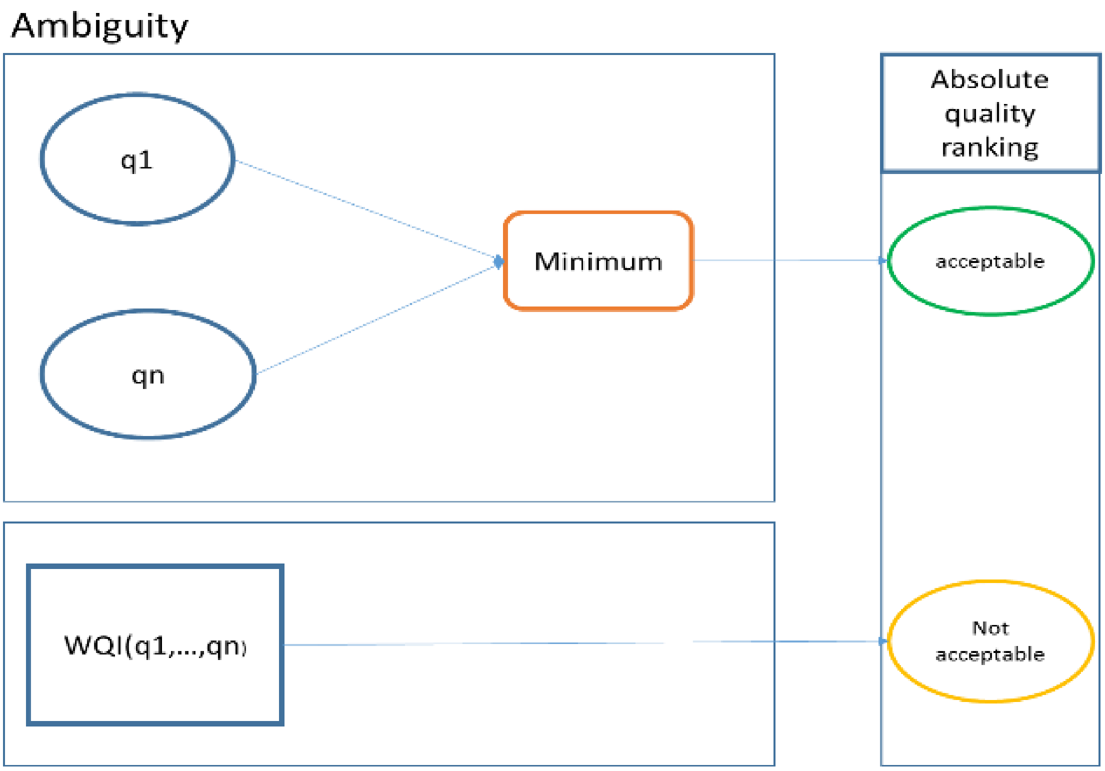

Figure 2.4: Clarification model of ambiguity

In the case of the example of the Red River of Pham (Pham et al., 2011) in Table 2.7, there is:

Table 2.11: Example of quality classification for the example of Red River

WQI-type	Basic WQI
WQI-Value	92.28 (Class 1)
Critical parameter	DO saturated 65.74 (Class 2)

Considering water of Class 1 as “acceptable”, the sub-index of DO is in Class 2, which is “not acceptable”. Because the WQI-value belongs to Class 1, the basic Vietnamese WQI suffers from eclipsing.

A natural WQI-function free of ambiguity and eclipsing is the minimum function (Abbasi and Abbasi, 2012):

$$WQI(q_1, \cdots, q_n) \; = min(q_1, \cdots, q_n)$$

Nevertheless, the minimum function fails to give a composite picture of water quality, since the minimum function does not reflect any change in the parameter, other than the lowest quality parameter. This function is unsuitable for aggregation. It can be used neither for trend tracking nor for the comparison of two sources.

3. Development of Modified Canadian Water Quality Index

3.1. Analysis of the Canadian Water Quality Index

In general, the CCME WQI is flexible concerning the type and number of water parameters tested in a period in the type of water body. CCME WQI compares observations to a benchmark instead of normalizing observed values to subjective rating curves, where the standard may be a water quality regulation or site-specific background concentration (CCME, 2011, Khan et al., 2004, Lumb et al., 2006). CCME WQI does not work with specific parameters, objectives, and periods and, indeed, could vary from region to region, depending on the local conditions (Khan et al., 2004). The index users do not need an expert committee to define weights for averages or sub-indices. Sub-indices are not generated in CCME WQI. The flexibility makes CCME WQI attractive and well applied by the water agencies in different countries with little modification. However, CCME WQI has also been pointed out by some researchers to exhibit sensitivities in statistical meaning.

The ability to represent measurements of a variety of parameters s in a single number and to combine various measurements with a variety of measurements in a single metric is advantageous to the CCME WQI. Moreover, the CCME WQI has limitations including the loss of information by combining several parameters to a single index value, the loss of interactions among parameters, the lack of portability of the index to different ecosystem types and the sensitivity of the results to the formulation of the index (Zandbergen and Hall, 1998). The CCME WQI was not developed to replace detailed parameter analysis, but rather as a tool to help water managers to communicate the overall quality of water in a more consistent and on-going manner.

Table 3.1 identifies the strengths and weaknesses of CCME WQI pointed out by Tyagi (Tyagi et al., 2013). The sensitivities of the CCME WQI are discussed in the following as the starting point for developing the new water quality index.

Table 3.1: Strengths and weaknesses of CCME WQI (Tyagi et al., 2013)

Strengths	Weaknesses
- Represents measurements of a variety of parameters in a single number - Flexibility in the selection of input parameters and objectives - Adaptability to different legal requirements and different water uses - Statistical simplification of complex multivariate data - Clear and intelligible diagnostic for managers and the general public - A suitable tool for water quality evaluation in a specific location - Easy to calculate - Tolerance to missing data - Suitable for analysis of data coming from automated sampling - Combines various measurements in a variety of different measurement units in a single metric	- Loss of information on a single parameter - Loss of information about the objectives specific to each location and particular water use - The sensitivity of the results to the formulation of the index - Loss of information on interactions between parameters - Lack of portability of the index to different ecosystem types - The choice of parameters, depending on the availability of data, can be manipulated easily (biased) - The same importance is given to all parameters - No combination with other indicators or biological data - Only partial diagnostic of the water quality - F_1 does not work properly when too few parameters are considered or when too much covariance exists.

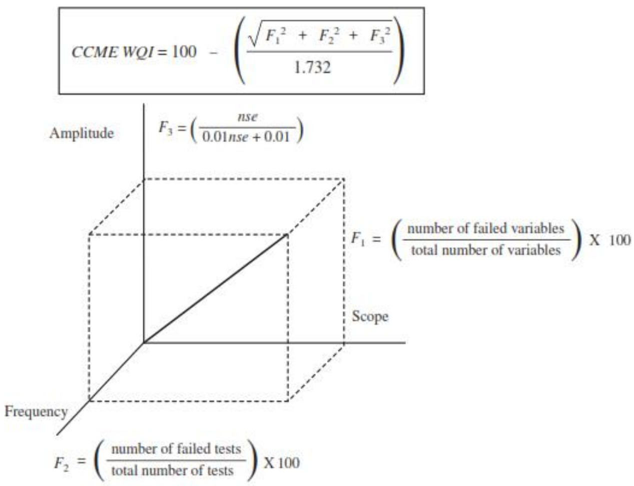

Figure 3.1: Graphical representation of the water quality index calculation, using the Euclidean length of the vector (F_1, F_2, F_3) in a three-dimensional space (Terrado et al. 2010)

The CCME WQI furnishes a mathematical framework for assessing ambient water quality conditions relative to water quality objectives. It is flexible concerning the type and number of water quality parameters to be tested, the period of application, and the water body type (stream, river reach, lake,…,etc.). Because these decisions are left to the user, the water bodies, periods, parameters, and appropriate objectives need to be defined before generating the index.

The water body to which the index will apply can be defined by one station (e.g., a monitoring site) or several different sample stations (e.g., sites throughout a lake). Individual stations work well, but only if there are enough data available to them. The more sample stations that are combined, the more general the conclusions will be.

The period chosen will depend on the amount of data available and the reporting requirements of the user. A minimum period of one year is often used because data are usually collected to reflect this period (monthly or quarterly monitoring data). Monitoring data from different years (and stations) may be combined even when monitoring in specific years is incomplete, but some data will be lost in detail.

The calculation of the CCME WQI requires at least four parameters to be sampled for a minimum of four times. However, the maximum number of parameters or samples is not specified. The selection of appropriate quality parameters for a particular region is necessary for the index to yield meaningful results. Choosing a small number of parameters, for which the objectives are not met, will provide a different picture than if a large number of parameters are considered, only some of which do not meet objectives. It is up to the user's professional judgment to determine which and how many parameters should be included in the CCME WQI to most adequately summarize water quality in a particular region.

3.1.1. Alarm Signals of CCME WQI Classification

The following notation of alarm signals is new and first proposed here. It produces a relation between the boundaries of the quality classes and the measured values.

It can be seen in Table 2.8, the water quality values range from 0 to 100 and are divided into five categories: Excellent (95-100), Good (80-94), Fair (65-79), Marginal (45-64) and Poor (0-44). This ranking is accorded to expert's opinions (the Delphi method), which has been done in France and forms the basis of the water quality ranking system used in Québec (CCME, 2003).

Considering the threshold value of 44 for the poor class exemplarily. According to Formula 2.8, CCME WQI = 44 means:

$$\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732} = 56$$

In the extreme case where $F_3 \approx 100$, the other factors must tend to 0 in order to fulfill this equation. Note that $F_3 = \frac{nse}{nse+1} * 100$ is always less than 100. Suppose that F_3 is precisely 100. For the calculation, this makes no difference with the case $F_3 \approx 100$, because of the continuity of the WQI-function in the three factors.

$$\text{CCME WQI} = 100 - \sqrt{\frac{1}{3} * (0^2 + 0^2 + 100^2)} = 100 - 57.73 = 42.27$$

This result shows that even water violating regulation thresholds (in this case, F_3) can have a water quality index near the upper bound of the poor quality class as long as this violation is very rare (F_2) and affects only one quality component (F_1). It is important to note that $F_3 \approx 100$ in this example is compensated by a perfect statistical behavior of the test series (F_1, F_2). More interesting is what happens when there is no compensation amongst the factors, i.e. when all factors are equal.

$$F_1 = F_2 = F_3 = F$$

It follows that

$$CCMEWQI(F_1, F_2, F_3) = 100 - \sqrt{\frac{1}{3} * (F^2 + F^2 + F^2)} = 44$$

$$100 - F = 44$$

Which means $F_1 = F_2 = F_3 = F = 56$

These are the alarm signals for water control.

$F_1 = 56$	56% percent of the monitored quality components have at least one *failed test* in the monitored region or period
$F_2=56$	56% of all tests failed
$F_3 = 56$	$\frac{nse}{nse+1} * 100 = 56$ or nse $= 1.27$ It means each quality component has a concentration 1.27 times higher than that allowed by regulation.

Finally, the alarm signals for all quality classes are presented in Table 3.2 to illustrate better how to interpret the quality index values.

Table 3.2: Alarm signals and the index value

Class	Description	Range	Alarm signal	Alarm Signal of the measured value
5	Excellent	95 - 100	≤ 94	> 1.06 * threshold of regulation
4	Good	80 - 94	≤ 79	> 1.26 * threshold of regulation
3	Fair	65 - 79	≤ 64	> 1.56 * threshold of regulation
2	Marginal	45 - 64	≤ 44	> 2.27 * threshold of regulation
1	Poor	0 - 44		

Table 3.2 shows the excellent water quality is in the index range of 95 to 100. If the index value tends downwards to 94, then this is an alarm signal that water could change to worse quality. An index value of 94 corresponds to a measured value that is 1.06 * threshold of regulation, refer to previous calculation. When a measured value is 6% higher than the threshold of the regulation, water quality could change from excellent to good, if the number of *failed tests* or *failed parameters* is too high. Therefore, the implementation of alarm signals makes sense.

3.1.2. Behaviors of CCME WQI

The strange behavior of CCME WQI due to factor F_1 in practical applications raised many discussions. CCME has asked the consulting agency Gartner and Lee (CCME, 2006) to find the solution. Gartner and Lee's study produced results that assessed the sensitivities of CCME WQI quantitatively to the number of parameters, parameter selection, number of measurements, and objective selection procedure. It proposed two alternative formulations of F_1, which are more correlated with all three factors. The reformulations of F_1, proposed by Gartner Lee Limited, reflect the following scenarios.

Scenario 1

$$F_1 = (F_{1a} + F_{1b})/2$$

Where:

- F_{1a} = (number of *failed parameters*/total number of parameters)*100 (same as the current formulation of F_1)
- F_{1b} = (number of samples showing values that exceed guidelines or objectives/total number of samples)*100

Scenario 2

$$F_1 = F_{1a}, \qquad if\ F_2 > 10$$

$$F_1 = (0.5 * F_{1a}), if\ F_2 \le 10$$

Where

- F_{1a} = (number of *failed parameters*/total number of parameters)*100 (same as the current formulation of F_1)
- F_2 = (total number of *failed tests*/total number of tests)*100.

The formulation of F_1 (in scenario 1) proposed by them produced the index most evenly correlated with all factors, while the second alternative formulation of F_1 (in scenario 2) tends to produce the highest WQI values and rankings. However, they have the same problem. In both scenarios, the effect of F_1 is at least half the responsibility relative to CCME WQI. By Gartner and Lee, the second formulation of F_1 discounts occasional exceedances of guidelines; if the frequency of exceedances within the index calculation period is less than or equal to 10%, the current F_1 formulation is divided by 2 (CCME, 2006).

CCME WQI, in its original form, was further used. The problems caused by F_1 and F_2 are presented in a new way in order to find a better solution.

Pathological Memory Effect of CCME WQI due to F_1

By defining the factors in Section 2.3.5, F_1 can only grow over time, while F_2, F_3, can decrease when water quality gets better along the time axis. The behavior of F_1 is reinforced by the fact that CCME WQI uses the Euclidean length of a vector with the factors as coordinates, compare to Figure 3.1. This different behavior of F_1 gave rise to some negative apprehension with the use of CCME WQI.

The following example, modified from CCME guidelines, helps to understand different behavior of F_1 over time.

Table 3.3: Example of CCME (CCME, 2001) modified by the author

DATE	DO mg/l	pH	TP mg/l	TN mg/l	FC CFU/100ml	As mg/l	Pb mg/l	Hg g/l	2,4-D g/l	Lindane g/l
7-Jan-97	**4.9**	**6.4**	**0.06**	**1.01**	**401**	**0.051**	**0.0041**	**0.11**	**4.1**	**0.011**
4-Feb-97	11.0	7.9	0.005	0.170	<4	<0.0002	0.0004	<0.05		
4-Mar-97	11.5	7.9	0.006	0.132	4	<0.0002	<0.0003	<0.05		
8-Apr-97	12.5	7.9	0.05	0.428	<4	<0.0002	0.0008	<0.05	0.004	<0.005
6-May-97	10.4	8.1	0.042	0.250	<4	0.0002	0.0008	<0.05		
3-Jun-97	8.9	8.2	0.05	0.707	26	0.0006	0.0013	<0.05		
Objective	*>=5*	*6.5-9.0*	*0.05*	*1*	*400*	*0.05*	*0.004*	*0.1*	*4*	*0.01*
Bold values do not meet the objectives										

This example uses a simplified data set from North Saskatchewan River at Devon, Alberta. Ten varibales are considered in the index calculation: dissolved oxygen (DO), pH, total phosphorus (TP), total nitrogen (TN), fecal coliform bacteria (FC), arsenic (As), lead (Pb), mercury (Hg), 2,4-D and lindane. The example period is 6 months (January 1997 - June 1997). The sampling frequency at this site is monthly for most varibales (one missing mercury sample) and quarterly for pesticides. The index calculations are shown as below.

All tests on 7-Jan-97 are failed. There was no violation of regulation for the rest of the year.

$$F_1 = \left(\frac{10}{10}\right) * 100 = \mathbf{100}$$

$$F_2 = \left(\frac{10}{52}\right) * 100 = \mathbf{19.23}$$

$$nse = \left(\frac{0.02 + 0.02 + 0.2 + 0.01 + 0.00025 + 0.002 + 0.0025 + 0.1 + 0.025 + 0.1}{52}\right) = \mathbf{0.0235}$$

$$F_3 = \left(\frac{0.0235}{0.01 * 0.0235 + 0.01}\right) = \mathbf{2.30}$$

$$CCMEWQI = 100 - \sqrt{\frac{100^2 + 19.23^2 + 2.30^2}{3}} = \mathbf{41.19}$$

When the evaluation continues for 6 months more. The evaluation period is now for one year (1997) and all tests on 7-Jan-97 are failed.

Table 3.4: Example of CCME (CCME, 2001) modified by the author

DATE	DO mg/l	pH	TP mg/l	TN mg/l	FC CFU/100ml	As mg/l	Pb mg/l	Hg g/l	2,4-D g/l	Lindane g/l
7-Jan-97	**4.9**	**6.4**	**0.06**	**1.01**	**401**	**0.051**	**0.0041**	**0.11**	**4.1**	**0.011**
4-Feb-97	11.0	7.9	0.005	0.170	<4	<0.0002	0.0004	<0.05		
4-Mar-97	11.5	7.9	0.006	0.132	4	<0.0002	<0.0003	<0.05		
8-Apr-97	12.5	7.9	0.05	0.428	<4	<0.0002	0.0008	<0.05	0.004	<0.005
6-May-97	10.4	8.1	0.042	0.250	<4	0.0002	0.0008	<0.05		
3-Jun-97	8.9	8.2	0.05	0.707	26	0.0006	0.0013	<0.05		
8-Jul-97	8.5	8.3	0.017	0.153	9	0.0002	0.0004			
5-Aug-97	7.5	8.2	0.008	0.153	8	<0.0002	<0.0003	<0.05	<0.005	<0.005
2-Sep-97	9.2	8.2	0.006	0.130	12	0.0003	0.0018	<0.05		
7-Oct-97	11.0	8.1	0.008	0.093	12	<0.0002	0.0011	<0.05	<0.005	<0.005
4-Nov-97	12.1	8.0	0.006	0.296	8	<0.0002	0.0004	<0.05		
1-Dec-97	13.3	8.0	0.004	0.054	4	<0.0002	<0.0003	<0.05		
Objective	*>=5*	*6.5-9.0*	*0.05*	*1*	*400*	*0.05*	*0.004*	*0.1*	*4*	*0.01*

The calculation is as follow:

$$F_1 = \left(\frac{10}{10}\right) * 100 = \mathbf{100}$$

$$F_2 = \left(\frac{10}{103}\right) * 100 = \mathbf{9.71}$$

$$nse = \left(\frac{0.02 + 0.02 + 0.2 + 0.01 + 0.00025 + 0.002 + 0.0025 + 0.1 + 0.025 + 0.1}{103}\right) = \mathbf{0.0119}$$

$$F_3 = \left(\frac{0.0119}{0.01 * 0.0119 + 0.01}\right) = \mathbf{1.17}$$

$$CCMEWQI = 100 - \left(\frac{\sqrt{100^2 + 9.7^2 + 0.5^2}}{1.732}\right) = \mathbf{41.99}$$

It can be seen that the CCME WQI values in both situations barely change (41.19 and 41.99). Based on the classification table (Table 2.8), the water quality is poor (0-44): Water quality is almost always threatened or impaired; conditions usually depart from natural or desirable levels. It can be seen that *failed tests* on 7-Jan-97 disqualifies water as inadequate for the whole year of 1997. Assuming that all samples stay within the thresholds of the regulation in the following nine years, calculating CCME WQI for the entire ten years results in poor water quality only because of the first failed sample. From this, the question is raised about whether F_1 plays a vital role in the CCME WQI assessment. Does $F_1=100$ consequently mean that water quality is poor? An analysis is carried out to address these questions as follows.

The aggregation equation of CCME WQI is written as:

$$CCME\ WQI = 100 - \sqrt{(F_1^2 + F_2^2 + F_3^2) * \frac{1}{3}} \qquad (3.1)$$

In the relative comparison to the factor F_1:

$$CCME\ WQI = 100 - \sqrt{(F_1^2 + F_2^2 + F_3^2) * \frac{1}{3}} \leq 100 - \sqrt{\frac{F_1^2}{3}}$$

If in the considered period or region all components have at least one *failed test*, then $F_1 = 100$ and

$$CCME\ WQI = 100 - \sqrt{(F_1^2 + F_2^2 + F_3^2) * \frac{1}{3}} \leq 100 - \sqrt{\frac{100^2}{3}} < 43$$

CCME WQI supports the evaluation of WQI for a set of samples over more extended periods. Considering the evaluation with CCME WQI over the years where in the first year, each component has at any point in time a *failed test*, and after this year, from the second year onwards, there is no *failed test*. The CCME WQI is expected to be good throughout the period. However, from $F_1 = 100$, it follows that $WQI < 43$, the badness of the components in the first year will never be forgotten. It can be revealed from the example that the factor F_1 is intended to determine the scope of guideline exceedances. F_1 increases with the number of measured parameters exceeding their water quality objectives during the index periods, which in this research, is named as the ***pathological memory effect***.

Strange Behavior of CCME WQI (in the case $F_1=F_2=100$, $F_3 \approx 0$)

If all tests are bad, we have $F_1=F_2=100$. Even if the failures are minimal, $F_3 \approx 0$, then

$$CCME\ WQI = 100 - \sqrt{(F_1^2 + F_2^2 + F_3^2) * \frac{1}{3}} \leq 100 - \sqrt{\frac{100^2 + 100^2 + 0^2}{3}} < 18.36$$

The two factors F_1 and F_2 indicate whether water quality is under control. However, in this case, where the violations of regulation are negligible, water quality itself is not bad. F_1 and F_2 overestimate the need for water quality control.

The pathological memory effect and this example show that for smoothening adverse effects, it should be better to use the multiplication (*) instead of the addition (+) in the formula. This modification will be discussed in the following section.

3.2. Modified Canadian Water Quality Index

3.2.1. Definition of MCWQI

The inherent mathematical problems of a standard method render it to be ill-suited for a variety of situations. Namely, those in which the pathological memory effect, the above-mentioned strange behaviors, and the resulting overestimated need for water quality control (even if the water quality is sufficient) occur. Therefore, it is pertinent that a modification of the CCME WQI that minimizes these issues should be carried out. The generation of a WQI function is a priori, not a mathematical problem. It depends highly on the perception of water quality. Based on this perception, it makes sense to decide the particular choice of a common type:

- The arithmetic mean is used to define the average contribution of each part of an object.
- Unlike the arithmetic mean, the geometric mean is used when considering an object as a whole. For this reason, it obtains the consensus of different viewpoints of an object. A standard application is the calculation of the average rate of change of an object.

Regarding the discussion from the previous section, CCME WQI has a pathological memory effect due to the factor F_1 (*Scope*). In CCME WQI, each factor adds its contribution to the index values and does not compensate for the proportion of other factors. The expression $\sqrt{(F_1^2 + F_2^2 + F_3^2) * \frac{1}{3}}$ is the Euclidean length of a vector with the three coordinates $\frac{1}{\sqrt{3}}F_1$, $\frac{1}{\sqrt{3}}F_2$ and $\frac{1}{\sqrt{3}}F_3$.

This coordinate-system should have orthogonal independent axes. Otherwise, the application of the Euclidean length of a vector is obsolete. The use of F_1, F_2, and F_3, as coordinates of vectors, is not correct because coordinates require free parameter coordinates. However there are dependencies: $F_1 = 0$ implies $F_2 = 0$ and $F_3 = 0$. In the same manner $F_2 = 0$ implies $F_1 = 0$ and $F_3 = 0$; $F_3 = 0$ implies $F_1 = 0$ and $F_2 = 0$. This purely mathematical argument shows that the Euclidean length is not the most suitable model.

Water quality is defined by the collection of *excursions* in the considered period. Therefore, it is obvious to consider this collection thoroughly and the factors F_1, F_2, F_3 as different viewpoints to the entire group.

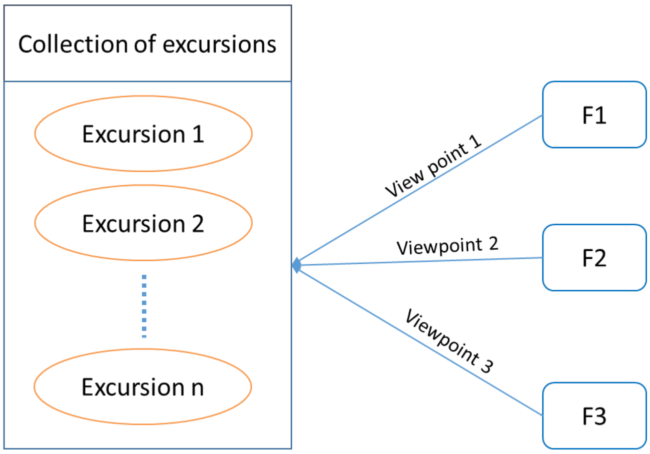

Figure 3.2: Factors of CCME WQI as viewpoints to water quality

As a rule of thumb, this suggests the application of geometric mean. A more practical argument is that the effort of Gartner and Lee (CCME, 2006) to save the plus sign in the formula of CCME WQI did not change the situation fundamentally. Following this idea, a new WQI is proposed based on the modification of CCME WQI using multiplication and geometric mean. From this point on, the new WQI will be called as Modified Canadian Water Quality Index (MCWQI). The essential idea of MCWQI is considering the factors F_1, F_2, F_3 as different viewpoints of water quality. The equation of MCWQI, which is introduced in the publication (Dao et al., 2020), is written below.

$$\boldsymbol{MCWQI} = \mathbf{100} - (\boldsymbol{F_1} * \boldsymbol{F_2} * \boldsymbol{F_3})^{\frac{1}{3}} \tag{3.2}$$

Alternatively, in another way of writing

$$\boldsymbol{MCWQI} = \mathbf{100} - \sqrt[3]{\boldsymbol{F_1} * \boldsymbol{F_2} * \boldsymbol{F_3}} \tag{3.3}$$

The formula of MCWQI shows that the factors F_2 and F_3 smoothen the memory effect of CCME WQI due to F_1 by using multiplication sign (geometric mean) instead of the plus sign (Euclidean length). According to the literature (Gallant, 2020), the geometric mean is most appropriate for series data and provides a far more accurate measurement than the arithmetic mean.

In the same manner, F_3, when tending to 0, smoothens the effect of F_1 and F_2. MCWQI has a higher value than CCME WQI because it has a smaller memory. The MCWQI considers different viewpoints of water quality (F_1, F_2, and F_3) by finding a compromise among these perceptions. Different viewpoints of the same thing may have dependencies.

The following questions arose during the study of CCME WQI: what is the primary failure in the approach of CCME using F_1, F_2, and F_3 as coordinates of a vector? Why F_1, F_2, F_3 are not looked upon as different pieces of a puzzle that fit together? Why should the perception of different viewpoints on the same subject do persist? Pieces that compose a whole are not allowed to have dependencies, while F_1, F_2, F_3 do, as shown above.

3.2.2. Quality Ranking for MCWQI

The MCWQI usually produces results that are different from those of the current CCME WQI. Therefore, the value classification of CCME WQI needs to be adjusted to suit the MCWQI. The following properties justify this:

- For $F_1=F_2=F_3=F$, it follows:
  MCWQI (F_1, F_2, F_3) = CCME WQI (F_1, F_2, F_3) = 100-F for all F
  MCWQI has the same alarm signals as CCME WQI.
- Continuity of both index-functions concerning the arguments (F_1, F_2, F_3)
- MCWQI reflects the quality ranking of CCME WQI better than CCME WQI because it is free of the pathological memory effect, as shown in Section 3.3.
- MCWQI reflects the quality ranking better than CCME WQI

For the sake of completeness, it is stated that always CCME WQI <= MCWQI

It is well-known mathematically that the geometrical mean of three numbers is always less than or equal to the arithmetic mean of those numbers.

$$\sqrt[3]{F_1^2 * F_2^2 * F_3^2} \leq \frac{(F_1^2 + F_2^2 + F_3^2)}{3}$$

Taking the square root on both sides leads to

$$\sqrt[3]{F_1 * F_2 * F_3} \leq \sqrt{\frac{(F_1^2 + F_2^2 + F_3^2)}{3}}$$

Square root on the left side of the inequation is performed by changing the term

$$(F_1^2 * F_2^2 * F_3^2) \text{ into } (F_1 * F_2 * F_3)$$

On the right side of the inequation, the square root sign is explicitly used.

Hence

$$100 - \sqrt{\frac{(F_1^2 + F_2^2 + F_3^2)}{3}} \leq 100 - \sqrt[3]{F_1 * F_2 * F_3}$$

$$CCME\ WQI(F_1, F_2, F_3) \leq MCWQI(F_1, F_2, F_3)$$

3.2.3. MCWQI for Single Parameters

As mentioned above, the usage of CCME WQI requires at least four parameters, sampled a minimum of four times (CCME, 2001). Therefore, it is impossible to calculate the most critical parameter by CCME

WQI. In order to have a detailed and composite picture of water quality, the individual parameters and their trends must be considered besides the water quality index. In consequence, the applicability of MCWQI must also extend to situations with a single parameter. In the case when only one quality parameter has been measured for at least two samples in a body of water, the index calculation is by including the two factors F_2 and F_3 in the same manner as that of three factors. It is justified by the following reasoning, which shows that F_1 depends on F_3, and F_2 does not depend on F_3.

- if $F_3 = 0$ then there is no violation of the regulation, hence $F_1=0$
- If $F_3 > 0$, then at least one bad quality parameter exists. Because there is only one bad quality parameter, this implies $F_1=100$.
- F_2 is needed. Because there is more than one sample, and it is not possible to say whether there is only one sample with a failed test or multiple samples with failed tests.

Consequently, F_1 is entirely determined by F_3 and, therefore, it is not necessary for the formula of MCWQI for single parameters, but F_2 and F_3 are needed. Applied to the MCWQI, this means in the case where there is one quality parameter in a sample series of at least two samples.

The alternative formula is:

$$\boldsymbol{S-MCWQI = 100 - \sqrt{F_2 * F_3}} \qquad (3.4)$$

The notation S-MCWQI stands for the application of the MCWQI method to the case of a single parameter.

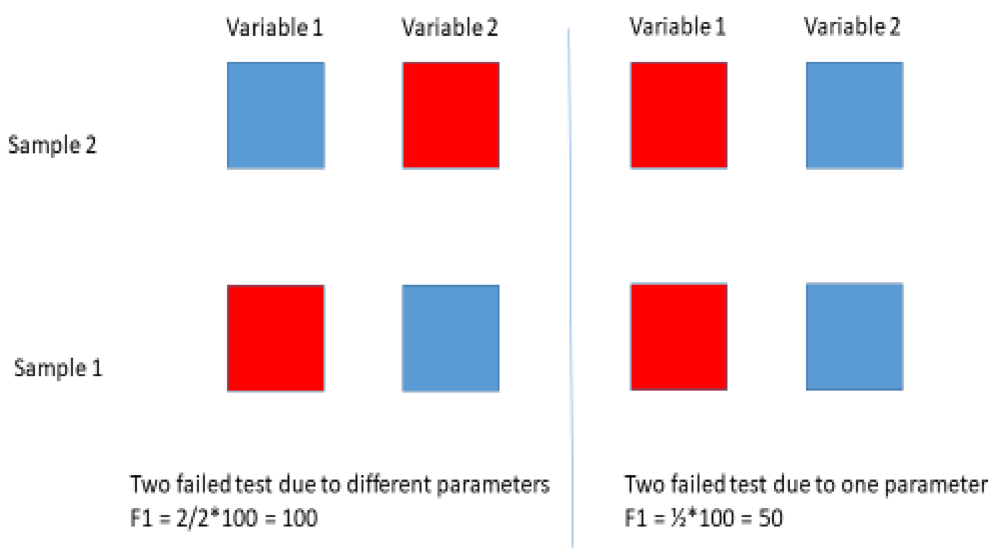

Figure 3.3: Different cases of failed parameters (red: failed, blue: good)

In Figure 3.3, the term “test” means the measurement of one quality parameter at a given time point. The term “sample” describes the collection of all tests taken at the same time point

The advantage of this adaptation is that S-MCWQI (p) uses the full range from 0 to 100. However, MCWQI (see Formula 3.3), applied to a series of samples with one single quality parameter, has a range gap [43, 100). This is not a good indicator of a series of tests with one single parameter.

- MCWQI(p) = 100, if $F_3=0$ (hence $F_1=F_2=0$)
- MCWQI(p) < 43, if $F_3>0$ (hence $F_1=100$, in this case of one single quality parameter)

The formula of S-MCWQI is applicable for the cases of a sample series with one quality parameter and more than one sample and by similar reasoning for one sample with more than one quality parameter. A similar argumentation is applicable to CCME WQI.

$$S - CCME\ WQI = 100 - \frac{\sqrt{F_2^2 + F_3^2}}{\sqrt{2}} \qquad (3.5)$$

3.2.4. Principal Remarks about the Application of CCME WQI and MCWQI

CCME WQI and MCWQI are based on a regulation that treats all quality parameters in the same manner. Namely, the regulation is violated if any of the quality parameters are out of regulation. It seems that all individual parameters have the same weight and effect by CCME WQI and MCWQI. However, the equalization of the effects of individual parameters' mutual reinforcement is a question of the regulation's design and must be done by the regulation. CCME WQI and MCWQI do not answer the question of whether water generally has good quality. They measure more the degree of violation of the relevant regulation over a period. Because the regulation equalizes the effects of mutual reinforcement of individual parameters, CCME WQI and MCWQI based on that regulation may treat all quality parameters in the same manner. If the WQI generation is based on sub-indices without reference to regulations, the effects of mutual reinforcement should be considered.

As discussed by CCME (CCME, 2001), it is suggested that at a minimum, four parameters sampled at least four times be used in the calculation of index values. In this research, we use CCME WQI and MCWQI for trend tracking year by year. For each year, there are two samples at each sample station with about 20 parameters contrarily to the above recommendation. However, from a mathematical viewpoint, in that case (F_1, F_2, F_3) is not over-determined, because, if there are two quality parameters and more than one sample in the series, then it cannot be concluded from F_2 and F_3, whether the failed tests are due to one quality parameter or both. The factors F_1, F_2, and F_3, are needed as factors. Hence, CCMEWQI (F_1, F_2, F_3) and MCWQI (F_1, F_2, F_3) are well defined in that case. Further, there are 40 tests yearly, such as the statistical basis is sufficient compared to the minimum of sixteen tests recommended above by CCME (CCME, 2001).

3.3. Example Calculations

3.3.1. Example of the Pathological Memory Effect due to the Factor F_1

The calculation to Table 3.3 has the result $F_1=100$, $F_2=19.23$, $F_3=2.30$

The CCME WQI is calculated by combining the three factors using root-mean-square aggregation	The MCWQI is calculated by combining the three factors using the geometric mean
$CCME\ WQI = 100 - \sqrt{\frac{100^2+19.23^2+2.30^2}{3}} = \mathbf{41.19}$	$MCWQI = 100 - \sqrt[3]{100 * 19.23 * 2.30} = \mathbf{83.59}$
According to table 2.8, the water quality is poor	According to table 2.8, the water quality is good

Table 3.4 has the result $F_1=100$, $F_2=9.71$, $F_3=1.17$

$CCME\ WQI = 100 - \sqrt{\frac{100^2+9.71^2+1.17^2}{3}} = \mathbf{41.99}$	$MCWQI = 100 - \sqrt[3]{100 * 9.71 * 1.17} = \mathbf{89.56}$
According to table 2.8, the water quality is poor	According to table 2.8, the water quality is good

As the results, the CCME WQI gives the number of 41.19 and 41.99 while MCWQI gives the number of 83.59 and 89.56. However, it can be seen that the CCME WQI values barely change while the MCWQI see an increase of about 6 point. This example shows that the quality status of each parameter improves over time. MCWQI reflects water quality for one year as expected, while CCME WQI defines water quality as poor for the considered whole period due to the pathological memory effect. As shown above, F_1 can only develop to the worse, and the usage of the length of a vector in the formula of CCME WQI causes the pathological memory effect. In the formula of MCWQI, the effect of F_1 can be smoothed by the other factors and is more accurate than CCME WQI.

3.3.2. Example of the Weakness of CCME WQI due to the Factor F_2

In the example below, all tests fail but only marginally, such that water quality cannot be poor. The statistical factor F_2 reinforces the negative effect of F_1, leading to a CCME WQI value near about 18, classifying water quality as very poor over the period. The example is very theoretical, but it shows a further weakness of the definition of CCME WQI.

Table 3.5: Example case, modified by author from (CCME, 2001)

DATE	DO mg/l	pH	TP mg/l	TN mg/l	FC CFU/100ml	AS mg/l	Pb mg/l	Hg g/l	2,4-D g/l	Lindane g/l
7-Jan-97	**4.99**	**6.49**	**0.051**	**1.01**	**401**	**0.051**	**0.0041**	**0.11**	**4.1**	**0.011**
4-Feb-97	**4.99**	**6.49**	**0.051**	**1.01**	**401**	**0.051**	**0.0041**	**0.11**		
4-Mar-97	**4.99**	**6.49**	**0.051**	**1.01**	**401**	**0.051**	**0.0041**	**0.11**		
8-Apr-97	**4.99**	**6.49**	**0.051**	**1.01**	**401**	**0.051**	**0.0041**	**0.11**	**4.1**	**0.011**
6-May-97	**4.99**	**6.49**	**0.051**	**1.01**	**401**	**0.051**	**0.0041**	**0.11**		
3-Jun-97	**4.99**	**6.49**	**0.051**	**1.01**	**401**	**0.051**	**0.0041**	**0.11**		
8-Jul-97	**4.99**	**6.49**	**0.051**	**1.01**	**401**	**0.051**	**0.0041**			
5-Aug-97	**4.99**	**6.49**	**0.051**	**1.01**	**401**	**0.051**	**0.0041**	**0.11**	**4.1**	**0.011**
2-Sep-97	**4.99**	**6.49**	**0.051**	**1.01**	**401**	**0.051**	**0.0041**	**0.11**		
7-Oct-97	**4.99**	**6.49**	**0.051**	**1.01**	**401**	**0.051**	**0.0041**	**0.11**	**4.1**	**0.011**
4-Nov-97	**4.99**	**6.49**	**0.051**	**1.01**	**401**	**0.051**	**0.0041**	**0.11**		
1-Dec-97	**4.99**	**6.49**	**0.051**	**1.01**	**401**	**0.051**	**0.0041**	**0.11**		
Regulation	>=5	6.5 - 9.0	0.05	1	400	0.05	0.004	0.1	4	0.01
Bold values do not meet the objectives										

Scope: All of parameters failed their respective objective at least once time, therefore: $F_1 = 100$

Frequency: There are 103 tests, all of them failed their respective objective, then: $F_2 = 100$

Amplitude: In this example, all tests are failed by greater than the objective, therefore: $F_3 = 2.44$

$CCME\ WQI = 18.34$ According to Table 2.8, water quality is very poor	$MWQI = 71.01$ According to Table 2.8, water quality is fair

MCWQI supports the perception that when the water has good quality determined by F_3, the parameters F_1 and F_2, which are more like parameters for the water quality control, are not so important. Because of the minimal violations of the regulation, water quality is therefore not calculated as poor by MCWQI. Based on this perception, MCWQI reflects water quality for one year better than CCME WQI. MCWQI smoothens the effect of F_1 and F_2 by the multiplication with F_3 and is a better choice.

3.4. Remarks

In standard cases, CCME WQI and MCWQI do not differ much. Mathematically this is because $CCMEWQI(F_1, F_2, F_3) = MCWQI(F_1, F_2, F_3) = 100 - F$, and CCME WQI and MCWQI are continuous functions. Because of this behavior of CCME WQI and MCWQI, the same quality classification for both water quality indices can be used. The conclusion is that CCME WQI is not always bad. However, MCWQI works better in situations where CCME WQI does not. Therefore MCWQI is proposed as the first choice in this research.

4. Case Study

4.1. Vietnamese Mekong Delta

4.1.1. General Information

As reported by WEPA (WEPA, 2019), the groundwater resources in Vietnam are abundant, with the total potential exploitable reserves of the aquifers estimated at approximately 60 billion m^3 per year. The availability varies from Mekong Delta with abundant resources to the North Central Region with somewhat limited resources. Despite the abundant storage, only around 5% of the total is exploited for the whole country. The abstraction of groundwater also varies. For example, groundwater exploitation is severe in the Northeast since the reserves are scattered and diverse. On the other hand, groundwater is exploited heavily for the irrigation of cash crops in the Central Highlands, resulting in shortages of water in parts of this region. In the Red River and Mekong River Deltas, groundwater is abstracted beyond Hanoi and Ho Chi Minh City's recharge capacity. The over-exploitation results in the falling of water tables – further causing land subsidence and saltwater intrusion, especially in the Mekong River Delta. Groundwater is emerging as a vital source of water for domestic, industrial, and agricultural uses. While the groundwater quality remains good, there are some pockets of contamination. There is evidence of pollution – from poorly maintained septic tanks, garbage dumping, industrial effluents, and overexploitation in parts of Hanoi, Ho Chi Minh City, and the Mekong River Delta. The economic liberalization, urbanization, industrialization, tourism development, and population growth depend extensively on the exploitation of natural resources, mostly water. This increased water demand and changes in water use, as well as the resulting conflicts in water usage, results in governance problems. Water resources management has been functional according to the national policy framework since the 1990s. In the following decades, water resources management has become more complicated with the Ministry of Natural Resources and Environment (MONRE). The water reservoir and water quality data are surveyed and reported frequently, in which the water quality monitoring data are collected and used for reporting the national environmental status every year by comparing individual parameters with the national standards.

The Vietnamese Mekong Delta, known as the Cuu Long or "nine dragons," is home to about 17 million inhabitants. On the authority of Ha (Ha et al., 2015), the Mekong Delta in Vietnam forms a triangle of 39.734km^2, stretching from Tien Giang in the east to An Giang and Dong Thap in the northwest, Ca Mau at the southernmost tip of Vietnam, the Gulf of Thailand to be the southwest, the East Sea to the south and southeast, and Cambodia to the north. Within Vietnam, the delta is divided into 13 provinces (Long An, Dong Thap, An Giang, Tien Giang, Ben Tre, Vinh Long, Tra Vinh, Hau Giang, Soc Trang, Bac Lieu, Kien Giang, Ca Mau provinces and Can Tho); the city of Can Tho could be considered the center of the Delta.

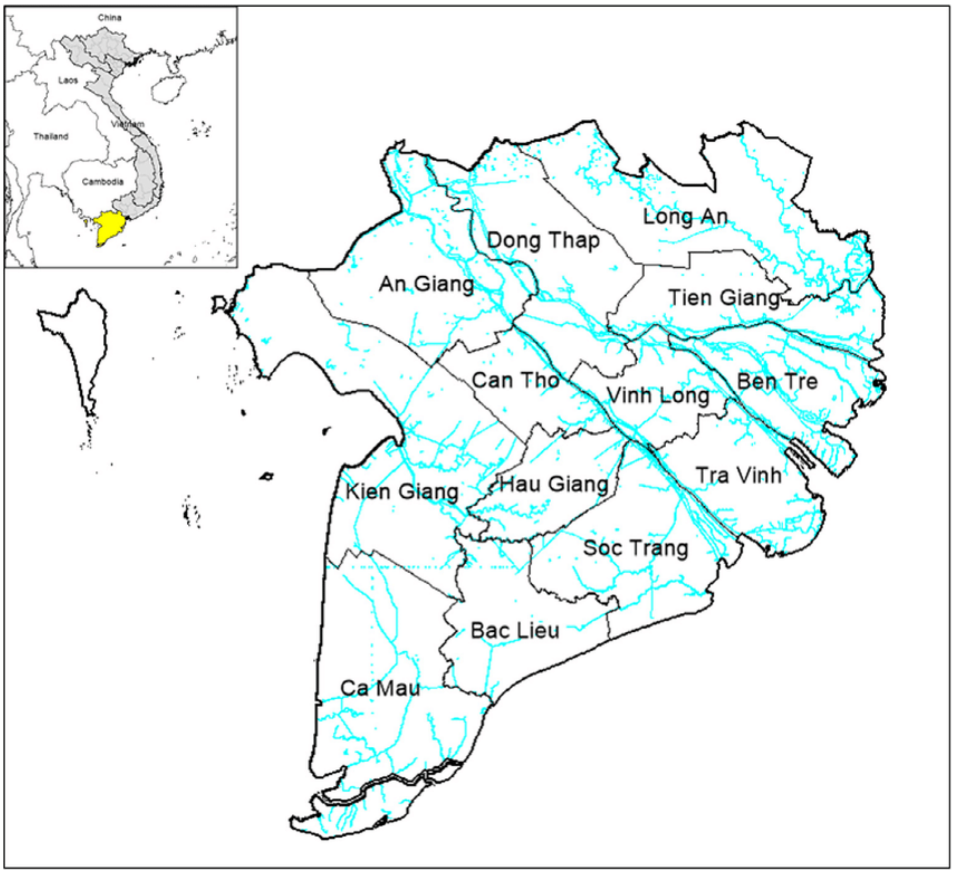

Figure 4.1: Location of the Mekong River Delta in the map of Vietnam (Yen et al., 2019)

With approximately 17 million people (nearly 20% of the Vietnamese population), the Mekong Delta is, similar to many deltas, densely populated. In 2012, only approximately 25% of the population lived in urban areas (compared to the national average of 32%), and 75% of the population was rural. The Mekong Delta river system consists of natural river systems and human-made canal systems. The central natural systems are the Tien River and Hau River system, the Vam Co River system, and the Cai Lon and Cai Be River system.

4.1.2. Groundwater Resources

The research of Wagner found that in Mekong Delta, there is a very heterogeneous structure of aquifers and aquicludes that intersect, and each hydrogeological unit consists of low permeable silt, clay, or silty clay upper part and a lower permeable part composed of fine to coarse sand gravel and pebble with a medium to high water yield (1→5l/s)(Wagner, 2012). The hydrogeological units are of artesian basin structure and can be distinguished into eight aquifers, namely, Holocene (qh), Upper Pleistocene (qp_3), Upper-Middle Pleistocene (qp_{2-3}), Lower Pleistocene (qp_1), Middle Pliocene (n_2^2), Lower Pliocene (n_2^1), Upper Miocene (n_1^3), and Upper-Middle Miocene (n_1^{2-3}) aquifers. Generally, the lithology of each aquifer consists of dining to coarse sand, gravel, and pebbles. The evolution and architecture of the Mekong Delta subsurface described in the report of Wagner (Wagner, 2012), shows that the sedimentary strata of the Mekong complex with relevance for groundwater supply last from the late Neogen (Miocene, Pliocene) up to recent Holocene time. Appendix 2. present a stratigraphic overview based on the geological studies by DGMS (DGMS, 2004, Wagner, 2012).

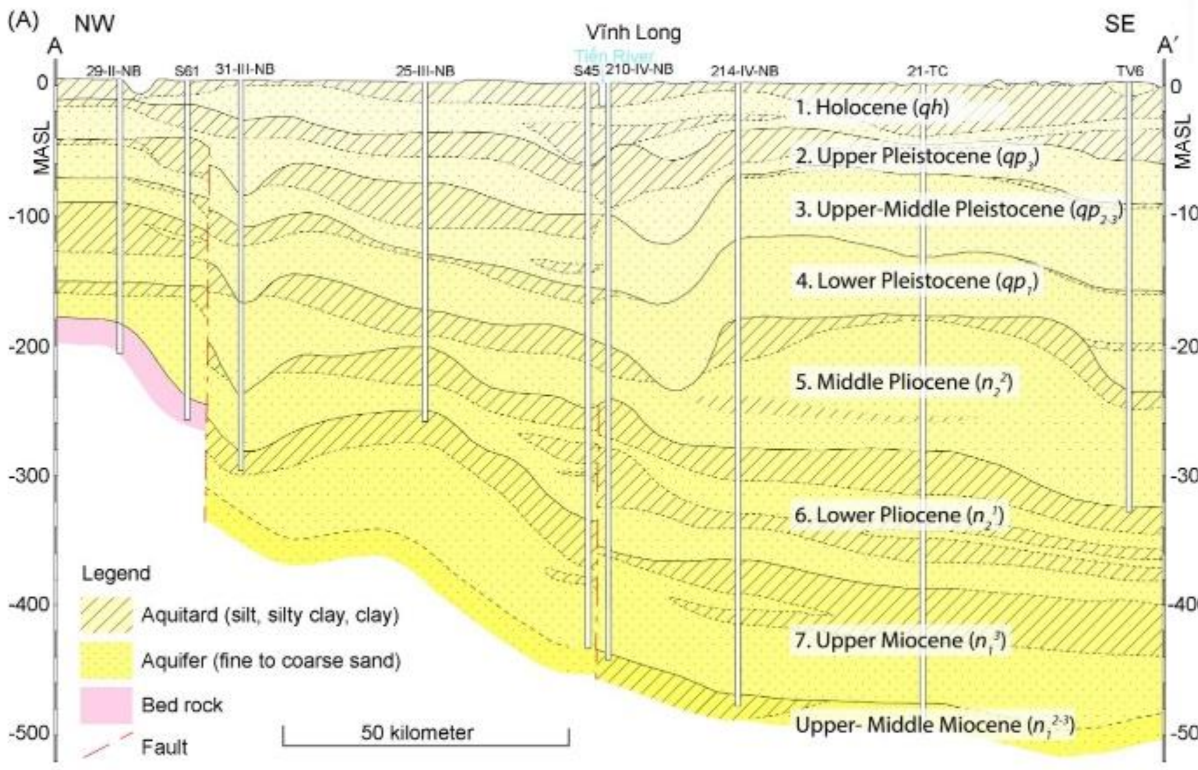

Figure 4.2: Hydrogeological cross-section with the interpretation of the aquifer-system (Minderhoud et al., 2017)

The cross-section illustrated in Figure 4.2 provides an overview of the spatial distribution and interconnection of the hydrogeological units within the complex architecture of the delta's subsurface.

Groundwater reserves have been assessed for four regions in the Delta:

- Dong Thap Muoi zone from the boundary of the Tien River up to the end area of Long An,
- The zone between two rivers, including the area between the Tien River and Hau River,
- Long Xuyen quadrangle zone, including the area from the Hau river Rach Gia – Ha Tien and the Gulf of Thai Lan,
- Ca Mau Peninsula zone.

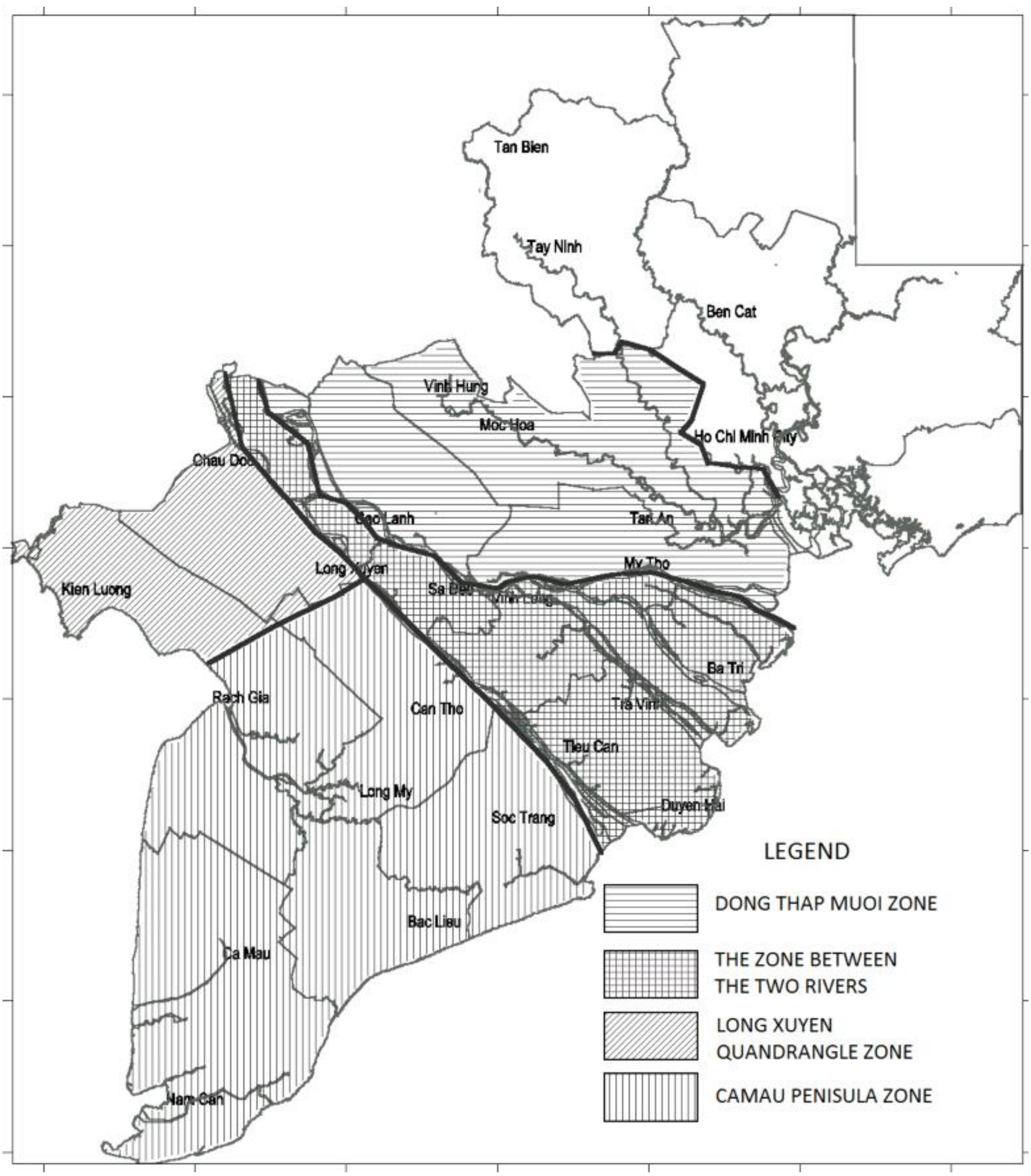

Figure 4.3: Hydrogeological - Groundwater zones in the Mekong Delta (Deltares, 2011)

As reported in (Ha et al., 2015), the usable fresh groundwater storage is approximately 22.5Mm^3/day. The usable saline groundwater storage is approximately 39.1 Mm^3/day. The results of an investigation in 2010 in 13 provinces/cities in the Mekong Delta pinpointed 553.135 exploitation wells with a total amount of groundwater abstraction of 1,923,681 m^3/day. Table 4.1 below shows the natural storage of groundwater in different aquifers. Vuong (Vuong B.T., 2014a) devided groundwater in Mekong Delta into 3 types of storage. Preatic (or gravity) storage occurs in unconfined aquifers, i.e. aquifers with a free water table. Elastic storage is the only storage occurring in confined (and semi-confined) aquifers, i.e. in aquifers without a water table, aquifer that are completely filled with water from floor to ceiling. Natural storage is the total volume of water in preatic and elastic storage. Due to the movement of saltwater, there are two kinds of groundwater in each storage: fresh groundwater and saline groundwater.

Table 4.1: Natural storage on the Mekong Delta (Vuong B.T., 2014a)

Aquifer		qp_3	qp_{2-3}	qp_1	n_2^2	n_2^1	n_1^3	Sum
Gravity storage m^3/day	Fresh GW	1,808,992	4,043,805	3,075,374	4,324,231	5,045,585	2,985,195	21,283,182
	Saline GW	5,892,479	6,004,019	5,974,966	7,449,900	5,475,699	5,915,494	36,712,557
Elastic storage m^3/day	Fresh GW	193,114	397,837	527,047	74,424	18,533	18,852	1,229,807
	Saline GW	516,710	649,651	1,061,648	125,920	23,035	34,804	2,441,768
Natural storage m^3/day	Fresh GW	2,002,106	4,441,642	3,602,421	4,398,655	5,064,118	3,004,047	22,512,989
	Saline GW	6,409,189	6,653,670	7,036,614	7,575,820	5,498,734	5,950,298	39,124,325

As mentioned above, groundwater is exploited for domestic, agricultural, and industrial needs, and hydraulic heads steadily declined in many aquifers over vast areas (Wagner, 2012). Hand-dug wells remain nationwide the primary source of water supply in rural areas, followed by drilling wells that are affordable only to wealthier households. The drilling capabilities improved during the 1960s. Therefore some wells with depths greater than 500m have been completed in various parts of the delta. Following UNICEF's interventions at the household level and the creation of the Center for Rural Water Supply and Sanitation (CERWASS), which set up small water supply stations for tapping groundwater in the region. Groundwater is currently accessed via unregulated private shallow tube-wells (more than one million) reaching depths of 80-120m and by regulated groundwater, plants accessing water in the deeper aquifers, at depths of 100-250m (Wagner, 2012).

In line with Deltares, the survey data of Hydrogeological Sub-division 806 in 2007 showed an estimated 465,230 groundwater abstraction wells with a total of 1,229,031 m^3/day, as shown in Table 4.2. This concerns mostly shallow dug wells that exploit only the Upper Holocene and Pleistocene aquifers.

Household shallow tube-wells access groundwater at a depth of 80-120, the wells for water supply units and industrial uses access groundwater at a depth of 100-250m with 60% of wells accessing the Pleistocene aquifer.

Water exploitation in the principal deeper aquifers is as follows:

- In aquifer qp_3 and $qp_{2\text{-}3}$: 588 wells occupied 59,6%
- In aquifer qp_2 and n_2^2: 164 wells, occupied 16,6%
- In aquifer n_2^1: 195 wells, occupied 20%
- In aquifer n_1^3: 38 wells, occupied 3,8%

Table 4.2: Number and density of groundwater abstraction wells by aquifer (Vuong B.T., 2014a)

No.	Province/City	Number of wells	Number of wells by aquifer							Density wells/km²
			qh	qp_3	qp_{2-3}	qp_1	n_2^2	n_2^1	n_1^3	
1	An Giang	6,374	302	4,571	877	0	662	2	0	1.8
2	Bac Lieu	93,369	0	12	74,644	18,688	24	0	0	36.0
3	Ben Tre	2,653	1,873	548	204	0	0	23	5	1.1
4	Ca Mau	67,328	0	0	16,135	8,535	42,353	304	0	12.6
5	Can Tho	48,797	0	0	48,693	0	105	0	0	34.9
6	Dong Thap	4,838	0	0	3,657	0	1,181	0	00	1.4
7	Hau Giang	40,572	0	9,821	28,638	2,113	0	0	0	25.3
8	Kien Giang	93,130	422	18,283	72,292	2,090	35	3	0	15.0
9	Long An	3,435	0	0	0	26	1,998	1,356	54	0.8
10	Soc Trang	80,069	804	011,051	65,311	2,814	4	0	85	24.8
11	Tien Giang	1,530	0	0	0	0	310	378	842	0.6
12	Tra Vinh	88,833	4,471	0	84,362	0	0	0	0	40.1
13	Vinh Long	22,207	0	0	22,191	0	0	16	0	15.1
Total		553,135	7,872	44,232	417,010	34,266	46,672	2,083	2,083	13.7

Table 4.3: Groundwater utilization in the Vietnam Mekong Delta (Deltares, 2011)

No	Province	Wells	Total amount (m^3/day)	Urban supply				Large rural supply				Small rural supply			
				Number	Total amount (m^3/day)	Aquifer	Depth (m)	Number	Total amount (m^3/day)	Aquifer	Depth (m)	Number	Total amount (m^3/day)	Aquifer	Depth (m)
1	Tra Vinh	88,923	147,301	8	32,210	qp_{2-3}	100-134	102	8,515	-	98-134	88,813	106,576	-	98-134
2	Soc Trang	50,111	100,090	12	31,903	-	-	109	8,199	qp_{2-3}	-	49,990	59,988	qp_{2-3}	-
3	Bac Lieu	88,741	63,681	1	15,165	qp_{2-3} qp_1 n_2^2	106-138 152-168 245	65	8,612	qp_{2-3} qp_1	80-142 146-154	88,675	39,904	-	-
4	Ca Mau	67,185	134,657	13	46,326	qp_{2-3} qp_1 n_2^2	90-110 206-260	132	7,883	qp_{2-3} qp_1 n_2^2	- - -	67,040	80,448	qp_{2-3}	
5	Can Tho	22,643	64,638	-	-	-	-	396	37,942	qp_{2-3}	82-114	22,247	26,696	-	-
6	Vinh Long	6,258	8,705	-	-	-	-	4	1,200	-	-	6,254	7,505	-	
7	Hau Giang	29,656	50,045	-	-	-	-	225	14,728	qp_{2-3}	62-118	29,431	35,317	qp_{2-3}	-
8	Tien Giang	1,029	37,695	8	21,148	n_2^1	303-307	78	15,415	n_2^2 n_2^1 n_1^3	253-260 253-347 342-464	943	1,132	-	-
9	Dong Thap	3,213	44,723	8	17,760	-	-	165	23,315	qp_1 n_2^2 n_2^1	- - -	3,040	3,648	-	-
10	An Giang	4,971	71,971	2	44,930	n_2^2	245-300	6	770	qp_{2-3} n_2^2	- -	4,963	26,217	qp_{2-3}	22-80
11	Ben Tre	2,063	6,683	17	3,342	-	-	20	910	-	-	2,026	2,431	-	-
12	Kien Giang	96,950	328,970	1	6,240	-	-	49	19,464	-	-	96,900	303,266	-	-
13	Long An	3,487	169,956	27	35,953	-	-	1,079	78,147	-	-	2,381	55,856	-	-
	Total amount	**465,230**	**1,229,061**	**97**	**254,977**			**2,430**	**225,100**			**465,703**	**748.984**		

The Vietnamese Mekong Delta is experiencing a sharp intensification of agricultural and aquacultural practices, and cities in the Delta are growing fast (Renaud and Kuenzer, 2012). Water plays a crucial role in shaping socio-ecological systems in the Mekong Delta, particularly for communities that depend on the Delta's water resources for their livelihoods and daily subsistence. The domination of water in the landscape constitutes problems for freshwater supplies in localities. Pressure on the existing natural resources is high, and the demand for freshwater is steadily increasing. Surface water resources in Mekong Delta are under increasing strain due to unplanned extraction, pollution, salinization, and climate change effects. Surface water is, therefore, costly to treat to acceptable drinking standards. Hence, many people, households, and communities still use polluted surface water throughout the region. In rural areas, only 8-12% of the Mekong Delta population has access to piped water, while 42-47% of the households use unprotected surface water (Renaud and Kuenzer, 2012).

For these reasons, groundwater has become an increasingly valuable resource since the 1990s (Wagner, 2012). Over 2 million m^3 of groundwater is extracted daily from the upper 500m of the multi-aquifer subsurface. Aquifer drawdown occurs at rates of 0.3-0.7 m/year (Wagner, 2012).

The Division for Water Resources Planning and Investigation (Wagner, 2012) shows two significant trends:

- The decline in groundwater levels by a reduction of water volume in the aquifer system, which from extensive drainage, exploitation, and the interception of recharge waters.
- The decline of groundwater quality is caused by urban growth, industrial development, and rural pollutants. It is also caused by the concentration of natural contaminants and the saltwater intrusion caused by excessive pumping of groundwater reserves.

It can be concluded that groundwater resources are degraded by direct and indirect human action: pollution by agrochemicals and other contaminations that affect surface waters, incompetent drilling methods, salinity by the saltwater intrusion that will be aggravated during this century by sea-level rise and over-abstraction. The major factors driving a decline in the quality of groundwater in the Delta are a combination of:

- Poor environmental practices in the Delta contributing to surface and aquifer pollution
- Over-exploitation inducing seawater intrusion, mixing and concentration of contaminants
- Poor wells construction that creates a direct pathway for inferior quality aquifer water and surface pollutants to mix with otherwise good quality groundwater layers.

Severe depletion of the groundwater table is reported over the country, often in the range 1-2m per year and more. The subsequent land subsidence is just one of the drawbacks, another being the increasing salinity of coastal aquifers as the seawater level continues to rise.

4.2. Materials and Methods

4.2.1. Database and Water standards

Database

Operated by the Division for Water Resources Planning and Investigation for the South (DWRPIS) since 1991, the national groundwater monitoring network represents a vital observation source for variations of groundwater quantity and quality over time. Today, the national monitoring network in the Mekong river plain (including Ho Chi Minh City Area) comprises 60 stations, where 210 monitoring wells are screened in eight unconsolidated aquifers and two hard rock aquifers.

Of these 210 monitoring wells, there are:

- 24 observation wells in the Holocene aquifer qh,
- 44 observation wells in the Upper Pleistocene aquifer qp_3,
- 31 observation wells in the Upper-Middle Pleistocene qp_{2-3},
- 27 observation wells in the Lower Pleistocene aquifer qp_1,
- 30 observation wells in the Middle Pliocene aquifer n_2^2,
- 29 observation wells in the Upper-Middle Miocene aquifer n_1^{2-3},
- 10 observation wells in basalt rock
- 2 observation wells in Mesozoic bedrock.

Water sampling and analysis were performed at an interval of twice per year (in April and October). Five types of water samples were taken and analyzed.

- Complete sample: Na^+, K^+, Ca^{2+}, Mg^{2+}, NH_4^+, Fe^{2+}, Fe^{3+}, HCO_3^-, Cl^-, SO_4^{2-}, NO_3^-, NO_2^-, CO_3^{2-}, CO_2, pH, Total Hardness (mainly $CaCO_3$)
- Iron sample: Fe_2^+, Fe_3^+
- Micro-element sample: As, Cd, Pb, Cr, Cu, Zn, Mn, Hg, Se, F and COD
- Phenol cyanide: Individual sample for phenol and cyanide
- Contaminated sample: NH_4^+, NO_2^-, NO_3^- and PO_4^{3-}

A database of 90491 tests of different quality parameters from 1995 to 2017 from 115 observation wells was developed over time. This database is provided by the Division of Water Resources Planning and Investigation for the South of Vietnam (DWRPIS), Ho Chi Minh City, Vietnam. In this research, due to the size of the database, the calculation is carried out using the recent monitoring data from 2010 to 2017 in Vietnam Mekong Delta. Aquifer Upper-Middle Miocene (n_1^{2-3}) has only one sample station and has less data than the other aquifers, herefore, the assessment in this research does not consider this aquifer. The analysis is carried out, as in practice, based on the water monitoring data independently and does not take groundwater direction, flow, movement, or other related factors. This research considers both WQI methods CCME WQI and MCWQI using two standards, i.e., Vietnam National Regulation for Groundwater (VNR) and the European Water Framework Directive (EU WFD). This analysis contains not only an assessment of groundwater quality but also a comparison of the capacities of MCWQI and CCME WQI. This comparison will provide different sets of parameters, whose analysis will show the potential applicability of the European Water Framework Directive in the Vietnamese context.

A data pretreatment phase is manually performed on the original Excel files to find meaningless data and interpret the water samples' formal structure. This proceeding is necessary to base the research on validated data. On the other hand, the support platform's initial data loading procedure stops when there are formal problems, e.g., concerning the use of commas or points in the measured values or the names of the quality parameters. Only a few original Excel files had to be manually changed, such that then a standard formalism applied to all Excel files. The loading procedure of the support platform was adapted to the results of this pretreatment. Some sample stations are no longer monitored or have no information about the location coordinates, and therefore they are not taken into account. The support platform's data loading procedure tests whether the measured values are in a plausible range and have the expected format, and the evaluation part of the support platform distinguishes between the absence of measured value (value *blank*) and the measured value zero.

Water standards

Vietnamese Groundwater Quality Regulation

As reported by WEPA (WEPA, 2019), there is no integrated strategy and action plan at the national or regional basin level in the water sector of Vietnam. However, strategy and action plans exist for several sub-sectors. Relevant legislation necessary for implementing many of the law’s objectives have not yet been developed. National Water Resource Council at the national level (in 2000) and three Boards for River Basin Planning and Management at a local level (in 2001) were established to work under the government as advisory, coordination, and planning bodies.

With the creation of a new Ministry of Natural Resources and Environment (MONRE) in 2002, the state management of water resources was allocated to the Agency of Water Resources Management within MONRE. This critical change represents a separation of state management and service functions for water resources. Previously, both water resources management and service functions were under the responsibility of the Agency of Water Resources and Hydraulic Works Management under MARD.

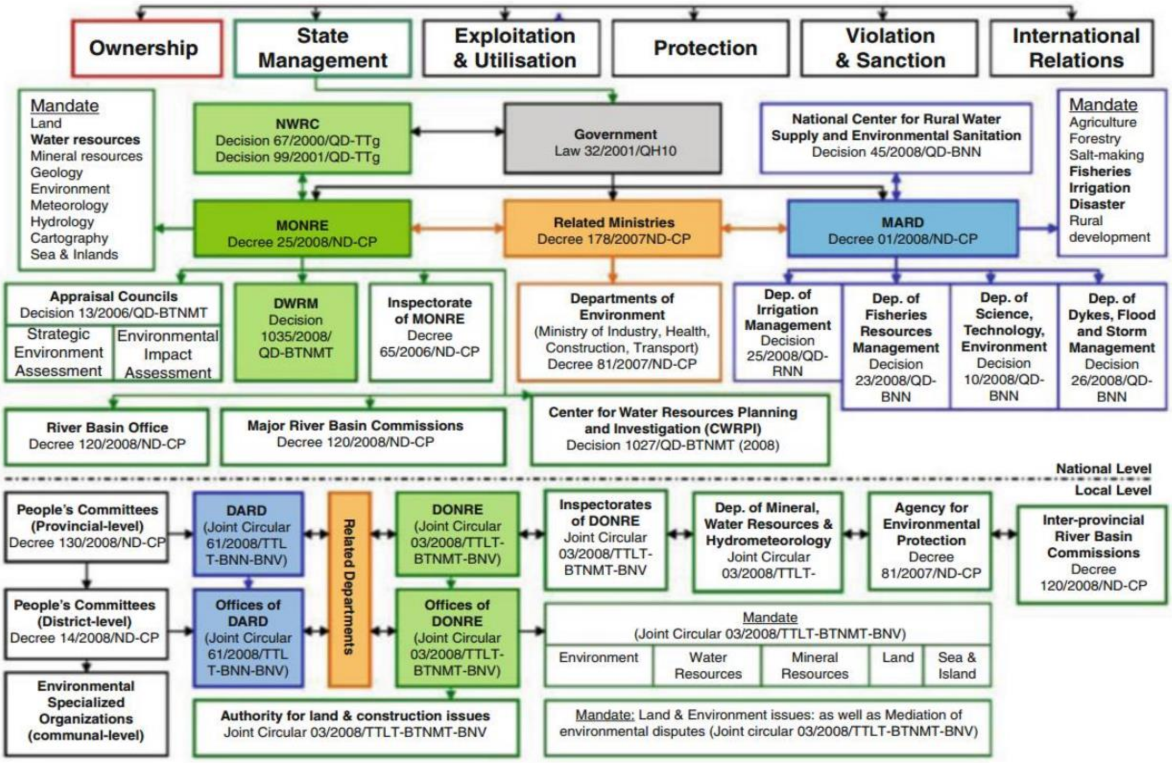

Figure 4.4: Ownership and management of State water resources in Vietnam (Nguyen, 2010)

The National Regulation QCVN 09-MT: 2015/BTNMT (MONRE, 2015) was compiled edited from QCVN 09:2008/BTNMT by the drafting committee of national technical regulations on groundwater quality, submitted by Vietnam Environment Administration, Department of Science and Technology, Department of Legal Affairs and promulgated in line with Circular No.66/2015/TT-BTNMT dated December 21, 2015, issued by Minister of Natural Resources and Environment. This regulation stipulates the maximum value of groundwater quality parameters. It is applied to assess and supervise groundwater resources' quality and acts as basic guidelines for different purposes of water use. The sampling method and determining groundwater parameter value standards are also mentioned in this regulation. The maximum values of groundwater quality parameters are specified in Table 4.4 in comparison with the water quality standard of the European Water Framework Directive.

European Water Framework Directive

The European groundwater regulatory framework came into existence at the end of the 1970s with the directive on the protection of groundwater against pollution caused by certain dangerous substances (EC, 2000). This directive provides a groundwater protection framework that requires the prevention of the (direct and indirect) introduction of high priority pollutants into groundwater and limiting the introduction into the groundwater of other pollutants to avoid pollution of this water by these substances.

The declaration of the Ministerial Seminar on Groundwater held at The Hague in 1991 recognized the need for further action to avoid long term deterioration of quality and quantity of freshwater resources. The European Parliament and the Council subsequently asked the Commission to set up a European water policy framework. This requirement led to the Water Framework Directive (WFD) adopted in October 2000.

Along with protecting groundwater as a resource with multiple uses, the WFD establishes for the first time that groundwater should be protected for its environmental value. The WFD establishes objectives but allows Member States flexibility to achieve based on milestones such as risk evaluation of anthropogenic pressures and impacts, monitoring programs, development of river basin management plans, and design and operation of programs of measures. Groundwater is one of the critical components of the WFD with groundwater focus on both quantitative and chemical status objectives.

The quantitative status objectives are apparent in the WFD. It is to ensure a balance between extraction and recharge of groundwater, but the chemical status criteria are more complex and were not fully resolved at the time the WFD was adopted. The components of the WFD dealing with groundwater cover some different steps for achieving functional (quantitative and quality) status. The characterization relies on system understanding, in particular on the knowledge of drivers (D), pressures (P), status (S), impacts (I), and responses (R), which constitute the backbone of river basin management planning.

It involves analyzing the pressures and impacts of human activity on groundwater quality to identify groundwater bodies at risk of not achieving EU WFD environmental objectives. This assessment has to evaluate risks linked to water uses and interactions with associated aquatic or terrestrial ecosystems interaction to the types of pressures and aquifer vulnerability. Groundwater monitoring networks based on the results of characterization and risk assessment provide a comprehensive overview of groundwater chemical and quantitative status.

Table 4.4: Comparison of water quality standards (MONRE, 2015, EC, 2000) compiled by author

Parameters	**EU WFD**	**VNR**
Oxidisability	5.0 mg/l O_2	Not mentioned
pH	Not mentioned	5.5-8.5
Conductivity	250 μS/cm	Not mentioned
Total Hardness ($CaCO_3$)	Not mentioned	500 mg/l
TDS	Not mentioned	1500 mg/l
Aluminium (Al^{3+})	0.2 mg/l	Not mentioned
Ammonium (NH_4^+)	0.50 mg/l	1 mg/l
Antimony (Sb)	0.005 mg/l	Not mentioned
Arsenic (As)	0.01 mg/l	0.05 mg/l
Boron (B)	1.00 mg/l	Not mentioned
Bromate (Br)	0.01 mg/l	Not mentioned
Cadmium (Cd)	0.005 mg/l	0.005 mg/l
Chromium VI (Cr^{6+})	0.05 mg/l	0.05 mg/l
Copper (Cu)	2.0 mg/l	1 mg/l
Iron (Fe)	0.2	5 mg/l
Lead (Pb)	0.01 mg/l	0.01 mg/l
Manganese (Mn)	0.05 mg/l	0.5 mg/l
Mercury (Hg)	0.001 mg/l	0.001 mg/l
Nickel (Ni)	0.02 mg/l	0.02 mg/l
Selenium (Se)	0.01 mg/l	0.01 mg/l
Sodium (Na^+)	200 mg/l	Not mentioned
Zinc (Zn)	Not mentioned	3 mg/l
Chloride (Cl^-)	250 mg/l	250 mg/l
Cyanide (CN^-)	0.05 mg/l	0,01 mg/l
Fluoride (F^-)	1.5 mg/l	1 mg/l
Sulfate (SO_4^{2-})	250 mg/l	400 mg/l
Nitrate (NO_3^-)	50 mg/l	15 mg/l
Nitrite (NO_2^-)	0.50 mg/l	1 mg/l
Escherichia coli	0 in 250 ml	Not found in 100ml
Enterococci	0 in 250 ml	Not mentioned
Pseudomonas aeruginosa	0 in 250 ml	Not mentioned
Clostridium perfringens	0 in 100 ml	Not mentioned

Parameters	EU WFD	VNR
Coliform bacteria	0 in 100 ml	3 in 100ml
Colony count 22°C	100/ml	Not mentioned
Colony count 37°C	20/ml	Not mentioned
Acrylamide	0.0001 mg/l	Not mentioned
Aldrin	Not mentioned	0.1 μg/l
Benzene (C_6H_6)	0.001 mg/l	0.02 μg/l
Benzo(a)pyrene	0.00001 mg/l	Not mentioned
1,2-dichloroethane	0.003 mg/l	1 μg/l
Dieldrin	Not mentioned	0.1 μg/l
Epichlorohydrin	0.0001 mg/l	Not mentioned
Heptachlor & Heptachlorepoxide	Not mentioned	0.2 μg/l
Permanganate index	Not mentioned	4 mg/l
Pesticides	0.0001 mg/l	Not mentioned
Pesticides - Total	0.0005 mg/l	Not mentioned
PAHs	0.0001 mg/l	Not mentioned
Tetrachloroethene	0.01 mg/l	Not mentioned
Total phenol	Not mentioned	0.001 mg/l
Total α radioactivity	Not mentioned	0.1 Bq/l
Total β radioactivity	Not mentioned	1 Bq/l
Trichloroethene	0.01 mg/l	Not mentioned
Trihalomethanes	0.1 mg/l	Not mentioned
Tritium (H3)	100 Bq/l	Not mentioned
Vinyl chloride	0.0005 mg/l	Not mentioned

For the comparison of the water standards and practice monitoring parameters, which have been carried out in Mekong Delta, there are two sets of parameters selected for two standards, namely, the European Water Framework Directive and the Vietnam National Regulation. All parameters refer to groundwater and not to a mixture of surface and groundwater.

- For the European Water Framework Directive, there are 20 parameters, including Al^{3+}, As, Cd, Cl^-, CN^-, Cr^{6+}, Cu, F^-, Fe, Hg, Mn, Na^+, NH_4^+, Ni, NO_2^-, NO_3^-, Pb, pH, Se, SO_4^{2-}.
- For the Vietnam National Regulation, there are 22 parameters, including As, Cd, Cl, CN^-, Cr^{6+}, Cu, F^-, Fe, TH (Total Hardness), Hg, Mn, NH_4^+, Ni, NO_{2-}, NO_{3-}, Pb, pH, Phenol, Se, SO_4^{2-}, TDS (Total Dissolved Solids), Zn.

The characteristics of these water quality parameters are recapitulated from EU WFD (EC, 2000), and the Guidelines of Environmental Protection Agency (EPA, 2001) described as follows:

Aluminum (Al^{3+}): Aluminum is one of the most abundant elements in the earth's crust. A salt, aluminum sulfate is very widely used for color- and colloid-removal in the treatment of waters for drinking purposes. Initially not considered to be a significant health hazard in drinking waters, aluminum has more recently been shown to pose a danger to persons suffering from kidney disorders. It causes neurological problems and has been cited as a contributory factor to Alzheimer's disease.

Arsenic (As): It is introduced into the water through the dissolution of minerals and ores, from industrial effluents and atmospheric deposition. Concentration in groundwater in some areas is sometimes elevated as a result of erosion from natural sources. Arsenic is very toxic to humans, and some arsenical compounds are carcinogens. There are a variety of other health effects as well.

Cadmium (Cd): Cadmium in water is due, nearly exclusively, to industrial discharges and landfill leachates. Cadmium is very highly toxic, hence severe restrictions on its concentrations in waters are established. The metal is very strongly adsorbed on muds, humus and organic matter, leading to the possibility of entry to the food chain via fish and fish food, and subsequent accumulation in human tissue.

Chloride (Cl^-): Chloride exists in all natural waters, commonly higher Cl^- is due to weathering from silicate rick rocks. The concentrations vary very widely and reach a maximum in seawater. In freshwaters, the sources include soul and rock formations, sea spray, and waste discharges. However, at levels above 250mg/l Cl^- water begins to taste salty and will become increasingly objectionable as the concentration rises further. High chloride levels may similarly render freshwater unsuitable for agricultural irrigation. In coastal areas, the elevated chloride values may be due to sea spray or seawater infiltration and not necessarily to discharges.

Chromium VI (Cr^{6+}): Chromium occurs in nature in ore but arises in waters from discharges from electroplating, tanning, textile, paint, and dyeing plants. Chromium’s toxicity varies with the form in which it occurs, whether as the trivalent or the hexavalent form. The latter is considered the more hazardous, but because it is difficult to distinguish by analysis, the figures quoted below refer mainly to the total chromium concentrations. It is considered that the element is carcinogenic at high concentrations, though much more evidence of this is needed, and it can act as a skin irritant. Hence its concentration is limited in domestic water supplies. The deaths of livestock resulting from watering in chromium-contaminated water have been reported from time to time.

Copper (Cu): Copper occurs in ores and water due to the discharges of the industrial plants. It is not particularly toxic to humans. However, astringent tastes in water can be caused by a high level. Copper is also an element the toxicity of which to fish varies widely with the hardness of the water.

Cyanide (CN^-): Cyanide is a common constituent of industrial wastes, especially from metal plating processes and electronic components manufacture. Cyanide is a reactive, highly toxic entity that will cause a quick death to humans and fish in excessive amounts.

Dissolved Oxygen (DO): Dissolved Oxygen is a natural characteristic of clean waters. Some inorganic waste discharges may also deplete the DO level of receiving water. The prime requirements for DO arise in connection with fish life. On the other hand, it is generally true that if water quality is suitable for fish, then water also meets the criteria for most if not all other beneficial use and is of functional ecological status. The cardinal point about the solubility of oxygen in water is that it has an inverse relationship with temperature.

Fluoride (F^-): The higher concentration of fluoride may be due to fluoride bearing biotitic and clay minerals in aquifers and leaching action from other sources. Fluoride is essential for human beings as a trace element. In the right concentration, it protects against tooth decay and enhances bone development. Nevertheless, a higher concentration of this element causes toxic effects in potable water.

Hydrogen Ion Concentration (pH): pH is a term used to express the intensity of the groundwater's acidic and alkaline conditions. It is an essential parameter in assessing water quality. Acidic conditions will prevail as pH value decreases, and alkaline conditions increase the pH value.

$$pH = -\log_{10} H^+$$

The knowledge of pH is essential in the selection of coagulants for water purification. The acidity will not affect the health of human beings, but slightly acidic groundwater is corrosive and can dissolve metals, especially copper pipes and pumps. The destructive shorten of the economic life of plumping and hot water cylinders is a further impact. In some cases, the dissolved minerals in the water may cause illness. A high pH value leads to scale formation in water heaters and reduces the germicidal potential of chlorine.

Iron (Fe): In practice, iron is monitored as Fe^{2+}, Fe^{3+}, and total Fe, but only total Fe is taken into account for the assessment and management. Therefore, this research also takes total Fe as a parameter (from this point on denoted as Fe). The iron occurs in significant amounts in geological formations. Many complex reactions that occur naturally in ground formations can give rise to more soluble forms of iron, which will be present in water passing through such formations. Appreciable amounts of iron may, therefore, be present in groundwater. Severe problems can be caused in drinking water supplies by the presence of iron, although there usually is no harmful effect on persons consuming waters with significant amounts of iron. The metal is quite harmful to aquatic life. Should the metal be converted to an insoluble form, then the iron deposits will interfere with fish food and spawning.

Lead (Pb): Lead is a cumulative toxic poison that leaches from ores. It occurs in water by effluent discharges and abrasion from water pipes. Lead is one of the most common heavy metals because it accumulates in body tissue, strict limits on its presence in raw and finished, drinking water must be imposed.

Manganese (Mn): As with iron, manganese if found widely in soils and is a constituent of many groundwaters. It may be brought into solution in reducing conditions, and the excess metal will be later deposited as the water is re-aerated. The general remarks for iron apply to manganese, but the staining problems with this metal may be even more severe, hence the quite stringent limits. A second effect of the presence of manganese much above the limits is an unacceptable taste problem.

Mercury (Hg): Mercury is a very toxic element, the hazards of which are magnified by the accumulation of organo-mercury compounds in fish. It is generally of industrial origin (i.e., as dental amalgams, anti-fouling paints, plastics manufacture, paper-making) though some Mercury comes from the natural environment.

Nickel (Ni): Nickel has principal sources in minerals and industrial wastes. It is another metallic element of moderate concern in terms of possible carcinogenicity as far as humans are concerned. It also has parameter harmful effects on aquatic life. It is toxic to plant life and is a hazard to fish.

Nitrate (NO_3^-): Nitrate is generally found in water due to bacterial action on ammonia and organic nitrogen. Increasing nitrate concentration in groundwater can be due to commonly used nitrogen fertilizers that are partially used by plants, and the rest infiltrates with rainfall into groundwater. During decomposition, bacteria break down protein molecules into ammonia. Specialized bacteria then oxidize ammonia to NO_2^- and then NO_3^-. NO_3^- is a non-essential contaminant with no minimum daily requirement. Excessive content of nitrate in groundwater may cause infant methemoglobinemia.

Nitrite (NO_2^-): Nitrite usually exists in low concentrations, and even in waste treatment plants, the effluent levels are relatively low, principally because the nitrogen will tend to exist in the more reduced ammonia NH_3 or oxidized NO_3^- forms. Levels in unpolluted waters are generally low. Values higher than this may indicate sewage pollution because nitrite is an intermediate in the oxidization of ammonia to ~~a~~ nitrate; such oxidation can proceed in soil and sewage and is a rich source of ammonia nitrogen. Waters that show any appreciable amounts of nitrite are regarded as being of highly questionable quality.

Phenol: Phenol originates in polluted surface waters like roads, roadwork's run-off, or industrial effluents. Many phenolic compounds are corrosive and toxic to a considerable extent, but their primary significance in waters is organoleptic. The main difficulties which arise are taste and odor, which are magnified exceedingly when the water is chlorinated. Severe problems are caused, and the rejection of supplies by consumers is likely.

Selenium (Se): Selenium has probably industrial origin. It is used as a chemical catalyst, e.g., in photographic equipment and processes, in electrical components. Although it is an essential biological requirement for both men and animals, selenium in more than minimal amounts is toxic, causing various illnesses.

Sodium (Na^+): Na^+ is always present in natural waters. It is an essential nutritional component, and the regular intake is as ordinary salt (sodium chloride NaCl) in food. The main reason for limiting it is the collective effect, which it exercises with sulfate because too excessive intake can cause hypertension. Higher sodium ions Na^+ in groundwater are mostly due to weathering of plagioclase bearing igneous rocks, dissolution of salt deposits, and isolated dispersed salt crystals and exchange reactions between calcium ions present in the groundwater.

Sulfate (SO_4^{2-}): SO_4^{2-} is a naturally occurring anion in all types of water. It may enter natural waters through weathering of SO_4^{2-} bearing minerals (gypsum $CaSO_4.2H_2O$, anhydrite $CaSO_4$, and potash salt deposits), metallic minerals, and the deposition of marine aerosols. SO_4^{2-} in water is generally bound to alkali and alkaline earth metals and is readily soluble. A wide range of SO_4^{2-} content in groundwater is due to various processes during its traverse through rock. SO_4^{2-} is also added in groundwater by the application of SO_4^{2-} as a soil conditioner. Sulfur in the form of sulfate is an essential nutrient for plants and is considered toxic to plants or animals at a lower concentration, but at higher concentrations, it imparts a bitter taste and may cause laxative effects on the human system.

Total dissolved solids (TDS): TDS is a term applied to the material left behind after a water sample is filtered and evaporated. It is the measure of material dissolved in water, such as carbonate, bicarbonate, chloride, phosphate, nitrate, calcium, magnesium, sodium, and other ions. Several processes may cause an increase in the dissolved solids content of groundwater. These processes include groundwater movement through rocks containing soluble minerals, salt concentration by evaporation and contamination due to wastewater disposal.

Total hardness (TH): Total hardness primarily represents the concentration of calcium and magnesium ions expressed as mg/l $CaCO_3$. Fe, Al, and Mn may also contribute to hardness, but many are not usually present. The deposition of calcium and magnesium salts increases the hardness of the water. Hardness is an essential parameter in decreasing the toxic effect of toxic elements. The widespread abundance of these metals in rock formations often leads to very considerable hardness levels in surface and groundwater. The absence of the hardness minerals in drinking water is not known to pose a health risk to users, but the hardness of water causes scaling of pipelines.

Zinc (Zn): Zinc is present in water due to natural geological occurrence and discharge of wastes. Zinc is essential to man, but if ingested in gross amounts, it has an emetic effect. However, water supply plants verify the impact on taste, not toxicity, and relatively high levels are permissible. The toxicity of zinc is dependent on the hardness of the water: it decreases with rising hardness.

4.2.2. Support Platform

As mentioned in the previous chapter, water monitoring provides the necessary information on water resources not only for quantity but also for quality. This information provides insight into environmental processes and helps all water stakeholders, especially the policy and decision-makers, understand water resources. Therefore, the information needs to be reliable, consistent, and appropriate. It leads to the need for good water quality monitoring programs, which can be integrated into all aspects, improving the decision-making process or promoting community awareness.

The critical questions of a monitoring program are why, what, where, when, and how (CCME, 2003). Typically, a monitoring program includes three main factors:

- Planning: defining the goals and objectives, selecting parameters and stations.
- Data collection activities: choosing frequencies and types of equipment, laboratory analysis.
- Communication and reporting: data verification, data analysis, and interpretation and reporting.

For this research, the last factor (communication and reporting) will be taken into account because the planning and compliance monitoring usually are regulated through regulation and policies. The research focuses on water quality monitoring, in terms of WQI generation, as mentioned in the previous chapter, it is challenging to calculate with the massive amount of data. The QUALIDEX software, which was introduced as a tool to generate some WQIs (Abbasi and Abbasi, 2012), is not available for CCME WQI and the new method MCWQI. Therefore, a support platform is constructed to support the WQIs generation as well as water resource management. This platform can support the translation of water parameter values into indices and transform them into information in various forms in consonance with the needs of the users. The platform has been coded using Visual Basic integrated with Microsoft Access, and the report compile uses Microsoft Excel through tables, and diagrams. This chapter describes and discusses the architecture, method, and working mechanism of the support platform. From this, some helper tables have been derived to guarantee referential integrity for the user.

Most importantly, the calculations of water quality indices are centralized in basic visual modules. This centralization has several advantages:

- Exact control over the behavior of mathematical algorithms
- Because all calculations use the same basic module, there are no hidden effects. It makes the validation of the mathematical kernel easier.
- The input data are not always completed. It is necessary to distinguish the absence of a value and the value 0. A concentration of 0 of a substance in water means that there is no pollution, indicating good water quality. A missing value may not be interpreted as good water quality.

The main framework of the platform furnishes:

- Comparison of different water resources
- Overview of the most critical quality parameters
- Estimation of relative and absolute water quality
- Visualization of trends
- The impression of the behavior of the new water quality index
- Tools for validation of mathematical calculations

The platform includes three main parts and six modules that illustrate the flow of data input and output: Data Input, Analysis Processing (Data Evaluation, Quality Parameter, WQI Generation, WQI Comparison), and Report Compilation. These modules are shown in Figure 4.5 and simplified in Figure 4.6.

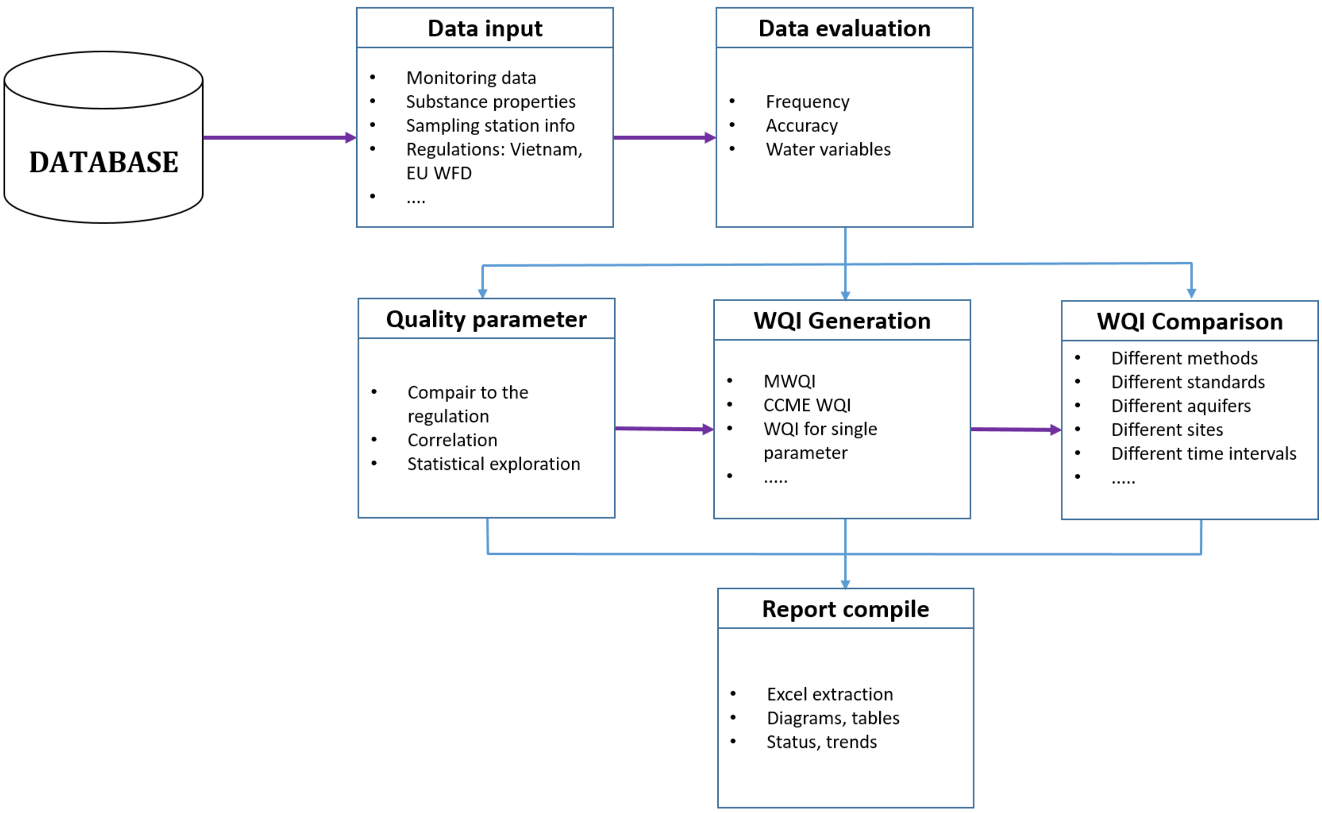

Figure 4.5: Framework of data analysis

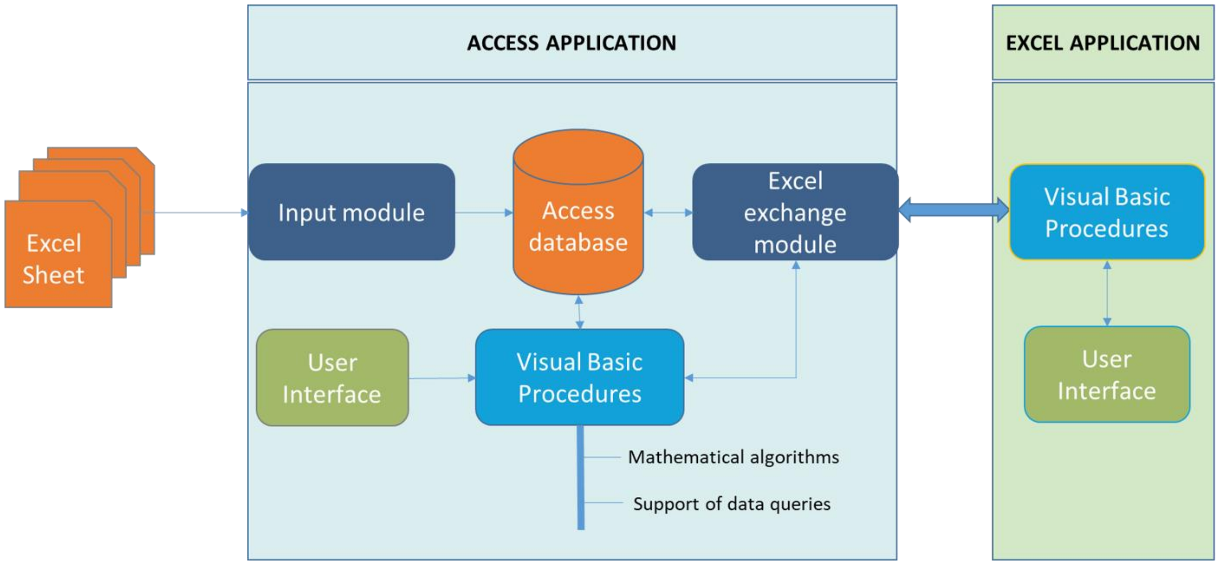

Figure 4.6: Design structure of the platform

The data input has two principal sources, namely, the original excel sheets and user dialogs. While the original excel sheets catalog the fundamental measure values of the quality parameters, the user dialogs define the prerequisites for data evaluation. These dialogs allow entering data of regulations or filtering data by particular views. For example, it is possible to select a province and evaluate data on the province level.

Monitoring data are loaded from Excel Sheets. The input module is sensitive to the column names of the Excel Sheets. Some of the columns are renamed for the use in the Access database. The input module is used for the database of Mekong Delta Groundwater with adaptations, from the original data, other tables are generated that support the filtering by the user concerning:

- List of used substances and their properties
- List of aquifers
- List of sample stations and geographical positions for use in ArcGIS

From the user input, the tables are generated:

- List of used regulations
- List of all views to data (e.g., a sample station, a province, or whole Mekong Delta)

These lists are convenient for users. The user can choose regulations, aquifers, sample stations, or substances from the input database. Furthermore, only meaningful combinations of filter data are selectable, e.g., for a given aquifer, only sample stations of that aquifer are choosable.

The basic model with referential integrity is illustrated in the following figure. This collection of tables is only a subset of all tables and queries.

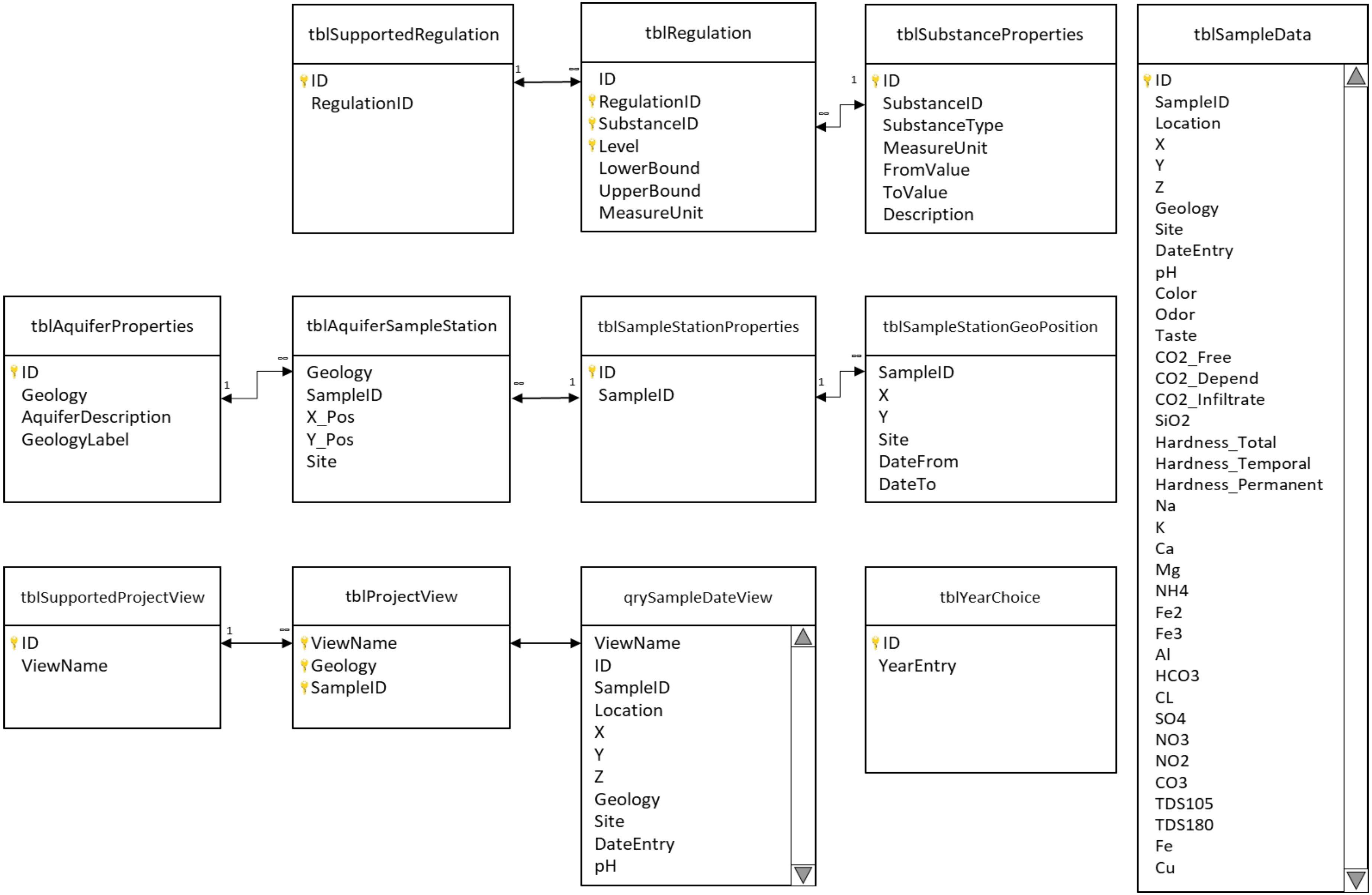

Figure 4.7: Subset of main table and queries

While tblSampleData is the central table, the main framework focuses more on the query qrySampleDataView that filters the data of tblSampleData. By this filter, the set of sample stations is restricted. The users can select data from the whole Mekong Delta or a province or one sample station or a whole aquifer. For this selection, table tblProjectView is essential. It catalogs aquifer-sample station combinations of each province. The term Geology is used here as field name instead of Aquifer because this is the notation in the original Excel sheets where geology denotes aquifers. The table tblSupportedProjectView collects all allowed views (e.g., provinces).

The relation of tables in the first row of the model is also considerable. To any given regulation, only substances in the table tblSubstanceProperties are evaluated. The regulation must be verified to ensure that the used substances are registered in the table tblSubstanceProperties, and the measurement units are accurate before the regulation is used.

In this framework, the mathematical algorithms refer to:

- Correlation
- Covariance
- Regression
- CCME WQI and MCWQI calculation
- CCME WQI and MCWQI ranking
- S –CCME WQI and S-MCWQI calculation

The algorithms are realized as Visual Basic procedures and validated. An essential point of the application is that all actions must be done using the corresponding central procedure. Even if some of the proceeding mathematical features are needed in MS Excel application, the calculation is delegated to a Visual Basic procedure in the MS Access application, and the MS Excel presentation is compatible with the result in the MS Application and, therefore, always works with validated mathematical algorithms.

Based on the framework structure, the main menu is organized with six register entries, as shown in Table 4.5 below.

Table 4.5: The main menu of MS Access application

User dialogs	This section collects the interactions of a user needed to interpret the data - Regulation - Project view
Violation of regulation	Aquifer level - Violation of regulation at the aquifer level - Good tests of components at the aquifer level - Water pollution level of components aquifer - Contribution of components to pollution aquifer Sample station level - Violation of regulation at the sample station - Original data components - Original data and regulation component
Correlation	Correlation matrix for aquifers Correlation matrix for sample station
WQI generation	Aquifer level - CCME WQI aquifer - CCME WQI ranking aquifer - S-CCME WQI aquifer - MCWQI aquifer - MCWQI ranking aquifer - S-MCWQI aquifer Sample station level - CCME WQI sample station - CCME WQI ranking sample station - S-CCME WQI sample station - MCWQI sample station - MCWQI ranking sample station - S-MCWQI sample station
WQI comparison	Aquifer level - CCME WQI comparison aquifer - CCME ranking comparison aquifer - S-CCME WQI components aquifer - MCWQI comparison aquifer - MCWQI ranking comparison aquifer - S-MCWQI components aquifer Sample station level - MCWQI Comparison sample station - S-CCME WQI components sample station - S-MCWQI components sample station
Crosstables	Aquifer level - CCME WQI at aquifer level - CCME WQI ranking at aquifer level - MCWQI at aquifer level year by year and over the period - MCWQI ranking at aquifer level Sample station level - CCME WQI aquifer – sample station - CCME WQI Ranking aquifer – sample station - MCWQI aquifer – sample station - MCWQI ranking aquifer – sample station

There are explicitly defined communication tables on the MS Access side to restrict access from the Excel side to the data tables. Specialized modules of communication update these tables. These modules can also be started from the Excel side. Because CCME WQI and MCWQI have inferential statistics over a period, the corresponding communication module needs to be restarted when selecting another period. Other evaluations are made yearly and need only be yearly updated data when the original data are completed. The MS Excel starts the calculation in MS Access and finally refreshes the data on the Excel side.

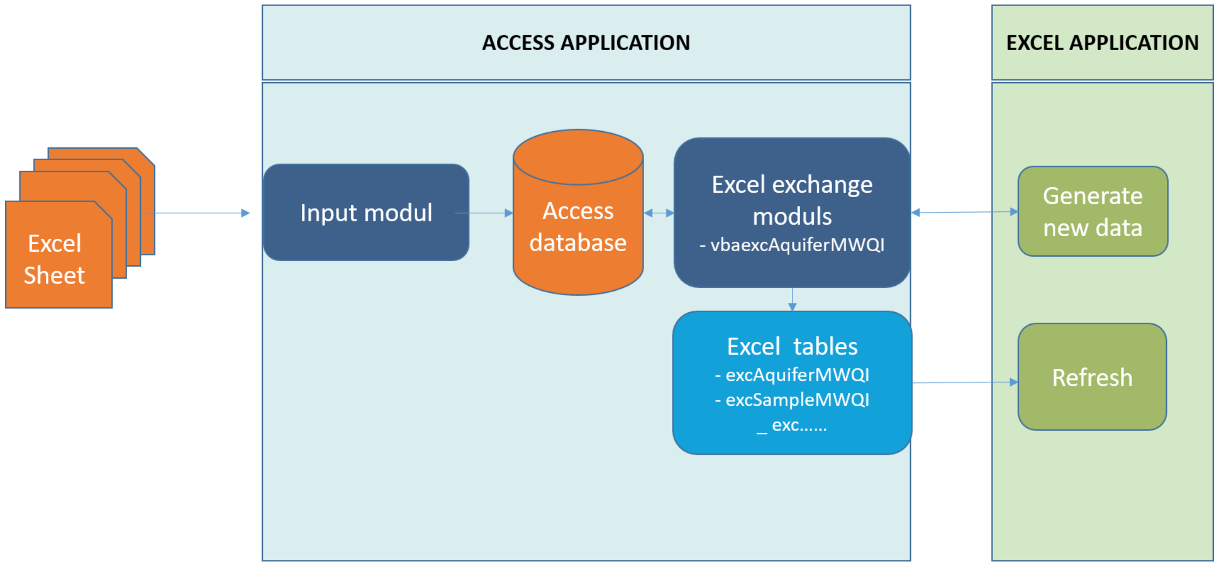

Figure 4.8: The Excel interface

The use of mathematical algorithms on the MS Access side is a fundamental principle in both applications' interaction. In this way, mathematical calculations are centralized and better to validate.

The use of the Excel application has some advantages. The graphic module implemented in Excel is more comfortable to handle and better for the dissertation presentations. Visual basic is also needed on the Excel side. The first use considers the interaction between MS Access and MS Excel. Furthermore, it is used for adaptations of the diagrams to the screen size. Besides the use of the Excel exchange modules, it is possible to use the access database directly from Excel by SQL. This feature is used to control the selected filters in forms on the Excel side. Principally MS Excel can be used as a user interface and MS Access as a container of the database.

4.2.3. Correlation Analysis

Correlation coefficients are determined to identify the highly correlated parameters and interrelated water quality parameters. The correlation coefficient is obtained for each pair of quality parameters. It is also known as the degree of association between the given two variables. When such correlations do exist, then

- by measuring a few critical parameters, the quality of water can be easily and quickly assessed

- highly correlated substances occur together in the water and could have the same origin of pollution (important when looking for polluters)
- One of two highly correlated substances may be a severe polluter, the other not.

The correlation is used to detect potential polluters of water. The presence of more than 200 parameters in groundwater has been documented, which have both natural and anthropogenic orgins. Constituents with a high but *constant* background concentration do not correlate with other constituents. Correlation measures more whether *constituents vary in the same manner*. E.g., if there is an industrial plant that discharges a production-specific combination of pollutants in the water, correlation can hint to find the polluter. Once one pollutant of this specific combination is severe, the question that may be asked is whether this industrial plant is the origin of the pollution. This correlation analysis and the calculation of WQI for single parameters (discussed in Section 5.2.2) help identify (and define) better the potential water problem and groundwater in Mekong Delta, Vietnam.

In this study, the correlation analysis is calculated by Pearson's correlation coefficient value (Wikipedia, 2020). For measured values X = (x_1, … , x_n) and Y = (y_1, … , y_n) the correlation coefficient used is the following formula:

$$Corr(X,Y) := \frac{\sum_{i=0}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{(\sum_{i=0}^{n}(x_i-\bar{x})^2)*(\sum_{i=0}^{n}(y_i-\bar{y})^2)}},$$

Where the mean values are defined as $\bar{x} = \frac{1}{n}\sum_{i=0}^{n} x_i$ and $\bar{y} = \frac{1}{n}\sum_{i=0}^{n} y_i$

Starting with the scalar product of the two deviation vectors $X - \bar{x} := (x_1 - \bar{x}, \dots, x_n - \bar{x})$ and $Y - \bar{y} := (y_1 - \bar{y}, \dots, y_n - \bar{y})$ of two variables X, Y.

$$\sum_{i=0}^{n}(x_i - \bar{x})(y_i - \bar{y}) = \sqrt{(\sum_{i=0}^{n}(x_i - \bar{x})^2)} * \sqrt{(\sum_{i=0}^{n}(y_i - \bar{y})^2)} * \cos\sphericalangle(X - \bar{x}, Y - \bar{y})$$

It follows

$$Corr(X,Y) = \cos\sphericalangle(X - \bar{x}, Y - \bar{y})$$

such that Corr(X, Y) is always between -1 and 1.

Corr(X,Y)=1 means $\cos\sphericalangle(X - \bar{x}, Y - \bar{y}) = 1$, i.e. $\sphericalangle(X - \bar{x}, Y - \bar{y}) = 0$. The vectors $X - \bar{x}, Y - \bar{y}$ have the same direction. Corr(X, Y)=-1 means that the vectors $X - \bar{x}, Y - \bar{y}$ have the opposite direction.

In order to calculate correlation coefficients, the correlation matrix was constructed by calculating the coefficients of different pairs of parameters.

Correlations are never lower than -1: A correlation of -1 indicates that the deviation vectors of two parameters are perfectly negatively linearly related:

$$Y - \bar{y} = \beta * (X - \bar{x}) \text{ for some } \beta < 0$$

$$Y = \vec{\alpha} + \beta * X \text{ with the constant vector } \vec{\alpha} = (\bar{y} - \beta * \bar{x}, \dots, \bar{y} - \beta * \bar{x})$$

The points form a straight line.

A correlation of 0 means that two parameters do not have any linear relation. However, some non-linear relation may exist between the two parameters.

Correlation coefficients are never higher than 1: A correlation coefficient of 1 means that the deviation vectors of two parameters are perfectly positively linearly related:

$$Y - \bar{y} = \beta * (X - \bar{x}) \text{ for some } \beta > 0.$$

$$Y = \vec{\alpha} + \beta * X \text{ with the constant vector } \vec{\alpha} = (\bar{y} - \beta * \bar{x}, \dots, \bar{y} - \beta * \bar{x})$$

The points $\{(x_i, y_i) | i = 1,\dots,n\}$ form a straight line.

The correlations among parameters are characterized as strong in the [±0.8, ±1.0] range, as moderate [±0.5, ±0.8], and as weak [0.0 to ±0.5].

It is worthy of mentioning that $\vec{\alpha} \neq 0$ is possible. E.g., the substance As may have a constant natural concentration, but could also arise together with Hg by the discharge of an industrial process, resulting in Corr (As, Hg)= 1.

The numerator and denominator of the formula are divided by n to avoid the rounding errors:

$$Corr(X,Y) = \frac{\frac{1}{n} * \sum_{i=0}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{(\frac{1}{n} * \sum_{i=0}^{n}(x_i - \bar{x})^2) * (\frac{1}{n} * \sum_{i=0}^{n}(y_i - \bar{y})^2)}}$$

$$Corr(X,Y) = \frac{(\frac{1}{n}\sum_{i=0}^{n} x_i y_i) - \bar{x} * (\frac{1}{n}\sum_{i=0}^{n} y_i) - (\frac{1}{n}\sum_{i=0}^{n} x_i) * \bar{y} + \bar{x}\,\bar{y}}{\sqrt{(\frac{1}{n} * \sum_{i=0}^{n}(x_i - \bar{x})^2) * (\frac{1}{n} * \sum_{i=0}^{n}(y_i - \bar{y})^2)}}$$

$$Corr(X,Y) = \frac{(\frac{1}{n}\sum_{i=0}^{n} x_i y_i) - \bar{x} * \bar{y} - \bar{x} * \bar{y} + \bar{x}\,\bar{y}}{\sqrt{(\frac{1}{n} * \sum_{i=0}^{n}(x_i - \bar{x})^2) * (\frac{1}{n} * \sum_{i=0}^{n}(y_i - \bar{y})^2)}}$$

$$Corr(X,Y) = \frac{(\frac{1}{n}\sum_{i=0}^{n} x_i y_i) - \bar{x}\,\bar{y}}{\sqrt{(\frac{1}{n} * \sum_{i=0}^{n}(x_i - \bar{x})^2) * (\frac{1}{n} * \sum_{i=0}^{n}(y_i - \bar{y})^2)}}$$

This leads to the formula used in the support platform (as shown in Table 4.5):

$$Corr(X,Y) = \frac{Avg(X * Y) - Avg(X) * Avg(Y)}{StDevP(X) * StDevP(Y)}$$

Limitation of the use of the Correlation function

Limitations are formulated for the case Corr(X, Y)=1 or explicitly:

$$Y_i = (\bar{y} - \beta * \bar{x}) + \beta * X_i, \text{ for i = 1, …, n and some } \beta>0.$$

It means Y_i is composed of the constant part $(\bar{y} - \beta * \bar{x})$ and the parameter part $\beta * X_i$, for i=1, …, n.

– Knowing the value of the quality parameter X, one can efficiently compute the Y's value by the above formula. The above equation is based on data from the past. When some event severely changes water quality, applying an equation based on data from the past may be wrong.
– A high correlation between substances discharged by some types of industrial production might hint a potential polluter, reducing research effort. On the other hand, a high correlation coefficient alone is not concrete proof of the relation between quality parameters, which may be completely random.
– Correlation does not explain the impacts of substances in the water, e.g., on the health of human beings or aquatic life. However, a regulation must control potential polluters. Therefore, a correlation is not suited as a basis for defining a standard.
– Correlation is based on the expression X-$\bar{x}$. If X is a severe polluter with high but constant pollution (X-$\bar{x}$ = 0), then Corr (X,Y)=0 for each other quality parameter Y. The quality parameter X is ignored by correlation.

Correlation is only used here to get a hint for possible polluters. The variability of the yearly data justifies its usage (measured values differ in the wet and dry season in the Mekong Delta).

The main objective of this research is to investigate the quality of groundwater in the Mekong Delta based on existing regulations. Therefore, the expression X – Objective_X is more relevant than the expression X-$\bar{x}$. The inferential statistic of MCWQI uses the expression X – Objective_X and is so anchored with water management reality by a regulation. Mathematical statistics use the expression X-$\bar{x}$, which is more a measure for the change of a parameter without relation to any water standards.

5. Results and Discussion

5.1. Correlation Results

As mentioned in the last sections, the assessment investigation is focused on the determination of 24 water parameters, include Al^{3+}, As, Cd, Cl^-, CN^-, Cr^{6+}, Cu, F, Fe, Hg, Mn, Na^+, NH_4^+, Ni, NO_2^-, NO_3^-, Pb, pH, Phenol, Se, SO_4^{2-}, TDS, TH, and Zn. From these characteristics presented in Section 4.2.1, it can be seen that pH is an essential parameter of acidity and alkalinity. It effects the resulting value of acidic-basic interaction of a number of its mineral and organic component. Most of the water samples contained an appreciable amount of chloride. Most of water samples containe considerable amount of Chloride ion. Large amounts of Cl^-, when Ca^{2+} and Mg^{2+} are also present, lead to an increase in water's corrosiveness. The elevated presence of Cl^- and Na^+ (sodium chloride) may be due to sea spray or seawater intrusion.

Metals with a specific gravity greater than five or often more are termed as heavy metals. Copper is an essential component of several enzymes. Sodium occurs as an essential caution in water samples. Fluoride contamination in groundwater has become a major geo-environmental issue in many parts of the world due to its toxic effects, even in trace quantities. TDS measures the material dissolved in water, such as Cl^-, HCO_3^-, PO_4^{3-}, NO_3^-, Ca^{2+}, Mg^{2+}, Na^+, and other ions.

In the following, two correlation tables are presented. Table 5.1 is based on the big data set of all aquifers of the whole Mekong Delta. It cannot be expected that correlation applied to all aquifers' data helps to find specific polluters. Table 5.2 furnishes the application to a particular aquifer with other results. The two tables show that usage and interpretation of a correlation matrix must be performed carefully.

The correlation coefficient values are shown in Table 5.1, the strong positive correlations between Cl^- and Na^+ (0.99), between Cl^- and TH (0.94) are found. It also shows the moderate correlations between Mn and Cl^- (0.56), Ni (0.61), Na^+ (0.58), SO_4^{2-} (0.68), TDS (0.58), between As and NH_4^+ (0.79), between SO_4^{2-} and Cl^- (0.67), Ni (0.66), between CN^- and Fe (0.73) and between Hg and F^- (0.71). The correlation between pH and Mn is moderate negative (-0.58). There are no correlations between Al^{3+} and CN^-, SO_4^{2-}; between As and F^-, Mn; between Cd and NH_4^+; between CN^- and F^-; between Cl^- and Pb; between Cu and Hg; between NO_2^- and Na^+; between Se and SO_4^{2-}.

The correlation analysis of water quality parameters reveals that all parameters are correlated with each other. It is observed from the correlation matrix that some of the parameters do not have a significant correlation among them, indicating the different origins of pollution. Nevertheless, each of these constituents may be a severe pollutant because of a high but *constant* background concentration. This fact cannot be detected by correlation analysis. The correlation examines more whether *consituents vary in the same manner.* A practical interpretation of the correlation shows that highly correlated parameters may have the same origin of pollution. For example, the saltwater intrusion from the Pacific Ocean causes the high correlations among Na^+, Cl^-, and TH; however, these parameters are not correlated with TDS for the above-used data set. The reason is that the table based on the big data set of all data of all aquifers of the Mekong Delta does not reveal the details of the different aquifers. The situation may differ from aquifer to aquifer, from province to province, and from sample station to sample station. The above table shows a negligible correlation between Cl^- and TDS of 0.03 for the big data set of all data of all aquifers of the Mekong Delta. This results from Corr(Cl^-, TDS) =-0.02 for aquifer qp_3.

For all other aquifers, the correlation between Cl^- and TSD is Corr(Cl^-, TDS)=1.

- Aquifer qh: Corr(Cl^-,TDS)=1
- Aquifer qp_3: Corr(Cl^-,TDS)=-0.02
- Aquifer $qp_{2\text{-}3}$: Corr(Cl^-,TDS)=1
- Aquifer qp_1: Corr(Cl^-,TDS)=1
- Aquifer n_2^2: Corr(Cl^-,TDS)=1
- Aquifer n_2^1: Corr(Cl^-,TDS)=1
- Aquifer n_1^3: Corr(Cl^-,TDS)=1

For all aquifers (except qp_3), TDS may be considered as an indicator of saltwater intrusion. The following Table 5.2 is a correlation calculation for aquifer n_2^2. There are high correlations among Na^+, Cl^-, TH, and TDS. On the other site, TDS is defined as a term applied to all salt (ions) dissolved in water samples. In the water administration praxis of Mekong Delta, the measured value of TDS<1 is taken as an indicator for the usability of the groundwater as drinking water. However, there is no correlation between TDS and other dangerous substances like As, Hg, Ni, or Pb.

Table 5.1: Correlation coefficient matrix from data of all aquifers of the whole Vietnam Mekong Delta in the period 2010 - 2017

Parameter	Al^{3+}	As	Cd	Cl^-	CN^-	Cr^{6+}	Cu	F^-	Fe	TH	Hg	Mn	Na^+	NH_4^+	Ni	NO_2^-	NO_3^-	Pb	pH	Phenol	Se	SO_4^{2-}	TDS	Zn
Al^{3+}	1																							
As	-0.06	1																						
Cd	-0.04	-0.03	1																					
Cl^-	0.1	-0.07	0.02	1																				
CN^-	0	0.29	0.05	0.16	1																			
Cr^{6+}	0.06	-0.01	-0.13	-0.03	0.01	1																		
Cu	-0.04	-0.02	-0.05	0.06	-0.03	-0.02	1																	
F^-	-0.05	0	-0.03	0.29	0	0.03	0.02	1																
Fe	0.08	0.03	0.02	0.21	0.73	-0.04	0.18	-0.04	1															
TH	0.06	-0.06	0.03	0.94	0.12	-0.02	0.06	0.33	0.24	1														
Hg	-0.03	-0.01	0.12	0.31	0.13	-0.03	0	0.71	0.15	0.32	1													
Mn	0.03	0	-0.02	0.56	0.45	-0.03	0.01	0.05	0.8	0.51	0.16	1												
Na^+	0.1	-0.08	0.01	0.99	0.18	-0.03	0.05	0.27	0.19	0.89	0.29	0.58	1											
NH_4^+	-0.01	0.79	0	0.16	0.15	-0.09	-0.02	-0.01	0.04	0.09	-0.04	-0.03	0.18	1										
Ni	0.07	0.03	0.1	0.3	0.03	-0.01	0.52	-0.11	0.3	0.26	-0.02	0.61	0.33	-0.06	1									
NO_2^-	0.03	0.03	-0.02	-0.02	0.02	-0.01	-0.02	-0.02	-0.04	-0.05	0.02	-0.07	0	0.01	-0.09	1								
NO_3^-	0.01	-0.01	-0.02	-0.08	-0.02	-0.02	-0.04	-0.02	-0.02	-0.09	0.03	-0.03	-0.08	-0.05	0.03	0.01	1							
Pb	-0.08	0.03	0.04	0	-0.01	-0.03	-0.02	0.01	0.01	-0.03	0.1	-0.01	0.02	0.05	-0.02	-0.05	0.03	1						
pH	-0.16	-0.06	-0.03	-0.34	-0.35	-0.02	-0.06	0.01	-0.49	-0.36	-0.11	-0.58	-0.28	-0.13	-0.5	0.08	-0.04	-0.02	1					
Phenol	0.09	-0.07	-0.03	-0.02	0	-0.1	0.14	-0.04	0	-0.03	0.07	0	-0.01	-0.04	-0.01	-0.05	0.01	0	0.08	1				
Se	0.02	-0.04	0.25	0.02	0.1	0.07	-0.02	-0.04	0.01	0.02	0.24	0.01	0.03	-0.05	0.28	0.05	0.1	0.02	0.02	-0.12	1			
SO_4^{2-}	0	-0.08	0.01	0.67	0.17	-0.05	-0.01	0.21	0.35	0.72	0.21	0.68	0.68	0.03	0.66	-0.08	-0.07	0.04	-0.18	0.02	0	1		
TDS	-0.02	-0.07	0.02	0.03	0.16	-0.03	0.05	0.28	0.22	0.01	0.3	0.58	0.04	0	0.34	-0.01	-0.01	0	-0.03	-0.01	0.03	0.03	1	
Zn	-0.04	-0.02	-0.04	0.04	-0.06	-0.02	1	-0.01	0.11	0.04	-0.02	-0.01	0.03	-0.02	0.43	-0.02	-0.04	-0.02	-0.05	0.04	-0.02	-0.03	0.03	1

Table 5.2: Correlation coefficient matrix for aquifer n22 in the period 2010 - 2017

Parameter	Al^{3+}	As	Cd	Cl^-	CN^-	Cr^{6+}	Cu	F^-	Fe	TH	Hg	Mn	Na^+	NH_4^+	Ni	NO_2^-	NO_3^-	Pb	pH	Phenol	Se	SO_4^{2-}	TDS	Zn
Al^{3+}	1																							
As	-0,1	1																						
Cd	-0,23	0,07	1																					
Cl^-	0,25	0	-0,04	1																				
CN^-	0,09	-0,05	-0,07	-0,06	1																			
Cr^{6+}	0,2	-0,03	-0,19	-0,02	0,13	1																		
Cu	-0,03	0,45	0,09	-0,04	-0,07	-0,08	1																	
F^-	-0,31	-0,13	0,36	-0,19	0,33	0,09	0,02	1																
Fe	0,22	0,26	0,19	0,18	-0,1	-0,06	0,13	-0,27	1															
TH	0,14	0,01	-0,03	0,96	-0,06	-0,03	-0,04	-0,21	0,21	1														
Hg	-0,05	0,25	0,36	-0,06	-0,03	-0,1	0,33	-0,09	0	-0,05	1													
Mn	0,15	0,04	-0,08	0,97	0	-0,01	-0,07	-0,27	0,51	0,97	-0,01	1												
Na^+	0,26	-0,03	-0,06	1	-0,06	-0,01	-0,04	-0,17	0,12	0,94	-0,08	0,95	1											
NH_4^+	0,27	-0,22	-0,09	0,47	0,27	-0,04	-0,09	0,34	-0,13	0,34	-0,13	-0,09	0,48	1										
Ni	-0,52	-0,14	0,28	0,1	-0,07	-0,8	-0,18	0,3	-0,15	0,1	0,64	0,12	0,1	-0,2	1									
NO_2^-	-0,17	-0,1	0,05	-0,29	-0,14	-0,06	0,09	-0,14	-0,07	-0,31	-0,01	-0,05	-0,27	-0,18	-0,21	1								
NO_3^-	0,03	-0,09	-0,03	0	0	-0,05	-0,09	-0,16	-0,02	-0,01	0,01	-0,01	0	-0,06	0,05	0,18	1							
Pb	-0,12	0,07	0,2	-0,06	-0,08	-0,11	-0,1	-0,06	0,11	-0,05	0,55	0,03	-0,09	-0,12	0,72	-0,1	-0,07	1						
pH	-0,4	-0,35	-0,14	-0,23	-0,15	-0,07	-0,08	0,14	-0,44	-0,2	-0,21	-0,35	-0,2	-0,33	-0,24	0,24	0,03	-0,21	1					
Phenol	0,16	0	0,01	-0,12	-0,18	0,17	0,15	-0,07	0,19	-0,12	0,03	-0,05	-0,13	-0,2	-0,37	-0,1	-0,02	-0,03	0,06	1				
Se	-0,1	0,03	0,04	-0,08	0,2	-0,03	0,08	-0,21	-0,04	-0,07	0,48	-0,04	-0,1	-0,1	0,11	0,29	-0,01	0,26	0	-0,17	1			
SO_4^{2-}	0,02	-0,09	0,08	0,72	0,39	0,14	-0,07	0,19	-0,23	0,78	0,01	-0,1	0,72	0,16	0,12	-0,21	-0,11	0	0,02	-0,12	-0,09	1		
TDS	0,24	-0,02	-0,05	1	-0,06	-0,02	-0,04	-0,18	0,16	0,97	-0,07	0,96	1	0,46	0,1	-0,29	0	-0,07	-0,21	-0,13	-0,09	0,74	1	
Zn	0,27	0,06	0,01	-0,11	-0,22	-0,11	0,46	0,1	0,14	-0,1	0,06	-0,07	-0,13	0,06	-0,24	-0,08	-0,21	-0,09	-0,24	0,42	-0,18	-0,32	-0,12	1

5.2. Assessment Results

5.2.1. Assessment Factors

The theoretical part in Chapters 2 and 3 shows that the calculation of CCME WQI and MCWQI is based on *Scope*, *Frequency*, and *Amplitude*, which answer how many parameters violate the regulations, how often these violations occur and how much are the differences from the concerned regulation. The datasets for groundwater quality span from 2010 to 2017, including seven aquifers (aquifer n_1^{2-3} is not included, see Section 4.2.1) with 141 sample stations. Before analyzing the data, it would be wise to identify the three factors based on the two water standards and have a good overview of the different aquifers' situation. It furnishes many details in the sense of the CCME WQI and MCWQI. The question arises whether only water quality is poor or also pollution control is poor. Statistics cannot answer this question. There exist many natural events that make water quality poor and that are not controllable. However, by the following statistics, it seems necessary to investigate whether human impacts or natural effects are responsible for the high number of bad quality parameters.

Table 5.3: Aquifer violation of regulation according to VNR in period 2010-2017

Aquifer	Failed Parameters	Total number of parameters	Failed Tests	Total number of tests	*nse*
qh	14	22	635	2237	1.79
qp_3	18	22	570	2042	1.97
qp_{2-3}	14	22	433	1985	1.71
qp_1	15	22	330	1618	1.55
n_2^2	12	22	284	1520	1.84
n_2^1	15	22	353	2111	1.04
n_1^3	12	22	141	1085	0.52

Each aquifer has a high number of quality parameters with *failed tests*. The quality parameters, respectively, the pollution of water, are not under control. This pollution may be due to natural impacts (like a saltwater intrusion from the Pacific Ocean) or human impacts. As mentioned before, a *nse*-value of 1.27 is an alarm signal. By the above table, most aquifers have a *nse*-value higher than 1.27 (except n_2^1 and n_1^3). Therefore, according to the Vietnam National Regulation, it cannot be expected that the water had good quality for the period 2010 – 2017.

Table 5.3 shows that aquifer qp_3 has 18 parameters out of 22 parameters with at least one *failed test* in the period 2010-2017, about 25% of *failed tests*, and a mean violation of amplitude of 197% (mean water pollution level of 2.97). The water pollution levels (*nse*+1) are mean water pollution levels over all quality parameters.

With the same procedure of analysis using the VNR, the application of the EU WFD may show some new aspects.

Table 5.4: Aquifer violation of regulation according to EU WFD in period 2010 - 2017

Aquifer	Failed Parameters	Total number of parameters	Failed Tests	Total number of tests	*nse*
qh	14	20	727	2212	14,57
qp_3	16	20	704	1975	6,69
qp_{2-3}	13	20	589	1931	5,54
qp_1	14	20	425	1530	12,43
n_2^2	11	20	424	1448	3,74
n_2^1	16	20	563	2020	4,66
n_1^3	12	20	300	1032	2,14

Compare to the *nse*-value of 1.27 as an alarm signal, all aquifers have more than 11 failed parameters out of 20 parameters, with *nse* higher than 2 (the highest is 14.57 of qh aquifer).

The calculation results can fall into many broad categories: water quality for different parameters, different aquifers, different sites, different sample stations, different periods, different uses purposes, etc. However, in this dissertation, the findings are divided into two main categories for the period from 2010 to 2017:

- The pollution effect of the single parameters on the base of S-MCWQI for details
- The overall water quality is based on MCWQI as well as CCME WQI for aquifers (yearly, accumulatively, and related sample stations) for an overview.

5.2.2. Water Quality Index for Single Parameters

The hydrochemical characteristics are responsible for the distribution of water quality parameters and help to have the potential to trace the origins and history of water. This information supports groundwater management, such as improved understanding of controlling processes, the impacts of contaminants on groundwater, and understanding the pollution and its origins. In general, the groundwater deterioration is caused by some main reasons like the effluents of industrial or sewage discharge, saline water intrusion along the coastal regions, rock-water interaction in the aquifers, underground bio-films microbial activities, hydrodynamic and dilution properties of aquifers as well as the intensity of pollution. Because of the movement, the chemistry in groundwater is affected by geochemical processes. The dissolved components of water not only change during transport but also react or redistribute among ions and cations.

The traditional way of water quality assessment is a time-series that compares each parameter's values over the time period. By using S-MCWQI, the pollution due to the individual water quality parameters can be easily seen by one number, the S-MCWQI value, especially a value < 45 for poor water quality, in order to identify the critical parameters by the aquifer. The calculation of WQI for single parameters is carried out with the aid of the support platform. The results are illustrated in Figure 5.1, and Figure 5.2, and more details are given in Table 5.5 and Table 5.6 below. S-MCWQI uses only the factors F_2 and F_3.

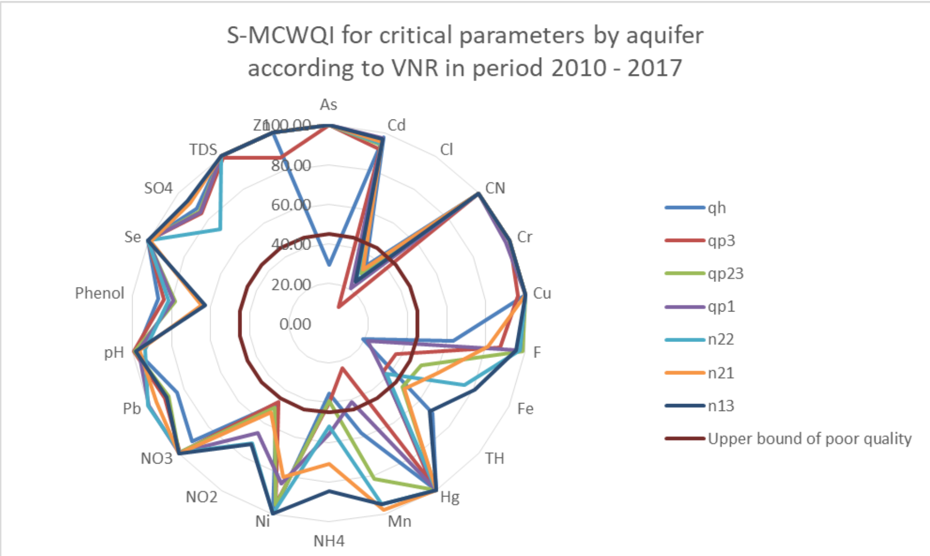

Figure 5.1: S-MCWQI for critical parameters by aquifer according to VNR in the period 2010 – 2017

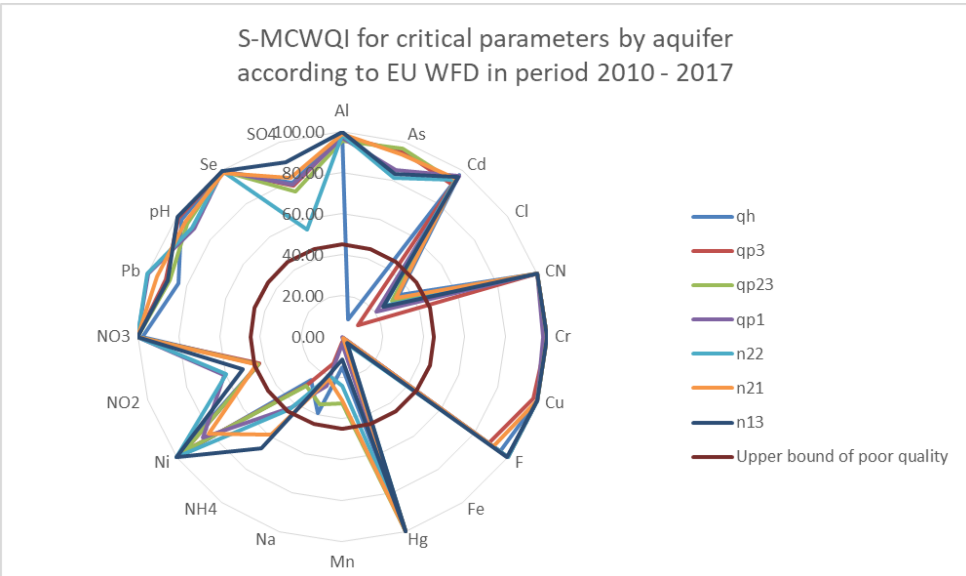

Figure 5.2: S-MCWQI for critical parameters by aquifer according to EU WFD in the period 2010 - 2017

The term "upper bound of poor quality" in the diagram denotes the WQI-value of 45. The S-MCWQI values inside the circle with S-MCWQI value = 45 correspond to critical quality parameters, e.g., for qp_3, these are Fe, Cl^-, TH, Mn, and NH_4^+. The following tables show in details.

Table 5.5: S-MCWQI for critical parameters at aquifer level according to VNR in the period 2010 - 2017

Parameter	qh	qp_3	qp_{2-3}	qp_1	n_2^2	n_2^1	n_1^3
As	29.54	100	100	100	100	100	100
Cd	97.57	91.43	93.62	97.10	94.33	95.11	96.50
Cl^-	34.22	9.43	30.05	20.92	25.50	32.22	24.70
CN^-	100	100	100	100	100	100	100
Cr^{6+}	100	100	100	98.22	100	99.88	100
Cu	100	96.18	100	100	100	100	100
F^-	63.45	87.11	98.44	97.22	97.00	81.01	95.53
Fe	18.79	37.21	51.29	21.77	75.17	60.39	81.08
TH	69.29	36.61	48.97	35.35	38.62	50.56	67.49
Hg	100	94.82	100	100	100	100	100
Mn	57.61	23.66	81.54	41.48	95.19	97.97	95.07
NH_4^+	35.33	39.88	39.37	55.86	51.87	71.02	84.67
Ni	100	95.17	95.42	84.02	100	80.70	100
NO_2^-	48.38	47.04	50.30	65.92	71.69	53.46	72.59
NO_3^-	90.85	99.15	99.61	99.61	99.45	100	100
Pb	84.01	90.66	88.67	99.63	100	95.24	89.62
pH	97.83	99.37	98.73	96.60	93.51	96.50	98.32
Phenol	86.59	84.04	77.90	78.99	81.55	64.85	62.64
Se	100	100	100	100	100	98.78	100
SO_4^{2-}	88.12	84.97	86.28	85.19	72.13	92.58	93.99
TDS	100	98.85	100	100	100	100	100
Zn	100	86.63	100	100	100	100	100

Table 5.6: S-MCWQI for critical parameters at aquifer level using EU WFD in the period 2010 - 2017

Parameter	qh	qp_3	qp_{2-3}	qp_1	n_2^2	n_2^1	n_1^3
Al^{3+}	98.75	97.71	95.75	97.10	98.33	98.88	100
As	8.86	95.11	96.43	85.30	81.73	93.65	83.61
Cd	97.57	91.43	93.62	97.10	94.33	95.11	96.50
Cl^-	34.22	9.43	30.05	20.92	25.50	32.22	24.70
CN^-	100	100	100	100	100	100	100
Cr^{6+}	100	100	100	98.22	100	99.88	100
Cu	100	98.05	100	100	100	100	100
F^-	95.17	88.27	100	100	100	91.39	99.75
Fe	1.03	0.71	2.48	0.24	4.07	0.93	3.82
Hg	100	94.82	100	100	100	100	100
Mn	15.05	2.53	32.76	3.46	23.90	31.29	11.17
Na^+	39.04	13.74	34.77	25.09	19.98	21.47	19.21
NH_4^+	25.87	29.25	29.65	42.51	43.71	58.89	67.13
Ni	100	95.17	95.42	84.02	100	80.70	100
NO_2^-	43.24	42.36	43.06	60.44	59.74	44.23	51.08
NO_3^-	97.63	100	100	100	100	100	100
Pb	84.01	90.66	88.67	99.63	100	95.24	89.62
pH	97.08	98.64	93.58	89.52	90.44	94.98	99.72
Se	100	100	100	100	100	98.78	100
SO_4^{2-}	79.05	77.70	74.33	78.04	54.81	81.48	89.29

5.2.3. Water Quality Index for Aquifers

As mentioned before, the MCWQI measures the degree of violation of regulation by the set of quality parameters. The result of this measurement is one value ranging in [0,100]. A WQI, which defines water quality status by a number, naturally loses detailed information. Therefore, a WQI cannot answer the water problem depth in detail. Each water problem needs to have a different evaluation method. The MCWQI, in this case, is useful to detect and identify the change of parameter over the time, at different aquifers, different sample stations, different periods, different sites… Then, based on the deviation of the control value (natural water quality, threshold value…etc.) a problem can be identified and defined.

In this research, the MCWQI assessment is generated using all three factors F_1, F_2, and F_3, and at the aquifer level. The calculations of CCME WQI are respectively, in order to see how both indices work.

Tables 5.7 and 5.8 present the comparison between CCME WQI and MCWQI using VNR and EU WFD in the period 2010 – 2017. This calculation takes the data for each year independently.

Tables 5.9 and 5.10 highlight the comparison between CCME WQI and MCWQI using VNR and EU WFD in the period 2010 – 2017. This calculation takes the data accumulatively. The next year's assessment includes the data of itself and the data of previous years.

The CCME WQI and MCWQI use the same classification ranking, which is illustrated by CCME (CCME, 2011). According to this ranking, poor water quality is given by a WQI value of less than 45. In the following tables, all WQI values under 45 are marked with red color. The order of presented aquifers follows the order of aquifers shown in Section 4.1.2.

Table 5.7: Comparison CCME WQI and MCWQI of groundwater in the Mekong Delta by aquifers and years according to VNR in the period 2010 - 2017

Aquifer	2010		2011		2012		2013		2014		2015		2016		2017	
	CCME	MCWQI	CCME	MCWQI	CCME	MCWQI	CCME	MCWQI	CCME	MCWQI	CCME	MCWQI	CCME	MCWQI	CCME	MCWQI
qh	39.3	45.38	48.41	53.01	50.2	55.95	49.26	54.17	45.73	52.2	44.68	48.77	47.08	51.62	63.12	69.54
qp_3	50.19	54.74	51.84	57.28	47.47	54.04	49.74	55.18	49.44	55.1	53.68	58.5	51.73	57.18	48.09	53.6
qp_{2-3}	53.48	59.51	55.87	62.77	59.11	65.57	51.66	58.24	53.35	61.66	46.63	54.91	38.39	47	57.53	71.67
qp_1	53.23	58.6	53.49	62.08	52.32	60.8	55.88	63.05	53.15	59.64	61.23	68.23	61.34	69.2		
n_2^2	49.22	58.14	53.3	63.54	53.76	64.42	61.82	70.41	55.31	63.31	67.2	72.88	63.22	70.59	62.81	63.58
n_2^1	65.51	71.7	50.05	58.57	54.25	63	58.43	67.11	58.58	65.9	70.76	74.02	73.7	76.65		
n_1^3	40.08	51.28	66.49	71.92	69.7	75.14	73.69	77.78	63.02	71.33	88.03	88.8	82.85	83.48		

Table 5.8: Comparison CCME WQI and MCWQI of groundwater in the Mekong Delta by aquifers and years according to EU WFD in the period 2010 - 2017

Aquifer	2010		2011		2012		2013		2014		2015		2016		2017	
	CCME	MCWQI	CCME	MCWQI	CCME	MCWQI	CCME	MCWQI	CCME	MCWQI	CCME	MCWQI	CCME	MCWQI	CCME	MCWQI
qh	28.95	38.66	32.19	42	33.28	44.72	32.04	41.58	32.73	41.28	33.45	42.36	34.76	43.99	46.18	62.03
qp_3	37.72	46.57	36.27	44.99	36.08	44.04	38.4	45.42	39.9	47.23	38.58	46.5	41.51	48.32	43.82	49.6
qp_{2-3}	39.3	46.79	42.08	51.07	42.02	52.86	37.18	46.2	39.91	49.87	30.16	39.12	32.29	38.95	48.02	61
qp_1	36.83	46.02	37.24	51.72	34	46.38	35.67	47.47	33.95	45.02	42.52	55.69	42.51	60.33		
n_2^2	40.08	46.86	40.6	48.65	43.56	53.39	45.56	53.57	43.82	52.44	55.24	60.93	50.08	54.77	40.89	41.4
n_2^1	42.08	52.85	33.97	43.94	37.25	47.98	39.16	47.97	42.13	50.24	47.8	53.88	57.79	62.21		
n_1^3	30.43	39.96	50.84	55.17	58.46	63.09	59.02	61.16	49.26	53.14	66.13	66.58	62.36	63.21		

Table 5.9: Comparison CCME WQI and MCWQI of groundwater in the Mekong Delta by aquifers accumulatively according to VNR in the period 2010 - 2017

Aquifer	2010		2010 - 2011		2010 - 2012		2010 - 2013		2010 - 2014		2010 - 2015		2010 - 2016		2010 - 2017	
	CCME	MCWQI	CCME	MCWQI	CCME	MCWQI	CCME	MCWQI	CCME	MCWQI	CCME	MCWQI	CCME	MCWQI	CCME	MCWQI
qh	39.3	45.4	47.3	51.7	46.6	51.8	46.9	52	45.1	51	45	50.8	45	50.7	45.3	51.3
qp_3	50.2	54.7	48.1	53.4	45.1	51.6	43.1	50.2	42.6	49.6	42.9	49.9	42.8	49.5	37.1	46.7
qp_{2-3}	53.5	59.5	54	60.6	53.1	60.1	49.1	57	46.9	55.8	47	55.8	46.8	55.5	46.7	55.6
qp_1	53.2	58.6	53.4	60.4	51.2	58.7	49	57.5	47.5	56.6	45.9	55.9	46	56.1	46	56.1
n_2^2	49.2	58.1	51.2	60.4	48.9	58.4	50.4	60.1	49.5	59.4	49.7	59.6	49.8	59.6	49.9	59.6
n_2^1	65.5	71.7	51.3	60	48.4	59.2	48.8	60.2	49.3	60.6	49.6	60.9	49.9	61.3	49.9	61.3
n_1^3	40.1	51.3	62.9	68.8	63.7	70.1	64.9	71.4	61.1	69.9	61.7	70.7	62.1	71.1	62.1	71.1

Table 5.10: Comparison CCME WQI and MCWQI of groundwater in the Mekong Delta by aquifers accumulatively according to EU WFD in the period 2010 - 2017

Aquifer	2010		2010 - 2011		2010 - 2012		2010 - 2013		2010 - 2014		2010 - 2015		2010 - 2016		2010 - 2017	
	CCME	MCWQI	CCME	MCWQI	CCME	MCWQI	CCME	MCWQI	CCME	MCWQI	CCME	MCWQI	CCME	MCWQI	CCME	MCWQI
qh	29	38.7	32.1	41,9	31	41.3	31.1	41.2	29.7	39.7	29.7	39.5	29.7	39.5	29.9	40.1
qp_3	37.7	46.6	34.3	42.4	30.2	39	30.4	38.8	30.4	38.5	30.4	38.5	30.5	38.5	28.7	37.2
qp_{2-3}	39.3	46.8	39.3	47.3	39.3	48	35.7	44.7	35.6	44.8	35.7	44.8	35.8	44.6	35.9	44.8
qp_1	36.8	46	36.1	47.9	33.5	45.3	30.8	43.1	30.9	42.9	31	43.2	31.1	43.5	31.1	43.5
n_2^2	40.1	46.9	39.3	46.4	40.2	48.2	41.2	49.3	41.7	49.9	41.9	50	41.9	44.9	42	49.7
n_2^1	42.1	52.9	34.3	44.1	30.1	41.8	30.7	42.3	31.3	42.8	31.5	42.9	31.8	43.2	31.8	43.2
n_1^3	30.4	40	42.2	50.9	36.9	53.5	47.5	54.5	43.7	50.2	44.4	50.6	45	50.8	45	50.8

Figure 5.3: Water quality status trend tracking of assessed aquifers by year in the period 2010 - 2017

Following the classification in Table 2.8, the natural groundwater of the study areas has been categorized as excellent, good, fair, marginal, and poor. A range of colors is recommended to illustrate the water quality classification that helps the community to have a better understanding of the water quality status when reading water quality index (see Table 5.11). It can also help to find the hot spots where the groundwater quality is bad. The detailed calculation results for each aquifer are presented in the next sub-sections below. All WQI values and rankings are also presented following this classification and color range.

Table 5.11: Classification of water quality index with a color range, edited from (CCME, 2001)

Classification	Ranges	Color	Explanation
Excellent	95-100		Water quality is protected with a virtual absence of threat or impairment, conditions very close to the natural or pristine level
Good	80-94		Water quality is protected with only a minor degree of threat or impairment; conditions rarely depart from natural or desirable levels
Fair	65-79		Water quality is usually protected but occasionally threatened or impaired; conditions sometimes depart from natural or desirable levels
Marginal	45-64		Water quality is frequently threatened or impaired; conditions often depart from natural or desirable levels
Poor	0-44		Water is almost always threatened or impaired; conditions usually depart from natural or desirable levels

Holocene Aquifer

The Holocene aquifer (qh) outcrops over an area of 17,676km^2 but is absent along the Vietnam-Cambodia boundary and in the northwestern part of the Vietnamese Mekong Delta. Wagner (Wagner, 2012) reported that the depth to the top of the aquifer varies from 0.00m to 61.50m, with an average of 16.78m. The depth to the bottom of the aquifer ranges from 2.8m to 89.00m, with an average of 32.89m. The thickness is from 0.9m to 72.00m, with an average of 15.48m. The groundwater levels are generally between 0.5m and 3.0m above sea level. The area of fresh groundwater (TDS < 1g/l) is 2,889$km^{2,}$ and that of saline groundwater is 14,788km^2. The amount of groundwater abstracted in 2010 was 17,851 m^3/day (Ha et al., 2015).

The overview results yielded the sign of pollution in aquifer qh because it locates underneath the ground (sometimes interface with surface water). Therefore, it is affected by not only human but also natural activities. Some of these are the presence of As, Cl^-, Fe, Na^+, etc. (Section 5.2.2). The groundwater quality assessment in aquifer qh is conducted for 21 sample stations span from 2010 to 2017. Figure 5.4 shows the MCWQI value of aquifer qh in the time with the trend line. It can be seen that the groundwater quality by VNR is mostly marginal and fair, while by EU WFD, it is mostly poor.

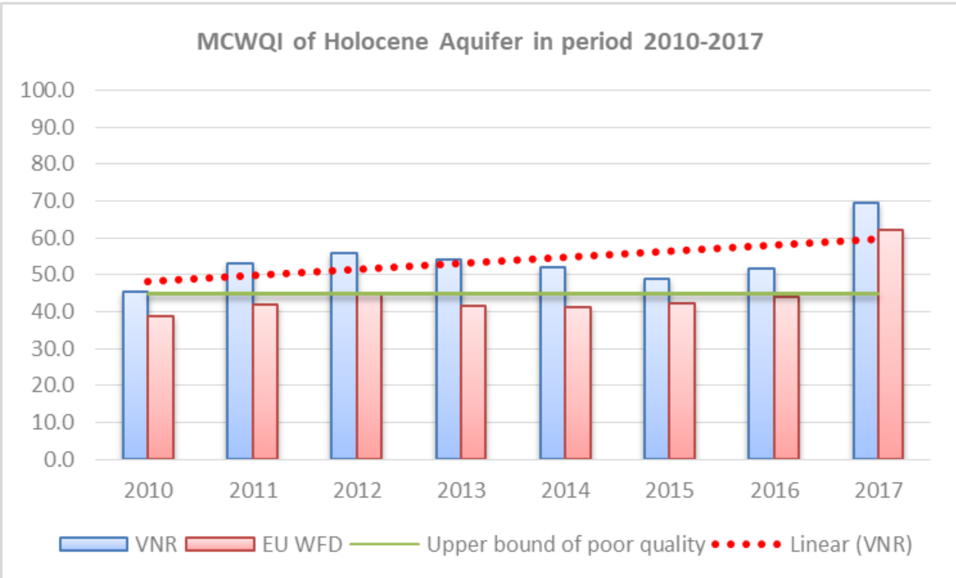

Figure 5.4: MCWQI of Holocene Aquifer in the period 2010 – 2020 with trend line

Table 5.12, 5.13, 5.14, and 5.15 present more details about the groundwater quality in Holocene Aquifer by sample station assessed by MCWQI and CCME WQI, according to VNR and EU WFD. The color range of these tables highlights the groundwater quality. As the same conclusion with Figure 5.4, the water quality in the sample stations of qh aquifer is also mostly poor, marginal, and fair.

Table 5.12: MCWQI of Holocene Aquifer by year according to VNR in the period 2010 - 2017

No.	Station	Aquifer	X	Y	Z	Site	2010	2011	2012	2013	2014	2015	2016	2017
1	Q003010	qh	508778	1179571	4.385	AnGiang,ChauDoc,VinhTe	73.51	86.3	76.47	72.92	88.41	71.87	81.75	
2	Q022010	qh	627775	1178163	1.543	Long An,ThanhHoa,TTThanhHoa	66.9	74.65	87.76	82.57	66.59			
3	Q031010	qh	545162	1173845	3.84	DongThap,ThanhBinh,AnPhong	61.1	71.5	58.86	59.36	57.31	60.02	59.25	74.1
4	Q07701A	qh	665622	1068966	3.833	TraVinh,DuyenHai,LongToan	92.2	100	100	91.72	88.78			
5	Q07701H	qh	664536	1066367	2.466	TraVinh,DuyenHai,LongToan	100	77.54	82.63	86.29	97.61			
6	Q104010	qh	466919	1137072	0.255	KienGiang,HaTien,KienLuong	46.86	41	40.31	53.62	38.34	39.24	33.61	
7	Q17701T	qh	516407	1016294	0.807	CaMau,TP.CaMau,P.9	39.38	33.02	43.2	42.46	62.16			
8	Q199010	qh	499584	968465	1.145	CaMau,NgocHien,TTNamCan	40.19	43.21	43.03	40.43	41.54			
9	Q203010M1	qh	518233.1	1186763	5.064	AnGiang,TanChau,LeChanh	70.16	70.16	75.26	68.68	75.86	76.99	71.02	90.46
10	Q20302TM1	qh	518233	1186763	5.06	AnGiang,TanChau,LeChanh	67.59	68.44	67.98	65.51	62.61	63.92	70.85	74.51
11	Q204010	qh	532046	1156182	2.934	AnGiang,ChauThanh,CanDang	59.09	58.49	70.26	54.88	62.08	53.48	53.57	58.09
12	Q206010M1	qh	570664.5	1136689	2.54	DongThap,LaiVung,HoaLong	40.15	43.82	45.52	47.07	50.48	37.45	49.2	
13	Q209010	qh	588160	1112819	2.033	VinhLong,Binh Minh,CaiVon	49.26	64.6	59.12	60.69	78.05			
14	Q211010	qh	562636	1070144	1.02	HauGiang,LongMy,TTLongMy	50.81	49.81	64.05	61.98	58.8	53.1	58.09	
15	Q214010	qh	617537	1118451	1.842	VinhLong,MangThit,TanLongHoi					58.05			
16	Q214010M1	qh	617537	1118451	1.842	VinhLong,MangThit,TanLongHoi	76.67	94.74	89.6	69.85	100			
17	Q217010	qh	663821	1065473	1.856	TraVinh,DuyenHai,LongToan	95.94	87.04	100	85.06	66.83			
15	Q219010	qh	674903	1110927	1.423	BenTre,Ba Tri,TT Ba Tri	43.14	46.2	49.35	43.14	52.73			
19	Q326010	qh	667327	1159843	1.728	Long An,TanTru,DucTan	37.99	34.74	46.9	38.65	44.52			
20	Q40101T	qh	517226	1094764	1.366	KienGiang,ChauThanh,TTMinhLuong	48.86	48.65	62.2	51.66	48.21	50.64	54.62	
21	Q59801T	qh	606472	1059135	1.858	SocTrang, TP.SocTrang, P.3	54.7	68.92	93.64	83.53	93.51			

Table 5.13: MCWQI of Holocene Aquifer by year according to EU WFD in the period 2010 - 2017

No.	Station	Aquifer	X	Y	Z	Site	2010	2011	2012	2013	2014	2015	2016	2017
1	Q003010	qh	508778	1179571	4.385	AnGiang,ChauDoc,VinhTe	67.45	58.62	67.18	48.46	75.68	61.61	68.99	
2	Q022010	qh	627775	1178163	1.543	Long An,ThanhHoa,TTThanhHoa	47.17	47.41	68.04	65.46	51.62			
3	Q031010	qh	545162	1173845	3.84	DongThap,ThanhBinh,AnPhong	58.92	64.41	47.89	55.7	55.45	55.87	53.09	70.71
4	Q07701A	qh	665622	1068966	3.833	TraVinh,DuyenHai,LongToan	78.74	81.12	80.78	70.82	57.39			
5	Q07701H	qh	664536	1066367	2.466	TraVinh,DuyenHai,LongToan	76.33	77.2	77.24	77.66	72.98			
6	Q104010	qh	466919	1137072	0.255	KienGiang,HaTien,KienLuong	45.79	45.91	45.59	54.5	41.89	42.54	40.32	
7	Q17701T	qh	516407	1016294	0.807	CaMau,TP.CaMau,P.9	38.3	38.8	41.63	41.23	48.7			
8	Q199010	qh	499584	968465	1.145	CaMau,NgocHien,TTNamCan	38.77	27.5	34.56	31.58	33.26			
9	Q203010M1	qh	518233.1	1186763	5.064	AnGiang,TanChau,LeChanh	63.5	58.97	58.78	55.67	64.22	56.71	64.48	74.52
10	Q20302TM1	qh	518233	1186763	5.06	AnGiang,TanChau,LeChanh	56.47	62.88	59.94	57.24	55.9	56.2	60.34	66.72
11	Q204010	qh	532046	1156182	2.934	AnGiang,ChauThanh,CanDang	55.06	47.23	65.32	48.29	41.33	46.45	51.13	52.34
12	Q206010M1	qh	570664.5	1136689	2.54	DongThap,LaiVung,HoaLong	33.69	44.39	41.93	40.21	42.26	34.97	42.1	
13	Q209010	qh	588160	1112819	2.033	VinhLong,Binh Minh,CaiVon	44.54	42.65	54.97	55.08	49.08			
14	Q211010	qh	562636	1070144	1.02	HauGiang,LongMy,TTLongMy	36.23	35.39	42.82	47.63	45.07	40.29	44.55	
15	Q214010	qh	617537	1118451	1.842	VinhLong,MangThit,TanLongHoi					53.33			
16	Q214010M1	qh	617537	1118451	1.842	VinhLong,MangThit,TanLongHoi	69.68	87.23	78.49	61.11	89.22			
17	Q217010	qh	663821	1065473	1.856	TraVinh,DuyenHai,LongToan	80.29	77.78	79.36	77.5	53.71			
15	Q219010	qh	674903	1110927	1.423	BenTre,Ba Tri,TT Ba Tri	40.42	43.53	54.59	41.64	50.9			
19	Q326010	qh	667327	1159843	1.728	Long An,TanTru,DucTan	33.05	29.09	37.82	35.5	41.72			
20	Q40101T	qh	517226	1094764	1.366	KienGiang,ChauThanh,TTMinhLuong	45.14	43.13	54.19	38.42	40.28	44.38	51.81	
21	Q59801T	qh	606472	1059135	1.858	SocTrang, TP.SocTrang, P.3	38.11	45.76	80.08	71.04	85.51			

Table 5.14: CCME WQI of Holocene Aquifer by year according to VNR in the period 2010 - 2017

No.	Station	Aquifer	X	Y	Z	Site	2010	2011	2012	2013	2014	2015	2016	2017
1	Q003010	qh	508778	1179571	4.385	AnGiang,ChauDoc,VinhTe	71.69	84.93	74.11	65.12	83.78	61.79	81.37	
2	Q022010	qh	627775	1178163	1.543	Long An,ThanhHoa,TTThanhHoa	63.81	68.8	87.75	80.81	65.3			
3	Q031010	qh	545162	1173845	3.84	DongThap,ThanhBinh,AnPhong	48.63	60.5	49.88	51.23	45.41	52.94	50.93	57.77
4	Q07701A	qh	665622	1068966	3.833	TraVinh,DuyenHai,LongToan	91.57	100	100	85.59	78.43			
5	Q07701H	qh	664536	1066367	2.466	TraVinh,DuyenHai,LongToan	100	69.88	73.88	84.92	92.83			
6	Q104010	qh	466919	1137072	0.255	KienGiang,HaTien,KienLuong	46.45	40.89	40.19	52.6	38.04	39.05	33.1	
7	Q17701T	qh	516407	1016294	0.807	CaMau,TP.CaMau,P.9	34.32	30.77	38.27	36.77	57.69			
8	Q199010	qh	499584	968465	1.145	CaMau,NgocHien,TTNamCan	35.91	38.3	37.93	36.37	34.78			
9	Q203010M1	qh	518233.1	1186763	5.064	AnGiang,TanChau,LeChanh	55.6	68.96	71.45	66.71	72.83	76.94	66.24	90.29
10	Q20302TM1	qh	518233	1186763	5.06	AnGiang,TanChau,LeChanh	57.16	65.87	67.56	59.08	59.35	62.87	65.15	70.52
11	Q204010	qh	532046	1156182	2.934	AnGiang,ChauThanh,CanDang	58.43	57.58	69.37	51.93	57.53	52.43	48.76	54.06
12	Q206010M1	qh	570664.5	1136689	2.54	DongThap,LaiVung,HoaLong	34.92	36.73	40.42	40.52	47.01	33.57	44.51	
13	Q209010	qh	588160	1112819	2.033	VinhLong,Binh Minh,CaiVon	44.62	62.68	50.58	54.59	74.09			
14	Q211010	qh	562636	1070144	1.02	HauGiang,LongMy,TTLongMy	47.63	48.22	52.48	60.92	55.48	47.74	54.07	
15	Q214010	qh	617537	1118451	1.842	VinhLong,MangThit,TanLongHoi					57.52			
16	Q214010M1	qh	617537	1118451	1.842	VinhLong,MangThit,TanLongHoi	71.57	91.86	83.73	64.48	100			
17	Q217010	qh	663821	1065473	1.856	TraVinh,DuyenHai,LongToan	92.8	86.36	100	81.95	61.62			
15	Q219010	qh	674903	1110927	1.423	BenTre,Ba Tri,TT Ba Tri	41.1	43.78	46.12	38.16	46.91			
19	Q326010	qh	667327	1159843	1.728	Long An,TanTru,DucTan	36.39	33.76	44.93	38.4	43.24			
20	Q40101T	qh	517226	1094764	1.366	KienGiang,ChauThanh,TTMinhLuong	47.87	44.86	60.54	49.88	44.04	48.3	50.91	
21	Q59801T	qh	606472	1059135	1.858	SocTrang, TP.SocTrang, P.3	53.88	68.73	91.71	81.14	91.68			

Table 5.15: CCME WQI of Holocene Aquifer by year according to EU WFD in the period 2010 - 2017

No.	Station	Aquifer	X	Y	Z	Site	2010	2011	2012	2013	2014	2015	2016	2017
1	Q003010	qh	508778	1179571	4.385	AnGiang,ChauDoc,VinhTe	43.89	55.12	54.88	37.76	72.44	50.19	68.8	
2	Q022010	qh	627775	1178163	1.543	Long An,ThanhHoa,TTThanhHoa	40.1	44.11	67.55	65.02	49.83			
3	Q031010	qh	545162	1173845	3.84	DongThap,ThanhBinh,AnPhong	41.23	44.27	36.22	40.27	39.46	40.84	39.84	46.01
4	Q07701A	qh	665622	1068966	3.833	TraVinh,DuyenHai,LongToan	54.13	67.26	65.59	58.08	52.83			
5	Q07701H	qh	664536	1066367	2.466	TraVinh,DuyenHai,LongToan	67.31	43.87	44.14	47.11	65.31			
6	Q104010	qh	466919	1137072	0.255	KienGiang,HaTien,KienLuong	43.09	43.28	42.73	50.68	39.01	40.11	36.16	
7	Q17701T	qh	516407	1016294	0.807	CaMau,TP.CaMau,P.9	32.1	33.15	35	34.1	44.96			
8	Q199010	qh	499584	968465	1.145	CaMau,NgocHien,TTNamCan	33.08	24.83	30.6	28.43	28.23			
9	Q203010M1	qh	518233.1	1186763	5.064	AnGiang,TanChau,LeChanh	40.33	41.4	40.7	40.17	43.47	43.57	44.54	56.86
10	Q20302TM1	qh	518233	1186763	5.06	AnGiang,TanChau,LeChanh	31.52	44.01	42.1	40.72	40.96	41.94	43.83	47.89
11	Q204010	qh	532046	1156182	2.934	AnGiang,ChauThanh,CanDang	51.77	45.45	61.66	44.18	38.69	44.2	43.15	46.02
12	Q206010M1	qh	570664.5	1136689	2.54	DongThap,LaiVung,HoaLong	23.31	33.19	32.23	30.75	33.04	28.39	32.66	
13	Q209010	qh	588160	1112819	2.033	VinhLong,Binh Minh,CaiVon	33.61	33.99	37.79	38.17	44.26			
14	Q211010	qh	562636	1070144	1.02	HauGiang,LongMy,TTLongMy	30.94	32.16	37.5	46.07	41.83	36.09	40.87	
15	Q214010	qh	617537	1118451	1.842	VinhLong,MangThit,TanLongHoi					51.11			
16	Q214010M1	qh	617537	1118451	1.842	VinhLong,MangThit,TanLongHoi	68.32	81.78	73.27	59.63	88.98			
17	Q217010	qh	663821	1065473	1.856	TraVinh,DuyenHai,LongToan	63.06	47.87	57.88	45.97	30.03			
15	Q219010	qh	674903	1110927	1.423	BenTre,Ba Tri,TT Ba Tri	36.35	38.93	45.94	35.01	42.56			
19	Q326010	qh	667327	1159843	1.728	Long An,TanTru,DucTan	27.84	25.17	35.91	34.44	38.7			
20	Q40101T	qh	517226	1094764	1.366	KienGiang,ChauThanh,TTMinhLuong	41.95	38.13	53.33	36.78	36.08	40.55	44.8	
21	Q59801T	qh	606472	1059135	1.858	SocTrang, TP.SocTrang, P.3	31.01	36.72	73.53	69.38	81.57			

Upper Pleistocene Aquifer

The Upper Pleistocene aquifer (qp_3) is distributed widely over an area of 39,468 km^2 but is absent in Tri Ton, Tinh Bien, Chau Doc, Thoai Son (An Giang), Hon Dat, Ha Tien and Kien Luong (Kien Giang Province) (Deltares, 2011). The depth to the top of the aquifer varies from 000m to 115.40m, with an average of 47.96m. The depth to the bottom of the aquifer ranges from 11.50m to 154.00m, with an average of 76.36m. The thickness is from 2.00m to 84.00m, with an average of 29.14m. The permeability varies from 022m/day to 65.82 m/day, with an average of 20.62 m/day. The groundwater levels are between -6.36m and 0.99m above sea level. The area of fresh groundwater is 10.494 km^2, and that of saline groundwater is 28,974 km^2. The amount of groundwater abstracted by 2010 was 114,945 m3/day (Ha et al., 2015).

The overview results yielded the sign of pollution in aquifer qp_3 with the presence of Cl^-, Fe, Na^+, Mn, NH_4^+, etc. (Section 5.2.2). The groundwater quality assessment in aquifer qp_3 is conducted for 21 sample stations span from 2010 to 2017. Figure 5.5 shows the MCWQI value of aquifer qp_3 in the time with the trend line. It can be seen that the groundwater quality by VNR is mostly marginal and fair, while by EU WFD, it is mostly in line with the upper bound of poor quality in the diagram.

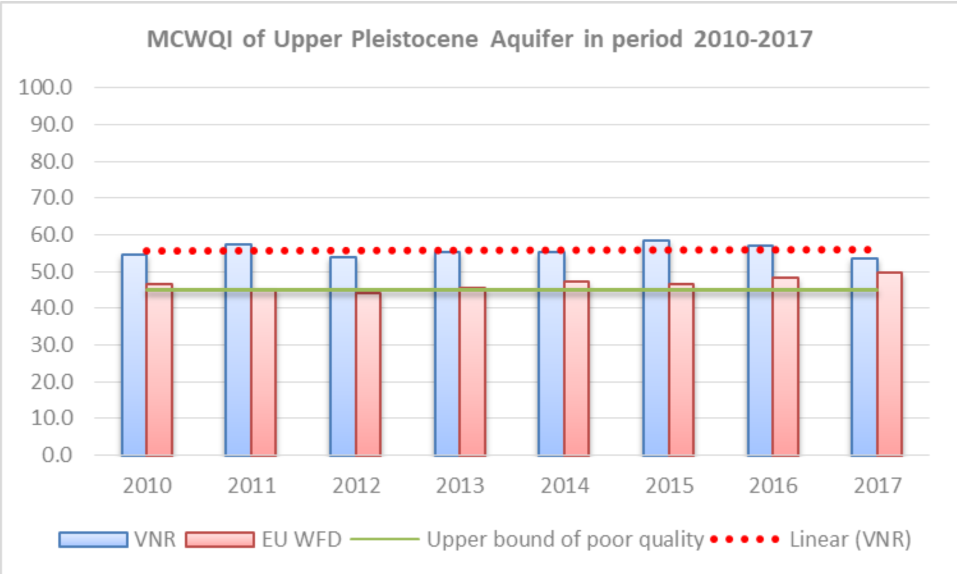

Figure 5.5: MCWQI of Upper Pleistocene Aquifer in the period 2010 – 2017 with trend line

Table 5.16, 5.17, 5.18, and 5.19 present more details about the groundwater quality in qp_3 aquifer by sample station assessed by MCWQI and CCME WQI according to VNR and EU WFD. The color range of these tables highlights the groundwater quality. As the same conclusion with Figure 5.5, the water quality in the sample stations is also mostly marginal and fair.

Table 5.16: MCWQI of Upper Pleistocene Aquifer by year according to VNR in the period 2010 - 2017

No.	Station	Aquifer	X	Y	Z	Site	2010	2011	2012	2013	2014	2015	2016	2017
1	Q02202T	qp3	627774	1178166	1.496	Long An,ThanhHoa,TTThanhHoa	57.63	71.17	73.04	72.37	53.11			
2	Q02702T	qp3	585616	1204221	2.758	Long An,VinhHung,TTVinhHung	74.99	74.07	66.95	71.07	57.44			
3	Q031020	qp3	545124.1	1173839	3.93	DongThap,ThanhBinh,AnPhong	69.57	74.57	79.91	69.15	75.18	73.91	76.8	62.45
4	Q17701Z	qp3	516404	1016295	0.855	CaMau,TP.CaMau,P.9			33.8					
5	Q17701ZM1	qp3	516373.8	1016292	1.15	CaMau,TP.CaMau,P.9	33.24	50.02	26.17	42.09	31.94			
6	Q20302ZM1	qp3	518233	1186763	5.06	AnGiang,TanChau,LeChanh	39.27	51.64	65.78	41.41	47.9	57.84	50.89	51.5
7	Q20402T	qp3	532050	1156186	2.979	AnGiang,ChauThanh,CanDang	50.22	57.45	56.29					
8	Q209020	qp3	588160	1112811	2.179	VinhLong,Binh Minh,CaiVon	68.79	63.68	62.18	62.46	59.66			
9	Q219020	qp3	674909	1110923	1.546	BenTre,Ba Tri,TT Ba Tri	56.05	46.24	46.1	45.64	44.85			
10	Q219020M1	qp3	674990.5	1110881	0.9	BenTre,Ba Tri,TTBaTri			45.27	30.41	37.05			
11	Q40101Z	qp3	517226	1094764	1.366	KienGiang,ChauThanh,TTMinhLuong	54.04	42.46	36.78	41.27	40.02	51.18	50.57	
12	Q40102T	qp3	517226	1094764	1.366	KienGiang,ChauThanh,TTMinhLuong	43.66	51.67	51.99	51.3	51.53	40.63	46.41	
13	Q402020M1	qp3	538382.8	1126029	2.26	CanTho,VinhThanh,ThanhTien	100	100	100	100	100	94.92	69.59	
14	Q404020	qp3	638494	1076964	1.424	TraVinh,TraCu,TapSon	85.57	89.64	100	90.24	78.5			
15	Q407020M1	qp3	638494	1076964	1.424	TraVinh,TraCu,TapSon		46.84		66.79	70.75	60.19	56.24	
16	Q408020	qp3	551365	1143944	2.539	AnGiang,TP.LongXuyen,MyThanh	66.59	63.68	69.97	74.72	74.21	63.27	60.17	52.52
17	Q409020	qp3	606539	1062656	1.624	SocTrang, TP.SocTrang, P.3		42.67	49.23					
15	Q409020M1	qp3	606418	1060972	1.9	SocTrang, TP.SocTrang, P.3	54.56	53.27	61.74	42.21	32.09			
19	Q597020	qp3	578632	1027669	1.902	BacLieu, TX.BacLieu, P.7		58.67	72.31					
20	Q597020M1	qp3	578632	1027669	1.9	BacLieu, TX.BacLieu,P.7	72.02	69.52	78.89	63.17	58.58			
21	Q606020	qp3	580625.3	1156304	3.08	DongThap,CaoLanh,MyTho	70.21	78.13	70.2	73.67	77.57	71.42	78.25	

Table 5.17: MCWQI of Upper Pleistocene Aquifer by year according to EU WFD in the period 2010 - 2017

No.	Station	Aquifer	X	Y	Z	Site	2010	2011	2012	2013	2014	2015	2016	2017
1	Q02202T	qp3	627774	1178166	1.496	Long An,ThanhHoa,TTThanhHoa	35.18	56.83	66.69	62.82	40.63			
2	Q02702T	qp3	585616	1204221	2.758	Long An,VinhHung,TTVinhHung	49.18	57.12	45.68	52.66	38.49			
3	Q031020	qp3	545124.1	1173839	3.93	DongThap,ThanhBinh,AnPhong	56.69	59.58	65.88	64.31	67.25	63.51	68.92	65.66
4	Q17701Z	qp3	516404	1016295	0.855	CaMau,TP.CaMau,P.9			32.93					
5	Q17701ZM1	qp3	516373.8	1016292	1.15	CaMau,TP.CaMau,P.9	32.35	49.61	24.76	34.22	31.22			
6	Q20302ZM1	qp3	518233	1186763	5.06	AnGiang,TanChau,LeChanh	27.88	36.45	50.21	35.98	35.98	43.62	36.5	43.68
7	Q20402T	qp3	532050	1156186	2.979	AnGiang,ChauThanh,CanDang	46.68	54.5	50.91					
8	Q209020	qp3	588160	1112811	2.179	VinhLong,Binh Minh,CaiVon	46.2	40.7	37.9	40.21	38.91			
9	Q219020	qp3	674909	1110923	1.546	BenTre,Ba Tri,TT Ba Tri	48.26	44.46	45.62	35.92	43.54			
10	Q219020M1	qp3	674990.5	1110881	0.9	BenTre,Ba Tri,TTBaTri			45.2	29.2	35.67			
11	Q40101Z	qp3	517226	1094764	1.366	KienGiang,ChauThanh,TTMinhLuong	51.75	38.55	34.82	39.54	31.36	34.49	49.44	
12	Q40102T	qp3	517226	1094764	1.366	KienGiang,ChauThanh,TTMinhLuong	42.47	42.78	50.83	50.27	50.59	39.59	38.35	
13	Q402020M1	qp3	538382.8	1126029	2.26	CanTho,VinhThanh,ThanhTien	77.86	84.18	84.31	77.22	88.47	76.11	54.8	
14	Q404020	qp3	638494	1076964	1.424	TraVinh,TraCu,TapSon	72.58	69.27	73.84	67.98	58.18			
15	Q407020M1	qp3	638494	1076964	1.424	TraVinh,TraCu,TapSon		29.32		57.58	56.66	45.97	43.22	
16	Q408020	qp3	551365	1143944	2.539	AnGiang,TP.LongXuyen,MyThanh	37.73	38.35	55.6	53.7	53.33	49.52	46.27	39.27
17	Q409020	qp3	606539	1062656	1.624	SocTrang, TP.SocTrang, P.3		42.11	45.05					
15	Q409020M1	qp3	606418	1060972	1.9	SocTrang,TP.SocTrang,P.3	53.12	46.13	56.48	41.86	31.35			
19	Q597020	qp3	578632	1027669	1.902	BacLieu,TX.BacLieu,P.7		52.69	59.23					
20	Q597020M1	qp3	578632	1027669	1.9	BacLieu,TX.BacLieu,P.7	56.59	54.46	66.06	60.03	54.83			
21	Q606020	qp3	580625.3	1156304	3.08	DongThap,CaoLanh,MyTho	40.32	63.51	55.22	57.98	59.96	54.21	57.28	

Table 5.18: CCME WQI of Upper Pleistocene Aquifer by year according to VNR in the period 2010 - 2017

No.	Station	Aquifer	X	Y	Z	Site	2010	2011	2012	2013	2014	2015	2016	2017
1	Q02202T	qp3	627774	1178166	1.496	Long An,ThanhHoa,TTThanhHoa	52.01	66.1	72.72	71.78	47.75			
2	Q02702T	qp3	585616	1204221	2.758	Long An,VinhHung,TTVinhHung	72.95	72.69	66.32	66.37	57.27			
3	Q031020	qp3	545124.1	1173839	3.93	DongThap,ThanhBinh,AnPhong	65.34	71.53	74.69	68.08	71.28	70.79	76.15	52.7
4	Q17701Z	qp3	516404	1016295	0.855	CaMau,TP.CaMau,P.9			28.65					
5	Q17701ZM1	qp3	516373.8	1016292	1.15	CaMau,TP.CaMau,P.9	27.74	40.28	24.13	35.98	29.02			
6	Q20302ZM1	qp3	518233	1186763	5.06	AnGiang,TanChau,LeChanh	33.44	49.11	64.5	37.56	41.73	52.49	43.8	45.19
7	Q20402T	qp3	532050	1156186	2.979	AnGiang,ChauThanh,CanDang	49.69	55.98	55.27					
8	Q209020	qp3	588160	1112811	2.179	VinhLong,Binh Minh,CaiVon	60.09	63.12	57.98	58.58	58.97			
9	Q219020	qp3	674909	1110923	1.546	BenTre,Ba Tri,TT Ba Tri	49.57	39.4	39.14	38.3	36.82			
10	Q219020M1	qp3	674990.5	1110881	0.9	BenTre,Ba Tri,TTBaTri			37.6	29.61	33.74			
11	Q40101Z	qp3	517226	1094764	1.366	KienGiang,ChauThanh,TTMinhLuong	49.73	36.75	34.32	37.91	35.58	43.25	41.73	
12	Q40102T	qp3	517226	1094764	1.366	KienGiang,ChauThanh,TTMinhLuong	39.19	44.45	45.2	43.55	44.13	37.61	40.16	
13	Q402020M1	qp3	538382.8	1126029	2.26	CanTho,VinhThanh,ThanhTien	100	100	100	100	100	92.72	69.42	
14	Q404020	qp3	638494	1076964	1.424	TraVinh,TraCu,TapSon	85.08	86.62	100	90.14	76.13			
15	Q407020M1	qp3	638494	1076964	1.424	TraVinh,TraCu,TapSon		45.14		65.56	69.16	51.81	50.02	
16	Q408020	qp3	551365	1143944	2.539	AnGiang,TP.LongXuyen,MyThanh	65.82	61.02	67.71	73.14	72.21	62.71	58.01	52.37
17	Q409020	qp3	606539	1062656	1.624	SocTrang, TP.SocTrang, P.3		32.6	35.64					
15	Q409020M1	qp3	606418	1060972	1.9	SocTrang,TP.SocTrang,P.3	45.5	40.19	44.01	36.24	29.27			
19	Q597020	qp3	578632	1027669	1.902	BacLieu,TX.BacLieu,P.7		58.28	72.02					
20	Q597020M1	qp3	578632	1027669	1.9	BacLieu,TX.BacLieu,P.7	70.09	66.93	78.66	62.58	57.71			
21	Q606020	qp3	580625.3	1156304	3.08	DongThap,CaoLanh,MyTho	65.55	76.46	68.24	72.27	77.1	68.84	77.78	

Table 5.19: CCME WQI of Upper Pleistocene Aquifer by year according to EU WFD in the period 2010 - 2017

No.	Station	Aquifer	X	Y	Z	Site	2010	2011	2012	2013	2014	2015	2016	2017
1	Q02202T	qp3	627774	1178166	1.496	Long An,ThanhHoa,TTThanhHoa	28.83	40.07	66.45	62.81	36.74			
2	Q02702T	qp3	585616	1204221	2.758	Long An,VinhHung,TTVinhHung	40.36	50.82	36.53	38.53	31.81			
3	Q031020	qp3	545124.1	1173839	3.93	DongThap,ThanhBinh,AnPhong	43.79	48.17	55.15	56.49	58.64	57.33	63.26	59.83
4	Q17701Z	qp3	516404	1016295	0.855	CaMau,TP.CaMau,P.9			27.21					
5	Q17701ZM1	qp3	516373.8	1016292	1.15	CaMau,TP.CaMau,P.9	26.26	39.2	22.19	29.99	27.81			
6	Q20302ZM1	qp3	518233	1186763	5.06	AnGiang,TanChau,LeChanh	23.03	31.39	43.98	30.46	30.46	36.27	31.49	36.41
7	Q20402T	qp3	532050	1156186	2.979	AnGiang,ChauThanh,CanDang	44.57	50.68	47.39					
8	Q209020	qp3	588160	1112811	2.179	VinhLong,Binh Minh,CaiVon	41.79	40.17	36.24	38.06	35.91			
9	Q219020	qp3	674909	1110923	1.546	BenTre,Ba Tri,TT Ba Tri	44.14	36.07	38.25	32.01	34.3			
10	Q219020M1	qp3	674990.5	1110881	0.9	BenTre,Ba Tri,TTBaTri			37.48	28.11	31.62			
11	Q40101Z	qp3	517226	1094764	1.366	KienGiang,ChauThanh,TTMinhLuong	44.63	32.63	31.05	34.64	28.04	30.49	38.74	
12	Q40102T	qp3	517226	1094764	1.366	KienGiang,ChauThanh,TTMinhLuong	36.77	37.43	42.38	40.95	41.77	35.92	33.34	
13	Q402020M1	qp3	538382.8	1126029	2.26	CanTho,VinhThanh,ThanhTien	67.84	79.38	79.78	75.57	88.44	74.55	54.77	
14	Q404020	qp3	638494	1076964	1.424	TraVinh,TraCu,TapSon	59.54	55.05	71.98	66.13	54.32			
15	Q407020M1	qp3	638494	1076964	1.424	TraVinh,TraCu,TapSon		25.25		56.19	54.67	38.9	38.32	
16	Q408020	qp3	551365	1143944	2.539	AnGiang,TP.LongXuyen,MyThanh	33.81	31.53	52.78	52.71	52.23	48.77	43.89	39.09
17	Q409020	qp3	606539	1062656	1.624	SocTrang, TP.SocTrang, P.3		31.48	31.76					
15	Q409020M1	qp3	606418	1060972	1.9	SocTrang,TP.SocTrang,P.3	39.4	28.38	34.67	35.49	28.03			
19	Q597020	qp3	578632	1027669	1.902	BacLieu,TX.BacLieu,P.7		50.15	53.35					
20	Q597020M1	qp3	578632	1027669	1.9	BacLieu,TX.BacLieu,P.7	42.09	38.74	58.54	57.76	51.33			
21	Q606020	qp3	580625.3	1156304	3.08	DongThap,CaoLanh,MyTho	35.2	46.48	41.43	43.26	46.88	39.63	48.66	

Upper – Middle Pleistocene Aquifer

The Upper – Middle Pleistocene (qp_{2-3}) aquifer covers an area of 39,279 km^2 but is absent in Tri Ton, Tinh Bien, Chau Doc, Thoai Son (An Giang Province), Hon Dat, Ha Tien and Kien Luong (Kien Giang Province) (Deltares, 2011). The depth to the top of the aquifer varies from 9.7m to 17800m, with an average of 86.88m. The depth to the bottom of the aquifer ranges from 24.50m to 207.00m, with an average of 129,13m. The thickness is from 2.00m to 100.30m, with an average of 41.45m. The permeability varies from 0.89m/day to 55.07m/day, with an average of 21.24 m/day. The area of fresh groundwater is 14,941 km^2, and that of saline groundwater is 24,338 km^2. The amount of groundwater abstracted by 2010 was 997,514 m3/day. (Ha et al., 2015).

The overview results yielded the sign of pollution in aquifer qp_{2-3} with the presence of Cl^-, Fe, Na^+, Mn, NH_4^+, etc. (Section 5.2.2). The groundwater quality assessment in the aquifer is conducted for 24 sample stations span from 2010 to 2017. Figure 5.6 shows the MCWQI value of aquifer qp_{2-3} in the time with the trend line. It can be seen that the groundwater quality by VNR is mostly marginal and good, while by EU WFD, it is mostly over the upper bound of poor quality in the diagram. In the monitoring practice, in 2015, 2016, and 2017, there were only 7 sample stations in aquifer qp_{2-3} that were monitored.

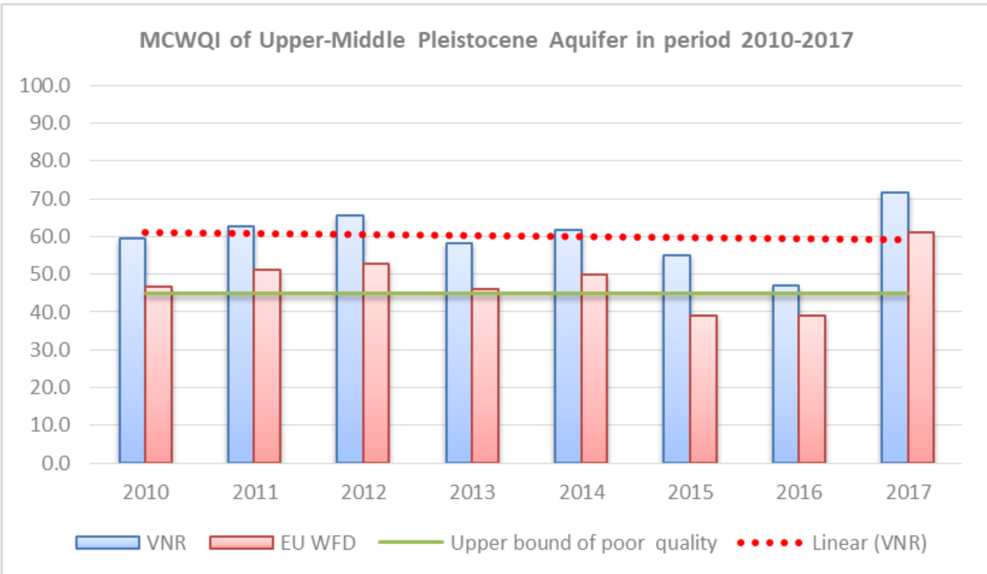

Figure 5.6: MCWQI of Upper - Middle Pleistocene Aquifer in the period 2010 – 2017 with trend line

Table 5.20, 5.21, 5.22, and 5.23 present more details about the groundwater quality in aquifer qp_{2-3} by sample station assessed by MCWQI and CCME WQI according to VNR and EU WFD. The color range of these tables highlights the groundwater quality. The water quality in the sample stations are also mostly marginal and good (same conclusion of Figure 5.6), some sample stations even have excellent quality.

Table 5.20: MCWQI of Upper-Middle Pleistocene Aquifer by year according to VNR in the period 2010 - 2017

No.	Station	Aquifer	X	Y	Z	Site	2010	2011	2012	2013	2014	2015	2016	2017
1	Q02202Z	qp23	627731	1178163	2.2	Long An,ThanhHoa,TTThanhHoa				42.9				
2	Q02202ZM1	qp23	627731	1178163	2.2	Long An,ThanhHoa,TTThanhHoa	33.48	39.48	34.98	42.89	39.29			
3	Q104020	qp23	466919	1137076	0.24	KienGiang,HaTien,KienLuong	91.36	90.91	89.38	65.43	73.76	68.8	68.32	
4	Q177020	qp23	516372.3	1016290	1.21	CaMau,TP.CaMau,P.9		78.68						
5	Q177020M1	qp23	516372.3	1016290	1.21	CaMau,TP.CaMau,P.9	68.52	77.14		60.51				
6	Q188020	qp23	516427	1014734	1.16	CaMau,TP.CaMau,P.5	56.35	48.99	52.13	45.94	58.67			
7	Q203040M1	qp23	518233	1186763	5.07	AnGiang,TanChau,LeChanh	27.27	53.97	46.34	54.28	35.4	38.34	32.16	41.93
8	Q20402Z	qp23	532052	1156188	2.96	AnGiang,ChauThanh,CanDang	74.91	73.53	89.7	75.59	68.1	89.58	80.27	80.03
9	Q206020M1	qp23	570666.1	1136688	2.53	DongThap,LaiVung,HoaLong	28.55	56.98	62.02	43.79	72.22	45.74	36.75	
10	Q209030	qp23	588159	1112821	2.15	VinhLong,Binh Minh,CaiVon	50.38	50.34	60.16	53.04	40.69			
11	Q211020	qp23	562634	1070142	1.03	HauGiang,LongMy,TTLongMy	71.8	75.54	70.58	63.72	55.41		63.4	
12	Q21402T	qp23	617540	1118449	1.89	VinhLong,MangThit,TanLongHoi					34.61			
13	Q21402TM1	qp23	617314.6	1118043	1.66	VinhLong,MangThit,TanLongHoi	43.8	54.58	46.75	54.4	43.19			
14	Q217020	qp23	663818	1065472	1.94	TraVinh,DuyenHai,LongToan	86.98	84.35	94.7	94.53	85.1			
15	Q326020	qp23	666257.5	1163586	1.55	Long An, TanTru, DucTan				30.94				
16	Q326020M1	qp23	666257.5	1163586	1.55	LongAn,TanTru,DucTan	42.31	57.04	48.95	60.17	45.74			
17	Q40102Z	qp23	517226	1094764	1.37	KienGiang,ChauThanh,TTMinhLuong	100	91.19	94.68	88.56	87.29	90.21	87.03	
15	Q403020	qp23	545027	1124421	2.27	CanTho,ThotNot,ThanhQuoi	94.22	95.3	92.23	85.7	86.44	96.16	97.61	97.45
19	Q40403T	qp23	638496	1076961	1.54	TraVinh,TraCu,TapSon	86.1	87.21	99.03	85.36	85.02			
20	Q40903A	qp23	606417.1	1060971	1.89	SocTrang, TP.SocTrang, P.3		59.32						
21	Q597030	qp23	578631	1027667	1.93	BacLieu,TX.BacLieu,P.7		100						
22	Q597030M1	qp23	578601.9	1027664	1.91	BacLieu,TX.BacLieu,P.7	93.67	81.8	90.89	81.85	91.15			
23	Q598020	qp23	606472	1059132	1.76	SocTrang,TP.SocTrang,P.3				79.43				
24	Q598020M1	qp23	606443.8	1059140	1.48	SocTrang,TP.SocTrang,P.3	73.98	91.05	82.18	76.27	92.76			

Table 5.21: MCWQI of Upper-Middle Pleistocene Aquifer by year according to EU WFD in the period 2010 - 2017

No.	Station	Aquifer	X	Y	Z	Site	2010	2011	2012	2013	2014	2015	2016	2017
1	Q02202Z	qp23	627731	1178163	2.2	Long An,ThanhHoa,TTThanhHoa				24.93				
2	Q02202ZM1	qp23	627731	1178163	2.2	Long An,ThanhHoa,TTThanhHoa	17.06	29.04	31.57	32.74	28.69			
3	Q104020	qp23	466919	1137076	0.24	KienGiang,HaTien,KienLuong	83.57	82.97	82.06	54.19	64.87	59.24	54.77	
4	Q177020	qp23	516372.3	1016290	1.21	CaMau,TP.CaMau,P.9		60.65						
5	Q177020M1	qp23	516372.3	1016290	1.21	CaMau,TP.CaMau,P.9	44.01	58		58.41				
6	Q188020	qp23	516427	1014734	1.16	CaMau,TP.CaMau,P.5	42.56	42.28	37.65	37.69	44.72			
7	Q203040M1	qp23	518233	1186763	5.07	AnGiang,TanChau,LeChanh	25.54	30.15	35.43	35.57	31.69	20.93	28.71	31.04
8	Q20402Z	qp23	532052	1156188	2.96	AnGiang,ChauThanh,CanDang	68.22	69.6	87.03	68.74	57.38	83	78.09	77.93
9	Q206020M1	qp23	570666.1	1136688	2.53	DongThap,LaiVung,HoaLong	22.42	42.14	48.07	29.63	66.14	40.77	29.69	
10	Q209030	qp23	588159	1112821	2.15	VinhLong,Binh Minh,CaiVon	49.29	41.19	57.24	52.14	30.43			
11	Q211020	qp23	562634	1070142	1.03	HauGiang,LongMy,TTLongMy	65.45	60.86	55.95	44.42	35.87		63.09	
12	Q21402T	qp23	617540	1118449	1.89	VinhLong,MangThit,TanLongHoi					32.83			
13	Q21402TM1	qp23	617314.6	1118043	1.66	VinhLong,MangThit,TanLongHoi	32.92	51.03	38.81	50.86	32.92			
14	Q217020	qp23	663818	1065472	1.94	TraVinh,DuyenHai,LongToan	75.97	73.93	82.25	83.18	74.08			
15	Q326020	qp23	666257.5	1163586	1.55	Long An, TanTru, DucTan				27.56				
16	Q326020M1	qp23	666257.5	1163586	1.55	LongAn, TanTru, DucTan	34.61	45.57	42.04	48.5	44.13			
17	Q40102Z	qp23	517226	1094764	1.37	KienGiang,ChauThanh,TTMinhLuong	81.81	74.34	70.92	67.79	72.78	68.97	69.39	
15	Q403020	qp23	545027	1124421	2.27	CanTho,ThotNot,ThanhQuoi	66.58	66.7	78.68	68.84	69.28	67.82	70.56	82.6
19	Q40403T	qp23	638496	1076961	1.54	TraVinh,TraCu,TapSon	70.23	67.99	92.17	64.41	64.11			
20	Q40903A	qp23	606417.1	1060971	1.89	SocTrang, TP.SocTrang, P.3		45.47						
21	Q597030	qp23	578631	1027667	1.93	BacLieu,TX.BacLieu,P.7		91.35						
22	Q597030M1	qp23	578601.9	1027664	1.91	BacLieu,TX.BacLieu,P.7	81.26	66.14	74.91	67.69	77.25			
23	Q598020	qp23	606472	1059132	1.76	SocTrang,TP.SocTrang,P.3				51.23				
24	Q598020M1	qp23	606443.8	1059140	1.48	SocTrang,TP.SocTrang,P.3	52.72	70.72	68.87	58.41	66.25			

Table 5.22: CCME WQI of Upper-Middle Pleistocene Aquifer by year according to VNR in the period 2010 - 2017

No.	Station	Aquifer	X	Y	Z	Site	2010	2011	2012	2013	2014	2015	2016	2017
1	Q02202Z	qp23	627731	1178163	2.2	Long An,ThanhHoa,TTThanhHoa				33.04				
2	Q02202ZM1	qp23	627731	1178163	2.2	Long An,ThanhHoa,TTThanhHoa	28.13	34.52	31.34	33.03	34.15			
3	Q104020	qp23	466919	1137076	0.24	KienGiang,HaTien,KienLuong	89.52	89.42	89.1	65.23	73.63	68.09	67.76	
4	Q177020	qp23	516372.3	1016290	1.21	CaMau,TP.CaMau,P.9		74.54						
5	Q177020M1	qp23	516372.3	1016290	1.21	CaMau,TP.CaMau,P.9	67.87	71.24		49.89				
6	Q188020	qp23	516427	1014734	1.16	CaMau,TP.CaMau,P.5	48.93	44.06	46.55	42.42	49.34			
7	Q203040M1	qp23	518233	1186763	5.07	AnGiang,TanChau,LeChanh	25.6	44.3	40.29	45.12	32.05	33.75	29.39	35.63
8	Q20402Z	qp23	532052	1156188	2.96	AnGiang,ChauThanh,CanDang	66.64	70.9	88.59	68.66	56.12	88.38	69.82	68.85
9	Q206020M1	qp23	570666.1	1136688	2.53	DongThap,LaiVung,HoaLong	28.21	50.89	60.98	39.43	65.66	42.99	34.27	
10	Q209030	qp23	588159	1112821	2.15	VinhLong,Binh Minh,CaiVon	41.24	41.12	57.98	41.7	28.57			
11	Q211020	qp23	562634	1070142	1.03	HauGiang,LongMy,TTLongMy	61.53	72.1	65.14	59.74	51.68		62.03	
12	Q21402T	qp23	617540	1118449	1.89	VinhLong,MangThit,TanLongHoi					29.95			
13	Q21402TM1	qp23	617314.6	1118043	1.66	VinhLong,MangThit,TanLongHoi	39.45	45.9	41.14	45.43	33.62			
14	Q217020	qp23	663818	1065472	1.94	TraVinh,DuyenHai,LongToan	82.9	83.63	91.34	93.51	83.91			
15	Q326020	qp23	666257.5	1163586	1.55	Long An, TanTru, DucTan				30.25				
16	Q326020M1	qp23	666257.5	1163586	1.55	LongAn,TanTru,DucTan	40.14	51.84	45.41	51.78	43			
17	Q40102Z	qp23	517226	1094764	1.37	KienGiang,ChauThanh,TTMinhLuong	100	90.18	92.69	83.79	86.79	85.49	86.35	
15	Q403020	qp23	545027	1124421	2.27	CanTho,ThotNot,ThanhQuoi	90.88	92.76	90.67	83.33	83.5	92.81	92.83	95.69
19	Q40403T	qp23	638496	1076961	1.54	TraVinh,TraCu,TapSon	84.5	86.66	92.74	83.89	83.64			
20	Q40903A	qp23	606417.1	1060971	1.89	SocTrang, TP.SocTrang, P.3		59.05						
21	Q597030	qp23	578631	1027667	1.93	BacLieu,TX.BacLieu,P.7		100						
22	Q597030M1	qp23	578601.9	1027664	1.91	BacLieu,TX.BacLieu,P.7	92.45	77.51	89.93	81.03	90.08			
23	Q598020	qp23	606472	1059132	1.76	SocTrang,TP.SocTrang,P.3				79.42				
24	Q598020M1	qp23	606443.8	1059140	1.48	SocTrang,TP.SocTrang,P.3	73.11	87.46	82.1	76.27	92.14			

Table 5.23: CCME WQI of Upper-Middle Pleistocene Aquifer by year according to EU WFD in the period 2010 - 2017

No.	Station	Aquifer	X	Y	Z	Site	2010	2011	2012	2013	2014	2015	2016	2017
1	Q02202Z	qp23	627731	1178163	2.2	Long An,ThanhHoa,TTThanhHoa				22.42				
2	Q02202ZM1	qp23	627731	1178163	2.2	Long An,ThanhHoa,TTThanhHoa	16.22	26.56	28.4	26.9	26			
3	Q104020	qp23	466919	1137076	0.24	KienGiang,HaTien,KienLuong	79.18	79.08	80.12	54.01	64.64	58.32	54.53	
4	Q177020	qp23	516372.3	1016290	1.21	CaMau,TP.CaMau,P.9		52.78						
5	Q177020M1	qp23	516372.3	1016290	1.21	CaMau,TP.CaMau,P.9	43.3	47.08		44.35				
6	Q188020	qp23	516427	1014734	1.16	CaMau,TP.CaMau,P.5	33.78	33.1	30.01	30.09	34.06			
7	Q203040M1	qp23	518233	1186763	5.07	AnGiang,TanChau,LeChanh	23.27	28.3	32.11	32.35	28.6	18.9	26.03	27.5
8	Q20402Z	qp23	532052	1156188	2.96	AnGiang,ChauThanh,CanDang	56.54	60.97	81.97	58.26	45.67	79.17	59.81	58.99
9	Q206020M1	qp23	570666.1	1136688	2.53	DongThap,LaiVung,HoaLong	20.65	34.83	47.92	27.5	55.68	37.01	27.59	
10	Q209030	qp23	588159	1112821	2.15	VinhLong,Binh Minh,CaiVon	38.33	34.02	52.26	39.07	22.96			
11	Q211020	qp23	562634	1070142	1.03	HauGiang,LongMy,TTLongMy	48.48	54.99	47.92	39.68	27.41		62.71	
12	Q21402T	qp23	617540	1118449	1.89	VinhLong,MangThit,TanLongHoi					27.05			
13	Q21402TM1	qp23	617314.6	1118043	1.66	VinhLong,MangThit,TanLongHoi	30.62	42.88	34.57	42.46	27.21			
14	Q217020	qp23	663818	1065472	1.94	TraVinh,DuyenHai,LongToan	65.46	62.99	76.54	80.17	68.46			
15	Q326020	qp23	666257.5	1163586	1.55	Long An, TanTru, DucTan				25.99				
16	Q326020M1	qp23	666257.5	1163586	1.55	LongAn,TanTru,DucTan	33.18	42.7	39.26	43.39	40.09			
17	Q40102Z	qp23	517226	1094764	1.37	KienGiang,ChauThanh,TTMinhLuong	70.41	70.2	66.01	56.92	70.24	67.18	61.88	
15	Q403020	qp23	545027	1124421	2.27	CanTho,ThotNot,ThanhQuoi	52.74	53.16	53.77	50.17	52.03	57.03	65.09	73.76
19	Q40403T	qp23	638496	1076961	1.54	TraVinh,TraCu,TapSon	64.2	57.58	91.59	57.94	61.81			
20	Q40903A	qp23	606417.1	1060971	1.89	SocTrang, TP.SocTrang, P.3		45.06						
21	Q597030	qp23	578631	1027667	1.93	BacLieu,TX.BacLieu,P.7		90.81						
22	Q597030M1	qp23	578601.9	1027664	1.91	BacLieu,TX.BacLieu,P.7	80.96	60.28	70.63	59.81	61.53			
23	Q598020	qp23	606472	1059132	1.76	SocTrang,TP.SocTrang,P.3				36.35				
24	Q598020M1	qp23	606443.8	1059140	1.48	SocTrang,TP.SocTrang,P.3	45.24	60.26	49.04	40.01	58.59			

Lower Pleistocene Aquifer

The Lower Pleistocene aquifer (qp_1) is distributed widely over an area of 39.340 km^2 but is absent in Tri Ton Tinh Bien, Chau Doc, Thoai Son (An Giang Province, Hon Dat, Ha Tien and Kien Luong (Kien Giang Province) (Deltares, 2011). The depth to the top of the aquifer varies from 62.00m to 221.00m, with an average of 146.53m. The depth to the bottom of the aquifer ranges from 69.50m to 298.00m, with an average of 185.98m. The thickness is from 3.5m to 92.60m, with an average of 38.08m. The permeability varies from 0.76m/day to 53.28m/day, with an average of 24.74/day. The groundwater levels are between -7.37m and -0.04m below sea level. The area of fresh groundwater is 13,647 km^2, and that of saline groundwater is 25,693km^2. The amount of groundwater abstracted by 2010 was 130,077 m^3/day (Ha et al., 2015).

The overview results yielded the sign of pollution in aquifer qp_1 with the presence of Cl^-, Fe, Na^+, Mn, NH_4^+, etc. (Section 5.2.2). The groundwater quality assessment in the aquifer is conducted for 16 sample stations span from 2010 to 2017. Figure 5.7 shows the MCWQI value of aquifer qp_1 in the time with the trend line. It can be seen that the groundwater quality by VNR is mostly fair and good, while by EU WFD, it is mostly over the upper bound of poor quality in the diagram. In the monitoring practice, in 2015, 2016, and 2017, only 3 sample stations in aquifer qp_1 were monitored.

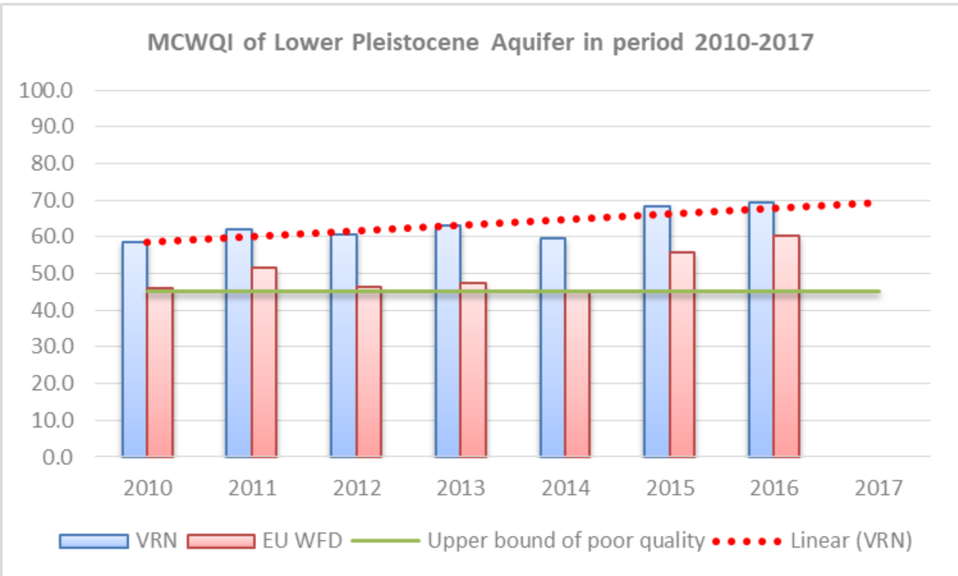

Figure 5.7: MCWQI of Lower Pleistocene Aquifer in the period 2010 – 2017 with trend line

Table 5.24, 5.25, 5.26, and 5.27 present more details about the groundwater quality in aquifer qp_1 by sample station assessed by MCWQI and CCME WQI according to VNR and EU WFD. The color range of these tables highlights the groundwater quality. The water quality by VNR is also mostly fair and good (same conclusion of Figure 5.7), while by EU WFD, it is poor and marginal.

Table 5.24: MCWQI of Lower Pleistocene Aquifer by year according to VNR in the period 2010 - 2017

No.	Station	Aquifer	X	Y	Z	Site	2010	2011	2012	2013	2014	2015	2016	2017
1	Q02204T	qp1	627773	1178171	1.58	Long An,ThanhHoa,TTThanhHoa	74.38	75.37	75.61	76.24	69.36			
2	Q027030	qp1	585616	1204224	2.77	Long An,VinhHung,TTVinhHung	64.7	67.26	63.46	63.38	61			
3	Q031030	qp1	545162	1173841	3.9	DongThap,ThanhBinh,AnPhong	52.45	34.62						
4	Q104030	qp1	466919	1137074	0.27	KienGiang,HaTien,KienLuong	56.88	64.71	64.04	64.5	64.03	54.2	51.27	
5	Q211030	qp1	562630	1070144	1.01	HauGiang,LongMy,TTLongMy	81.95	92.39	90.89	87.59	72.37	74.72	72.59	
6	Q21402Z	qp1	617336	1118045	1.82	VinhLong,MangThit,TanLongHoi					33.3			
7	Q21402ZM1	qp1	617307.9	1118037	1.64	VinhLong,MangThit,TanLongHoi	32.53	42.73	42.32	50.69	25.58			
8	Q219030	qp1	674911	1110922	1.63	BenTre,Ba Tri,TT Ba Tri	53.7	56.33	58.16	58.43				
9	Q326030	qp1	666255.8	1163583	1.55	Long An, TanTru, DucTan				80.49				
10	Q326030M1	qp1	666255.8	1163583	1.55	LongAn,TanTru,TTTanTru	88.33	91.98	82.47	73.22	74.27			
11	Q401030	qp1	517226	1094764	1.37	KienGiang,ChauThanh,TTMinhLuong	90.16	94.69	94.31	96.15	94.96	96.07	93.95	
12	Q40903A	qp1	606417.1	1060971	1.89	SocTrang, TP.SocTrang, P.3			50.65					
13	Q40903AM1	qp1	606417.1	1060971	1.89	SocTrang,TP.SocTrang,P.3	47.69	51.25	50.27	57.73	66.95			
14	Q598030	qp1	606473	1059133	1.77	SocTrang,TP.SocTrang,P.3	44.13	43.29	34.37	44.42				
15	Q612040	qp1	652505.3	1195998	2.13	Long An,DucHoa,HoaKhanhNam	92.59	90.67	93.28	95.86	92.5			
16	Q616040	qp1	662920	1175118	2.36	Long An,BenLuc,TTBenLuc	24.43	49.88	47	34.64	27.26			

Table 5.25: MCWQI of Lower Pleistocene Aquifer by year according to EU WFD in the period 2010 - 2017

No.	Station	Aquifer	X	Y	Z	Site	2010	2011	2012	2013	2014	2015	2016	2017
1	Q02204T	qp1	627773	1178171	1.58	Long An,ThanhHoa,TTThanhHoa	55.9	65.17	58.59	56.59	54			55.9
2	Q027030	qp1	585616	1204224	2.77	Long An,VinhHung,TTVinhHung	46.74	50.15	62.3	61.86	58.74			46.74
3	Q031030	qp1	545162	1173841	3.9	DongThap,ThanhBinh,AnPhong	51.2	29.98						51.2
4	Q104030	qp1	466919	1137074	0.27	KienGiang,HaTien,KienLuong	56.58	56.15	55.37	55.92	63.62	42.54	50.48	56.58
5	Q211030	qp1	562630	1070144	1.01	HauGiang,LongMy,TTLongMy	69.88	77.16	75.72	72.36	64.68	63.22	65.4	69.88
6	Q21402Z	qp1	617336	1118045	1.82	VinhLong,MangThit,TanLongHoi					31.97			
7	Q21402ZM1	qp1	617307.9	1118037	1.64	VinhLong,MangThit,TanLongHoi	24.91	42.01	31.59	42.21	24.29			24.91
8	Q219030	qp1	674911	1110922	1.63	BenTre,Ba Tri,TT Ba Tri	39.38	46.21	58.97	58.65				39.38
9	Q326030	qp1	666255.8	1163583	1.55	Long An, TanTru, DucTan				47.9				
10	Q326030M1	qp1	666255.8	1163583	1.55	LongAn,TanTru,TTTanTru	60.99	63.1	62.9	51.06	55.06			60.99
11	Q401030	qp1	517226	1094764	1.37	KienGiang,ChauThanh,TTMinhLuong	74.05	77.14	78.81	73.91	78.3	76.15	79.23	74.05
12	Q40903A	qp1	606417.1	1060971	1.89	SocTrang, TP.SocTrang, P.3			26.26					
13	Q40903AM1	qp1	606417.1	1060971	1.89	SocTrang,TP.SocTrang,P.3	33.82	26.15	33.83	42.16	35.09			33.82
14	Q598030	qp1	606473	1059133	1.77	SocTrang,TP.SocTrang,P.3	42.38	41.92	32.29	42.31				42.38
15	Q612040	qp1	652505.3	1195998	2.13	Long An,DucHoa,HoaKhanhNam	70.21	80.75	70.52	76.18	68.45			70.21
16	Q616040	qp1	662920	1175118	2.36	Long An,BenLuc,TTBenLuc	21.89	45.35	37.09	25.7	25.4			21.89

Table 5.26: CCME WQI of Lower Pleistocene Aquifer by year according to VNR in the period 2010 - 2017

No.	Station	Aquifer	X	Y	Z	Site	2010	2011	2012	2013	2014	2015	2016	2017
1	Q02204T	qp1	627773	1178171	1.58	Long An,ThanhHoa,TTThanhHoa	71.04	72.42	71.03	73.6	64.27			71.04
2	Q027030	qp1	585616	1204224	2.77	Long An,VinhHung,TTVinhHung	64.46	66.74	62.97	62.85	60.88			64.46
3	Q031030	qp1	545162	1173841	3.9	DongThap,ThanhBinh,AnPhong	46.28	32.89						46.28
4	Q104030	qp1	466919	1137074	0.27	KienGiang,HaTien,KienLuong	44.52	54.55	52.45	53.89	52.41	44.91	43.47	44.52
5	Q211030	qp1	562630	1070144	1.01	HauGiang,LongMy,TTLongMy	77.88	87.15	79.02	87.19	70.64	73.28	65.35	77.88
6	Q21402Z	qp1	617336	1118045	1.82	VinhLong,MangThit,TanLongHoi					27.82			
7	Q21402ZM1	qp1	617307.9	1118037	1.64	VinhLong,MangThit,TanLongHoi	30	37.32	36.46	42.03	23.33			30
8	Q219030	qp1	674911	1110922	1.63	BenTre,Ba Tri,TT Ba Tri	49.04	50.23	47.43	48.03				49.04
9	Q326030	qp1	666255.8	1163583	1.55	Long An, TanTru, DucTan				80.48				
10	Q326030M1	qp1	666255.8	1163583	1.55	LongAn,TanTru,TTTanTru	87.42	89.8	81.52	72.85	73.66			87.42
11	Q401030	qp1	517226	1094764	1.37	KienGiang,ChauThanh,TTMinhLuong	88.19	93.29	92.39	93.81	93.08	93.18	93.69	88.19
12	Q40903A	qp1	606417.1	1060971	1.89	SocTrang, TP.SocTrang, P.3			43.22					
13	Q40903AM1	qp1	606417.1	1060971	1.89	SocTrang,TP.SocTrang,P.3	42.88	44.36	42.49	52.25	54.05			42.88
14	Q598030	qp1	606473	1059133	1.77	SocTrang,TP.SocTrang,P.3	40.09	38.44	29.58	36				40.09
15	Q612040	qp1	652505.3	1195998	2.13	Long An,DucHoa,HoaKhanhNam	91.4	89.32	92.79	93.79	91.86			91.4
16	Q616040	qp1	662920	1175118	2.36	Long An,BenLuc,TTBenLuc	23.25	32.09	33.65	30	25.6			23.25

Table 5.27: CCME WQI of Lower Pleistocene Aquifer by year according to EU WFD in the period 2010 - 2017

No.	Station	Aquifer	X	Y	Z	Site	2010	2011	2012	2013	2014	2015	2016	2017
1	Q02204T	qp1	627773	1178171	1.58	Long An,ThanhHoa,TTThanhHoa	41.26	44.79	42.05	42.71	38.97			41.26
2	Q027030	qp1	585616	1204224	2.77	Long An,VinhHung,TTVinhHung	42.84	46.38	61.39	60.75	57.94			42.84
3	Q031030	qp1	545162	1173841	3.9	DongThap,ThanhBinh,AnPhong	43.31	26.27						43.31
4	Q104030	qp1	466919	1137074	0.27	KienGiang,HaTien,KienLuong	43.82	49.79	47.93	49.27	51.05	36.93	41.48	43.82
5	Q211030	qp1	562630	1070144	1.01	HauGiang,LongMy,TTLongMy	58.42	67.07	62.12	53.69	45.37	43.32	42.09	58.42
6	Q21402Z	qp1	617336	1118045	1.82	VinhLong,MangThit,TanLongHoi					25.62			
7	Q21402ZM1	qp1	617307.9	1118037	1.64	VinhLong,MangThit,TanLongHoi	23.22	35.8	28.44	36.23	21.52			23.22
8	Q219030	qp1	674911	1110922	1.63	BenTre,Ba Tri,TT Ba Tri	38.11	43.8	49.22	48.5				38.11
9	Q326030	qp1	666255.8	1163583	1.55	Long An, TanTru, DucTan				35.25				
10	Q326030M1	qp1	666255.8	1163583	1.55	LongAn,TanTru,TTTanTru	51.29	49.83	49.58	33	42.32			51.29
11	Q401030	qp1	517226	1094764	1.37	KienGiang,ChauThanh,TTMinhLuong	48.22	67.01	73.16	65.6	71.6	73.46	74.39	48.22
12	Q40903A	qp1	606417.1	1060971	1.89	SocTrang, TP.SocTrang, P.3			20.42					
13	Q40903AM1	qp1	606417.1	1060971	1.89	SocTrang,TP.SocTrang,P.3	27.88	20.24	23.57	32.8	28.63			27.88
14	Q598030	qp1	606473	1059133	1.77	SocTrang,TP.SocTrang,P.3	36.58	35.62	26.14	31.87				36.58
15	Q612040	qp1	652505.3	1195998	2.13	Long An,DucHoa,HoaKhanhNam	42.98	58.02	56.33	60.6	54.73			42.98
16	Q616040	qp1	662920	1175118	2.36	Long An,BenLuc,TTBenLuc	19.94	26.47	24.53	23.49	23.08			19.94

Middle Pliocene Aquifer

The Middle Pliocene aquifer (n_2^2) is distributed widely over an area of 36,267 km^2 but is absent in Tri Ton, Tinh Bien, Chau Doc, Thoai Son (An Giang Province, Hon Dat, Ha Tien, and Kien Luong (Kien Giang Province)(Deltares, 2011). The depth to the top of the aquifer varies from 42.60m to 318.90m, with an average of 206.47m. The depth to the bottom of the aquifer ranges from 125.00m to 415.40m, with an average of 258.92m. The thickness is from 4.0m to 147.00m, with an average of 51.33m. The permeability varies from 0.17m/day to 67.29m/day. The groundwater levels are between -20.14m and -7m above sea level. The area of fresh groundwater is 14,014 km^2, and that of saline groundwater is 22,253km^2. The amount of groundwater abstracted by 2010 was 477,395 m^3/day (Ha et al., 2015).

The overview results yielded the sign of pollution in the aquifer n_2^2 with the presence of Cl^-, Fe, Na^+, Mn, NH_4^+, etc. (Section 5.2.2). The groundwater quality assessment in the aquifer is conducted for 16 sample stations span in the period from 2010 to 2017. Figure 5.8 shows the MCWQI value of aquifer n_2^2 in the time with the trend line. It can be seen that the groundwater quality by VNR is mostly fair and good, while by EU WFD, it is mostly marginal and fair. In the monitoring practice, in 2015, 2016, and 2017, only 3 sample stations in the aquifer n_2^2 were monitored.

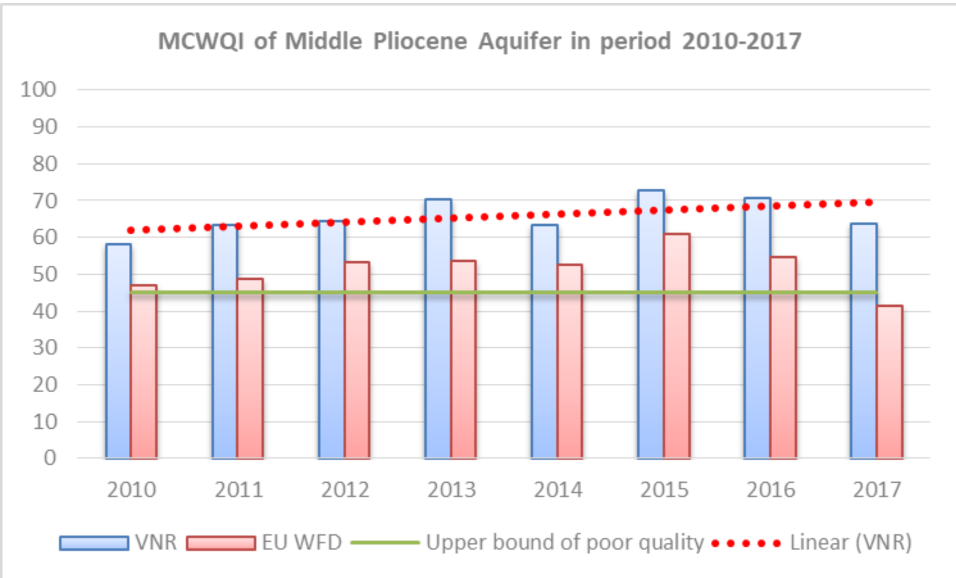

Figure 5.8: MCWQI of Middle Pliocene Aquifer in the period 2010 – 2017 with trend line

Table 5.28, 5.29, 5.30, and 5.31 present more details about the groundwater quality in the aquifer n_2^2 by sample station assessed by MCWQI and CCME WQI, according to VNR and EU WFD. The color range of these tables highlights the groundwater quality. The MCWQI by VNR is also mostly fair and good (same conclusion of Figure 5.8), while by EU WFD, it is marginal and fair. The CCME WQI by both VNR and EU WFD is also mostly poor.

Table 5.28: MCWQI of Middle Pliocene Aquifer by year according to VNR in the period 2010 - 2017

No.	Station	Aquifer	X	Y	Z	Site	2010	2011	2012	2013	2014	2015	2016	2017
1	Q02204Z	n22	627766	1178168	1.52	Long An,ThanhHoa,TTThanhHoa	95.01	99.22	96.78	96.9	88.39			
2	Q02704T	n22	585619	1204233	2.73	Long An,VinhHung,TTVinhHung	60.07	52.41	58.11	49.04	38.53			
3	Q02704Z	n22	585607	1204209	2.83	Long An,VinhHung,TTVinhHung		100						
4	Q17704T	n22	516374.5	1016287	1.16	CaMau,TP.CaMau,P.9			63.29					
5	Q17704TM1	n22	516374.5	1016287	1.16	CaMau,TP.CaMau,P.9			99.05	94.33	90.02			
6	Q204040	n22	532018.6	1156184	3.47	AnGiang,ChauThanh,CanDang		61.51	100					
7	Q206030M1	n22	570669.8	1136687	2.47	DongThap,LaiVung,HoaLong	100	97.81	97.81	100	100	100	100	
8	Q21104T	n22	562631	1070143	1.03	HauGiang,LongMy,TTLongMy	29.71	39.66	42.41	43.02	43.38	34.4	25.23	
9	Q214030	n22	617333	1118047	1.79	VinhLong,MangThit,TanLongHoi					33.46			
10	Q214030M1	n22	617305	1118039	1.72	VinhLong,MangThit,TanLongHoi	43.43	50.44	33.85	42.8				
11	Q217030	n22	663814	1065470	1.96	TraVinh,DuyenHai,LongToan	91	86.33	86.44	88.33	85.39			
12	Q32604T	n22	666254	1163581	1.54	Long An, TanTru, DucTan			38.86					
13	Q32604TM1	n22	666254	1163581	1.54	LongAn,TanTru,DucTan	39.78	53.44		41	40.33			
14	Q40104T	n22	517226	1094764	1.37	KienGiang,ChauThanh,TTMinhLuong	67.62	73.51	72.92	60.35	66.53	64.02	61.14	63.58
15	Q406040	n22	658378	1080470	2.73	TraVinh,CauNgang,LongSon	24.95	41.79	49.74	49.76	31.7			
16	Q409040	n22	606415.8	1060968	1.86	SocTrang, TP.SocTrang, P.3				36.31				
17	Q409040M1	n22	606415.8	1060968	1.86	SocTrang,TP.SocTrang,P.3	43.26	43.82	35.93		35.87			
18	Q59804T	n22	606472	1059138	1.92	SocTrang,TP.SocTrang,P.3	31.57	38.51	32.49	52.63				
19	Q604050	n22	655661	1172842	1.45	Long An,ThuThua,NhiThanh	94.27	97.01	91.15	96.01	93.49			

Table 5.29: MCWQI of Middle Pliocene Aquifer by year according to EU WFD in the period 2010 - 2017

No.	Station	Aquifer	X	Y	Z	Site	2010	2011	2012	2013	2014	2015	2016	2017
1	Q02204Z	n22	627766	1178168	1.52	Long An,ThanhHoa,TTThanhHoa	79.82	76.59	67.7	76.42	69.1			
2	Q02704T	n22	585619	1204233	2.73	Long An,VinhHung,TTVinhHung	49.11	39.23	57.66	39.28	28.74			
3	Q02704Z	n22	585607	1204209	2.83	Long An,VinhHung,TTVinhHung		76.53						
4	Q17704T	n22	516374.5	1016287	1.16	CaMau,TP.CaMau,P.9			52.13					
5	Q17704TM1	n22	516374.5	1016287	1.16	CaMau,TP.CaMau,P.9			72.1	76.44	84.63			
6	Q204040	n22	532018.6	1156184	3.47	AnGiang,ChauThanh,CanDang		55.24	100					
7	Q206030M1	n22	570669.8	1136687	2.47	DongThap,LaiVung,HoaLong	73.64	81.78	87.26	83.65	78.93	90.05	86.51	
8	Q21104T	n22	562631	1070143	1.03	HauGiang,LongMy,TTLongMy	38.61	38.79	32.64	41.92	42.33	33.13	31.85	
9	Q214030	n22	617333	1118047	1.79	VinhLong,MangThit,TanLongHoi					32.34			
10	Q214030M1	n22	617305	1118039	1.72	VinhLong,MangThit,TanLongHoi	35.72	49.82	32.79	41.78				
11	Q217030	n22	663814	1065470	1.96	TraVinh,DuyenHai,LongToan	75.79	72.09	71.15	72.17	75.06			
12	Q32604T	n22	666254	1163581	1.54	Long An, TanTru, DucTan			28.77					
13	Q32604TM1	n22	666254	1163581	1.54	LongAn,TanTru,DucTan	35.67	37.34		39.22	37.94			
14	Q40104T	n22	517226	1094764	1.37	KienGiang,ChauThanh,TTMinhLuong	34.65	38.4	41.17	31.55	41.78	42.39	37.05	41.4
15	Q406040	n22	658378	1080470	2.73	TraVinh,CauNgang,LongSon	31.93	41.25	41.27	49.34	38.45			
16	Q409040	n22	606415.8	1060968	1.86	SocTrang, TP.SocTrang, P.3				35.08				
17	Q409040M1	n22	606415.8	1060968	1.86	SocTrang,TP.SocTrang,P.3	32.55	33.24	34.82		26.44			
18	Q59804T	n22	606472	1059138	1.92	SocTrang,TP.SocTrang,P.3	23.83	30.46	23.35	34.81				
19	Q604050	n22	655661	1172842	1.45	Long An,ThuThua,NhiThanh	70.67	76.93	81.13	71.37	75.67			

Table 5.30: CCME WQI of Middle Pliocene Aquifer by year according to VNR in the period 2010 - 2017

No.	Station	Aquifer	X	Y	Z	Site	2010	2011	2012	2013	2014	2015	2016	2017
1	Q02204Z	n22	627766	1178168	1.52	Long An,ThanhHoa,TTThanhHoa	94.66	97.07	96.3	96.04	87.77			
2	Q02704T	n22	585619	1204233	2.73	Long An,VinhHung,TTVinhHung	53.06	46.49	47.32	44.32	35.92			
3	Q02704Z	n22	585607	1204209	2.83	Long An,VinhHung,TTVinhHung		100						
4	Q17704T	n22	516374.5	1016287	1.16	CaMau,TP.CaMau,P.9			46.04					
5	Q17704TM1	n22	516374.5	1016287	1.16	CaMau,TP.CaMau,P.9			96.63	93.94	89.73			
6	Q204040	n22	532018.6	1156184	3.47	AnGiang,ChauThanh,CanDang		60.21	100					
7	Q206030M1	n22	570669.8	1136687	2.47	DongThap,LaiVung,HoaLong	100	97.01	97	100	100	100	100	
8	Q21104T	n22	562631	1070143	1.03	HauGiang,LongMy,TTLongMy	27.61	34.87	32.06	33.28	33.98	29.62	22.83	
9	Q214030	n22	617333	1118047	1.79	VinhLong,MangThit,TanLongHoi					28.1			
10	Q214030M1	n22	617305	1118039	1.72	VinhLong,MangThit,TanLongHoi	37.6	41.39	28.73	32.84				
11	Q217030	n22	663814	1065470	1.96	TraVinh,DuyenHai,LongToan	84.11	84.81	85.19	87.12	84.16			
12	Q32604T	n22	666254	1163581	1.54	Long An, TanTru, DucTan			36.4					
13	Q32604TM1	n22	666254	1163581	1.54	LongAn,TanTru,DucTan	38.65	48.48		39.39	38.48			
14	Q40104T	n22	517226	1094764	1.37	KienGiang,ChauThanh,TTMinhLuong	67.2	71.7	70.54	59.76	65.73	63.14	60.76	62.81
15	Q406040	n22	658378	1080470	2.73	TraVinh,CauNgang,LongSon	22.45	35.34	39.55	39.61	28.63			
16	Q409040	n22	606415.8	1060968	1.86	SocTrang, TP.SocTrang, P.3				32.62				
17	Q409040M1	n22	606415.8	1060968	1.86	SocTrang,TP.SocTrang,P.3	38.39	39.49	32.02		31.94			
18	Q59804T	n22	606472	1059138	1.92	SocTrang,TP.SocTrang,P.3	28.4	32.55	26.48	50.06				
19	Q604050	n22	655661	1172842	1.45	Long An,ThuThua,NhiThanh	91.87	96.21	90.86	95.79	89.73			

Table 5.31: CCME WQI of Middle Pliocene Aquifer by year according to EU WFD in the period 2010 - 2017

No.	Station	Aquifer	X	Y	Z	Site	2010	2011	2012	2013	2014	2015	2016	2017
1	Q02204Z	n22	627766	1178168	1.52	Long An,ThanhHoa,TTThanhHoa	57.02	64.87	51.96	61.69	51.31			
2	Q02704T	n22	585619	1204233	2.73	Long An,VinhHung,TTVinhHung	44.33	33.38	46.29	37.01	27.52			
3	Q02704Z	n22	585607	1204209	2.83	Long An,VinhHung,TTVinhHung		64.07						
4	Q17704T	n22	516374.5	1016287	1.16	CaMau,TP.CaMau,P.9			32.82					
5	Q17704TM1	n22	516374.5	1016287	1.16	CaMau,TP.CaMau,P.9			69.92	72.67	80.73			
6	Q204040	n22	532018.6	1156184	3.47	AnGiang,ChauThanh,CanDang		52.12	100					
7	Q206030M1	n22	570669.8	1136687	2.47	DongThap,LaiVung,HoaLong	72.2	81.7	86.56	80.74	78.86	87.96	82.64	
8	Q21104T	n22	562631	1070143	1.03	HauGiang,LongMy,TTLongMy	32.76	33.13	26.74	31.09	31.91	27.55	25.4	
9	Q214030	n22	617333	1118047	1.79	VinhLong,MangThit,TanLongHoi					26.23			
10	Q214030M1	n22	617305	1118039	1.72	VinhLong,MangThit,TanLongHoi	31.59	39.77	26.99	30.81				
11	Q217030	n22	663814	1065470	1.96	TraVinh,DuyenHai,LongToan	64.76	60.98	52.65	59.6	67.28			
12	Q32604T	n22	666254	1163581	1.54	Long An, TanTru, DucTan			27.55					
13	Q32604TM1	n22	666254	1163581	1.54	LongAn,TanTru,DucTan	34.67	35.18		36.92	35.06			
14	Q40104T	n22	517226	1094764	1.37	KienGiang,ChauThanh,TTMinhLuong	34.5	37	40.77	30.77	40.46	41.33	36.89	40.89
15	Q406040	n22	658378	1080470	2.73	TraVinh,CauNgang,LongSon	25.55	34.14	34.19	38.46	32.42			
16	Q409040	n22	606415.8	1060968	1.86	SocTrang, TP.SocTrang, P.3				30.7				
17	Q409040M1	n22	606415.8	1060968	1.86	SocTrang,TP.SocTrang,P.3	30.02	31.12	30.29		24.5			
18	Q59804T	n22	606472	1059138	1.92	SocTrang,TP.SocTrang,P.3	21.64	26.48	20.18	34.7				
19	Q604050	n22	655661	1172842	1.45	Long An,ThuThua,NhiThanh	44.7	60.53	61.31	56.49	61.96			

Lower Pliocene Aquifer

The Lower Pliocene aquifer (n_2^1) is distributed widely over an area of 34,546 km^2 but is absent in the western and north-western parts of the study area (Deltares, 2011). The depth to the top of the aquifer varies from 134.00m to 432.20m, with an average of 274.77m. The depth to the bottom of the aquifer ranges from 180.00m to 435.10m, with an average of 330.16m. The thickness is from 2.0m to 131.00m, with an average of 53.78m. The permeability varies from 1.05m/day to 48.14m/day, with an average of 13.63m/day. The groundwater levels are between -1.37 and -5.89m above sea level. The area of fresh groundwater is 16.269 km^2, and that of saline groundwater is 18.277km^2. The amount of groundwater abstracted in 2010 was 87,652 m^3/day (Ha et al., 2015).

The overview results yielded the sign of pollution in the aquifer n_2^1 with the presence of Cl^-, Fe, Na^+, Mn (Section 5.2.2). The groundwater quality assessment in the aquifer n_2^1 is conducted for 25 sample stations span from 2010 to 2017. Figure 5.9 shows the MCWQI value of aquifer n_2^1 in the time with the trend line. It can be seen that the groundwater quality by VNR is mostly fair and good, while by EU WFD, it is mostly over the upper bound of poor quality in the diagram. In the monitoring practice, in 2015, 2016, and 2017, only 5 sample stations in the aquifer n_2^1 were monitored.

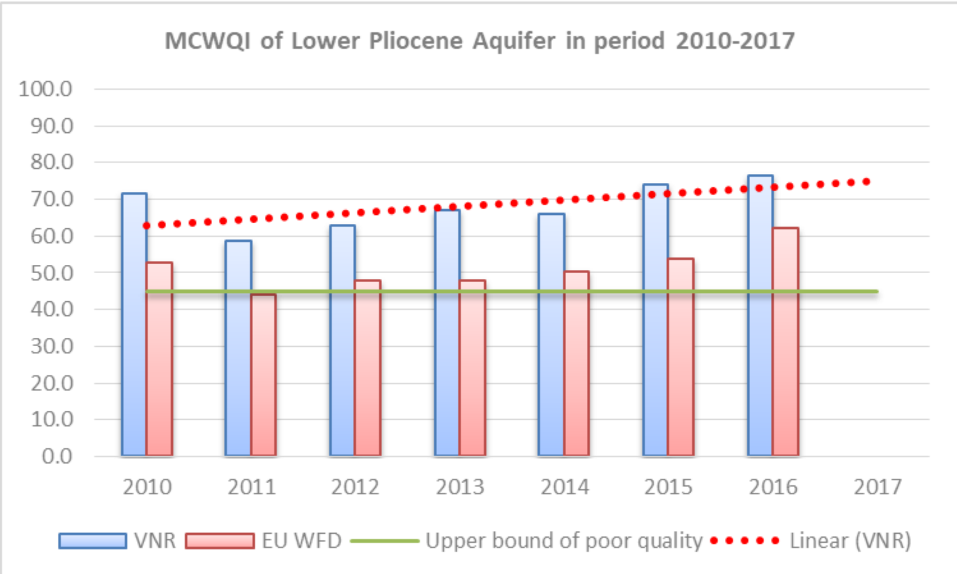

Figure 5.9: MCWQI of Lower Pliocene Aquifer in the period 2010 – 2017 with trend line

Table, 5.32, 5.33, 5.34, and 5.35 present more details about the groundwater quality in the aquifer n_2^1 by sample station assessed by MCWQI and CCME WQI, according to VNR and EU WFD. The color range of these tables highlights the groundwater quality. The MCWQI by VNR is also mostly fair and good (same conclusion of Figure 5.9), while by EU WFD, it is poor and marginal. The CCME WQI by both VNR and EU WFD is also mostly poor.

Table 5.32: MCWQI of Lower Pliocene Aquifer by year according to VNR in the period 2010 - 2017

No.	Station	Aquifer	X	Y	Z	Site	2010	2011	2012	2013	2014	2015	2016	2017
1	Q022050	n21	627764	1178167	1.5	Long An,ThanhHoa,TTThanhHoa	100	94.81	96.23	100	100			
2	Q02704T	n21	585619	1204233	2.73	Long An,VinhHung,TTVinhHung		72.71						
3	Q02704Z	n21	585607	1204209	2.83	Long An,VinhHung,TTVinhHung	93.71	100	93.52	100	100			
4	Q031040	n21	545154	1173841	4.08	DongThap,ThanhBinh,AnPhong	100	100	97.42	95.99	98.7	93.46	99.1	
5	Q17704ZM1	n21	516376.9	1016291	1.17	CaMau,TP.CaMau,P.9				40.07				
6	Q19904Z	n21	499551.2	968458.1	1.03	CaMau,NgocHien,TTNamCan			63.09					
7	Q19904ZM1	n21	499551.2	968458.1	1.03	CaMau,NgocHien,TTNamCan	62.87	70.52	65.01	67.31	61.08			
8	Q206040M1	n21	570662.7	1136690	2.55	DongThap,LaiVung,HoaLong	85.06	81.61	90.12	91.67	91.96	92.47	97.92	
9	Q20904T	n21	588159	1112817	2.12	VinhLong,Binh Minh,CaiVon	74.71	68.24	48.94	72.93	79.73			
10	Q21104ZM1	n21	562597.4	1070129	1.12	HauGiang,LongMy,TTLongMy	56.01	44.57	62.57	53.22	58.07	63.48	58.96	
11	Q214040	n21	617337	1118051	1.79	VinhLong,MangThit,TanLongHoi					35.6			
12	Q214040M1	n21	617309.3	1118042	1.67	VinhLong,MangThit,TanLongHoi	43.98	53.81	35.5	43.32				
13	Q217040	n21	663811	1065470	1.99	TraVinh,DuyenHai,LongToan	89.54	87.05	82.78	88.71	87.75			
14	Q32604Z	n21	667330	1159841	1.79	Long An,TanTru,DucTan	73.03	78.03	81.78	84.63	57.88			
15	Q40104Z	n21	517226	1094764	1.37	KienGiang,ChauThanh,TTMinhLuong	63.2	59.41	59.27	57.06	54.11	56.69	58.64	
16	Q40404T	n21	638472.8	1076960	1.74	TraVinh,TraCu,TapSon		23.48						
17	Q40404TM1	n21	638472.8	1076960	1.74	TraVinh,TraCu,TapSon		37.74	34.52	32.76	42.44			
18	Q40404Z	n21	638470	1076958	1.84	TraVinh,TraCu,TapSon					34.65			
19	Q405050M1	n21	643080.4	1065322	1.99	TraVinh, TraCu, DaiAn		50.04	45.3	53.38	32.33			
20	Q59704T	n21	578627	1027667	1.79	BacLieu, TX.BacLieu, P.7		78.1						
21	Q59704TM1	n21	578627	1027667	1.79	BacLieu,TX.BacLieu,P.7	82.84	81.91	82.21	87.51	84.13			
22	Q59804Z	n21	606472	1059142	1.98	SocTrang,TP.SocTrang,P.3	41.94	41.42	42.13	52.78				
23	Q604060	n21	655664	1172842	1.52	Long An,ThuThua,NhiThanh	35.56	47.66	53.18	68.25	51.89			
24	Q606060	n21	580616.3	1156305	3.09	DongThap,CaoLanh,MyTho	56.19	73.59	68.34	75.1	72.36	72.79	65.38	
25	Q612060	n21	652506.5	1195997	2.09	Long An,DucHoa,HoaKhanhNam	89.93	89.07	97.5	96.21	100			

Table 5.33: MCWQI of Lower Pliocene Aquifer by year according to EU WFD in the period 2010 - 2017

No.	Station	Aquifer	X	Y	Z	Site	2010	2011	2012	2013	2014	2015	2016	2017
1	Q022050	n21	627764	1178167	1.5	Long An,ThanhHoa,TTThanhHoa	80.66	84.27	81.67	74.99	81.33			80.66
2	Q02704T	n21	585619	1204233	2.73	Long An,VinhHung,TTVinhHung		58.73						
3	Q02704Z	n21	585607	1204209	2.83	Long An,VinhHung,TTVinhHung	73.26	82.66	75.01	74.37	88.49			73.26
4	Q031040	n21	545154	1173841	4.08	DongThap,ThanhBinh,AnPhong	75.2	84.93	69.68	69.17	76.74	65.21	76.02	75.2
5	Q17704ZM1	n21	516376.9	1016291	1.17	CaMau,TP.CaMau,P.9				35.63				
6	Q19904Z	n21	499551.2	968458.1	1.03	CaMau,NgocHien,TTNamCan			39.74					
7	Q19904ZM1	n21	499551.2	968458.1	1.03	CaMau,NgocHien,TTNamCan	33.91	39.55	41.23	43.17	44.09			33.91
8	Q206040M1	n21	570662.7	1136690	2.55	DongThap,LaiVung,HoaLong	69.39	64.64	81.77	75.46	72.15	72.54	83.5	69.39
9	Q20904T	n21	588159	1112817	2.12	VinhLong,Binh Minh,CaiVon	41.96	47.12	45.66	49.87	49.2			41.96
10	Q21104ZM1	n21	562597.4	1070129	1.12	HauGiang,LongMy,TTLongMy	28.68	32.49	44.69	38.13	38.92	43.82	39.96	28.68
11	Q214040	n21	617337	1118051	1.79	VinhLong,MangThit,TanLongHoi					34.45			
12	Q214040M1	n21	617309.3	1118042	1.67	VinhLong,MangThit,TanLongHoi	39.26	35.25	26.9	25.45				39.26
13	Q217040	n21	663811	1065470	1.99	TraVinh,DuyenHai,LongToan	73.47	76.79	80.18	68.79	71.71			73.47
14	Q32604Z	n21	667330	1159841	1.79	Long An,TanTru,DucTan	67	67.4	77.17	67.48	50.89			67
15	Q40104Z	n21	517226	1094764	1.37	KienGiang,ChauThanh,TTMinhLuong	47.24	47.85	55.37	53.65	49.94	52.15	54.83	47.24
16	Q40404T	n21	638472.8	1076960	1.74	TraVinh,TraCu,TapSon		19.69						
17	Q40404TM1	n21	638472.8	1076960	1.74	TraVinh,TraCu,TapSon		35.71	33.2	31.7	41.48			
18	Q40404Z	n21	638470	1076958	1.84	TraVinh,TraCu,TapSon					33.08			
19	Q405050M1	n21	643080.4	1065322	1.99	TraVinh, TraCu, DaiAn		45.24	43.21	48.84	29.22			
20	Q59704T	n21	578627	1027667	1.79	BacLieu, TX.BacLieu, P.7		53.91						
21	Q59704TM1	n21	578627	1027667	1.79	BacLieu,TX.BacLieu,P.7	52.49	58.01	57.99	61.8	60.44			52.49
22	Q59804Z	n21	606472	1059142	1.98	SocTrang,TP.SocTrang,P.3	40.97	38.14	41.31	51.98				40.97
23	Q604060	n21	655664	1172842	1.52	Long An,ThuThua,NhiThanh	26.3	41.95	50.25	52.78	48.07			26.3
24	Q606060	n21	580616.3	1156305	3.09	DongThap,CaoLanh,MyTho	41.96	56.85	65.03	59.48	57.66	63.51	55.89	41.96
25	Q612060	n21	652506.5	1195997	2.09	Long An,DucHoa,HoaKhanhNam	69.48	72.81	78.24	71.21	82.17			69.48

Table 5.34: CCME WQI of Lower Pliocene Aquifer by year according to VNR in the period 2010 - 2017

No.	Station	Aquifer	X	Y	Z	Site	2010	2011	2012	2013	2014	2015	2016	2017
1	Q022050	n21	627764	1178167	1.5	Long An,ThanhHoa,TTThanhHoa	100	93.82	94.08	100	100			100
2	Q02704T	n21	585619	1204233	2.73	Long An,VinhHung,TTVinhHung		63.33						
3	Q02704Z	n21	585607	1204209	2.83	Long An,VinhHung,TTVinhHung	90.96	100	92.82	100	100			90.96
4	Q031040	n21	545154	1173841	4.08	DongThap,ThanhBinh,AnPhong	100	100	96.91	95.5	96.6	90.65	96.6	100
5	Q17704ZM1	n21	516376.9	1016291	1.17	CaMau,TP.CaMau,P.9				35.04				
6	Q19904Z	n21	499551.2	968458.1	1.03	CaMau,NgocHien,TTNamCan			57.6					
7	Q19904ZM1	n21	499551.2	968458.1	1.03	CaMau,NgocHien,TTNamCan	53.41	64.98	61.12	61.81	59.54			53.41
8	Q206040M1	n21	570662.7	1136690	2.55	DongThap,LaiVung,HoaLong	84.58	81.17	89.07	90.22	91.59	91.84	96.58	84.58
9	Q20904T	n21	588159	1112817	2.12	VinhLong,Binh Minh,CaiVon	72.8	65.58	43.97	68.35	79.41			72.8
10	Q21104ZM1	n21	562597.4	1070129	1.12	HauGiang,LongMy,TTLongMy	52.66	43.06	57.39	51.72	53	60.63	54.94	52.66
11	Q214040	n21	617337	1118051	1.79	VinhLong,MangThit,TanLongHoi					31.52			
12	Q214040M1	n21	617309.3	1118042	1.67	VinhLong,MangThit,TanLongHoi	37.72	43.85	31.36	33.87				37.72
13	Q217040	n21	663811	1065470	1.99	TraVinh,DuyenHai,LongToan	89.52	86.94	81.3	87.7	85.16			89.52
14	Q32604Z	n21	667330	1159841	1.79	Long An,TanTru,DucTan	53.06	68.3	70.28	80.76	53.77			53.06
15	Q40104Z	n21	517226	1094764	1.37	KienGiang,ChauThanh,TTMinhLuong	62.43	58.67	58.68	55.34	53.23	56.09	57.79	62.43
16	Q40404T	n21	638472.8	1076960	1.74	TraVinh,TraCu,TapSon		22.03						
17	Q40404TM1	n21	638472.8	1076960	1.74	TraVinh,TraCu,TapSon		30.78	29.82	26.94	32.13			
18	Q40404Z	n21	638470	1076958	1.84	TraVinh,TraCu,TapSon					30.02			
19	Q405050M1	n21	643080.4	1065322	1.99	TraVinh, TraCu, DaiAn		47.32	37.66	51.18	31.9			
20	Q59704T	n21	578627	1027667	1.79	BacLieu, TX.BacLieu, P.7		68.5						
21	Q59704TM1	n21	578627	1027667	1.79	BacLieu,TX.BacLieu,P.7	74.68	77.73	72.14	80.4	79.22			74.68
22	Q59804Z	n21	606472	1059142	1.98	SocTrang,TP.SocTrang,P.3	31.13	34.53	31.52	34.51				31.13
23	Q604060	n21	655664	1172842	1.52	Long An,ThuThua,NhiThanh	34.15	41.2	52.03	64.07	50.22			34.15
24	Q606060	n21	580616.3	1156305	3.09	DongThap,CaoLanh,MyTho	52.96	69.26	65.8	68.92	65.51	66.46	58.76	52.96
25	Q612060	n21	652506.5	1195997	2.09	Long An,DucHoa,HoaKhanhNam	89.83	88.76	93.42	95.86	100			89.83

Table 5.35: CCME WQI of Lower Pliocene Aquifer by year according to EU WFD in the period 2010 - 2017

No.	Station	Aquifer	X	Y	Z	Site	2010	2011	2012	2013	2014	2015	2016	2017
1	Q022050	n21	627764	1178167	1.5	Long An,ThanhHoa,TTThanhHoa	59.46	76.09	63.52	66.6	68.24			59.46
2	Q02704T	n21	585619	1204233	2.73	Long An,VinhHung,TTVinhHung		50.6						
3	Q02704Z	n21	585607	1204209	2.83	Long An,VinhHung,TTVinhHung	49.54	78.47	56.08	69.23	71.12			49.54
4	Q031040	n21	545154	1173841	4.08	DongThap,ThanhBinh,AnPhong	74.69	84.16	59.96	53.47	70.52	47.54	70.1	74.69
5	Q17704ZM1	n21	516376.9	1016291	1.17	CaMau,TP.CaMau,P.9				29.74				
6	Q19904Z	n21	499551.2	968458.1	1.03	CaMau,NgocHien,TTNamCan			37.65					
7	Q19904ZM1	n21	499551.2	968458.1	1.03	CaMau,NgocHien,TTNamCan	31.93	38.65	39.71	41.15	42.58			31.93
8	Q206040M1	n21	570662.7	1136690	2.55	DongThap,LaiVung,HoaLong	68.15	64.23	80.12	70.18	71.2	71.78	82.69	68.15
9	Q20904T	n21	588159	1112817	2.12	VinhLong,Binh Minh,CaiVon	41.85	39.98	36.48	45.85	47.23			41.85
10	Q21104ZM1	n21	562597.4	1070129	1.12	HauGiang,LongMy,TTLongMy	28.36	30.63	41.48	36.6	35.92	41.64	37.66	28.36
11	Q214040	n21	617337	1118051	1.79	VinhLong,MangThit,TanLongHoi					29.7			
12	Q214040M1	n21	617309.3	1118042	1.67	VinhLong,MangThit,TanLongHoi	33.41	31.8	25.12	23.14				33.41
13	Q217040	n21	663811	1065470	1.99	TraVinh,DuyenHai,LongToan	66.56	65.66	76.91	67.29	68.86			66.56
14	Q32604Z	n21	667330	1159841	1.79	Long An,TanTru,DucTan	30.23	31.93	43.61	44.02	36.88			30.23
15	Q40104Z	n21	517226	1094764	1.37	KienGiang,ChauThanh,TTMinhLuong	43.78	41.63	52.36	48.93	47.14	50.6	51.33	43.78
16	Q40404T	n21	638472.8	1076960	1.74	TraVinh,TraCu,TapSon		16.92						
17	Q40404TM1	n21	638472.8	1076960	1.74	TraVinh,TraCu,TapSon		27.11	27.66	25.16	30.2			
18	Q40404Z	n21	638470	1076958	1.84	TraVinh,TraCu,TapSon					27.46			
19	Q405050M1	n21	643080.4	1065322	1.99	TraVinh, TraCu, DaiAn		42.12	33.65	43.97	28.13			
20	Q59704T	n21	578627	1027667	1.79	BacLieu, TX.BacLieu, P.7		49.15						
21	Q59704TM1	n21	578627	1027667	1.79	BacLieu,TX.BacLieu,P.7	50.54	55.8	52.83	57.15	57.85			50.54
22	Q59804Z	n21	606472	1059142	1.98	SocTrang,TP.SocTrang,P.3	29.14	31.78	29.85	32.43				29.14
23	Q604060	n21	655664	1172842	1.52	Long An,ThuThua,NhiThanh	20.48	32.29	49.73	52.63	46.73			20.48
24	Q606060	n21	580616.3	1156305	3.09	DongThap,CaoLanh,MyTho	37.86	51.75	56.31	53.82	52.14	56.66	48.81	37.86
25	Q612060	n21	652506.5	1195997	2.09	Long An,DucHoa,HoaKhanhNam	40.22	58.7	70.14	55.84	71.96			40.22

Upper Miocene Aquifer

The Upper Miocene aquifer (n_1^3) is distributed widely over an area of 39,468 km^2 but is absent in the western and north-western parts of the study area (Deltares, 2011). The depth to the top of the aquifer varies from 215.00m to 444.00m, with an average of 360.58m. The depth to the bottom of the aquifer ranges from 220.50m to 508.00m, with an average of 391.96m. The thickness is from 2.5m to 200.10m, with an average of 58.79m. The permeability varies from 1.05m/day to 48.14m/day, with an average of 9.01m/day. The groundwater levels are between -6.36m and 0.99m above sea level. The area of fresh groundwater is 10.494 km^2, and that of saline groundwater is 28.974km^2 (Ha et al., 2015).

The overview results yielded the sign of pollution in the aquifer n_1^3 with the presence of Cl^-, Fe, Na^+, Mn (Section 5.2.2). The groundwater quality assessment in the aquifer n_1^3 is conducted for 13 sample stations span from 2010 to 2017. Figure 5.10 shows the MCWQI value of the aquifer n_1^3 in the time with the trend line. It can be seen that the groundwater quality by VNR is mostly fair and good, as well as by EU WFD. In the monitoring practice, there were only 5 sample stations in 2015 and 2016, and no sample station in 2017 in the aquifer n_3^1 was monitored.

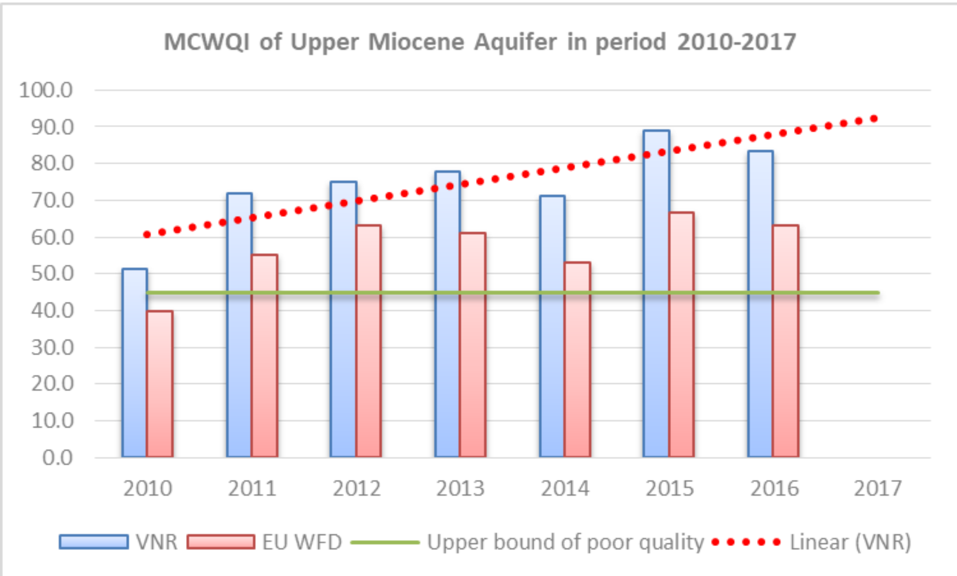

Figure 5.10: MCWQI of Upper Miocene Aquifer in the period 2010 – 2017 with trend line

Table 5.36, 5.37, 5.38, and 5.39 present more details about the groundwater quality in the aquifer n_1^3 by sample station assessed by MCWQI and CCME WQI according to VNR and EU WFD. The color range of these tables highlights the groundwater quality. The WQI by VNR is also mostly good and excellent, while by EU WFD, it is fair and good.

Table 5.36: MCWQI of Upper Miocene Aquifer by year according to VNR in the period 2010 - 2017

No.	Station	Aquifer	X	Y	Z	Site	2010	2011	2012	2013	2014	2015	2016	2017
1	Q017050	n13	579393	1097804	1.71	HauGiang,ChauThanhA,TanPhu	79.95	74.89	67.34	71.38	79.2	86.41	79.15	
2	Q027050	n13	585562.2	1204190	2.95	Long An,VinhHung,TTVinhHung		71.24						
3	Q027050M1	n13	585562.2	1204190	2.95	Long An,VinhHung,TTVinhHung	71.43	63.68	66.87	58.95	67.41			
4	Q214050	n13	617339	1118046	1.86	VinhLong,MangThit,TanLongHoi					34.44			
5	Q214050M1	n13	617311	1118039	1.7	VinhLong,MangThit,TanLongHoi	34.73	50.79	43.61	54.42				
6	Q402040M1	n13	538384	1126030	2.28	CanTho,VinhThanh,ThanhTien		87.03	91.68	88.61	81.65	87.36	83.32	
7	Q59704Z	n13	578620	1027663	1.9	BacLieu, TX.BacLieu, P.7			86.71					
8	Q59704ZM1	n13	578620	1027663	1.9	BacLieu,TX.BacLieu,P.7	100	85.49	84.36	85.59	85.32			
9	Q598050	n13	607861.5	1061471	1.86	SocTrang,TP.SocTrang,P.4				100				
10	Q598050M1	n13	607861.5	1061471	1.86	SocTrang,TP.SocTrang,P.4		100	100	94.66	98.93			
11	Q604070	n13	655666.5	1172841	1.63	Long An,ThuThua,NhiThanh	92.43	100	97.87	97.35	93.95			
12	Q606070	n13	580620.8	1156304	3.08	DongThap,CaoLanh,MyTho	91.47	88.38	87.88	91.4	94.93	94.69	89.02	
13	Q616070	n13	662920.8	1175116	2.33	Long An,BenLuc,TTBenLuc	37.96	69.68	65.11	59.16	57.21			

Table 5.37: MCWQI of Upper Miocene Aquifer by year according to EU WFD in the period 2010 - 2017

No.	Station	Aquifer	X	Y	Z	Site	2010	2011	2012	2013	2014	2015	2016	2017
1	Q017050	n13	579393	1097804	1.71	HauGiang,ChauThanhA,TanPhu	73.43	65.69	60.19	60.43	58.34	63.47	55.6	73.43
2	Q027050	n13	585562.2	1204190	2.95	Long An,VinhHung,TTVinhHung		51.64						
3	Q027050M1	n13	585562.2	1204190	2.95	Long An,VinhHung,TTVinhHung	52.29	41.54	68.09	58.44	59.86			52.29
4	Q214050	n13	617339	1118046	1.86	VinhLong,MangThit,TanLongHoi					33.2			
5	Q214050M1	n13	617311	1118039	1.7	VinhLong,MangThit,TanLongHoi	33.66	42.4	42.76	43.25				33.66
6	Q402040M1	n13	538384	1126030	2.28	CanTho,VinhThanh,ThanhTien		64.19	74.64	69.75	60.2	66.45	63.81	
7	Q59704Z	n13	578620	1027663	1.9	BacLieu, TX.BacLieu, P.7			64.55					
8	Q59704ZM1	n13	578620	1027663	1.9	BacLieu,TX.BacLieu,P.7	92.28	64.73	58.71	62.06	62.1			92.28
9	Q598050	n13	607861.5	1061471	1.86	SocTrang,TP.SocTrang,P.4				70.33				
10	Q598050M1	n13	607861.5	1061471	1.86	SocTrang,TP.SocTrang,P.4		69.99	65.2	64.69	68.17			
11	Q604070	n13	655666.5	1172841	1.63	Long An,ThuThua,NhiThanh	62.91	75.76	73.1	73.56	72.56			62.91
12	Q606070	n13	580620.8	1156304	3.08	DongThap,CaoLanh,MyTho	66.76	70.47	74.67	71.37	70.59	75.03	74.72	66.76
13	Q616070	n13	662920.8	1175116	2.33	Long An,BenLuc,TTBenLuc	33.66	44.27	60.32	58.81	47.07			33.66

Table 5.38: CCME WQI of Upper Miocene Aquifer by year according to VNR in the period 2010 - 2017

No.	Station	Aquifer	X	Y	Z	Site	2010	2011	2012	2013	2014	2015	2016	2017
1	Q017050	n13	579393	1097804	1.71	HauGiang,ChauThanhA,TanPhu	78.98	72.21	66.2	70.24	78.82	86.21	78.78	78.98
2	Q027050	n13	585562.2	1204190	2.95	Long An,VinhHung,TTVinhHung		69.35						
3	Q027050M1	n13	585562.2	1204190	2.95	Long An,VinhHung,TTVinhHung	69.65	63.42	64.27	58.62	65.14			69.65
4	Q214050	n13	617339	1118046	1.86	VinhLong,MangThit,TanLongHoi					29.68			
5	Q214050M1	n13	617311	1118039	1.7	VinhLong,MangThit,TanLongHoi	30.15	42.29	34.43	38.64				30.15
6	Q402040M1	n13	538384	1126030	2.28	CanTho,VinhThanh,ThanhTien		87	91.56	88.27	81.4	86.99	82.47	
7	Q59704Z	n13	578620	1027663	1.9	BacLieu, TX.BacLieu, P.7			86.29					
8	Q59704ZM1	n13	578620	1027663	1.9	BacLieu,TX.BacLieu,P.7	100	83.07	82.57	83.32	82.65			100
9	Q598050	n13	607861.5	1061471	1.86	SocTrang,TP.SocTrang,P.4				100				
10	Q598050M1	n13	607861.5	1061471	1.86	SocTrang,TP.SocTrang,P.4		100	100	91.94	92.83			
11	Q604070	n13	655666.5	1172841	1.63	Long An,ThuThua,NhiThanh	91.34	100	97.01	96.78	89.76			91.34
12	Q606070	n13	580620.8	1156304	3.08	DongThap,CaoLanh,MyTho	90.88	88.22	87.79	91.23	94.92	94.68	88.12	90.88
13	Q616070	n13	662920.8	1175116	2.33	Long An,BenLuc,TTBenLuc	31.17	62.01	58.85	49.63	45.27			31.17

Table 5.39: CCME WQI of Upper Miocene Aquifer by year according to EU WFD in the period 2010 - 2017

No.	Station	Aquifer	X	Y	Z	Site	2010	2011	2012	2013	2014	2015	2016	2017
1	Q017050	n13	579393	1097804	1.71	HauGiang,ChauThanhA,TanPhu	73.33	65.5	59.9	60.2	57.6	63.42	55.22	73.33
2	Q027050	n13	585562.2	1204190	2.95	Long An,VinhHung,TTVinhHung		51.29						
3	Q027050M1	n13	585562.2	1204190	2.95	Long An,VinhHung,TTVinhHung	52.05	37.19	66.21	58	59.68			52.05
4	Q214050	n13	617339	1118046	1.86	VinhLong,MangThit,TanLongHoi					27.67			
5	Q214050M1	n13	617311	1118039	1.7	VinhLong,MangThit,TanLongHoi	28.42	36.63	32.77	33.74				28.42
6	Q402040M1	n13	538384	1126030	2.28	CanTho,VinhThanh,ThanhTien		61.69	71.72	67.21	59.22	65.62	62.54	
7	Q59704Z	n13	578620	1027663	1.9	BacLieu, TX.BacLieu, P.7			64.42					
8	Q59704ZM1	n13	578620	1027663	1.9	BacLieu,TX.BacLieu,P.7	91.28	62.9	56.83	60.68	60.74			91.28
9	Q598050	n13	607861.5	1061471	1.86	SocTrang,TP.SocTrang,P.4				69.93				
10	Q598050M1	n13	607861.5	1061471	1.86	SocTrang,TP.SocTrang,P.4		69.81	65.07	64.57	68.04			
11	Q604070	n13	655666.5	1172841	1.63	Long An,ThuThua,NhiThanh	53.49	70.34	60.67	68.09	64.01			53.49
12	Q606070	n13	580620.8	1156304	3.08	DongThap,CaoLanh,MyTho	63.99	70.44	74.66	71.16	70.39	74.51	73.47	63.99
13	Q616070	n13	662920.8	1175116	2.33	Long An,BenLuc,TTBenLuc	23.25	32.55	42.56	48.87	40.9			23.25

5.3. Discussion

Figure 5.1 and Table 5.5 show the severe presence of Cl^- in all aquifers and the severe presence of other parameters like As, Fe, TH, Mn, NH_4^+, NO_2^- in different aquifers like qh, qp_3, $qp_{2\text{-}3}$, qp_1, n_2^2. Both deeper aquifers n_2^1 and n_1^3 have only severe problems with Cl^-.

As argued, WFD is stricter than VNR; therefore, the critical parameters by aquifer are also different accordingly. Figure 5.2 and Table 5.6 above show the severe presence of:

- Cl^-, Fe, Mn and Na^+ in all aquifers,
- As only in qh
- NO_2^- in four aquifers qh, qp_3, $qp_{2\text{-}3}$, and n_2^1
- NH_4^+ in aquifer qh, qp_3, $qp_{2\text{-}3}$, qp_1, and n_2^2

In comparison, the other substances also contribute to pollution when the S-MCWQI <100. However, they are not severe according to the quality classification by CCME.

From both analyses, it can be seen that groundwater in Mekong Delta is facing now with some problems, i.e., arsenic contamination, trace metals, or saline water intrusion. For both regulations, the q-aquifers are generally worse than the deeper n-aquifers.

Taken altogether, the calculation results of S-MCWQI presented here provide evidence that the groundwater issues of Mekong Delta are mainly related to the high salinity, arsenic, and only occasionally related to other components like heavy metals. This finding is consistent with the results (presented in Section 4.1.2.) of previous studies conducted for particular water problems as well as the practical development trend in Mekong Delta. The use of S-MCWQI simplifies the finding of critical parameters in comparison to previous researches. The main task is delegated to a computer program that calculates the index values. The result is a detailed picture of the situation of groundwater quality status. Mainly, S-MCWQI is an index for water quality and water quality control. The aspect of water quality control as the statistical quality feature is a new approach to groundwater quality in Mekong Delta.

A cursory glance at Tables 5.7, 5.8, 5.9, and 5.10 reveals that the groundwater in Mekong Delta is generally at the poor and marginal quality. It can be inferred from the tables that:

- In general, the CCME WQI values are smaller than MCWQI values in both independently and accumulatively.
- For each assessing method (year by year or accumulatively), there are no significant gaps between the WQI values in the period 2010 – 2017.
- The comparison shows that the WQI values assessed by EU WFD are smaller than the WQI values by VNR.

The results of data analysis confirm that a water quality index denoting the combined effect of the various parameters, which are relevant and significant to a particular use, can express the water quality for different uses. CCME WQI and MCWQI have successfully demonstrated their capability of describing the groundwater quality of Mekong Delta.

Table 5.40: Comparing CCME WQI and MCWQI of aquifers according to VNR and EU WFD in the period 2010 - 2017

Aquifer	CCME WQI		MCWQI		Ranking of badness*
	VNR	WFD	VNR	WFD	
qh	45.3	29.9	51.3	40.1	2
qp_3	37.1	28.7	46.7	37.2	1
qp_{2-3}	46.7	35.9	55.6	44.8	3
qp_1	46	31.1	56.1	43.5	4
n_2^2	49.9	42	59.6	49.7	5
n_2^1	49.9	31.8	61.3	43.2	6
n_1^3	62.1	45	71.1	50.8	7
*Based on MCWQI by VNR					

Table 5.40 illustrates the comparison of CCME WQI and MCWQI of assessed aquifer according to VNR and EU WFD in the period 2010 – 2017. Figure 5.3 is a graphic summary of the groundwater quality status trend of assessed aquifers by year in the period 2010 – 2017. As shown in Table 5.40 and Figure 5.3, a significant difference in groundwater quality in aquifers was observed. The Holocene aquifer qh has the worst water quality while aquifers Lower Pliocene (n_2^1) and Upper Miocene (n_1^3) have the best water quality. The deeper aquifer is, the better the groundwater quality is.

According to the result of this research, MCWQI improves the previous method CCME WQI, which has many valuable characteristics such as no requirement of sub-indices, no limitation on parameters (number and kind of parameter), adaptable to the local situation or applicability purposes. Therefore, MCWQI can easily be customized, modified, or adapted to meet all requirements. MCWQI furnishes a WQI value accumulatively for different periods depending on the users' intentions.

Using the MCWQI, the quality status trend year by year or accumulatively for different periods can also be tracked and compared. MCWQI also furnishes the WQI for a period, depending on the purpose of using the index.

The calculation results provide convincing evidence that MCWQI measures the degree of violation of the regulation in concern and treats all individual quality parameters in the same manner. This simplification process of WQI-generation has the potential for distortion of information, as generally explained in Section 2.4.4. Therefore, MCWQI can only give an overview of the situation of groundwater pollution in the Mekong Delta. In this research, the MCWQI function is used to see improvements in time. MCWQI shows improvements in time, even if water samples do not fulfill the regulation at some point in time.

A water supply company is interested in details because the procedures and costs of groundwater treatment depend on the particular bad substances in the water. The use of MCWQI, together with S-MCWQI for individual quality parameters, gives a detailed and composite picture of the situation of groundwater in Mekong Delta in the period from 2010 to 2017.

The surface water regulation in Vietnam has considered the water standards according to using purposes, while groundwater regulation focuses only on usability. However, the actual situation shows that climate change, dam constructions in the upstream of the Mekong River, and urban development influences groundwater quality as well as quantity. The results yielded the proof that EU WFD is stricter than VNR because EU WFD treats the groundwater resources basically at nature level of water constituents and as the most crucial resource for drinking water abstraction, whereas the VNR considers groundwater as an available resource for all uses. There is no comprehensive groundwater protection in Vietnam with uniform minimum requirements for the water constituents to be achieved and their concentration levels. However, there is high, uncontrolled consumption of untreated groundwater by private wells for drinking, domestic uses, and irrigation purposes. The application of the EU WFD in this research shows that there may be health risks associated with untreated groundwater consumption. Therefore, the EU WFD can be adapted to suit the Vietnamese context. It can be a potential direction for Vietnam in water resources management besides the VNR and WHO’s standards.

6. Summary and Outlook

This dissertation's main theoretical task is selecting a compatible water quality index that indicates water quality for protection. The Canadian Water Quality Index, CCME WQI, has this property. It is a statistical index that describes the situation of a water resource in a given period. The index considers how many parameters have failed tests or how often regulation is violated, and, naturally, the violation's amplitude. The CCME WQI has some weaknesses such as insensitivity to good water quality, pathological memory effect, dependencies of the factors F_1, F_2, and F_3, contradicting the use of a length of a vector in the WQI-formula. Whether there are small or big violations of regulations, CCME WQI makes no difference in accounting failed tests.

The strange behavior of CCME WQI is due to the factor F_1 (failed parameters), which is always a point of discussion in the literature. The notable "pathological memory effect" is first introduced in this thesis. The research has made a more in-depth analysis of the construction of CCME WQI and has another perception. The factors F_1, F_2, and F_3, are more viewpoints of the collection of *excursions* as a whole and not pieces that compose water quality. In such a situation, using of a geometric mean instead of some additive expression (arithmetic mean, Euclidean length) is mathematically and technically justified.

Present research supports identifying the most critical parameters by presenting the corresponding aggregation functions denoted as S-MCWQI and respectively S-CCMEWQI. These functions can be considered as playing the role of sub-indices. S-CCMEWQI, respectively, allows the user to have a WQI value for a single parameter and one water sample.

The realization of the above quality model is mathematically demanding. Therefore, this research establishes a mathematical framework based on Microsoft Access. All WQI calculations are realized by one central module to avoid calculation errors. In this way, the validation of the framework is more straightforward. The application of the quality model to the data of Mekong Delta suggests an investigation of the individual quality parameters by S-MCWQI, a detailed overview with the aid of the factors *Scope* (F_1), *Frequency* (F_2), and *Amplitude* (F_3) for each aquifer and diagrams for trend tracking, based on MCWQI is presented.

The research scope focuses on the water quality parameters, and the dataset of practical water quality monitoring was limited to other aspects (like water flow, water flow direction, hydrogeology characteristics, etc.). Future studies can continue to explore the application of MCWQI and look at ways to have the integrations between MCWQI and:

– Hydrogeochemical: Hydrogeochemical studies are used to understand the subsurface geological environment, the direction of movement of groundwater, recharge-discharge relationships, the influence of climate and anthropogenic contaminants, presence of ore bodies, and the economic evaluation of mineral-rich waters.

- Geographic Information System (GIS): water quality assessment needs a large volume of multidisciplinary data from various sources. The integration of GIS and WQI can help integrate, analyze, and represent spatial information and databases. It could be adapted for planning resource development, environmental protection, scientific researches, and investigation.
- Morphometric analysis: Morphometric analysis is a quantitative description and investigation of landforms as practiced in geomorphology that may be applied to small sub-basins or river basins or large areas generally. The morphometric analysis of the drainage basin and channel network plays a vital role in understanding the drainage basin's hydrogeological behavior and expresses the prevailing climate, geology, geomorphology, structural conditions, etc.

References

ABBASI, T. & ABBASI, S. A. 2011. Water quality indices based on bioassessment: The biotic indices. *Journal of Water and Health,* 9, 330-348.

ABBASI, T. & ABBASI, S. A. 2012. *Water Quality Indices*, Elsevier Science.

AL-SHUJAIRI, D. S. O. H. 2013. Develop and Apply Water Quality Index to Evaluate Water Quality of Tigris and Euphrates Rivers in Iraq. *International Journal of Modern Engineering Research (IJMER),* Vol. 3, Issue. 4, Jul - Aug. 2013 pp-2119-2126.

ALEXAKIS, D., TSIHRINTZIS, V. S. A., TSAKIRIS, G. & GIKAS, G. D. 2016. Suitability of Water Quality Indices for Application in Lakes in the Mediterranean. *Water Resources Management,* 30, 1621-1633.

ALMEIDA, C. A., QUINTAR, S., GONZÁLEZ, P. & MALLEA, M. A. 2007. Influence of urbanization and tourist activities on the water quality of the Potrero de los Funes River (San Luis – Argentina). *Environmental Monitoring and Assessment,* 133, 459-465.

BACKMAN, B., BODIŠ, D., LAHERMO, P., RAPANT, S. & TARVAINEN, T. 1998. *Application of a groundwater contamination index in Finland and Slovakia*.

BATABYAL, A. K. & CHAKRABORTY, S. 2015. Hydrogeochemistry and Water Quality Index in the Assessment of Groundwater Quality for Drinking Uses. *Water Environ Res,* 87, 607-17.

BHARGAVA, D. S. 1983. Use of a Water-Quality Index for River Classification and Zoning of Ganga River. *Environmental Pollution Series B-Chemical and Physical,* 6, 51-67.

BHATTI, M. T. & LATIF, M. 2011. Assessment of Water Quality of a River Using an Indexing Approach during the Low-Flow Season. *Irrigation and Drainage,* 60, 103-114.

BOLTON, P. W., CURRIE, J. C., TERVET, D. J. & WELSH, W. T. 1978. *An index to improve water quality classification*.

BROWN, D. 2018. Oregon Water Quality Index Data Summary Water Years 2008-2017 (Oct. 1, 2008 through Sept. 30, 2017). *Department of Environmental Quality (DEQ), State of Oregon,* .

BROWN, R. M., MCCLELLAND, N. I., DIENINGER, R. A. & TOYER, R. G. 1970. A water quality index: Do we dare? *Water & Sewage Works,* 117, 339-343.

CCME 2001. *Canadian Water Quality Guidelines for the Protection of Aquatic Life - CCME WATER QUALITY INDEX 1.0 User's Manual,* , Canadian Council of Ministers of the Environment 2001.

CCME 2014. Canadian Water Quality Index (CWQI). *In:* MICHALOS, A. C. (ed.) *Encyclopedia of Quality of Life and Well-Being Research.* Dordrecht: Springer Netherlands.

CCME, C. C. O. M. O. T. E. A Path Forward for Consistent Implementation and Reporting. CCME National Water Quality Index Workshop

2003 Halifax, Nova Scotia. 81pp.

CCME, C. C. O. M. O. T. E. 2006. A sensitivity analysis of the Canadian Water Quality Index. *In:* LIMITED, G. L. (ed.). Ontario, Canada: Canadian Council of Ministers of the Environment.

CCME, C. C. O. M. O. T. E. 2011. Canadian Water Quality Guidlines for the protection of aquatic life: CCME Water Quality Index 1.0. *Canadian Environmental Guidelines 1999.* Canadian Council of Ministers of the Environment Winnigpeg.

COSGROVE, W., RIJSBERMAN, F. & WORLD WATER, C. 2000. *World Water Vision: Making Water Everybody's Business*.

COUILLARD, D. & LEFEBVRE, Y. 1985. Analysis of Water-Quality Indices. *Journal of Environmental Management,* 21, 161-179.

COUILLARD, D. & LEFEBVRE, Y. 1986. The Water-Quality Index for Detecting the Impact of Diffused Urban Pollution. *Canadian Journal of Civil Engineering,* 13, 631-638.

CUDE, C. G. 2001. Oregon Water Quality Index: A tool for evaluating water quality management effectiveness. *Journal of the American Water Resources Association,* 37, 125-137.

DAO, V., URBAN, W. & HAZRA, S. B. 2020. Introducing the modification of Canadian Water Quality Index. *Groundwater for Sustainable Development*, 100457.

DARAPU, S. S. K. & CHANDRA SEKHAR, M. 2011. *Determining Water Quality Index for the Evaluation of Water Quality of River Godavari.*

DE ROSEMOND, S., DURO, D. C. & DUBE, M. 2009. Comparative analysis of regional water quality in Canada using the Water Quality Index. *Environmental Monitoring and Assessment,* 156, 223-240.

DEBELS, P., FIGUEROA, R., URRUTIA, R., BARRA, R. & NIELL, X. 2005. Evaluation of water quality in the Chillan River (Central Chile) using physicochemical parameters and a modified Water Quality Index. *Environmental Monitoring and Assessment,* 110, 301-322.

DELTARES 2011. Mekong Delta Water Resources Assessment Studies. Vietnam-Netherlands Mekong Delta Masterplan project.

DGMS 2004. Research of geological structure and classification of N-Q sediments in Mekong Delta. *In:* VIETNAM, D. O. G. A. M. O. T. S. O. (ed.).

DINIUS, S. H. 1987. Design of an Index of Water-Quality. *Water Resources Bulletin,* 23, 833-843.

DOJLIDO, J., RANISZEWSKI, J. & WOYCIECHOWSKA, J. 1994. Water-Quality Index Applied to Rivers in the Vistula River Basin in Poland. *Environmental Monitoring and Assessment,* 33, 33-42.

DUNNETTE, D. A. 1979. Geographically Variable Water-Quality Index Used in Oregon. *Journal Water Pollution Control Federation,* 51, 53-61.

EARTHHOW. 2019. *Global water distribution: sources of fresh and salt water* [Online]. Available: https://earthhow.com/global-water-distribution/ [Accessed 28.02.2019].

EC, T. E. P. A. T. C. O. T. E. U. 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy.

EPA 2001. *Parameters of Water Quality: Interpretatin and Standards,* Ireland.

EUROPE, C. O. 1968. *European Water Charter*, Council of Europe.

FERREIRA, N. C., BONETTI, C. & SEIFFERT, W. Q. 2011. Hydrological and Water Quality Indices as management tools in marine shrimp culture. *Aquaculture,* 318, 425-433.

GALLANT, C. 2020. *The Difference Between the Arithmetic Mean and Geometric Mean* [Online]. Available: https://www.investopedia.com/ask/answers/06/geometricmean.asp#:~:text=The%20geometric%20mean%20differs%20from,returns%20than%20the%20arithmetic%20mean. [Accessed 17th August 2020].

GRAY, N. E. 1996. The use of an objective index for the assessment of the contamination of surface water and groundwater by Acid Mine Drainage. *Water and Environment Journal,* 10, 332-340.

HA, K., NGOC, N. T. M., LEE, E. & JAYAKUMAR, R. 2015. *Current Status and Issues of Groundwater in the Mekong River Basin*, Korea Institute of Geoscience and Mineral Resources (KIGAM)

CCOP Technical Secretariat

UNESCO Bangkok Office.

HANDA, B. K. 1981. An Integrated Water-Quality Index for Irrigation Use. *Indian Journal of Agricultural Sciences,* 51, 422-426.

HARKINS, R. D. 1974. Objective Water-Quality Index. *Journal Water Pollution Control Federation,* 46, 588-591.

HORTON, R. K. 1965. An index number system for rating water quality index. *Journal - Water Pollution Control Federation,* 37, 300-305.

HOUSE, M. & ELLIS, J. B. 1980. Water-Quality Indexes - an Additional Management Tool. *Water Science and Technology,* 13, 413-423.

HOUSE, M. A. 1989. A Water-Quality Index for River Management. *Journal of the Institution of Water and Environmental Management,* 3, 336-344.

HURLEY, T., SADIQ, R. & MAZUMDER, A. 2012. Adaptation and evaluation of the Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI) for use as an effective tool to characterize drinking source water quality. *Water Research,* 46, 3544-3552.

INHABER, H. 1975. Approach to a Water-Quality Index for Canada. *Water Research,* 9, 821-833.

INHABER, H. 1976. Indexing Quality of Water. *Abstracts of Papers of the American Chemical Society*, 79-79.

JOUNG, H. M., MILLER, W. W., MAHANNAH, C. N. & GUITJENS, J. C. 1979. Generalized Water-Quality Index Based on Multivariate Factor-Analysis. *Journal of Environmental Quality,* 8, 95-100.

JUWANA, I., PERERA, B. & MUTTIL, N. 2010. *A water sustainability index for West Java - Part 2: Refining the conceptual framework using Delphi technique*.

KHAN, A. A., PATERSON, R. & KHAN, H. 2004. Modification and application of the Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI) for the communication of drinking water quality data in Newfoundland and Labrador. *Water Quality Research Journal of Canada,* 39, 285-293.

LANDWEHR, J. M., DEININGE.RA, MCCLELLA.NL, BROWN, R. M. & HARKINS, R. D. 1974. Objective Water-Quality Index. *Journal Water Pollution Control Federation,* 46, 1804-1809.

LANDWEHR, J. M. & DEININGER, R. A. 1976. Comparison of Several Water-Quality Indexes. *Journal Water Pollution Control Federation,* 48, 954-958.

LIOU, S. M., LO, S. L. & WANG, S. H. 2004. A generalized water quality index for Taiwan. *Environmental Monitoring and Assessment,* 96, 35-52.

LOHANI, B. N. & TODINO, G. 1984. Water-Quality Index for Chao-Phraya River. *Journal of Environmental Engineering-Asce,* 110, 1163-1176.

LUMB, A., HALLIWELL, D. & SHARMA, T. 2006. Application of CCME Water Quality Index to monitor water quality: A case study of the Mackenzie River basin, Canada. *Environmental Monitoring and Assessment,* 113, 411-429.

MELLOUL, A. J. & COLLIN, N. 1998. A proposed index for aquifer water-quality assessment: the case of Israel's Sharon region. *Journal of Environmental Management,* 54, 131-142.

MEYER, M. A. & BOOKER, J. M. 2001. *Eliciting and analysing expert judment: a practice guide*, Statistical Sciences Group, Los Alamos National Laboratory, Los Alamos, New Mexico.

MONRE 2015. National Technical Regulation on Groundwater Quality QCVN 09-MT:2015/BTNMT. Hanoi: Ministry of Natural Resources and Environment

NAZARATUL ASHIFA ABDULLAH, S., ABDUL KHALIK, W., ALIAS MOHD, Y., MOHD SUHAIMI, H., MD SUHAIMI, E. & SHAMSIAH ABDUL, R. A study of arsenic and chromium contamination in freshwater sediments. Nuclear Malaysia R and D 2008 Seminar, 2008 Malaysia. Malaysian Nuclear Agency.

NGWA, T. G. A. 2019. *Facts About Global Groundwater Usage* [Online]. Available: https://www.ngwa.org/what-is-groundwater/About-groundwater/facts-about-global-groundwater-usage [Accessed 04.04 2019].

OTT, W., MONITORING, U. S. E. P. A. O. O. & SUPPORT, T. 1978. *Water quality indices: a survey of indices used in the United States*, Environmental Protection Agency, Office of Research and Development, Office of Monitoring and Technical Support.

PHAM, T. M. H., STHIANNOPKAO, S., BA, D. T. & KIM, K. W. 2011. Development of Water Quality Indexes to Identify Pollutants in Vietnam's Surface Water. *Journal of Environmental Engineering-Asce,* 137, 273-283.

RENAUD, F. & KUENZER, C. 2012. *The Mekong Delta System - Interdisciplinary Analyses of a River Delta*.

RICHARDSON, A. M. 1997. *Development of an estuarine water quality index (eWQI) for New South Waves.* BSc. (Honours), Univserity of Sydney.

ROCCHINI, R. & SWAIN, L. G. 1995. The British Columbia Water Quality Index. Water Quality Branch, Environmental Protection deparment Britisch Columbia Ministry of Environment, Lands and Parks.

RUDNICKA, J. 2020. *Entwicklung der Weltbevölkerungszahl von Christi Geburt bis 2020* [Online]. Available: https://de.statista.com/statistik/daten/studie/1694/umfrage/entwicklung-der-weltbevoelkerungszahl/ [Accessed 2020].

SAEEDI, M., ABESSI, O., SHARIFI, F. & MERAJI, S. H. 2009. *Development of groundwater quality index*.

SMITH, D. G. 1990. A Better Water-Quality Indexing System for Rivers and Streams. *Water Research,* 24, 1237-1244.

SOLTAN, M. E. 1999. *Evaluation Of Ground Water Quality In Dakhla Oasis (Egyptian Western Desert)*.

STAMBUK-GILJANOVIC, N. 1999. Water quality evaluation by index in Dalmatia. *Water Research,* 33, 3423-3440.

STIGTER, T. Y., RIBEIRO, L. & DILL, A. M. M. C. 2006. Application of a groundwater quality index as an assessment and communication tool in agro-environmental policies - Two Portuguese case studies. *Journal of Hydrology,* 327, 578-591.

SUTADIAN, A. D., MUTTIL, N., YILMAZ, A. G. & PERERA, B. J. C. 2016. Development of river water quality indices-a review. *Environmental Monitoring and Assessment,* 188.

SWAMEE, P. & TYAGI, A. 2000. Describing Water Quality with Aggregate Index. *Journal of Environmental Engineering-asce - J ENVIRON ENG-ASCE,* 126, 451-455.

SWAMEE PRABHATA, K. & TYAGI, A. 2007. Improved Method for Aggregation of Water Quality Subindices. *Journal of Environmental Engineering,* 133, 220-225.

TERRADO, M., BARCELO, D., TAULER, R., BORRELL, E. & CAMPOS, S. 2010. Surface-water-quality indices for the analysis of data generated by automated sampling networks. *Trends in Analytical Chemistry - TrAC,* 29, 40-52.

TIRKEY, P., BHATTACHARYA, T. & CHAKRABORTY, S. 2013. Water quality indices- important tools for water quality assessment: a review. 1.

TYAGI, A., MONDAL, P. & SIDDIQUI, N. A. 2018. Quality Assessment of Groundwater Using Water Quality Index at Yamunanagar, Haryana. *Advances in Health and Environment Safety*, 369-376.

TYAGI, S., SHARMA, B., SINGH, P. & DOBHAL, R. 2013. Water Quality Assessment in Terms of Water Quality Index. *American Journal of Water Resources,* 1, 34-38.

WAGNER, F. 2012. Groundwater Resources in the Mekong Delta: Availability, Utilization and Risks.

WALSKI, T. M. & PARKER, F. L. 1974. Consumers Water-Quality Index. *Journal of the Environmental Engineering Division-Asce,* 100, 593-611.

WEPA, W. E. P. I. A. 2019. *State of water environmental issues in Vietnam* [Online]. Available: http://www.wepa-db.net/policies/state/vietnam/overview.htm [Accessed 2019].

WEPENER, V., N, E., VAN VUREN, J., PREEZ, H. & SJOBERG, A. 1992. *The development of an aquatic toxicity index as a tool in the operational management of water quality in the Olifants River (Knsger National Park)*.

WEPENER, V., O'BRIEN, G. C., CYRUS, D., LA, V. & WADE, P. 2006. *Development of a Water quality index for Estuarine water quality management in South Africa*.

WHO & UNICEF 2000. Global water supply and sanitation assessment 2000 report.

WIKIPEDIA. 2020. *Pearson Correlation Coeficient* [Online]. Wikipedia. Available: https://en.wikipedia.org/wiki/Pearson_correlation_coefficient [Accessed 18.03 2020].

YEN, B., SON, N., TUNG, L., AMJATH BABU, T. & SEBASTIAN, L. 2019. Development of a participatory approach for mapping climate risks and adaptive interventions (CS-MAP) in Vietnam's Mekong River Delta. *Climate Risk Management,* 24.

ZANDBERGEN, P. A. & HALL, K. J. 1998. Analysis of the British Columbia Water Quality Index for Watershed Managers: a Case Study of Two Small Watersheds. *Water Quality Research Journal,* 33, 519-550.

Appendices

Appendix 1: List of Water Quality Index updated from (Couillard and Lefebvre, 1985, Wepener et al., 2006)

Author	Selected variables	Variable transformation and weighting	Variable aggregation	Applicability
		GENERAL WATER QUALITY INDICES		
Horton (1965) Quality Index	Ten variables, SEWAGE., pH, conductivity, %DO, T.coli, CCE, Alkalinity, Cl, °C, OP.	Parameter's weightings interrelated; rating curves used to produce dimensionless scale 0-100	Weighted sum multiplied by two coefficients	No specific use considered; Rivers, USA
Brown et al. (1970, 1973)* National Sanitation Foundation WQI	11 variables selected by Delphi type technique; fecal coliform, pH, BOD_5, NO_3, PO_4, °C, Turbidity, TS, %DO, pesticides, and toxic compounds	Delphi technique used for unequal weighting of variables; Rating curves to produce dimensionless scale 0-100	Additive aggregation (first version) Multiplicative aggregation (second version)	A general assessment of the state of water quality but it cannot be used for toxicity evaluation
Scottish Research Development Department (SRDD) Index (1976)	Ten parameters: DO, BOD5, free and saline ammonia, pH, total oxidized (TO), N, P, SS, temperature, conductivity, E.Coli	Parameters are directly taken as sub-indices using rating curves developed by expert's opinion.	Additive	General water quality assessment but it cannot be used for toxicity evaluation
McDuffie and Haney's River Pollution Index (RPI)	Selected eight parameters: Percent Oxygen Deficit, Biodegradable Organic Matter, Refractory Organic Matter, Coliform Count, Nonvolatile Suspended Solids, Average	Rating scale increasing from 0 to 1000+		
Ross (1977) * WQI System	The author selected four variables based on those being indicative of pollution, SS, BOD, DO, NH3.	Scale 0 to 10; 0= polluted and 10= pristine; the relative weighting of variables incorporated in rating curves; descending order of importance; NH3 and BOD, SS, DO, and %DO.	Aggregation method - summation of transformed values divided by the total weight of all the variables	No specific use is considered; River, UK.
Bolton et al. (1978)	Ten variables DO, BOD, NH_3, E.coli, pH, TON, PO_4, SS, Conductivity, °C	Rating curves used to produce a dimensionless scale between 0 and 100; variables weighted to a total weighting of 1, based on the importance of the variable.	Weighted geometric or weighted Solway mean	No specific use considered; Rivers, UK
Dunnette (1979) Orgon index	6 parameters (first version): DO, pH, FC, BOD5, TS, $NO3^+$ammonia Eight parameters (second version): two adddition parameters are TP, temperature	Parameters are directly taken as sub-indices Unequal weights with the sum of weights equal to 1 (first version) Equal weights (second version)	Additive (first version) Unweighted. The harmonic mean of squares of the sub-indices (second version)	General water quality assessment

Author	Selected variables	Variable transformation and weighting	Variable aggregation	Applicability
Bascarón (1979)	26 parameters: pH, BOD5, DO, temperature, T.coli, color, turbidity permanganate reduction, detergents, hardness, DO, pesticides, oil, and grease, SO_4, NO_3, cyanides, sodium, free CO_2, ammonia-N, Cl^-, conductivity, Mg, P, NO_2, Ca and apparent aspect	Parameters are directly taken as sub-indices through a piecewise (segmented) linear transformation. Unequal weights. Sum of weights is 54	Modified additive	The original index for general water quality assessment but later modified indices were used for specific uses such as assessing suitability for aquaculture
Beron et al. (1979; 1980, 1982) * Groupe de recherche sur l'eau en milieu urbain Index	Numerous parameters depend on use; umber of uses considered: potable water, aquatic life, pollution sensitive and pollution tolerant spp., recreation, and agriculture—three sets of variables; primary, accessory, and supplementary. The latter includes mainly toxic substances and is optional.	Weighting dependents on the intended use; Rating curves vary according to use; Scale between -50, and 100.	Weighted Sum	Developed for multiple uses; Rivers
Steinhart et al. (1982) Great Lakes Nearshore Index	Nine variables from 4 different categories: chemical, COND, Cl, Ptot; physical, SS, OP; biological, F.coli, Cl, A; and toxic, TOS, TIS.	Rating curves vary according to the variable category; to produce a dimensionless scale between 0 and 100; Categories or sub-indices have different weightings	Weighted Sum	General use index, Lakes, USA
House (1986, 1989,1990) WQI	Some selection criteria used to select nine variables, DO; NH_3-N, BOD, SS, NO_3, pH, °C, Cl, T.coli	Delphi technique used to determine weightings; Sum of weights is 1. Rating curves based on accepted standards used to produce the dimensionless scale of 10 to 100	Solway modified weighted sum	No specific use considered; Rivers, UK
Ved Prakash et al. (1990)	Four parameters: DO, FC, pH, and BOD	Parameters are directly taken as sub-indices Unequal weights. Sum of weights is 1	Additive	General water quality index assessment
Dojilido et al. (1994) WQI	Seven primary variables, BOD_5; SS; PO4; NH3; DS; COD-Mn; DO 19 additional parameters: Fe, phenols, organic nitrogen, hardness, Mn, SO_4^{2-}, Cl, COD-Cr, NO_3^-, Pb, Hg, Cu, chromium (IV), total chromium, Zn, Ca, Ni, and free cyanides	Dimensionless scale; variables not weighted, values of 0-100 based on government standards	The square root of the harmonic mean	General use and specific use by variation in variables selected; Rivers, Poland

Author	Selected variables	Variable transformation and weighting	Variable aggregation	Applicability
Cooper et al. (1994) WQI	Authors selected seven variables from 3 estuarine impairment categories, DO, OA, NH_4, F.coli, NO_3-N, PO_4-P	Use of rating curves to produce dimensionless scale range between 0 and 10, weighted impairment categories equally, and unequal weighting of variables.	Solway modified weighted sum	No specific use considered; Estuaries, South Africa
Canadian Council of Ministers of the Environment (CCME) (1997) Water Quality Index	At least four parameters Maximum number of parameters is not specific	No sub-index used No weights used	No aggregation method used	The original index for general water quality assessment
Oudin et al. (1999) Status and sustainability index	15 alteration classes based on their similar nature and its impact on the environment: NO_3^-, phosphorus matter, suspended particles, color, temperature, mineralization, acidification, microorganisms, phytoplankton, micro-mineral pollutants, metals in bryophytes, pesticides, organic micro-pollution, and non-pesticides	Thre alteration classes, NO3-, color, temperature: directly taken as sub-indices Other alteration classes only one parameter that has the worst value in the same alteration class is considered as sub-indices (minimum operator) Equal weights	Minimum operator	General water quality assessment
Hallock (2002) Water quality index for Ecology's stream monitoring	Eight parameters: temperature, DO, pH, FC, TN, TO, TSS and turbidity	Temperature, pH, FC are directly taken as sub-indices using continuous scaling developed from the permissible limits. Turbidity and TSS are aggregated to generate one sub-indices using average mean. Equal weights Other parameters are directly taken as sub-indices using the distribution of historical data TP and TN have a lower scale compared to other sub-indices	Additive	General assessment
DoE Malaysia (2002) Malaysia index	Six parameters: COD, ammonia-N, NO_3^-, PO_4^{3-} and sulfates and pH	Parameters are directly taken as sub-indices. Unequal weights. Sum of weights is 1	Additive	General water quality assessment
Ocampo-Duque et al. (2006) Fuzzy-based indices	No guidelines	Using fuzzy logic	Unequal weights Using fuzzy logic	General water quality index

Author	Selected variables	Variable transformation and weighting	Variable aggregation	Applicability
		SPECIFIC USE WATER QUALITY INDEX		
Nemewor and Sumitomo (1970) Water Pollution Index	Recommended at least 15 parameters include: temperature, color, turbidity, pH, FC, TDS, SS, TN, alkalinity, hardness, Cl, Fe, Mn, SO_4, DO	Parameters directly are taken as sub-indices using average and maximum values of the ratio between the concentration of the respective parameter over the permissible limits Equal weights	The root mean square	Specific uses for assessing suitability for direct human contact use (drinking, swimming, etc) indirect contact use (fishing, agriculture, etc) and remote contact use (navigation, industries, etc)
Deininger and Landwehr's (1971) Public Water Supply Index (PWS)	Employed 11 parameters for surface water and 13 for groundwater		Additive and geometric mean	
Prati et al. (1971) Implicit Index of Pollution	Authors selected 13 variables; pH, %DO, BOD, COD, SS, NH_3, NO_3, Cl, Fe, Mn, ABS, CCE, C.KUB;	equal weighting; the dimensionless scale of 0-14 based on standards (for potable water) from various organizations, a value higher than 8 = heavily polluted	Unweighted arithmetic mean	Specific use: Potable water; Rivers, Canada
Dinius (1972) Water Quality Index	Selected 12 parameters: %DO, BOD_5, Total Coliforms, Fecal Coliforms, Specific conductance, F, Cl, Hardness, Alkalinity, °C, pH, Color	Parameters are directly taken as sub-indices Weights range from 0.5 to 5	Additive version of the NSF-WQI	Streams in Alabama, USA
O'conner (1972) Fish and Wildlife Water Quality Index (FAWL) Public Water Supply Water Quality Index (PWS)	Delphi technique for selecting nine parameters for FAWL and 13 parameters for PWS		Weighted Sum	

Author	Selected variables	Variable transformation and weighting	Variable aggregation	Applicability
Padgett and Stanford (1973)* Industrial Water Pollution Index	Variable selection is up to the user.	Normalized values reflect scores for the different observations; Weight-ing is optional;	The weighted or unweighted sum of the normalized values	Particularly to industrial use; discharge
Walski and Parker (1974)** Consumers WQI	SS, turbidity, nutrients, grease, color, threshold odor, pH, temperature, toxicity, and coliform count	Parameters are directly taken as sub-indices Sensitivity functions based on negative exponential equations, user give own weightings for variables rating between 0 and 1; no weighting for different uses,	Geometric mean (weighted product); Unequal weights Sum of weights is 1	Developed for recreational use; Waterways, USA
Keilani et al. (1974)* National Water Quality Economic Index	Delphi technique used to determine five variables for each of eight uses; User selects use with regards to a particular area	Delphi technique was used to determine weightings (add up to 1) and rating curves for the different variables. The scale ranges between 0 and 100.	Aggregation formula is a weighted sum with two different weights; one for the variable I of use j, and one for the use j itself.	Applicable to eight different uses; Lakes moreover, rivers of a specific region
Inhaber (1975)	Two sub-indices: (1) general quality — consists of trace metal sub-index (Cd, Li, Cu, Zn, Cr, HARD); turbidity and effects on potable water sub-index; and commercial fishing sub-index. (2) Sub-index for punctual discharges (BOD, SS, NH_3, TP, Phenols, Cyanide)	No weighting for parameters or uses; use of rating curves; special weighting for some variables not for uses, rating curves included but not clear.	Root mean square; Weighted sum. Combined aggregation formula is: ICQE=I2AMB+I2RT/2	More of a general environmental quality index. Lake, river or discharge
Ibbotson (1977)*	Author suggests T.coli/ F.coli, DO, TN, TP, pH, °C, TDS, TM and turbidity.	All variables of equal weighting in calculating sub-indices, sub-indices are weighted; Rating curves developed from accepted standards ranging between 1 and 10.	The final calculation is a weighted sum	Various uses considered, potable water, recreation, agricultural and aquatic life; Rivers
Stoner (1978)*	Variable selection according to use; generally two groups: Toxic substances, (II) health or aesthetic parameters; 21 parameters used for irrigation and 39 for potable water.	(I) no weighting, step function rating curves; (II) parameters weighted, National Academy of Sciences standards used as the basis for rating curves; Scores range between -100 and 100	Aggregation formula is: $I = \sum T_i + \sum w_i q_i$	Specific use considered, namely: irrigation and Potable water; Rivers

Author	Selected variables	Variable transformation and weighting	Variable aggregation	Applicability
Yu and Fogel (1978) Combined WQI	Two components were used Five water quality variables, SS, ABS, T.coli, NO_3, PO_4, and (b) an economic variable		The index is an absolute value	Water treatment, USA
Joung et al. (1979), Miller et al. (1986) WQI for Nevada	Ten variables selected particular to Nevada and common to 5 freshwater impairment categories, °C, BOD, TP, PO_4-P, TN, NO_3-N, EC, TURB, pH, DODP.	Combination of PCA and multiple regression analysis used to weight variables; Rating equations were developed by polynomial regression analysis to produce a dimensionless scale of 0 to 100.	Weighted Sum	Rivers specific to Nevada, USA
Porcella et al. (1980) Lake Evaluation Index	Authors selected six variables SD, TP, TN, Cl, DO, MAC; Empirical functions used to aggregate each of the variables	Use of rating scale between 0 (not polluted) and 100 (polluted); variables weighting not clear.	Weighted Sum	Assumption main source of pollution is nutrient enrichment; Lakes, Canada
St.Louis and Legendre (1982) Microbial WQI	Only bacteriological variables were included, T.coli, Fecal, Streptococci	Data log-transformed and discriminate analysis done to determine weightings and rating curves on a scale between 0 and 1	The aggregation method is the discriminate scoreless the min. The value obtained for a sample divided by the max. Less the min. for the same sample	Lakes Beaches
Lohani and Todino (1984)	Authors selected 13 variables, pH, °C, Do, turbidity, SS, Cl, NO_2, NO_3, TN, PO_4, BOD, T.Coli, COND	Principal component analysis was used to determine variable Weights; multiple regression was used to produce a scale of 0 — 100;	Aggregation formula is: $I(i) = \sum_{j=1}^{n} \frac{a\,(ji)\gamma\,(j)}{\lambda(i)}$ Where a(ji) = factor loading on variable j on factor I; ϒ(j)= standardized form of variable; λ(i) = the eigenvalue of factor I Modified weighted sum	Very data specific, Chao Phraya River, Thailand
Bhargava (1985)	Four different groups: coliform organisms, heavy metals, physical parameters, and organic and inorganic parameters	Parameters in the same group are aggregated to obtain four different group sub-indices Unequal weights Sum of weights is 1	Modified multiplicative	Specific use for assessing suitability for drinking water supply

Author	Selected variables	Variable transformation and weighting	Variable aggregation	Applicability
Dinius (1987) Index of Water Quality	Delphi type technique used to select 12 variables, DO, BOD_5, Coli., E. coli., pH, Alkalinity, hardness, Cl, COND, °C, COL	Four-round Delphi evaluation using a seven-member panel used to weight variables; importance rated on a scale of 0 to 5	Multiplicative aggregation function	Several uses considered; Freshwater, USA
Smith (1989, 1990) WQI System	Delphi method of variable selection nine variables; DO, pH, SS, turbidity, °C change, BOD_5, NH_3, F.coli.	Delphi method and accepted standards were used to produce rating curves on a scale of 0-100	Initially used weighted multiplicative, latter replaced with a minimum operator	Considered the following uses general, bathing, water supply, and fish spawning; Waterways, New Zealand
Wepener et al. (1992)	14 variables, DO, pH, Turbidity, TDS, F, K, OP, Zn, Mn, Cr, Cu, Pb, Ni;	No weightings used; scale Use of existing and modified rating curves using WQ standards to produce a scale between 0-100,	Solway modified unweighted additive aggregation function and a minimum operator	No specific use considered Rivers, South Africa
Erondu and Nduka (1993) WQI	Eight variables, °C, pH, DO, BOD, NH_3-N, Sulphate, Silica, hardness		Exponential model of the Geometric Mean, which is as follows: WQI= exp in fi (Pi) x 100 Where fi is a sensitivity function of parameter index I, and n is the number of relevant observations	Includes specific uses such as bathing, public water supply, fish culturing and industrial uses; Rivers, Nigeria
Karydis (1996)	Four variables of measures of eutrophication; PO_4, NO_2; NO_3; NH_3	Log transformation and standardization of variables using the following formula: $$Z_{ij} = \frac{X_{ij} - Y_i}{\sigma_i}$$ Scale 0-100		Coastal/Marine
Gray (1996) Acid Mine Drainage Index	7 variables, pH, SO_4, Fe, Zn, Al, Cu, CD	Variables weighted and water quality rating table used to obtain WQ scores between 0 and 25	Modified weighted arithmetic mean	Use in acid mine drainage contamination

Author	Selected variables	Variable transformation and weighting	Variable aggregation	Applicability
Richardson (1997)	The author selected eight variables; DO, NH_3, pH, F.coli, TURB, NO_3-N, OP, Chl-a	Use of rating curves based on water quality guidelines; the dimensionless scale of 0 to 100; user decides on weighting	Unweighted harmonic square mean	Estuaries, New South Wales, Australia
Boyacioglu (2007)	12 parameters: TC, cadmium, cyanide, Hg, Se, As, F, NO_3-N, DO, pH, BOD_5, TP	Parameters are directly taken as sub-indices using the permissible limits of water standards Unequal weights. Total weight is 1	Additive	Specific use of assessing suitability for drinking water supply
Pham et al. (2011)	At least ten parameters: SS, turbidity, DO, COD, BOD5, orthophosphate, ammonium N, TC, temperature, toxicity, and pH	Parameters are directly taken as sub-indices using the permissible limits of water standards All parameters are directly taken as sub-indices using TC taken as "bacteria" sub-indices DO, COD, BOD5, ammonia nitrogen, and orthophosphate are aggregated to obtain "organics and nutrients" sub-indices Sand turbidity are aggregated to obtain "particulates" sub-indices Equal weights	Combination of additive and multiplicative means The additive method is used to aggregate parameters in similar characteristic (organics, particulates, and microorganism) The multiplicative method is used to aggregate all sub-indices.	
Almeida et al. (2012)	9 parameters: pH, COD, No3, phosphate, detergents, enterococci, TC, FC and E.coli	Parameters are directly taken as sub-indices Unequal weights Sum of weights is 1	Multiplicative	Specific use of assessing suitability for recreational use
PLANNING WATER QUALITY INDICES				
Dee et al. (1972, 1973) Environmental Evolution System (EES)	78	Decreasing 0 to 1000	The index was calculated with and without considering the proposed water resources project. The difference between the two scores provided a measure of the environmental impact on the project: $EI = \sum^{78} W_i I_i\ (with) - \sum^{78} W_i I_i\ (without)$	

Author	Selected variables	Variable transformation and weighting	Variable aggregation	Applicability
Zeoteman (1973) Potential pollution Index	3	Increasing 0 to 1000+	$PPI = {}^{NG}/_{Q}x10^{-6}$ Where N is the number of people living in a drainage area. G is the average per capita Gross National Product (GNP)- Q is the yearly flow rate (I/s)	
Inhaber (1974) Environmental Quality Index	A composite of four indices, representing air, water, land, and different aspects of environmental quality.	The weights were assigned on the advice of experts.	Root-mean-square-method	For Canada
Truett et al. (1975)* Prevalence duration Intensity	3 parameters selected; (P) spatial extent; (D) duration and (I) intensity of effect. (I) consists 3 sub-parameters: ecological, practical and aesthetic scopes.	No rating curves, the (D) score is that proportion of the year that a standard is not stateside, (I) score is the sum of 3 sub-parameters of impact levels. Weighting is according to use	Aggregation formula: $PDI = \frac{P * D * I}{M}$ Where M = miles in the covered administrative unit set by state/county	To assess the general water quality of rivers
Truett et al. (1975) National Planning Priorities Index (NPPI)	Any number can be included	Increasing 0 to 1	$NPPI_i = \sum_j a_j f_j(x_{ij})$ Where I designate a particular planning area (or BDU) $NPPI_i$ id the index value for that BDU j designates a particular parameter aj is the importance weighting assigned to that parameter $\sum a_j = 1$ x_{ij} is the value of the j^{th} parameter for the ith BDU and f_i is the transform (or value function) for the j^{th} parameter *BDU block development unit	

Author	Selected variables	Variable transformation and weighting	Variable aggregation	Applicability
Johanson & Johanson (1976) Pollution Index (PI)	Any number can be included	Increasing 0 to 1000+	$$PI = \sum_{i=1}^{a} W_i C_i$$ Where Wi is the weight for pollutant variable I Ci is the highest concentration of pollution variable I reported in a location of interest	
Ott (1978) National Planning Priorities Index	Ten sub-indices	Sub-index computed using a segmented linear function	$$NPPI = \sum_{i=1}^{10} W_i I_i$$	
House and Ellis (1987) Water Quality Indices for Operational Management	Nine parameters: DO, NH3-N, BOD, No3, Cl, SS, pH, Temperature, T.Coli	Weighting using questionnaire study. Unequal weights, the sum of weights is 1 Rating curves, scale from 10 to 100	The aggregation function using additive $$WQI = \frac{1}{100}\left[\sum_{i=1}^{n} q_i w_i\right]$$ Where q_i- the WQR for the ith parameter w_i – the weighting for the ith parameter n – the number of parameters	Classification of several rivers in the Greater London region, UK
STATISTICAL METHOD				
Harkins (1974)*	No guidelines Selection and number of variables used, up to the user.	No weightings and no rating curves were used. Parameters are standardized using the target value (usually the permissible limit)	Statistical procedures through Multivariate Kendall's statistic (non-parametric multivariate ranking procedure)	Lake, river or discharge
Tiwari and Mishra (1985)	Subjectively done by different authors based on past experiences	Weight assignment (W_i) is done correspondent to WHO or Indian Council of Medical Research standards of parameters $$W_i = \frac{K}{O_i}$$ where $K = \frac{1}{(\sum 1/O_i)}$	$$WQI = antilog \sum_{i=1}^{n} w_i log q_i$$	India

Author	Selected variables	Variable transformation and weighting	Variable aggregation	Applicability
Melloul and Collin(1998) Index of Aquifer Water Quality	Authors selected two variables Cl, NO (for preliminary testing of the index) use of additional variables up to the user	Use of rating curves based on accepted standards to produce a dimensionless scale 0 to 10; Weighted according to relative Importance.	Modified weighted sum	Aquifers, particular interest in salinization and pollution
Backman et al. (1998) Groundwater Contamination Index	For the calculation of the contamination index for health-risk aspects: F-, NO3-, UO22-, As, B, Ba, Cd, Cr, Ni. Pb, Rn, and Se For the technical, aesthetic aspect: TDS, SO42-, Cl-, F-, NO3-, H4+, Al, As, Ba, Cd. Cr, Cu, Fe, Hg, Mn, Pb, Sb, Se and Zn	No weights	$C_d = \sum_{i=1}^{n} C_{fi}$ Where $C_{fi} = \frac{C_{Ai}}{C_{Ni}} - 1$ Cfi is th contamination factor for the ith component CAi is the analytical value of the ith component CNi is the upper permissible concentration for the ith component N representing the normative value	
Stambuk-Glijanovik (1999) - Index for surface water and groundwater quality	Nine variables, °C; Mineralisation, Corrosion coefficient, %DO, BOD_5; T-N; Protein N; T.coli	Weighted on a dimensionless scale of 0-100;	Weighted Sum	Groundwater for use as drinking water, Dalmatia
Stigter et al. (2006) Index development using correspondence factor analysis	12 parameters: EC, Na, K, Mg, Ca, NH_4, Cl, HCO_3, SO_4, NO_3, PO_4			Portugal
Mohamad Roslan et al. (2007) Groundwater quality index to study the impact of landfills	Seven parameters which influence the water quality the most: electric conductivity, TDS, Salinity, Nitrate, Nitrite, COD, Ferum	Benchmarking encompassed a 0-10 scale		Sabak area in Malaysia

Author	Selected variables	Variable transformation and weighting	Variable aggregation	Applicability
Soltan (1999), Ramakrishnaian et al. (2009), Banoeng-Yakubo et al. (2009), Vasanthavigar et al. (2010), Banerjee and Srivastava (2011)	Twelve parameters: TDS, HCO_3, Cl, SO_4, PO_4, NO_3, F, Ca, Mg, Na, K, and Si. Chlorine and EC can serve as indicators of groundwater pollution	Weight (wi) is assigned according to their perceived importance in the overall quality of water for drinking purposes. The WQI ranges from <50 to >300	$WQI = \sum SI_i$ Where SI_i is the subindex of the i^{th} parameter q_i is the rating based on the concentration of i^{th} parameter n is the number of parameters	
Pei-Yue et al. (2010) The information entropy-based groundwater WQI	Fourteen parameters were selected and weighted.	assignment of a quality rating scale for each parameter, done by $q_i = \frac{C_j}{S_j} * 100$ Based on WQI scores, groundwater quality was classified into four ranks from excellent to extremely poor	$WQI = \sum_{j=1}^{n} w_j q_j$ wj is defined as the entropy weight of j^{th} parameter which calculated by $w_j = \frac{1 - e_j}{\sum_{j=1}^{n}(1 - e_j)}$ q_j is the	

Appendix 2: Time scale of Late Cenozoic Strata separate in geological and hydrogeological units of the Mekong Delta (DGMS, 2004, Wagner, 2012)

Era	System	Series	Subseries	Geological unit	Hydrogeol.unit	Facies type[a]	Base age (Mio a BP)
Cenozoic	Quaternary	Holocene	Upper	Q_{II}^{3}	qh_3	mv, b, mb, m, ab, am, a	0.002
			Middle	Q_{II}^{2-3}	qh_{2-3}	bm, mb, am, ab	0.006
			Lower	Q_{II}^{1-2}	qh_1	m, am, a	0.012
		Pleistocene	Upper	Q_{I}^{3}	qp_3	m, am, a	0.126
			Middle	Q_{I}^{2-3}	qp_{2-3}	m, am, a	0.781
			Lower	Q_{I}^{1}	qp_1	m, am, a	1.806[b]
				N_2^3	-	m, am, a	2.588[b]
	Neogene	Pliocene	Middle	N_2^2	n_2^2	m, am, a	3.600
			Lower	N_2^1	n_2^1	m, am, a	5.332
		Miocene	Upper	N_1^3	n_1^3	m	11.608
			Middle	N_1^{2-3}	n^{2-3}	Am	15.97
			Lower	N_1^1	-	-	23.03

Associated base ages are modified to IUGS-ICS ratification in 2009 (Gibbard et a. 2010)

[a](a) – alluvial; (m) – marine; (b) – swamp, bog; (v) – aeolian; according to DGMS Vietnam

[b]Quantery base has been redefined by IUGS-ICS in 2009 to 2.58 Mio a BP, including the former upper Pliocene

M.Sc. Pham Van Hung
Division for Water Resource Planning and Investigation for the South of Vietnam
No. 59, Street 2, Binh An Ward, District 2
Ho Chi Minh City, Vietnam

hungtnnmn@gmail.com

21.01.2019

Ms. Van Dao Thi Bich

Technical University of Darmstadt| Institute IWAR
Franziska-Braun-Straße 7
64287, Darmstadt
Germany

Letter of Acceptance

Dear Ms. Van Dao Thi Bich,

Firstly, I would like to thank for your requesting letter on the database of groundwater monitoring and management in Southern of Vietnam. I am writing to confirm our acceptance and permission granted for the use of the following material:

- General information about water resources and groundwater resources
- Monitoring data (quality and quantity) of groundwater of Vietnam Mekong Delta from 1995-2018
- Management information of groundwater resources of Vietnam Mekong Delta

Permission includes non-exclusive world rights in all languages to use the material for resulting thesis and will not limit any future related reports, publications, -including future editions and revisions by us or other authorized by us.

If you require any additional information, please do not hesitate to contact me by the given email and telephone number.

Yours faithfully,

M.Sc. Pham Van Hung