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An integrated approach to evaluate challenges and opportunities to address water resource management issues in Can Tho City, Vietnam

(ベトナム、カントー市における水資源管理問題への取り組みのための課題と機会の評価の統合的アプローチ)

Ph. D. Thesis Submitted by

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A dissertation submitted in partial fulfilment

of the requirement for the degree of

DOCTOR OF PHILOSOPHY

in

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of the

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Abstract

Rapid industrialization, urbanization, land-use change, and climate change are the key drivers of complex water pollution especially in developing regions globally. Being no exception, Can Tho City is currently experiencing water stress, especially surface water quality (SWQ), driven by rapid local and global changes. Using the multivariate analytical techniques, Weighted Arithmetic Water Quality Index (WAWQI) estimation, Water Evaluation and Planning (WEAP) tool, and systematical review, this research thoroughly assesses the Can Tho City's past, current, and future SWQ status under rapid land-use and climate changes; and later part of the research focuses on the water governance (WG) issues to further strengthen science-policy interface and proposes mitigation and adaptive measures to improve SWQ and WG using integrated water resource management (IWRM) approach in Vietnam including its rapidly growing Can Tho City in particular and the Asian developing countries in general. The SWQ dataset with 14 physico-chemical SWQ parameters at 73 sampling sites of the study area and 145 reviewed WG publications were collected, assessed, and analyzed in this research.

As assessed, average levels of biochemical oxygen demand (BOD), chemical oxygen demand (COD), dissolved oxygen (DO), total coliform (TC), turbidity, total suspended solids (TSS), and phosphate (PO_4^{3-}) exceeded the national permissible limits. Spatially, cluster analysis (CA) was divided the city's river basin into three different zones: mixed urban-industrial, agricultural, and mixed urban-rural zones. Principal component/factor analysis (PCA/FA) identified key SWQ pollution sources, mainly related to domestic wastewater, industrial effluents, farming runoff, soil erosion, and severe droughts. Discriminant analysis (DA) also explored that COD, DO, nitrate (NO_3^-), PO_4^{3-}, and turbidity were the key parameters discriminating SWQ in the city among seasons and land-use zones. The temporal analysis results from WAWQI revealed the deterioration of SWQ conditions, whereby, the total polluted monitoring sites of the city increased from 29% in 2013 to 51% in 2019, mainly due to the expansion in built-up and industrial land areas, farming runoff, and droughts. Regarding the city's future SWQ simulation, the Business as Usual (BAU) scenario; scenarios with measures (WMs) i.e., wastewater treatment plants (WWTPs) for treating 75% (WM75) and 100% (WM100) of total future wastewater generated; and the optimistic scenario (WM_Opt. i.e., WM100 + additional treatment plants for river water (RWTPs)), were applied. As simulated, the average values of BOD, TC, NO_3^-, and PO_4^{3-} in the wet season of 2030 under BAU scenario will be

increased by 16.01%, 40.85%, 30.49%, and 20.22%, respectively as compared to those of the current year. In the dry season, these rates will be increased by 27.80%, 65.94%, 31.05%, and 20.64%, respectively. Under WM75 and WM100, although SWQ was improved but did not reach the desired limits, especially for BOD and PO_4^{3-} levels. However, under the WM_Opt., the average values of BOD and PO_4^{3-} will be significantly declined by 76.53% and 63.96%, respectively as compared to the current situation and achieve SWQ under Class-A.

Compared to existing plants, the robust IWRM including an effective WG is considered a more effective solution for sustaining the acceptable status of the future SWQ especially in developing regions like Vietnam and its growing Can Tho City. Due to a lack of the Vietnamese WG information, WG in the Asian developing countries comprising Vietnam was systematically reviewed to explore their governance challenges and measures to improve IWRM. Thus, extensive review of 145 publications related to WG in the Asian regions were done. As reviewed, geographically, the countries in the Southeast Asian (SEA) (Vietnam, Thailand, Laos, and Cambodia), South Asian (SA) (India, Bangladesh, and Nepal), and East Asian (EA) (China) regions were the main hotspots for studying WG-related issues. This is mainly due to these countries' and regions' unique characteristics within Asia such as the largest areas and highest population (e.g., China and India), abundant water resources (e.g., China India, Vietnam, Thailand, and Laos), and complex WG issues. Noticeably, transboundary water, water quality, irrigation, and hydropower management were considered key challenging drivers of WG in many Asian countries including Vietnam, mainly due to a lack of joint agreements in the cross-border river basins there. Moreover, inadequate legal and institutional framework, limited stakeholder engagement, poor coordination and cooperation, and unstable politics and power were the main reasons behind the complex WG in various countries, especially in Vietnam and its rapidly developing cities like Can Tho. To analyze these issues, diverse frameworks were used. One of the most applied ones was the legal and institutional framework (LIF) that are being popularly applied for WG not only in Vietnam but also in other developing countries in Asia. Noticeably, many applied frameworks were rooted in the Ostrom's work. Besides, the OCED's framework has been also frequently utilized in recent years. Similarly, a wide range of governance elements was included in these frameworks for analysis. Legal and institutional arrangements, stakeholder engagement, and cooperation and coordination were respectively the most-discussed elements reflecting the fact that inadequate laws, institutions, stakeholder cooperation were chronic governance challenges in this continent in general and Vietnam in particular. Remarkably, the number

of elements analyzed had temporally increased from six (legislation, regulation, instrument, and policy; management arrangement; stakeholder engagement; cooperation and coordination; monitoring and evaluation; and appropriate scales within basin system) in the early 2000s to ten (six previous elements and four additional ones including clear role and responsibility; integrity and transparency; data, information, and knowledge sharing; and capacity development) after 2015. However, in case of Vietnam, this developing country only applied the LIF with no significant change in the number of key governance elements included to govern its water resources, only three main elements such as legislation, regulation, instrument, and policy; management arrangement; and stakeholder engagement. Based on the obtained findings, an optimal framework was proposed for assessing WG in the Asian developing countries including Vietnam and its growing Can Tho City; and finally, governance challenges during the implementation process of this proposed framework as well as key recommendations were given.

Overall, the research presents an overall picture of SWQ as well as its complex variations in Can Tho City. The obtained findings will help local policymakers to thoroughly review, assess, and adjust existing water policies and master plans towards achieving the city's desired SWQ standard as well as a robust and comprehensive IWRM. Besides, the research also provides useful knowledge for local planners and technical staff to enhance their capacity in applying advanced approaches and tools for evaluating water quality at their respective watershed levels. Moreover, this research will also aid the city in designing relevant management policies and strategies in a timely and appropriate manner to achieve its sustainable development goals (SDGs), particularly SDG 6. Furthermore, the key findings acquired from the case of developing Can Tho can be considered and widely applied not only to other cities in Vietnam but also to other international ones where are facing difficulties and challenges in their IWRM, especially urban SWQ management.

Keywords: Land-use change, surface water quality, multivariate statistical approach, water quality index, water quality modeling, water governance, integrated water resource management, the Asian developing countries, Can Tho City, Vietnam.

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Nguyen Hong Duc

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List of Key Abbreviations

Abbreviation	Definition
ADB	Asian Development Bank
ASCARB	Aral Sea-Central Asia River Basin
BAU	Business as Usual
CA	Cluster analysis
CAs	Central Asia
COP	Climate Change Conference of the Parties
CPR	Common pool resource
DA	Discriminant analysis
DARD	Department of Agriculture and Rural Development
DF	Discriminant function
DFID	Department for International Development
DOC	Department of Construction
DOHM	Department of Hydro-Meteorology
DONRE	Department of Natural Resources and Environment
DSI	Demand sites for industrial zone
DSR	Demand sites for residential zone
DWRM	Department of Water Resources Management
EA	East Asia
Fuzzy-AHP	Fuzzy Analytic Hierarchy Process
GBMRB	Ganges-Brahmaputra-Meghan River Basin
GCM	Global Climate Model
GIS	Geographic Information System
GWP	Global Water Partnership
HEC-RAS	Hydrologic Engineering Center River Analysis System
IDW	Inverse distance-weighted
IUCN	International Union for Conservation of Nature
IRB	Indus River Basin
IWRM	Integrated water resource management
JICE	Japan International Cooperation Center
LIF	Legal and institutional framework

LULC	Land use land cover
MAPE	Mean absolute percentage error
MARD	Ministry of Agriculture and Rural Development
MDG	Millennium development goal
MIROC5	Model for Interdisciplinary Research on Climate Version 5
MODFLOW	Modular Three-Dimensional Finite-Difference Ground-Water Flow
MOET	Ministry of Education and Training
MONRE	Ministry of Natural Resources and Environment
MRICGCM3	Meteorological Research Institute Coupled Atmosphere-Ocean General Circulation Model version 3
NGCWQI	National Guideline for the Calculation of the Water Quality Index
NTRSWQ	National Technical Regulation on Surface Water Quality
NWRC	National Water Resources Council
ODA	Official Development Assistance
OECD	Organization for Economic Co-operation and Development
PCA/FA	Principal component/factor analysis
PC	Principal component
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RA	Regression analysis
RCP	Representative Concentration Pathway
RIBASIM	River Basin Simulation Model
RMSE	Root mean square error
RS	Remote sensing
RWTP	River water treatment plant
SA	South Asia
SDG	Sustainable development goal
SEA	Southeast Asia
SWAT	Soil and Water Assessment Tool
SWMM	Storm Water Management Model
SWQ	Surface water pollution
SPSS	Statistical Package for the Social Sciences
TMDL	Total maximum daily load

TWINS	Transboundary Water Interaction Nexus
UASB-SBR	Up-flow anaerobic sludge blanket-sequencing batch reactor
UASB-TF	Up-flow anaerobic sludge blanket-trickling filter
UN	United Nations
UN DESA	United Nations Department of Economic and Affairs
UNDP	United Nations Development Programme
WA	West Asia
WAWQI	Weighted Arithmetic Water Quality Index
WBalMo	Water Balance Model
WEAP	Water Evaluation and Planning
WG	Water governance
WGF	Water Governance Facility
WGIMF	Water Governance Indicator and Measurement framework
WHO	World Health Organization
WM	With measure
WQI	Water quality index
WRM	Water resource management
WWTP	Wastewater treatment plant
VMD	Vietnamese Mekong Delta

Chapter 1

Introduction

1.1 Background

Water resources have become a focal point for sustainable and inclusive development of human societies globally (FAO AQUASTAT, 2016; Guppy et al., 2019). Particularly, in developing regions like Asia that often face a scarcity of clean water (Saraswat et al., 2017; Duc et al., 2021), this natural resource has even signified its importance not only in their socio-economic development (Moglia et al., 2012) but also in their achievement of sustainable development goals (SDGs) (Duc et al., 2021). Thus, an effective implementation of IWRM to support easy access to clean and safe water for the entire population is significantly recommended in SDG 6 (UN, 2015; Benson et al., 2020). However, this implementation in many Asian countries including Vietnam is often affected by various challenges mainly posed by the increasing demand for clean water supplies (Duc et al., 2021). The situation is exaggerated by periodic droughts and contamination of both surface and groundwater (Wakida and Lerner, 2005; UNDP, 2006b; Moglia et al., 2008, 2012). Noticeably, rapidly developing urban centers are acting as the focal point for this clean water scarcity (Grohmann, 2009; Henriques, 2011; Hoekstra et al., 2018). Thus, this has implications for a more comprehensive IWRM mainly focusing on water policies, institutions, planning, and especially governance, which are urgently required to secure adequate safe water supplies for the future (UNDP, 2006b; Duc et al., 2021).

However, IWRM, especially for the river bodies, is a complex task in growing urban areas with a great number of difficulties and challenges (Phung et al., 2015; Hoekstra et al., 2018; Trung et al., 2019a) (Table 1.1). Specifically, in developing regions like Asia, these key difficulties and challenges are rapid population growth and industrial urbanization (Hoekstra et al., 2018; Duc et al., 2021), unsustainable agriculture practices (Duc et al. 2021), irregular land use (Kumar et al., 2019b), inadequate wastewater management infrastructure, lack of awareness and common practices, and poor governance (Colloff et al., 2019; Trung et al., 2019a; Li et al., 2021). Besides, water sustainability is further skewed by extreme weather conditions viz. floods and droughts, induced due to climate change (Konings, 2012; Mukate et al., 2018; Colloff et al., 2019; Trung et al., 2019a). Consequently, these lead to situations of too little, too much or too polluted waters globally and hence bring with them serious implications to meeting key societal and environmental objectives such as safe drinking water supply, wastewater management, food and energy security, improved health, poverty eradication, sustained economic growth, and sustainable ecosystems (OECD, 2018a).

Table 1.1 The currently and potentially key difficulties and challenges as well as their main characteristics and relevant threats for the implementation process of IWRM in developing regions like Asia (Dore and Lebel, 2010; Araral and Yu, 2012; Chen et al., 2013; Ha et al., 2013; Bettini et al., 2015; Phung et al., 2015; Wu and Leong, 2016; Xing, 2017; Bichsel, 2018; Delavari and Abdi, 2018; Hoekstra et al., 2018; OECD, 2018a; Williams, 2018; Kumar et al., 2019b; Otsuka, 2019b; Trung et al., 2019a; Zinzani and Hussein, 2019; Sehring, 2020; Bourdais et al., 2021; Duc et al., 2021)

<table>
<tr><th>Key difficulties/ challenges</th><th>Main characteristics</th><th>Relevant threats</th><th>Future trend</th></tr>
<tr><td>Overpopulation</td><td>Rapid population growth and unbalanced distribution (urban overcrowding and rural depopulation)</td><td rowspan="5">High water demand, water overexploitation, clean water shortage, water conflicts, water pollution, poor sanitation, health hazards, degraded environmental quality, and economy-ecology unbalance, food and energy insecurity, increased poverty, etc.</td><td rowspan="5">Most of these threats will be more serious</td></tr>
<tr><td>Irregular land use</td><td>Fast and unplanned urbanization, intensive and uncontrolled industrialization, and unsustainable agricultural practices (intensive cultivation, inorganic fertilizer overuse, etc.)</td></tr>
<tr><td>Inadequate and aging infrastructure</td><td>Deficient and poor water storage, distribution, supply, drainage, and wastewater treatment infrastructures</td></tr>
<tr><td>Poor governance</td><td>Weak legal accountability and institutional framework, limited stakeholder involvement and public participation, inadequate governance capabilities, ineffective coordination and cooperation, unequal power and unstable political regime, and restricted funding and budget</td></tr>
<tr><td>Climate change</td><td>Extreme weather events (high temperature, abnormal precipitation, sea level rise, floods, droughts, etc.)</td></tr>
</table>

It is noteworthy that these difficulties and challenges are assessed as current top global risks and continue to drive water availability and quality now in the future. Thus, accessible and high-quality freshwater will be still a limited and highly variable resource in space and time. In fact, according to OECD (2012, 2018a) and Vo et al. (2017), it is projected that 40% of the world's population currently lives in water-stressed river basins, and that water demand will rise by 55% by 2050. In terms of groundwater, over-abstraction and contamination of aquifers worldwide is also posing significant damages to food security, the health of ecosystems and safe drinking water supply. In 2050, 240 million people are expected to remain without access to clean water, and 1.4 billion without access to basic sanitation, despite global efforts to tackle this shortage. In addition, economic risks and financial burdens are also highly potential in the future since a significant investment is also required to renew and upgrade infrastructures, estimated at USD 6.7 trillion by 2050 for water supply and sanitation and wastewater treatment, and including a wider range of water-related infrastructure that could triple that cost by 2030 (OECD, 2015, 2018a). Therefore, the achievement of comprehensive IWRM as well as SDGs especially in developing areas is really a challenging task and it will require these challenges to be addressed (OECD, 2018a; Downing, 2012; Benson et al., 2020; Li et al., 2021).It is acknowledged that although the implementation of IWRM is a complex process due to its coordination with other diverse natural resources, its role is vital for sustainable development in many developing countries, of which Vietnam and its developing urban centers are not an exception. As defined by the GWP (2017), IWRM is understood as "a process which promotes the coordinated development and management of water, land and related resources to maximize economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems". Basically, the IWRM process uses nexus approach (linkage between water-land-climate-agriculture-industry) in a more coordinated manner in order to cater socio-economic development in more sustainable way (GWP and INBO, 2009; Katusiime and Schütt, 2020). In addition, this process also facilitates science-policy integration by translating these scientific results into appropriate policy actions and hence effectively managing water resources in the city (Katyaini and Barua, 2016). This interface is a social process linking scientists and other actors in policy process and allowing for exchanges, co-evolution, and joint construction of knowledge with the aim of enriching decision-making (Wesselink et al., 2013; Ramachandran et al. 2014; Katyaini and Barua, 2016). According to Hecker et al. (2018) and Roque et al. (2022), different transdisciplinary scientific approaches like citizen science, community-based participatory research, participatory mapping, participatory modeling, and projecting plausible future scenarios are being used in different combination with aim of empowering different beneficiaries and stakeholders, increasing knowledge exchange benefits and uptake of results, and hence improving decision-making in the implementation process of IWRM.

To effectively implement the process of IWRM, addressing poor governance should be one of the primary priorities. In fact, according to OECD (2015) and Di Vaio et al. (2021), in an effective and sustainable IWRM process, governance plays a crucial role. Otsuka (2019b) also stated that to put IWRM into practice effectively, good WG has to be successfully fulfilled since failure in this area impedes comprehensive IWRM implementation. As previously mentioned, since IWRM is a process of promoting the coordinated development and management of water, land, and related resources; and WG refers to the political, social, economic and administrative systems in place that influence water's use and management (Chan et al., 2016). In addition, many scientific studies have also shown that water insecurity and crises are oftentimes rooted in governance crises (OECD, 2011, 2018a; Chan et al., 2016), and that improving WG is widely regarded as the key to solving these negative problems particularly in developing countries (Rogers and Hall, 2003; Gopalakrishnan et al., 2004; Kashyap, 2004; Saleth and Dinar, 2005; Hoekstra and Chapagain, 2007; Rijsberman and Zwane, 2008; Briscoe, 2009; Biswas and Tortajada, 2010; Araral and Yu, 2012, 2013; Araral and Wang, 2013; Araral and Ratra, 2016). Therefore, to address effectively interrelated issues of securing access to sustainable sources of safe water for the world's populations, scholars and practitioners have suggested fostering improved modes of WG that significantly support the implementation of IWRM (Chan et al., 2016; Jiménez et al., 2020).

Moreover, it is also noteworthy that due to its sectorial cross-cutting nature, IWRM including an effective WG regime has the potential to support the achievement of SDGs, not only SDG 6 but also other non-water related SDGs, by moving beyond its current water centric focus to recognize the importance of water resources to wider sustainable development (Pires et al., 2017; Guppy et al., 2019; Benson et al., 2020). According to Nilsson (2016); Guppy et al. (2019); UN (2019); Benson et al. (2020); Fonseca et al. (2020); ISC (2021); and Li et al. (2021); although IWRM is considered the key to many the SDGs such as 1, 2, 5, 7, 10, 15, 16, and 17; but more precisely, it mostly focuses on SDGs 3, 6, 11, 12, 13, and 14 that are especially interactive. In fact, implementing IWRM at all levels as well as achieving SDG 6 (accessing safe drinking water and sanitation) will significantly contribute to promoting SDG 3 (ensuring healthy lives and promote well-being) (Nilsson, 2016; Fonseca et al., 2020; ISC, 2021), 11 (making cities inclusive, safe, resilient and sustainable) (Benson et al., 2020; Fonseca et al., 2020), 12 (ensuring sustainable consumption and production patterns) (UN, 2019; Fonseca et al., 2020), 13 (combating climate change and mitigate its impacts), and 14 (conserving and sustaining the river and marine resources) (Nilsson, 2016; Benson, et al. 2020; Stibbe and Prescott, 2020; ISC, 2021). Figure 1.1 shows the key SDGs as well as their main targets that are interactively related to the implementation process of IWRM.

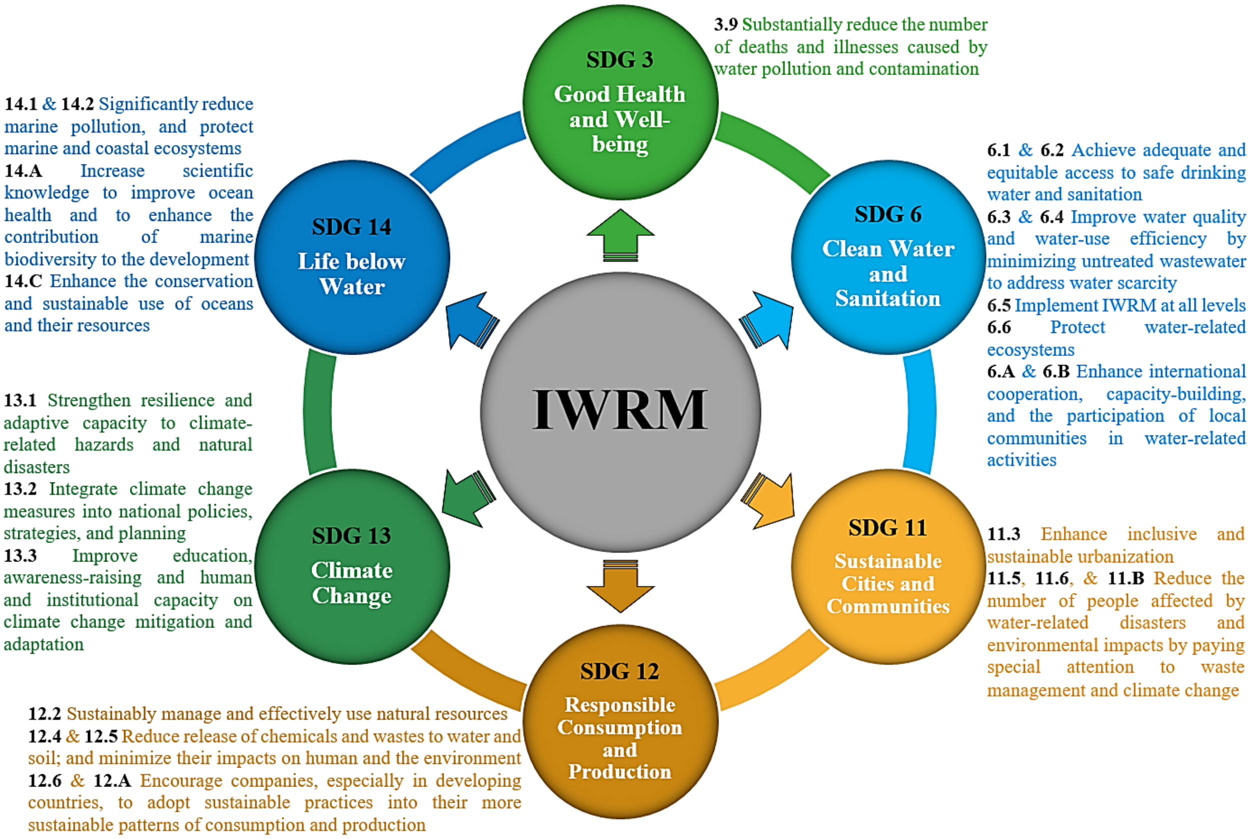


Figure 1.1 The key SDGs and their main targets interactively related to IWRM

Among Southeast Asia (SEA) countries in the Mekong and Red River Basins, Vietnam (Figure 1.2) is the lowest riparian and a rapidly developing one with many metropolitan municipalities (Duc et al., 2021). The country has a dense river network of which 2,360 rivers have a length of more than 10 km, and it is significantly susceptible to water resource changes (WEPA, 2012). As a responsible member country of the United Nations, Vietnam has been actively engaging in implementing the global SDGs, especially the goal 6. In the national context, 17 global SDGs have been nationalized into 115 Vietnam SDG targets since the period of 2015–2017 and are closely integrated into the national development policy and strategy systems (MOPI, 2018b). In these systems, the "Law on Water Resources" and "National Strategy on Water Resources" are two crucial guiding policies for implementing the IWRM process and especially achieving the global SDG 6 in Vietnam (MOPI, 2018b; WB, 2019). Regarding initially obtained achievements, the rate of households nationwide with access to clean water reached more than 93% in 2016. To 2017, 84.5% of urban residents were supplied clean water through concentrated water supply systems. It is also estimated that the target of 100% of households accessing clean water nationwide could be met by the early 2030s (MOPI, 2018b).

However, it is noteworthy that although the clean water demand and supply capacity in Vietnam have increased by nearly twofold compared to the last decade, the nation's current water infrastructure systems, especially wastewater treatment ones, have not kept pace with this mounting demand due to rapidly increased urban population, intensive urbanization, and mushrooming industrial parks. Specifically, in 2017, only 64.2% of industrial parks in Vietnam met solid waste and wastewater treatment standards, and 54% of hospitals had standard sewage treatment systems. Among 781 municipalities, only 44 have sewage treatment facilities up to the required standards. Noticeably, the ratio of collected and treated wastewater in the country was only 12% by the end of 2017, and the untreated remaining was directly discharged into water bodies (MOPI, 2018). As a result, water quality pollution in many river basins has not decreased and currently become one of the greatest challenges for many urban cities in Vietnam (Trung et al., 2019a; Duc et al., 2021). Especially, SWQ in these river basins is intensively contaminated with both organic and inorganic matters, and the main cause is untreated or inadequately treated wastewater discharged from industrial parks, domestic activities, urban services, agricultural practices, and other point and non-point pollution sources (MOPI, 2018a; Trung et al., 2019a; Duc et al., 2021). This negative situation is considered one of the existing shortcomings directly related to poor and inadequate WG in the most of Vietnamese urban centers. Furthermore, based on this situation, WB (2019) predicted that water stresses in Vietnam will be widespread by 2030, affecting 11 out of 16 national river basins mainly due to rapidly increasing water demand and quality degradation. Thus, it is recognized that the national target set for 2030 will be relatively ambitious to achieve without effectively boosting IWRM.

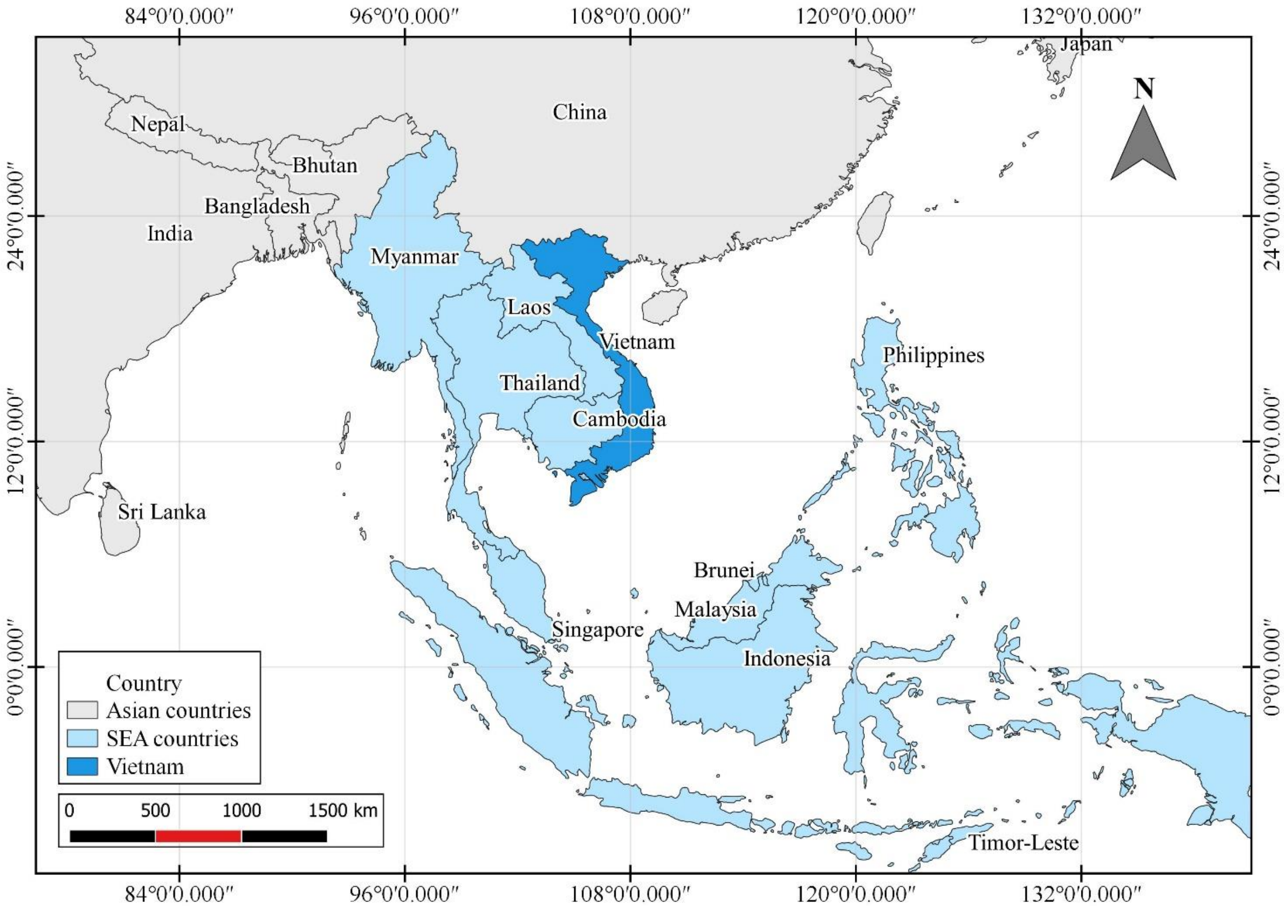


Figure 1.2 Map of Vietnam located in the SEA region

1.2 Objectives

Generally, as shown in the aforementioned facts, the water resources status in Vietnam, especially SWQ in developing urban cities, has been experiencing negative and irreversible changes in recent years and is predicted to be worse in the future. This is mainly due to rapid population growth, industrial urbanization, climate changes, and especially poor governance in this country. Therefore, to respond to this negative situation, inclusive and transdisciplinary research is one of the current matters of critical urgency for the country to boost its comprehensive IWRM including a robust WG that can help to completely resolve water-related problems, especially the increasingly complex pollution of SWQ. However, since the systems of the natural environment and anthropogenic sources are multivariate and complicated; IWRM, particularly focusing on SWQ management and WG, requires a fundamental understanding of spatiotemporal variations in the water characteristics (including hydro-morphological, chemical, and biological parameters (Phung et al., 2015)) as well as the broader aspects of water issues (including political, social, economic and administrative factors). Moreover, to design a robust and comprehensive water quality management plan, there is a requirement for both current water quality conditions and also possible future scenarios. The formulation of water quality management strategies requires an interdisciplinary analysis of various potential causes of water quality degradation and poor WG as well as corresponding solutions (Kannel et al., 2007; Mishra et al., 2017; Li et al., 2021).

1.2.1. General Objectives

Based on these complex knowledge requirements as well as an urgent need for both addressing the current and future SWQ pollution thoroughly, assessing the current IWRM inclusively, and proposing appropriate solutions for sustainable water resource management (WRM) at a later stage in Vietnam in general and its developing urban centers in particular, this research including three main studies has selected one of the most developing cities in this country, namely Can Tho, as the key study area and focused on the following general research objectives: (i) to comprehensively evaluate both the past, current, and future SWQ statuses in the massive river network of Can Tho City under the context of rapid land-use and climate changes; (ii) to systematically review the current status of IWRM focusing on WG in the Asian developing regions including Vietnam; and hence (iii) to propose timely and appropriate measures and recommendations to improve SWQ management, WG, as well as IWRM in this country and its developing Can Tho City.

1.2.2. Specific Objectives

The specific key objectives of this research are as follows:

- To evaluate the past and current status of SWQ in Can Tho City by analyzing the spatiotemporal variation and classification of SWQ in various zones of study area from 2013 to 2019;
- To trace the key drivers of such variation and classification and provide scientific evidence-based information in support of estimating and assessing the future condition of SWQ in the city;
- To estimate the future status of SWQ and evaluate the city's WG policies, specifically the effectiveness of currently applied and proposed countermeasures for the 2030 SWQ management in the city, based on analyzing SWQ condition in four different future scenarios of development and mitigation;

- To analyze, assess, and reflect how WG is conceptualized, interested, performed, evolved, and challenged in the Asian developing countries including Vietnam by systematically reviewing both the Asian and Vietnamese WG systems in the period of 2000–2020;
- To propose (i) potentially general and specific countermeasures for addressing both the current and future SWQ pollution in the city, (ii) an optimally analytical framework for WG in Vietnam and its developing Can Tho City, and (iii) key guiding recommendations to respond to potential governance-related challenges during the implementation process of this suggested framework towards achieving a more effective WG as well as a more robust and comprehensive IWRM in Can Tho City.

Chapter 2

Study Area and Methodology

2.1 Study Area

In this research, Can Tho City is considered the main study area. In Vietnam, this city (9°55'08"N–10°19'38"N and 105°13'38"E–105°50'35"E) is the main regional urban center located in the middle of the Vietnamese Mekong Delta (VMD) (CTCPC, 2020) (Figure 2.1). Comprising five urban and four rural districts, it covers nearly 1,440 km^2 (around 80% of which for agricultural production) (CTCSO, 2020a; DONRE, 2020b). Noticeably, all urban districts (Cai Rang, Ninh Kieu, Binh Thuy, O Mon and Thot Not) are located along the Hau River in the city's northeast. This river is one of two Mekong River's main tributaries flowing through the Vietnamese territory (Figure 3.1)and the key source of water supply for the city (Duc et al., 2021). Considered the fourth most populous city in Vietnam (nearly 1.24 million in 2019) with approximately 66% living in urban and peri-urban areas, its population is projected to be 2.1 million by 2030 (UN DESA, 2019; VNGSO, 2020a; Duc et al., 2021).

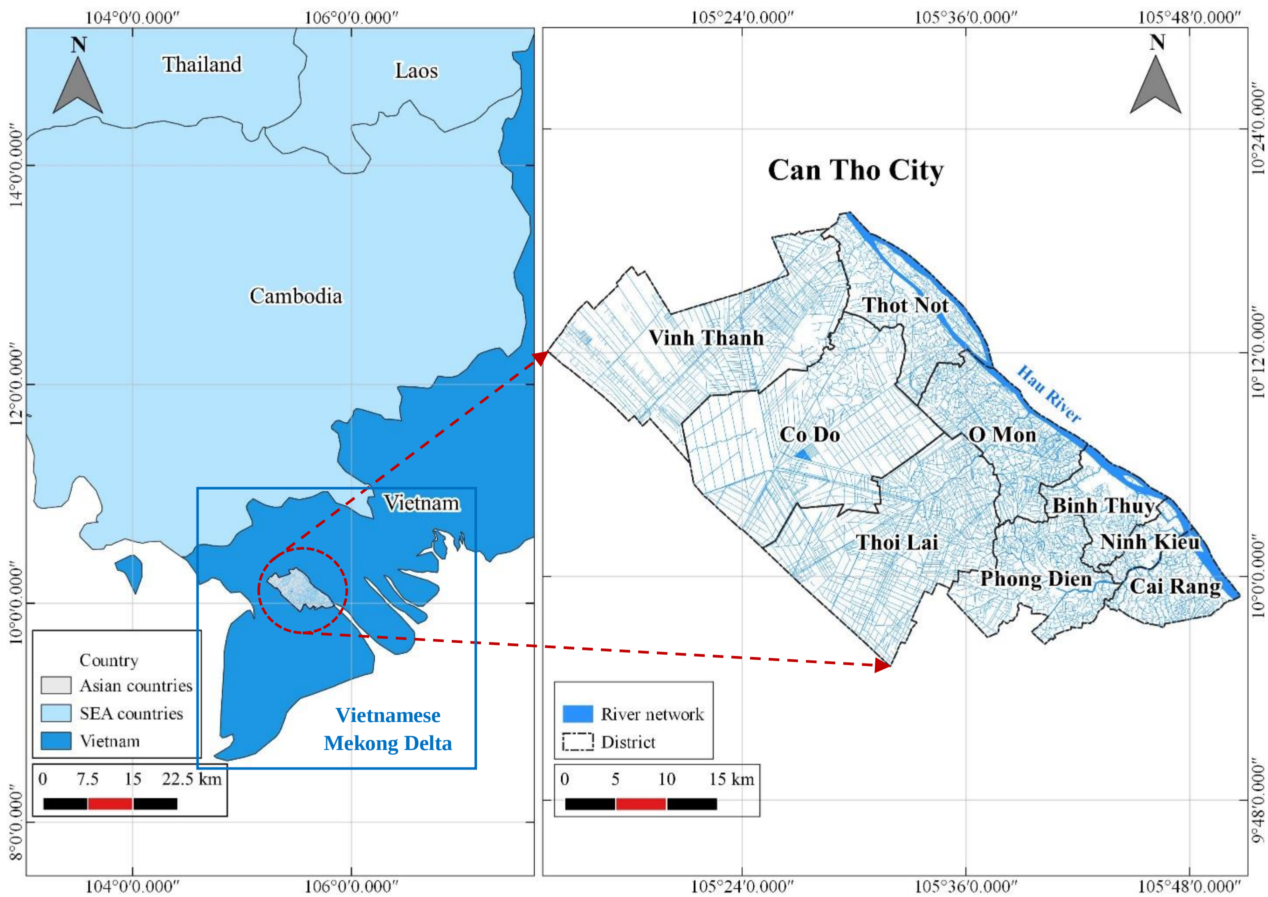


Figure 2.1 Can Tho City with its river network in the VMD

In the middle of VMD, Can Tho City is characterized by flat terrain with an elevation of 1 m above seawater level. The city lies in a tropical and monsoonal climate with two distinctive seasons, i.e., wet (May to November) and dry (December to April) (Figure 2.2); causing the seasonal SWQ variation in the city. Its average annual humidity and rainfall are 83% and 1,650 mm (90% of which is being received in the wet season), respectively. Remarkably, the city has a dense waterway network of more than 3,405 km (Konings, 2012). In the flooding season from September to October, the average water flow in the Hau River reaches 15,000 – 16,000 m^3/s, leading to serious inundation in the city; while this flow drops to 1,600 – 1,700 m^3/s during the dry season from March to April, causing clean water shortages (Neumann et al., 2011; Minh et al., 2020). With the enormous river network, water is key to everyday life and underpins the city's diverse economic sectors, including industry, agriculture, aquaculture, transportation, services, and tourism (Konings, 2012; Nguyen et al., 2016).

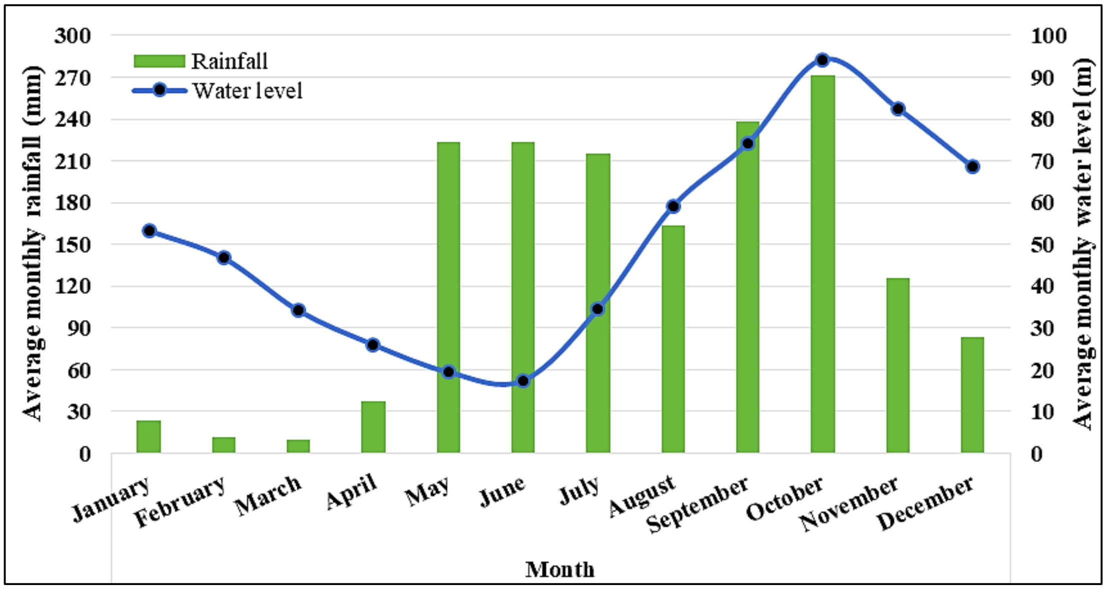


Figure 2.2 The city's average monthly rainfall and Hau River water level for the 2013–2019 period

Nationally, Can Tho City is a major dynamically developing economic center (Konings, 2012; Duc et al., 2021). This city is making great efforts to achieve its SDGs, and the City Resilience Strategy for 2030 has been planned in 2016 describing these efforts. Based on the city's SDG targets, this strategy has clearly identified future opportunities and challenges in the categories of health and well-being, economy and society, infrastructure and environment, and governance. Moreover, specific immediate and long-term actions have been planned to support the development of Can Tho as a green, sustainable, and proactive river city (CTCPC, 2019a). However, in the recent past, the city has witnessed rapid population and unplanned industrial urbanization accompanied by irreversible land-use changes, leading to multiple water-related stresses considered threats to achieving the city's SDGs, especially the goal 6 (Duc et al., 2021). These main stresses include recurring seasonal flooding (mainly by high rainfall and tidal surges), riverbank erosion, extreme heat waves and droughts, and especially severe water pollution. Currently, they are still growing in severity and unpredictability and have increasingly placed enormous pressure on the city's river network (CTCPC, 2019a; Trung et al., 2019a, 2019b; Duc et al., 2021). Moreover, the situation has worsened due to the low levels of local residents' awareness and water consumption behavior, inadequate and aging water infrastructure, and especially absence of effective WG (Quan et al., 2013; Trung et al., 2019a, 2019b). Consequently, the city's total length of the river and canal system has been cut dramatically during the past 20 years, especially in the inner city area (e.g., O Mon, Ninh Kieu, and Cai Rang districts lost more than 67, 94, and 116 km, respectively). In addition, the total green area in the city also decreased by 22,845 ha from 1990 to 2018 mainly due to the expansion of urban residential and industrial areas (CTCPC, 2019a). These losses have led to a significant decline in the natural water storage and drainage capacity of the city.

Regarding SWQ, although the rapid population growth and industrial urbanization have caused an increase in wastewater, the city's investment for the wastewater management infrastructure does not keep pace with the increase in demand (Long and Cheng, 2018; Trung et al., 2019a). Moreover, the city's current WRM is limited. For instance, currently, collecting wastewater from both non-point and point sources of pollution is significantly restricted. Noticeably, as prescribed in the current environmental policies, domestic wastewater in the city can be freely released into river bodies without treatment. Thus, a huge amount of untreated wastewater is directly discharged into the city's river network (Duc et al., 2021), causing contamination with various physical, chemical, and biological pollutants and exceeding the desirable Class-A rating of the National Technical Regulation on Surface Water Quality (NTRSWQ) (CTCPC, 2019b; DOC, 2019; Trung et al., 2019a). In addition, although SWQ has been experiencing negative changes in recent years, a comprehensive evaluation of SWQ variations in the city is still rare (Duc et al., 2021). Considering these specific conditions, to become a green, sustainable, proactive, and integrated river city as oriented in the master plans as well as to achieve SDG 6, the city's IWRM, particularly focusing on water quality management and governance, needs to be studied, reviewed, and reformed comprehensively.

2.2 Methodology

As mentioned earlier, the research includes three main studies applying various research objectives mainly aiming at analyzing and evaluating SWQ management in Can Tho City and WG in the Asian developing countries including Vietnam, and hence providing an overview of WG as well as IWRM in this country in general and Can Tho City in particular. Based on these objectives, the research focuses on analyzing and assessing the past and current SWQ conditions, quantifying and simulating the future SWQ status, and reviewing WG-related issues that are often complexly influenced by multiple factors in developing regions. Therefore, the methods and database applied in the research are significantly diverse. Specifically, regarding the research's structure, it is organized into six chapters; of which Chapters 3, 4, and 5 have respectively shown research findings of three main studies performed in the research, and Chapter 6 presents the proposed solutions as well as relevant recommendations and suggestions. The studies in these chapters had applied various approaches, techniques, and tools, ranging from data-driven analytical approaches, multivariate statistical techniques, weighted arithmetic calculating tools, and computer-based mathematical models to systematic literature reviews. Their applications depend on different requirements mainly according to data availability, calculation time, and intended output variables. Thus, they have been selected and applied based on carefully reviewing literature as well as considering the city's actual conditions. These main applied methods and the target objectives are shown in Figure 2.3 and briefly presented as follows. More detailed information on their application is thoroughly provided in specific research contents of the chapters.

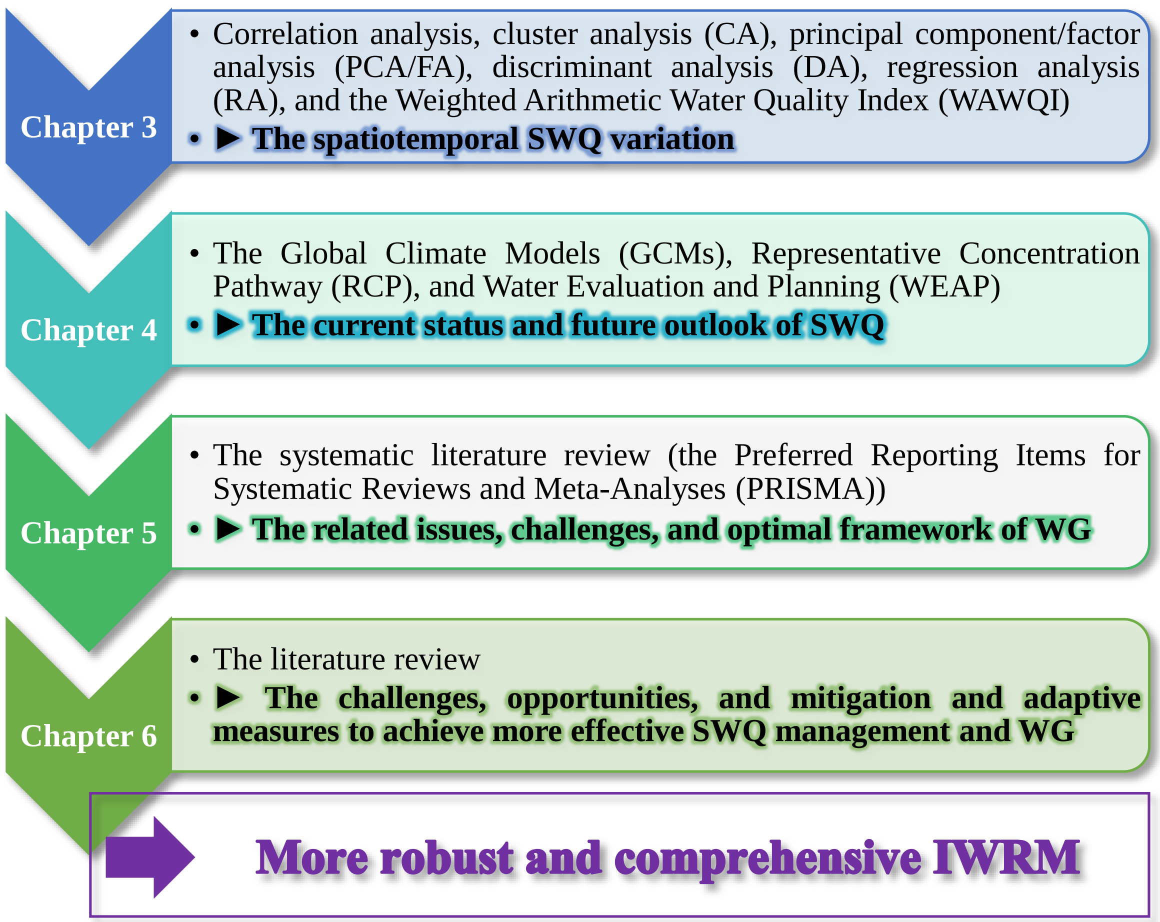


Figure 2.3 Flowchart of the main research methods applied in the research

In Chapter 3, the study was begun with multivariate statistical techniques including correlation analysis, CA, PCA/FA, and DA to explore the spatial SWQ variation in Can Tho City; then the WAWQI estimation and regression analysis (RA) were applied to evaluate the temporal SWQ variation and identify key drivers responsible for these variations in the city.

In Chapter 4, the study applied the Global Climate Models (GCMs), Representative Concentration Pathway (RCP), and a literature review on the city's master plans to build different future scenarios first; and then the WEAP – a computer-based mathematical model – was performed to simulate rainfall-runoff and water quality variables in these scenarios to predict the city's future SWQ status as well as assess the effectiveness of currently applied and proposed countermeasures.

In Chapter 5, the study reflected on related issues and challenges, bridged knowledge gaps, and provided a more comprehensive understanding of WG in the Asian developing countries including Vietnam; and hence proposed an optimal framework for WG in Vietnam as well as Can Tho City by performing a systematic literature review following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines.

In Chapter 6, based on the findings obtained from Chapter 3, 4, and 5, a literature review was performed to overall evaluate the current status of WG, explore opportunities, and propose mitigation and adaptive measures for dealing with the SWQ pollution in Can Tho City as well as key guiding recommendations towards more robust and comprehensive WG as well as IWRM in this city in particular and Vietnam in general.

Chapter 3

Hydrochemical Indices as a Proxy for Evaluating Land-Use Impacts on SWQ in Can Tho City, Vietnam

3.1 Introduction

Throughout history, human societies have witnessed the intrinsic link between their sustainable and inclusive development and water resources (Hermanowicz, 2008; Guppy et al., 2019). However, finite freshwater resources facing different pressures like water pollution, over-extraction led shortage, especially in rapidly developing nations including Vietnam due to land use land cover (LULC) changes, population growth, industrial urbanization, climate change, and poor governance (Hoekstra et al., 2018; Colloff et al., 2019; Kumar et al., 2019b; Li et al., 2021). With a rapidly increasing water scarcity around the globe, United Nations SDG 6 calls for universal access to safe water for everyone (UN, 2015; Benson et al., 2020). In this avenue, assessing water quality variations and proposing effective and sustainable IWRM solutions has been a vital policy priority to improve future water quality. As the aforementioned characteristics of Can Tho City, this dynamically developing economic center is experiencing water stresses driven by many complex and rapid changes, leading to the increasing serious SWQ pollution that is currently considered one of the most complicated WG-related challenges in the city (Trung et al., 2019; Duc et al., 2021). Despite this critical situation, no comprehensive evaluation of SWQ in the city is yet available. Therefore, a comprehensive analysis and report of spatiotemporal variation in SWQ in the city is essential for decision-makers and planners developing robust IWRM plans and will support progress toward achieving several SDGs.

In recent years, sophisticated data-driven analytical approaches, fuzzy theory, and hydrological models have been widely adopted as reliable tools to improve complex water quality assessments in rapidly developing cities like Can Tho. Selection of the optimal tool for water quality assessment depends on data availability, calculation time, intended output variables, and typical water quality characteristics in case study areas (Mishra et al., 2017; Duc et al., 2021). Some tools that are commonly used by surface water researchers around the world include the Fuzzy Analytic Hierarchy Process (Fuzzy-AHP), Storm Water Management Model (SWMM), System Dynamic Model

(VENSIM), River Basin Simulation Model (RIBASIM), WEAP, Water Balance Model (WBalMo), Soil and Water Assessment Tool (SWAT), Hydrologic Engineering Center River Analysis System (HEC-RAS), and MIKE (Kumar et al., 2017, 2019a; Mishra et al., 2017; Minh et al., 2019a; Angello et al., 2020; Duc et al., 2021). However, most of these tools are data intensive and relatively complex to operate, which limits their usability for the overall evaluation of SWQ in data-deficient regions (Kumar et al., 2017, 2019a; Duc et al., 2021).

To address these problems, multivariate statistical techniques such as correlation analysis, CA, PCA/FA, DA, RA, and the use of water quality indexes (WQIs) have been extensively applied in recent years to improve water quality assessments in more meaningful ways. These tools are significantly useful and reliable for modeling and interpretation of large and complex datasets of water quality to clarify their variation and identify hydrological processes responsible for sophisticated water quality changes (Kumar et al., 2010; Avtar et al., 2011; Duan et al., 2016). Indeed, based on previous studies, the application of these tools has been proved to be helpful to gain better insight into the SWQ management and deduce the processes governing water quality evolution at spatiotemporal scale and ecological status of the studied systems. More specifically, for Vietnam, previous studies (Phung et al., 2015; Ngoc et al., 2017; Minh et al., 2019b, 2020; Duc et al., 2021) have utilized CA, PCA/FA, and DA to evaluate partly variations in water quality in Can Tho, Vung Tau, and An Giang Cities. For other countries, water quality changes in Khambhat (India), Limpopo (South Africa), and Sylhet Cities (Bangladesh) have been also assessed respectively by Kumar et al. (2019b), Molekoa et al. (2019), and Kadir et al. (2022) using similar statistical techniques. However, these previous studies also have some research limitations. None of them have evaluated jointly variation in water quality over a long period of time, identified the correlated relationships among key drivers (e.g., land-use and policy changes) and variation in water quality, assessed overall water quality using integrated mathematical tools (e.g., WQIs and integrated pollution indexes (IPIs)), or proposed specific potential solutions for improving water quality in the studied areas.

It is also noteworthy that although the cities included in the above-mentioned studies and Can Tho have common characteristics such as a tropical and monsoonal climate (characterized in both Can Tho, Vung Tau, An Giang, Khambhat, and Sylhet), abundant water resources (Can Tho, An Giang, and Sylhet), poor water infrastructures and governance (all cities), and rapid population growth and urbanization (Can Tho, Vung Tau, Khambhat, and Sylhet); these cities are still distinguished from Can Tho by water quality features. For instance, only agricultural activity is mainly responsible for water quality variations in An Giang and Khambhat (Kumar et al., 2019b; Minh et al., 2019b, 2020), urbanization is the key driver merely controlling water quality in Sylhet (Kadir et al., 2022), mining activity is the single factor to water quality degradation in Limpopo (Molekoa et al., 2019), and only industrialization and saline intrusion are responsible for water pollution in Vung Tau (Ngoc et al., 2017); while a more complicated situation can be found in Can Tho, where water quality is cumulatively influenced by diverse and complex factors including not only population growth, industrial urbanization, agriculture, climate change, but also water use-related activities in the upper regions (CTCPC, 2019b; DONRE, 2020a). A study of Duc et al. (2021) assessing the water quality status of a part of Can Tho City's river network (only SWQ variation along the Hau River) has also reflected this complicated situation.

Based on these knowledge gaps as well as the current status of SWQ and progress towards achieving more comprehensive IWRM and the SDGs in Can Tho City, the study presented in this chapter comprehensively evaluates the spatiotemporal SWQ variation in the data-scarce river network of Can Tho City during rapid land-use changes from 2013 to 2019 using an integrated approach of multivariate statistical techniques and WAWQI estimation. The specific key objectives of this study are as follows: (i) to evaluate the spatiotemporal variation and classifications of SWQ in the city's various zones, and (ii) to trace the key drivers of such variation and classification. Noticeably, this study provides useful baseline information for local policy planners and technical staff to enhance their capacity and understanding of applying multivariate analytical techniques for monitoring and evaluating water quality at their respective watershed levels. The obtained results will also aid policymakers in designing management policies in a timely manner to achieve the SDGs, particularly SDGs 6 (clean water and sanitation), 3 (human well-being), 11 (sustainable cities), 12 (effective natural resource consumption), 13 (climate change mitigation), and 14 (river ecosystem conservation), allowing those policymakers to be actively involved in helping their regions reach these global targets. Furthermore, this study's findings will be considered the scientific evidence-based information in support of implementing the research targets of the following studies, towards achieving a more robust and comprehensive IWRM in the city.

3.2 Study Area

As presented in Chapter 2, Can Tho City consists of nine districts covering the total of approximately 1,440 km^2 and is the home of more than 1.23 million people in 2019 (CTCSO, 2020a; DONRE, 2020b). Located in the VMD, the city is characterized by a tropical and monsoonal climate (including two distinctive wet and dry seasons) and a dense river network (including a nearly 60-km main tributary of the Mekong River, namely the Hau River) (Konings, 2012). Remarkably, from 2013, the city has invested and set up a more relatively adequate SWQ monitoring network with the total of 73 sampling sites located at key points throughout this dense river network (DONRE, 2020a). Figure 3.1 and Table 3.1 shows the detailed location, area, population, and SWQ monitoring network characteristics of nine districts in the city.

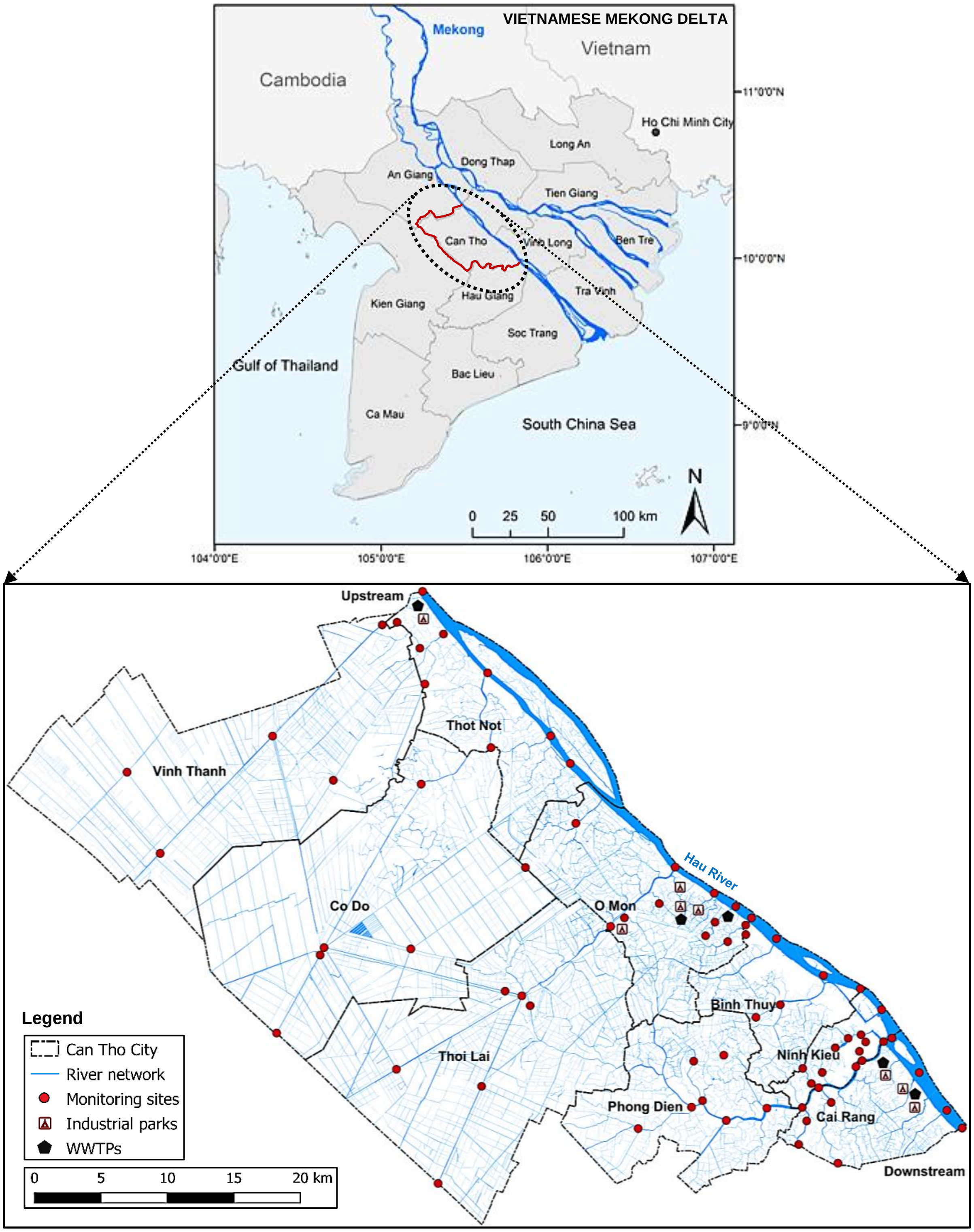


Figure 3.1 Can Tho City with its river network, 73 SWQ monitoring sites, industrial parks, and locations of industrial and domestic WWTPs

Table 3.1 The area, 2019 population, and SWQ monitoring network characteristics of nine districts in Can Tho City

No.	District		Area (km^2)	Population (people)	Rate of the total pop. (%)	Rate of urban/ rural residence (%)	SWQ monitoring network	
	Name	Type					Number of sampling sites	Code
1	Thot Not	Urban	121	155,360	12.58	65.75	10	TN1-TN10
2	O Mon		132	128,677	10.42		9	OM1-OM9
3	Binh Thuy		71	142,164	11.51		9	BT1-BT9
4	Ninh Kieu		29	280,494	22.71		13	NK1-NK13
5	Cai Rang		67	105,393	8.53		9	CR1-CR9
6	Vinh Thanh	Rural	307	98,399	7.97	34.25	5	VT1-VT5
7	Co Do		320	116,576	9.44		5	CD1-CD5
8	Thoi Lai		267	109,684	8.88		6	TL1-TL6
9	Phong Dien		125	98,424	7.96		7	PD1-PD7
Total	**9 (urban: 5, rural: 4)**		**1,439**	**1,235,171**	**100**	**100**	**73**	**73**

Despite its water abundance, the city recently faces clean water shortages in the dry season (Neumann et al., 2011; Duc et al., 2021). Besides, the significant growth of point pollution sources has increasingly become a matter of concern for SWQ management for the city. On the other hand, only four industrial (the total daily treatment capacity: 14,500 m^3) and one domestic wastewater treatment plants (WWTPs) (30.000 m^3) are currently functional in the city (CTCPC, 2019b; Duc et al., 2021). As shown in Figure 3.1, these five plants are located near the city's eight largest industrial parks and crowded residential zones in the most industrialized (Thot Not, O Mon, and Cai Rang) and populous districts (Ninh Kieu and Cai Rang) to mainly treat wastewater discharged from these industrial parks and nearly 62.800 out of 359.400 households of the city (CTCPC, 2019b). However, these WWTPs are able to cater only 20% and 60% of total domestic and industrial wastewater generated in the city (DOC, 2019; CTCPC, 2019b; CTCSO, 2020a). And this situation has become one of the city's most concerning WG problems in recent years. Noticeably, the local policies and master plans are currently focusing on sustaining rapid industrial urbanization in the city; and especially, since 2018, they have strongly emphasized the city's top priorities on improving the current SWQ of Class-B to achieve the future ambient SWQ of Class-A prescribed by the NTRSWQ (CTCPC, 2016, 2019a; Long and Cheng, 2018).

3.3 Methodology

3.3.1 Monitored Parameters and Analytical Methods

In all, 14 SWQ parameters (Table 3.2) were recorded on a monthly basis for the period of 2013–2019 at 73 sampling sites by the Department of Natural Resources and Environment (DONRE) (DONRE, 2020a). At each sampling site, the collection of water samples was implemented monthly on the day of the lowest tide. On this day, two samples were respectively collected at the times of the highest and lowest water levels, then brought to the laboratory in ice chests, stored below 4˚C, and analyzed for SWQ parameters (DONRE, 2020a). First, to identify key spatiotemporal characteristics, correlations, similarities, and dissimilarities among these parameters, the Statistical Package for the Social Sciences (SPSS) was applied for descriptive and correlation analyses, CA, PCA/FA, and DA. Then, annual WAWQI values were estimated and compared with the national and World Health Organization (WHO) guidelines to classify and assess spatiotemporal variation in SWQ in the city. Finally, the correlations between these WAWQI values and annual land-use changes were analyzed using RA to trace the key drivers responsible for the city's SWQ changes. The research methodology is briefly illustrated in Figure 3.2.

Table 3.2 The SWQ parameters monitored for the period of 2013–2019 in the city's river network

No.	Parameter	Abbreviation	Unit
1	Potential of hydrogen	pH	-
2	Biochemical oxygen demand by 5-day test	BOD_5 (20^oC)	mg/l
3	Chemical oxygen demand	COD	mg/l
4	Dissolved oxygen	DO	mg/l
5	Total coliform	TC	CFU/100 ml
6	Turbidity	Turbidity	NTU
7	Total suspended solids	TSS	mg/l
8	Fluoride	F^-	mg/l
9	Nitrite	NO_2^-	mg/l
10	Nitrate	NO_3^-	mg/l
11	Phosphate	PO_4^{3-}	mg/l
12	Ammonium	NH_4^+	mg/l
13	Chromium	Cr_6^+ [Cr(VI)]	mg/l

14	Iron	Fe	mg/l
Note: CFU - Colony forming units; NTU - Nephelometric turbidity units			

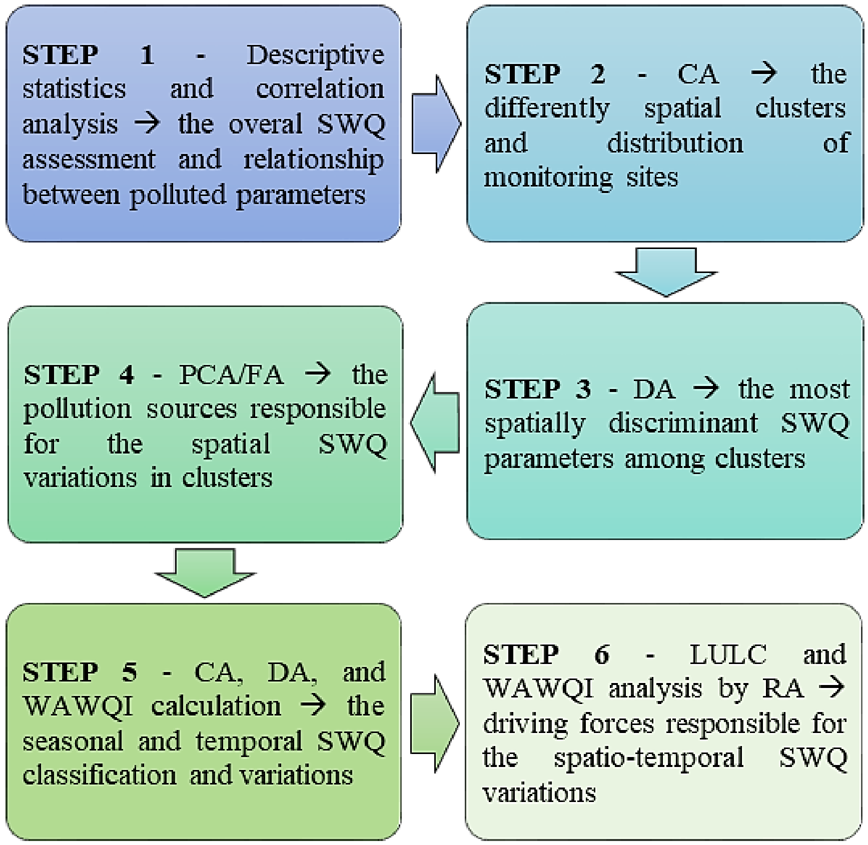


Figure 3.2 Flowchart of the research methodology

3.3.2 Statistical Analysis

3.3.2.1 Descriptive Statistics and Correlation Analysis

The descriptive statistics of 14 SWQ parameters were determined to assess the overall SWQ of the city. The mean parameter values for each season and the whole year (2013–2019) were calculated for comparison with each other and with the permissible limit of Class-A (more specifically, Class-A1 – the highest standard for residential use (Table 3.4) – was applied for this comparison), as well as to identify important pollution parameters for further analysis. These selected parameters were subjected to correlation analysis using Spearman's rank coefficient. This coefficient is based on the ranking of the data but not their absolute value to explore significant relationships between their concentrations and potential sources.

3.3.2.2 Cluster Analysis

Can Tho is a large city with diverse characteristics of water, land use, and climate. Therefore, CA – the task of grouping a set of objects into clusters based on their similar characteristics (Shrestha and Kazama, 2007; Minh et al., 2019) – was utilized to examine the spatial and seasonal variation in the city's SWQ. Employing Ward's method of agglomerative hierarchical clustering and squared Euclidean distance, comparisons among 73 sampling sites and 12 months were conducted based on the similarity of their SWQ characteristics (Otto, 1998; Singh, et al. 2004). The most common approach starts at each site with the cluster that is most similar to a predetermined selection criterion. Then, the sites are joined together in a separate cluster until only one cluster remains (Singh et al., 2005; Shrestha and Kazama, 2007; Minh et al., 2019). In this study, this process was separately conducted for spatial CA and seasonal CA. Each site (for spatial CA) and month (for seasonal CA) was examined and combined to determine which group they belong to. Ward's method identifies clusters by measuring linkage distances between them, in which D_{link}/D_{max} represents the ratio of the linkage distance of the identified cluster to the maximal linkage distance (Simeonov et al., 2004; Duan et al., 2016). The optimal number of clusters is opted based on coefficient values in the agglomeration schedule. This schedule assists in identifying at what point two combined clusters are considered too different to form a homogeneous group, as evidenced by the first large rise in these coefficient values (Yim and Ramdeen, 2015).

3.3.2.3 Discriminant Analysis

To determine the optimal SWQ parameters for identifying the variation in spatial and seasonal clusters, DA was applied. The principle of DA is to determine whether clusters differ concerning the mean of a variable and then use that variable to predict membership (Singh et al., 2004; Qadir et al., 2008). In the process of DA, the stepwise method with Wilks' lambda mode for all sampling sites into different clusters was applied to constructs discriminant functions (DFs) (Duan et al., 2016; IBM, 2020; Minh et al., 2020). These sites and clusters were used as dependent variables, and the SWQ parameters were considered independent ones. The F test of Wilks' lambda identifies parameters that contribute significantly, i.e., increased F and decreased lambda value for a variable indicate an increase in the variable's contribution to the distinction between totals (Abdullah, 2019; IBM, 2020). In the stepwise forward mode, variables are input gradually, starting with the most significant improvement of fit until no changes occurred. In the stepwise reverse mode, variables are removed beginning with the smallest improvement of fit until significant changes occur (Abdullah, 2019; IBM, 2020; Minh et al., 2019b, 2020).

3.3.2.4 Principal Component/Factor Analyses

In CA and DA, only quantitative and qualitative results on the spatial SWQ variation were given. Thus, the PCA/FA technique was separately applied to spatial clusters to investigate their possible pollutant sources. PCA/FA is considered a dimensionality reduction technique to simplify the dataset and support the visualization by finding a set of principal components (PCs) (Jolliffe, 2002; Yidana et al., 2008; Minh et al., 2019b). PCA begins with a covariance matrix used to extract eigenvectors and eigenvalues (>1.0), with the highest values indicating the most significant PCs (Mazlum et al., 1999; Jolliffe, 2002; Avtar et al., 2011). PCs, which provide information about the most meaningful variables, are obtained by multiplying an eigenvector (which is a list of coefficients (loading or weighting)) with the original correlated variables. The information on the most meaningful variables are provided from these obtained PCs (Vega et al., 1998; Duan et al., 2016).

In the following step, FA gives factors' meaning by the transformation process using Varimax rotation. In this process, FA reduces the contributions of less-significant variables obtained from PCA, and new groups of variables known as factors (Fs) are generated (Zhang et al., 2011; Duan et al., 2016). The degree of association between each variable and each factor is given by its loading on that factor. The largest loading, either positive or negative, suggests the meaning of the dimensions (Lawrence and Upchurch, 1982). The most significant variables in the factors represented by high loadings (> 0.5) are considered for the interpretation and evaluation. Absolute loading values > 0.75, 0.75 – 0.50, and 0.50 – 0.30 are designated 'strong', 'moderate', and 'weak' respectively (Liu et al., 2003; Avtar et al., 2011; Minh et al., 2020).

3.3.2.5 Weighted Arithmetic Water Quality Index

WAWQI offers a simple and reliable tool for measuring, evaluating, classifying, and managing overall water quality (Horton, 1965; Kizar, 2018; Minh et al., 2020). This tool combines physicochemical and biological parameters into single values that can be compared to the appropriate regulatory standards (Kizar, 2018; Minh et al., 2020). Therefore, water suitability for domestic or any specific purpose can be represented in terms of WAWQI (Kachroud et al., 2019; Nihalani and Meeruty, 2020). Annual WAWQI values were calculated by aggregating all 14 SWQ parameters.

These index values were compared to the allowable standards for drinking water as recommended by the National Guideline for the Calculation of the Water Quality Index (NGCWQI) (MONRE, 2019) and WHO (WHO, 2017) guidelines to explore spatiotemporal variation in SWQ in the city. Water quality status was evaluated as summarized in Table 3.3. The WAWQI was estimated using the Horton method (Equation (1)) (Horton, 1965; Kachroud et al., 2019).

$$\mathrm{WAWQI_i} = \frac{\sum_{i=1}^{n} Q_i * W_i}{\sum_{i=1}^{n} W_i} \tag{1}$$

where Q_i is a quality rating of the n^{th} parameter, $Q_i = [(V_i - V_{di})/(S_i - V_{di})]*100$ in which V_i is the estimated value of the n^{th} parameter, V_{di} is the ideal value in pure water of the n^{th} parameter (V_{di} = 0, except pH = 7 and DO = 14.6 mg/L), S_i is the permissible limit of the n^{th} parameter, and W_i is the unit weight of n^{th} parameter (this value varies from 0 to 1 and its sum equals 1), defined as $W_i = K/S_i$ in which K is a proportionality constant, $K = 1/\sum_{i=1}^{n}(1/S_i)$.

Table 3.3 Water quality classification (with corresponding colors) for human consumption using the WAWQI values as recommended by the NGCWQI and WHO guidelines

WAWQI range	Water quality classification
0 – 25	Excellent
26 – 50	Good
51 – 75	Moderate
76 – 90	Bad
91 – 100	Very bad
Above 100	Unsuitable for drinking

To enhance the observation of SWQ variations, the spatiotemporal contour maps of WAWQI were generated using the inverse distance-weighted (IDW) interpolation technique to compute the contour profile from 73 sampling points. This technique is an algorithm widely used to spatially interpolate point data, estimating the values at locations other than the measured sample points. It works on the assumption that each measured point has a local influence that fades with distance, and the highest influences are always close to the point of observations (Kumar et al., 2019b).

3.3.2.6 Land-Use Changes

To quantify land-use changes during the research period, the annual maps and areas of land-use classes were collected from the city's DONRE and used as the primary input. Based on the collected dataset, five major land-use in the city classes were present, namely, water bodies, built-up land, perennial land, paddy fields, and fallow land (CTCSO, 2020b; DONRE, 2020b). Particularly, perennial land and paddy fields represent the agricultural area, and fallow land represents the dry land zone in the city. The annual areas of each land-use class and average WAWQI values were analyzed using RA with stepwise mode to determine their correlations and identify the key factors responsible for the city's spatiotemporal variation in SWQ. The coefficient of determination (R^2 ranging from 0 to 1) and significance test (P-value) were used to verify the applicability of RA (Udovicic et al., 2007; Sarstedt et al., 2017).

3.4 Results and Discussion

3.4.1 Overall Assessment of SWQ

A statistical summary of the huge SWQ dataset used in this study is provided in Table 3.4. As indicated, compared to the permissible limits of Class-A1, the annual mean levels of BOD, COD, DO, TC, turbidity, TSS, and PO_4^{3-} during the research period were unacceptable for residential use. Thus, these SWQ factors were considered the primary parameters and used for further analyses. In addition, NO_3^- was included because it sporadically exceeds the desirable concentration due to intensive agricultural activities (Minh et al., 2020) in the city (CTCSO, 2020a).

Table 3.4 Statistically seasonal and whole year summary of SWQ parameters' mean concentrations in the study area for the period of 2013–2019

No.	Parameter	Unit	Dry season				Wet season				Whole year				Permissible limits set by the NTRSWQ			
															A		B	
			Min.	Max.	Mean	SD	Min.	Max.	Mean	SD	Min.	Max.	Mean	SD	A1	A2	B1	B2
1	pH	-	7.13	7.34	**7.24**	0.04	6.99	7.47	**7.23**	0.06	7.10	7.38	**7.23**	0.04	6–8.5	6–8.5	5.5–9	5.5–9
2	BOD_5 (20°C)	mg/l	7.87	18.94	**10.40**	1.79	4.66	15.40	**7.14**	1.60	5.85	18.38	**8.60**	2.09	4	6	15	25
3	COD	mg/l	14.85	30.16	**18.61**	2.59	5.78	22.11	**10.16**	2.36	11.32	25.27	**14.12**	2.31	10	15	30	50
4	DO	mg/l	2.23	3.64	**3.21**	0.27	4.23	5.92	**5.47**	0.29	3.27	5.53	**4.50**	0.52	≥ 6	≥ 5	≥ 4	≥ 2
5	TC	CFU/ 100 ml	2,581	8,432	**3,960**	809	1,047	5,554	**2,501**	875	1,579	8,005	**3,192**	935	2,500	5,000	7,500	10,000
6	Turbidity	NTU	20.19	48.58	**30.89**	6.75	39.52	70.07	**56.20**	6.15	25.85	60.17	**39.22**	7.82	5	5	-	-
7	TSS	mg/l	24.96	76.80	**38.11**	8.12	50.61	83.70	**60.87**	6.53	37.21	69.99	**50.40**	8.40	20	30	50	100
8	F^-	mg/l	0.04	0.59	**0.14**	0.08	0.02	0.25	**0.10**	0.04	0.04	0.34	**0.12**	0.05	1	1.5	1.5	2
9	NO_2^-	mg/l	0.01	0.04	**0.02**	0.01	0.01	0.07	**0.03**	0.02	0.02	0.04	**0.03**	0.005	0.05	0.05	0.05	0.05
10	NO_3^-	mg/l	0.73	1.57	**1.05**	0.20	1.04	2.02	**1.41**	0.23	0.92	1.83	**1.25**	0.23	2	5	10	15
11	PO_4^{3-}	mg/l	0.028	0.371	**0.086**	0.056	0.025	0.619	**0.130**	0.089	0.06	0.15	**0.11**	0.02	0.1	0.2	0.3	0.5
12	NH_4^+	mg/l	0.10	0.37	**0.20**	0.06	0.10	0.68	**0.23**	0.08	0.11	0.67	**0.22**	0.10	0.3	0.3	0.9	0.9
13	Cr_6^+	mg/l	0.0030	0.0131	**0.0062**	0.0021	0.0001	0.0170	**0.0039**	0.0031	0.0014	0.0115	**0.0050**	0.0020	0.01	0.02	0.04	0.05
14	Fe	mg/l	0.21	0.81	**0.34**	0.09	0.17	0.56	**0.29**	0.07	0.20	0.63	**0.32**	0.07	0.5	1	1.5	2

Notes: Min. - Minimum; Max. - Maximum; SD - Standard deviation; A1 - For residential use and other purposes; A2 - For residential use with proper treatment, preservation of aquatic plants or other purposes; B1 - For irrigation or other purposes requiring the similar quality of water or other purposes; and B2 - For water transport and other purposes requiring low quality

The results of correlation analysis are shown in Table 3.5. They indicate strong and moderate positive correlations among BOD, COD, TC, turbidity, and TSS, suggesting common sources of point pollution such as poor management of domestic and industrial wastewater, urban drainage, and septic systems. Moreover, TC in the river can be attributed to farming activities involving the excess application of microbial mineralization and feedlot runoff (Phung et al., 2015; Duan et al., 2016; CPI, 2017). Excess soil erosion and sediment flows are seasonal drivers of high turbidity and TSS in surface water (Abd Wahab et al., 2018; Leigh et al., 2019; Duc et al., 2021). A moderate positive correlation was observed between NO_3^- and PO_4^{3-}, suggesting a common origin, most likely agricultural runoff polluted with inorganic fertilizers containing nitrogen and phosphorus (Kumar et al., 2010, 2019b; Minh et al., 2020). In addition, heavy rainfall and soil erosion during floods can transport nitrogen and phosphorus from adjacent agricultural lands into water bodies (WRWC, 2018; Alewell et al., 2020; Duc et al., 2021). On the other hand, inverse associations were found for DO with COD, BOD, turbidity, and TSS. High BOD, COD, turbidity, and TSS are indicators of both organic and inorganic pollutants in the aquatic environment that decompose and deplete DO. A negative association between TC and NO_3^- was found. The main driver of this relationship is that during the wet season, when water is turbid and DO is low, coliform bacteria rely on NO_3^- as an oxygen source, leading to an increase in coliform bacteria and a decrease in NO_3^- concentration.

Table 3.5 Correlation matrix of eight SWQ parameters in Can Tho City

Parameter	**BOD_5 (20°C)**	**COD**	**DO**	**TC**	**Turbidity**	**TSS**	**NO_3^-**	**PO_4^{3-}**
BOD_5 (20°C)	**1**							
COD	0.894	**1**						
DO	-0.89	-0.887	**1**					
TC	0.738	0.797	-0.779	**1**				
Turbidity	0.564	0.634	-0.687	0.789	**1**			
TSS	0.836	0.841	-0.881	0.748	0.745	**1**		
NO_3^-	-0.743	-0.751	0.658	-0.726	-0.522	-0.642	**1**	
PO_4^{3-}	-0.260	-0.307	0.241	-0.383	-0.226	-0.184	0.512	**1**
Note: Correlation coefficients range from -1 (red) to 1 (green) **-1** … **1**								

3.4.2 Spatial Variation in SWQ

3.4.2.1 Spatial Distribution of Monitoring Sites

In the spatial CA process, an agglomeration schedule and dendrogram were generated, which are shown in Figures A1a and 3.3, respectively. As shown in Figures A1a, the optimal number of clusters was three, which is consistent with the result obtained from the dendrogram based on (D_{link}/D_{max}) *100 < 10. The SWQ monitoring sites in these three clusters are shown on the 2019 land-use map of the city (Figure 3.4). Cluster 1 was the largest, comprising 38 sites. Aside from CD1, all of these sites were located in mixed urban-industrial zones of five urban districts along the Hau River, which are dominated by residential, commercial, and industrial uses. Cluster 2 included only five sites in agricultural zones of rural districts, including Co Do, Phong Dien, and particularly Vinh Thanh, where a strong reliance on farming practices was observed. The 30 remaining sites belonged to Cluster 3, representing mixed urban-rural areas in rural and partly urban districts. Notably, despite being occupied by agricultural land, most of these sites were closely surrounded by rural residential zones and market areas with relatively high population density.

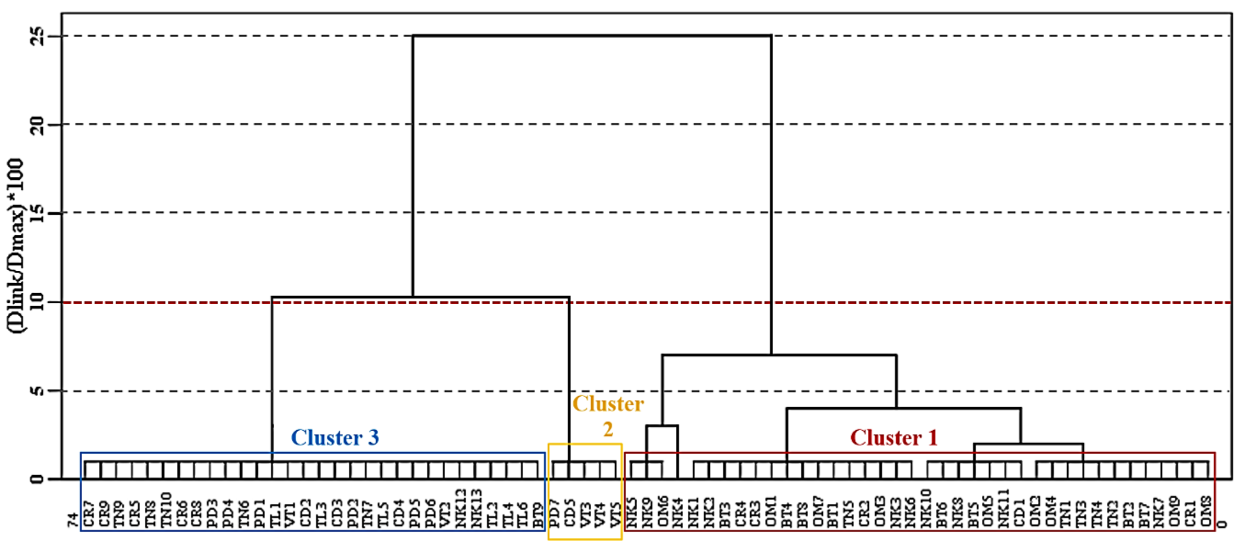


Figure 3.3 Dendrogram illustrating the spatial clustering of 73 monitoring sites according to their SWQ characteristics

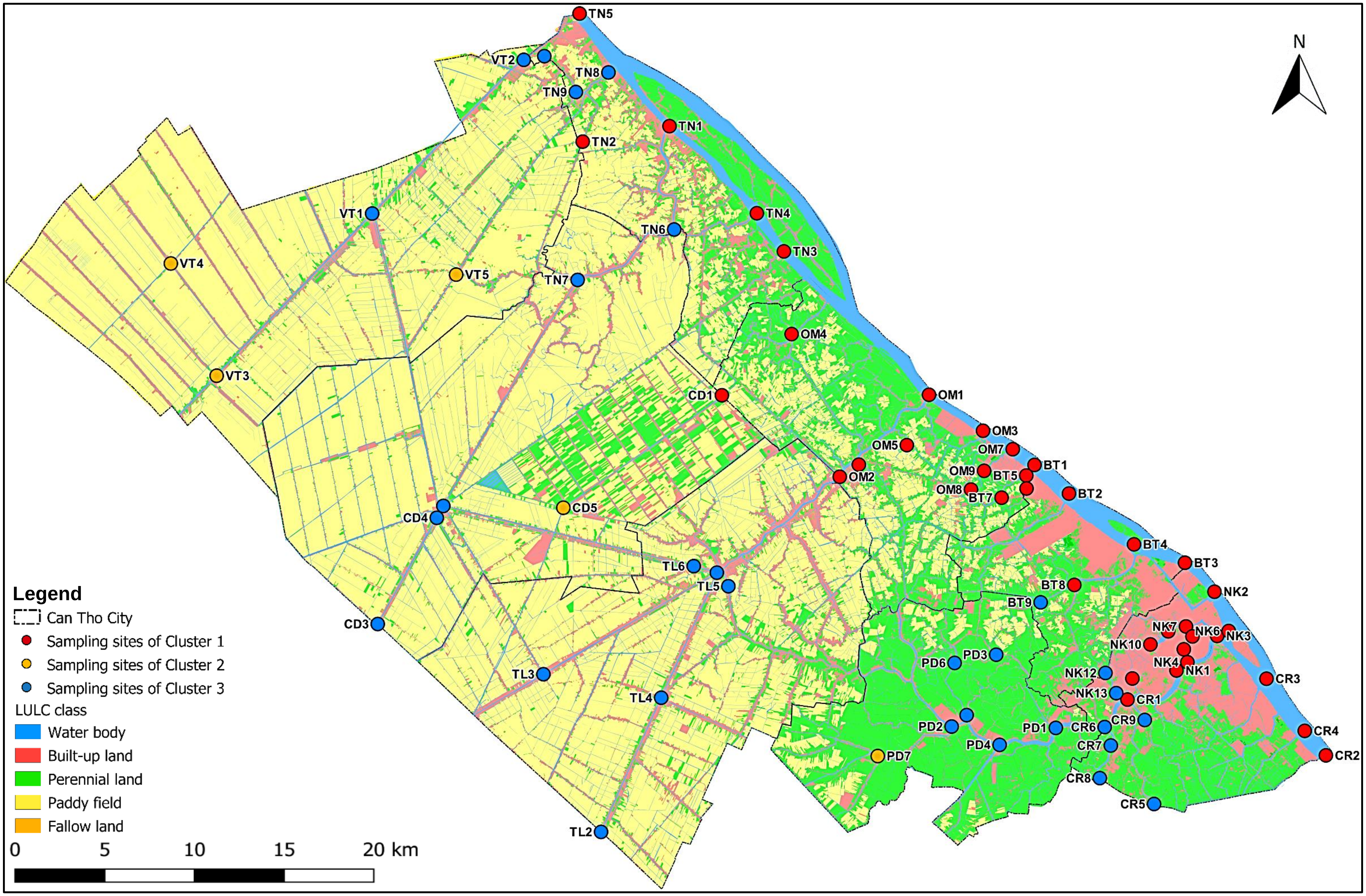


Figure 3.4 The three spatial clusters and associated SWQ sampling sites on the 2019 land-use map of Can Tho City

3.4.2.2 Spatial Variation in SWQ

To further explore spatial variation in SWQ among clusters, DA was performed. Table B1 lists the calculated F and Wilks' lambda values, and Table 3.6 shows the final results. DO, NO_3^-, COD, and PO_4^{3-} were the most significant SWQ parameters for discriminating spatially among clusters. Box and whisker plots indicating the average levels of these parameters are shown in Figure 3.5. While COD dominated Cluster 1 in both concentration and range, a contrasting pattern was observed in Clusters 2 and 3, in which DO had its first and second highest levels, respectively. Similarly, Cluster 2 clearly showed the highest levels of NO_3^- and PO_4^{3-}. Remarkably, Cluster 3 showed moderate levels of all parameters. To clarify these patterns, mean levels of BOD, TC, turbidity, and TSS are also provided in Table B2. Cluster 1 had the highest levels of these parameters, followed by Clusters 3 and 2, respectively.

Table 3.6 The most discriminant variables of the spatial and seasonal variations in SWQ in the study area

Step	Variables entered/removed $^{(a)(b)}$	Wilks' lambda	Exact F	P value
Spatial variables				
1	DO	0.157*	187.722	0.000
2	NO_3^-	0.041*	136.628	0.000
3	COD	0.029*	110.125	0.000
4	PO_4^{3-}	0.025*	88.706	0.000
Seasonal variables				
1	DO	0.008*	1244.243	0.000
2	Turbidity	0.004*	1146.079	0.000
3	PO_4^{3-}	0.003*	1062.018	0.000
4	COD	0.002*	1121.684	0.000

Notes: Significance levels are denoted as follows: $^*P < 0.001$. A Wilks' lambda value of 1 indicates that the means of SWQ parameters between clusters were not different, and a value of 0 shows that the means of SWQ parameters between clusters were totally different

a. Minimum partial F to Enter is 3.84; and b. Maximum partial F to Remove is 2.71

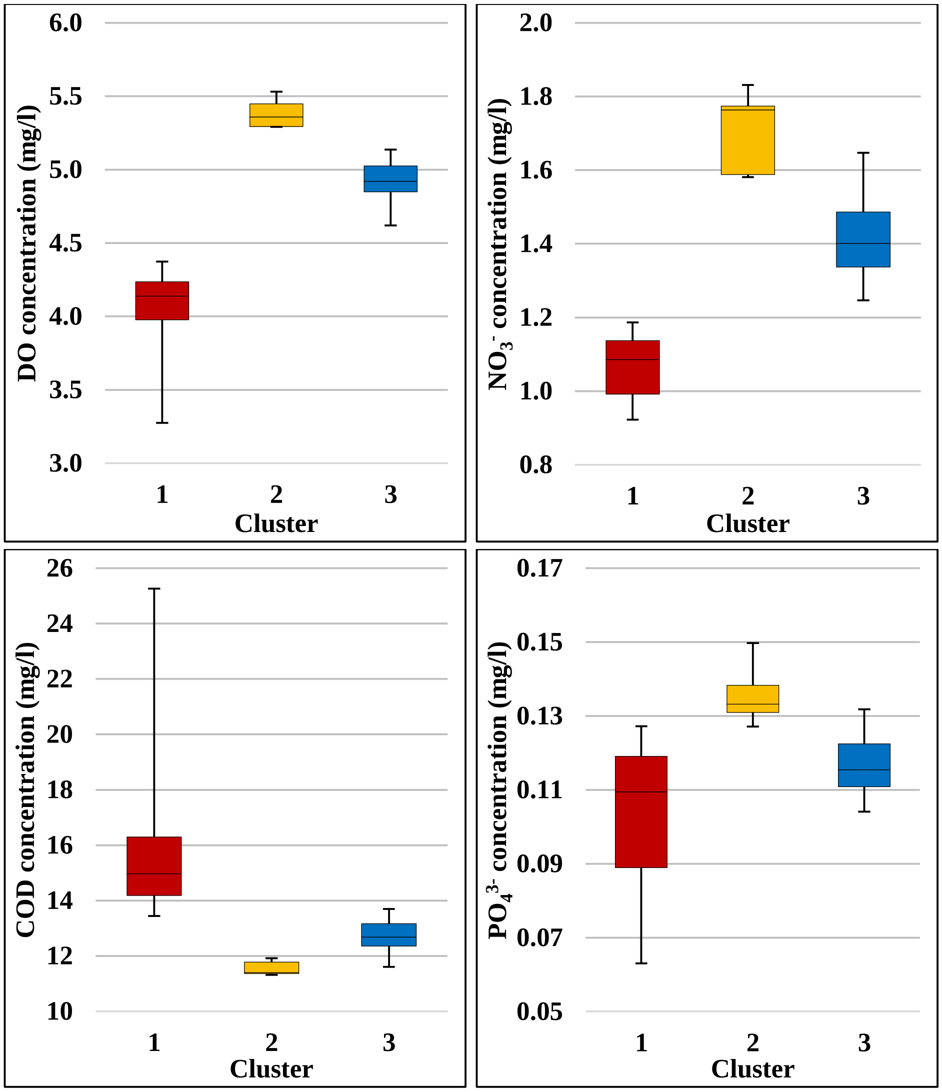


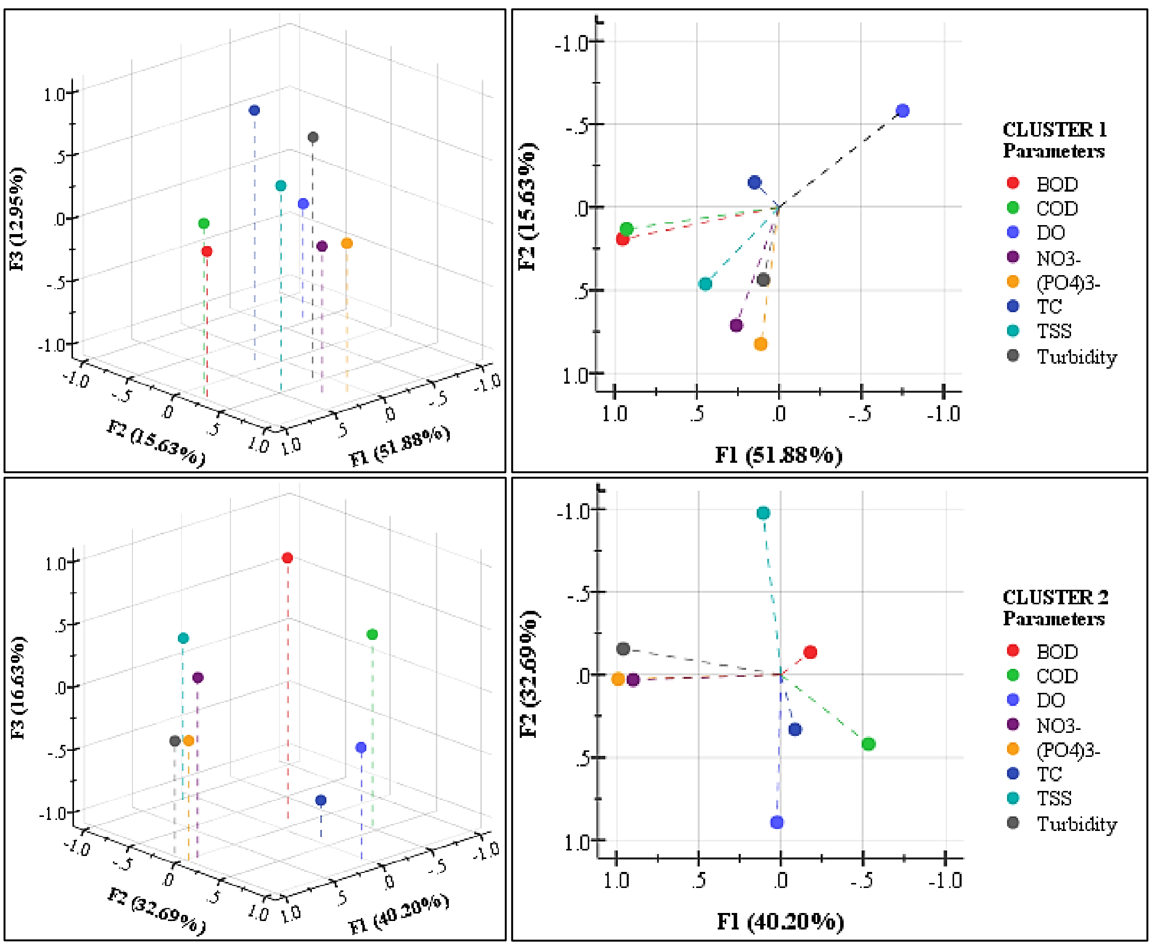
Figure 3.5 Mean levels of the most spatially discriminant SWQ parameters

3.4.2.3 Determination of Pollution Sources

The PCA/FA technique was employed to identify potential SWQ pollution sources for each cluster. Figure A2 shows eigenvalues (>1), and Table 3.7 and Figure 3.6 provide the loadings of SWQ parameters corresponding to factors in each spatial cluster. Clusters 1, 2, and 3 each had three PCs, explaining 80.46%, 89.52%, and 70.37%, respectively, of the total variance in the SWQ dataset.

Table 3.7 The multivariate FA scores (> 0.5) of eight experimental variables according to spatial clusters

Parameter	Cluster 1			Cluster 2			Cluster 3		
	F1	F2	F3	F1	F2	F3	F1	F2	F3
BOD_5 (20ºC)	0.951					0.973	-0.753		
COD	0.927			-0.533			0.585		
DO	-0.751				0.892			-0.802	
TC			0.877			-0.816	0.774		
Turbidity			0.806	0.959			0.883		
TSS			0.515		-0.977				0.730
NO_3^-		0.712		0.898				0.871	
PO_4^{3-}		0.824		0.988					0.801
Eigenvalue	4.150	1.250	1.036	3.216	2.615	1.331	2.692	1.884	1.053
Percentage of variance (%)	51.88	15.63	12.95	40.20	32.69	16.63	33.65	23.55	13.17
Cumulative percentage (%)	**51.88**	**67.51**	**80.46**	**40.20**	**72.89**	**89.52**	**33.65**	**57.20**	**70.37**



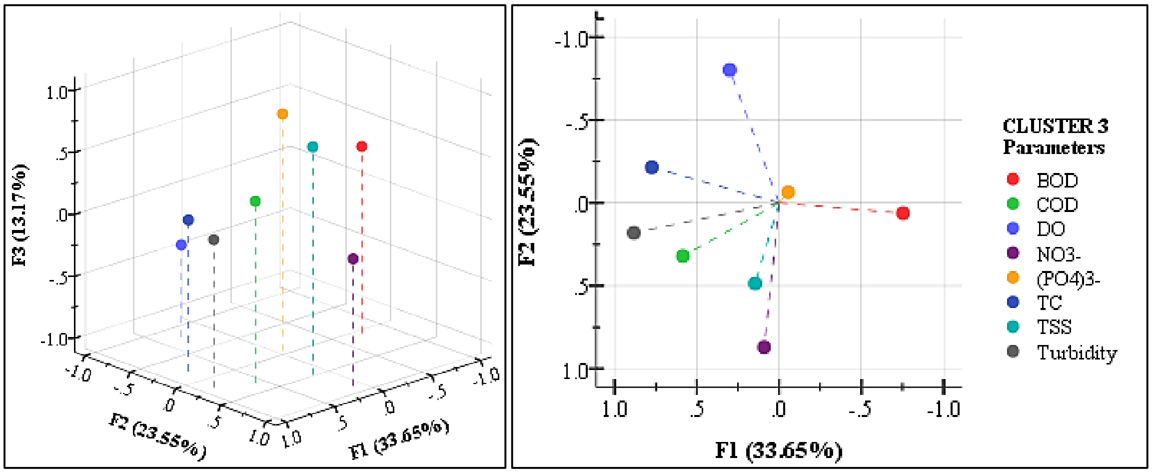


Figure 3.6 3D and 2D scatter plots showing SWQ parameter loadings for the PCs of spatial clusters

For Cluster 1, factor 1 was the most significant factor, explaining nearly 52% of the dataset variance. This factor showed strong and moderate loadings for COD, BOD, and DO. As noted above, these parameters indicate the dominance of point pollution sources associated with anthropogenic activities, such as wastewater discharge from industrial urbanization zones. Two less-significant factors, namely, 2 (15.63%) and 3 (12.95%), exhibited high and moderate loadings for NO_3^-, PO_4^{3-}, TC, turbidity, and TSS. These results demonstrate impacts of both urban drainage and farming runoff on SWQ. For Cluster 2, the two most significant factors were 1 and 2, with a cumulative variance of 72.89%, which had high loadings for NO_3^-, PO_4^{3-}, DO, turbidity, and TSS. These factors are indicative of agricultural practices, such as large inputs of inorganic fertilizers and disturbed soil erosion. Factor 3 (16.63%) indicated strong loadings for BOD and TC, suggesting influences from urban activities. For Cluster 3, factors 1 (33.65%) and 2 (23.55%) had high loadings for BOD, COD, DO, TC, turbidity, and NO_3^-, indicating diverse drivers (e.g., residential, industrial, and agricultural sources) of variation in SWQ. Factor 3 (13.17%) showed moderate loadings for TSS and PO_4^{3-}, representing both urban and agricultural activities.

Generally, the PCA/FA findings were consistent with those obtained from spatial CA and DA. The most significant factors strongly indicated that SWQ in the Thot Not, O Mon, Binh Thuy, Ninh Kieu, and Cai Rang districts were strongly influenced by industrial and urban processes, while agricultural practices were mainly responsible for the SWQ status of Cluster 2 (Vinh Thanh and parts of Co Do and Phong Dien districts). Notably, both farming and urbanization were key drivers of SWQ in Cluster 3 (parts of Cai Rang and Thot Not, and most of Phong Dien, Thoi Lai, and Co Do districts).

3.4.3 Seasonal and Temporal Variation in SWQ

3.4.3.1 Seasonal Distribution of SWQ

In the seasonal CA process, SWQ characteristics during all 12 months were grouped into two clusters (Figure A1b) at (D_{link}/D_{max}) *100 < 5 (Figure 3.7). Notably, this clustering result is consistent with the city's tropical monsoonal climate, which shows distinct alternation between the dry and wet seasons. Cluster 1 included January, February, March, April, and December and corresponded closely to the dry season in the city, characterized by periods of low flow and drought (Figure 2.2). Cluster 2 contained the remaining months, reflecting the wet season with periods of high flow, rain, and flooding. A statistical summary of seasonal mean concentrations of SWQ parameter is provided in Table 3.4. As indicated, the mean levels of pH, BOD, COD, TC, fluoride (F^-), chromium (Cr_6^+), and iron (Fe) were higher in the dry season than the monsoon season, while the opposite trend was observed for the seven remaining parameters. This variation may have arisen from diverse impacts of the local climatic (dry and wet seasons) and hydrological conditions (low- and high-flow periods).

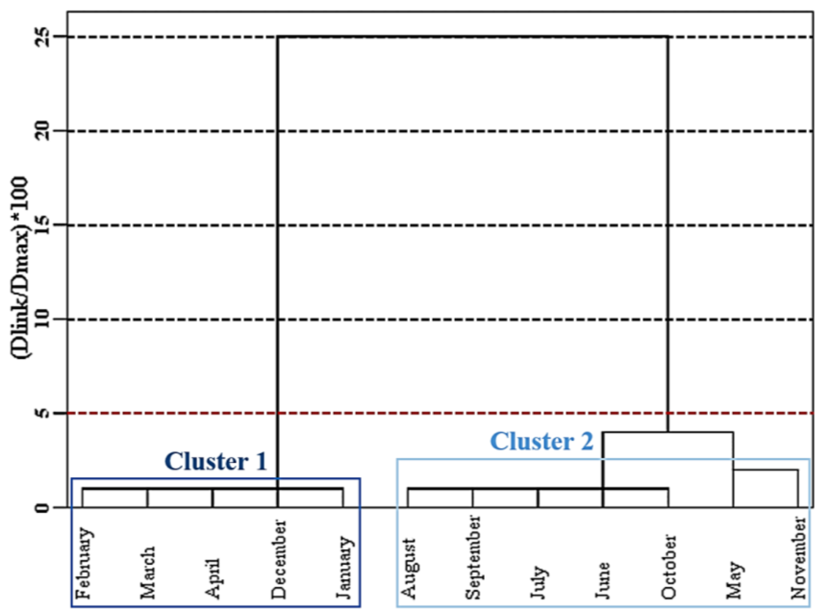


Figure 3.7 Dendrogram illustrating seasonal clustering of 12 months according to their SWQ characteristics

3.4.3.2 Seasonal Variation in SWQ

As analyzed using DA and shown in Tables B1 and 3.6, DO, turbidity, PO_4^{3-}, and COD were the most significant SWQ parameters for discriminating between the dry (Cluster 1) and wet (Cluster 2) seasons. Their average levels are compared in Figure 3.8. The average DO level was much lower in the dry season than during the wet season; the reason underlying this difference is local climatic diversity. DO concentrations are controlled in part by water temperature (Chen et al., 2015). Thus, the warmer river water present during the city's dry period (Tam et al., 2022) becomes saturated with oxygen more easily and can hold less DO (Shrestha and Kazama, 2007; FED, 2014; Duan et al., 2016). This lower DO level was also driven by the higher levels of COD (Figure 3.8) and BOD (Table 3.4) in the dry season, representing organic and inorganic matter in the water that requires oxygen for decomposition. Notably, lower water levels combined with direct discharge of domestic, industrial, and farming wastewater into water bodies may be responsible for the high levels of COD and BOD pollution in the city during the dry season.

During the wet season, high levels of turbidity and PO_4^{3-} were observed, due in part to the transboundary nature of the river systems (Minh et al., 2019b). As part of the VMD's downstream area, the city receives large amounts of alluvial flows carrying nutrients (phosphorus and nitrogen) due to erosion of disturbed soil and agricultural activities in the upstream areas (e.g., An Giang, an intensively agricultural province; Figure 3.1) during the rainy and flooding periods (Minh et al., 2019b, 2020; Duc et al., 2021). In addition, the high levels of turbidity, PO_4^{3-}, TSS, and NO_3^- during the wet season were driven by high local runoff of inorganic fertilizers, anaerobic wastewaters, and urban activities in the city (Phung et al., 2015; Tam et al., 2022).

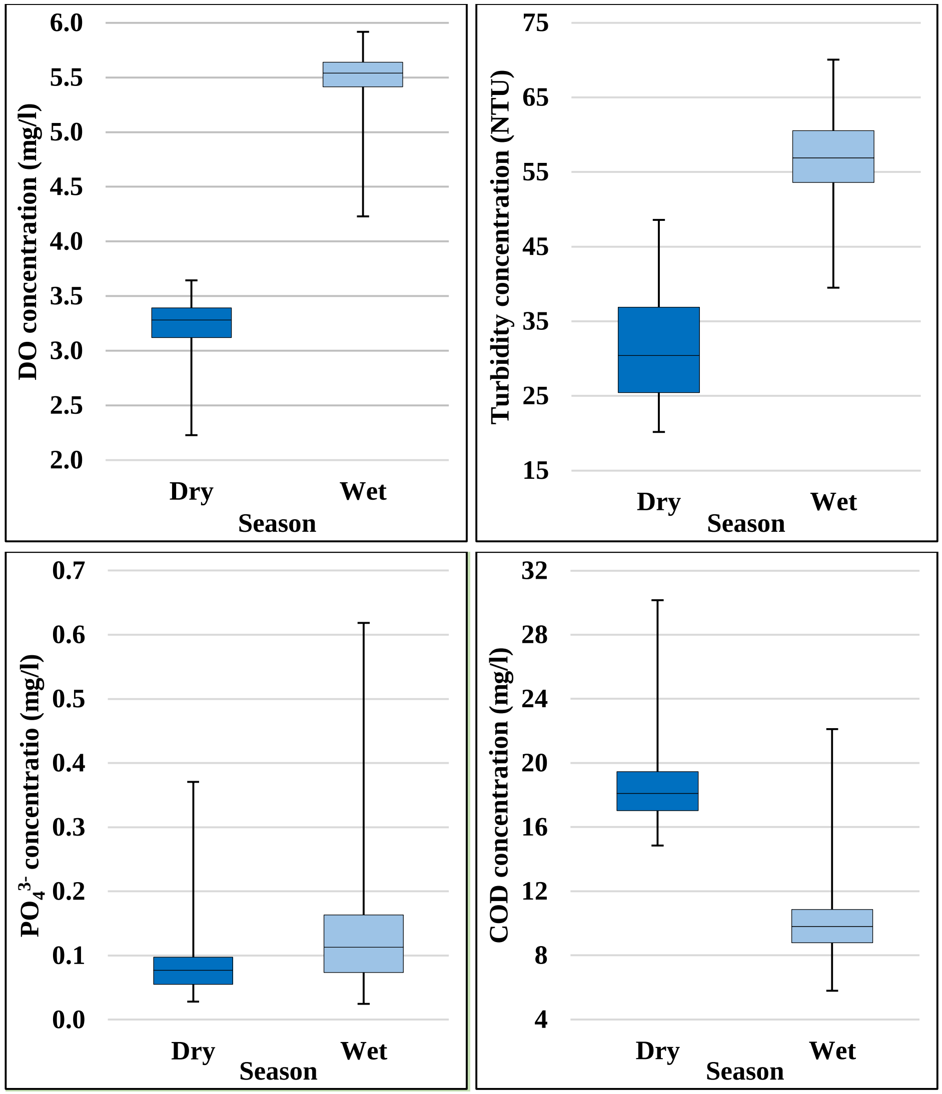


Figure 3.8 Mean levels of the most important SWQ parameters for discriminating between the dry and wet seasons

3.4.3.3 Temporal Classification of SWQ

For temporal SWQ classification, annual WAWQI values were calculated and compared (Tables 3.8 and B3). Higher levels of SWQ parameters would cause higher index values. The WAWQI values and their distributions on contour maps in 2013 and 2019 are shown in Figures 3.9 and 3.10, respectively. The estimated mean index values in 2013 and 2019 were 62 and 72, respectively. Most of the indexes were higher in 2019 than in 2013, with 66 indexes compared to 7 that were higher in 2013.

Table 3.8 The WAWQI values calculated for SWQ classification (with corresponding colors) at 73 sampling sites throughout the study area in the years 2013 and 2019

No.	**Code**	**Year**		**No.**	**Code**	**Year**		**No.**	**Code**	**Year**	
		2013	**2019**			**2013**	**2019**			**2013**	**2019**
1	TN1	37	45	26	BT7	76	86	51	VT1	40	47
2	TN2	59	68	27	BT8	40	47	52	VT2	47	48
3	TN3	52	76	28	BT9	52	63	53	VT3	38	48
4	TN4	62	76	29	NK1	36	44	54	VT4	35	52
5	TN5	76	92	30	NK2	40	51	55	VT5	55	51
6	TN6	65	72	31	NK3	73	82	56	CD1	54	78
7	TN7	53	65	32	NK4	126	122	57	CD2	76	82
8	TN8	59	79	33	NK5	153	128	58	CD3	38	51
9	TN9	49	73	34	NK6	74	84	59	CD4	79	89
10	TN10	59	77	35	NK7	72	85	60	CD5	55	68
11	OM1	78	92	36	NK8	76	92	61	TL1	47	44
12	OM2	85	91	37	NK9	91	151	62	TL2	37	47
13	OM3	64	78	38	NK10	61	76	63	TL3	68	69
14	OM4	77	85	39	NK11	59	74	64	TL4	54	71
15	OM5	81	94	40	NK12	59	77	65	TL5	53	59
16	OM6	96	107	41	NK13	57	77	66	TL6	59	69
17	OM7	96	93	42	CR1	80	77	67	PD1	41	41
18	OM8	90	91	43	CR2	76	79	68	PD2	67	77
19	OM9	91	95	44	CR3	92	83	69	PD3	52	56
20	BT1	37	46	45	CR4	76	86	70	PD4	40	52
21	BT2	76	84	46	CR5	45	53	71	PD5	58	79
22	BT3	30	34	47	CR6	63	74	72	PD6	49	59
23	BT4	57	66	48	CR7	41	47	73	PD7	41	49
24	BT5	43	46	49	CR8	44	77	**Min/Max**		**30/164**	**34/151**
25	BT6	57	61	50	CR9	59	81	**Mean ± SD**		**62 ± 23**	**72 ± 21**

In 2013, SWQ at 26.03% of all sites was bad or very bad for domestic usage. These sites were mainly located in the most populous and industrialized districts, particularly Ninh Kieu (NK8 and NK9 at Bung Xang and Xang Thoi lakes), Cai Rang (CR1–CR4 in the Hung Phu industrial zone), O Mon (OM1, OM2, and OM4–OM9 at O Mon market and in the Tra Noc industrial park), and Thot

Not (TN5 in the Thot Not industrial zone) (Figure 3.9). Only 2.74% of all sites (NK4 and NK5, along the highly polluted Tham Tuong canal) had intensively polluted and unusable water. Notably, the remaining sites (over 71%) showed good or moderate SWQ status. In 2019, the total proportion of sites classified with bad and very bad SWQ conditions was greater than 45%, predominantly located in urban zones along the Hau River. Notably, the number of sites with unsuitable status was double that in 2013, reaching 5.48%. This shift was mainly due to considerable growth of industrial parks (five new large parks including O Mon, Northern O Mon, Tra Noc 2, and Hung Phu 2A and 2B) and their WWTPs (that were built and located near these new industrial parks) in urban districts along the Hau River (Figure 3.10)) during the period of 2014–2018 (MOC, 2011; VNGO, 2015; CTCPC, 2019b; MOPI, 2020). Only 49.32% of the total water samples were suitable for daily consumption, mostly from Thoi Lai, Phong Dien, and Vinh Thanh districts. The unacceptable SWQ at CD1, CD2, CD4, PD2, and PD5 was notable, as these sites are surrounded by large rural residential areas and local food production facilities.

The results obtained from WAWQI calculation were highly consistent with the classification of spatial SWQ clusters and land-use characteristics (Figure 3.4) in the city, as described above. The majority of polluted sites with high WAWQI values (from 75 to over 100) in both 2013 and 2019 belonged to Cluster 1, which is dominated by residential, commercial, and industrial lands along the Hau River and canals. Moderate SWQ status with tolerable index values ranging from 50 to 75 was recorded at most of the monitoring locations in Cluster 3, while SWQ at all sites of Cluster 2 (mainly large areas of agricultural land in rural districts) was generally acceptable for human consumption, as demonstrated by low WAWQI values ranging from 35 to 50.

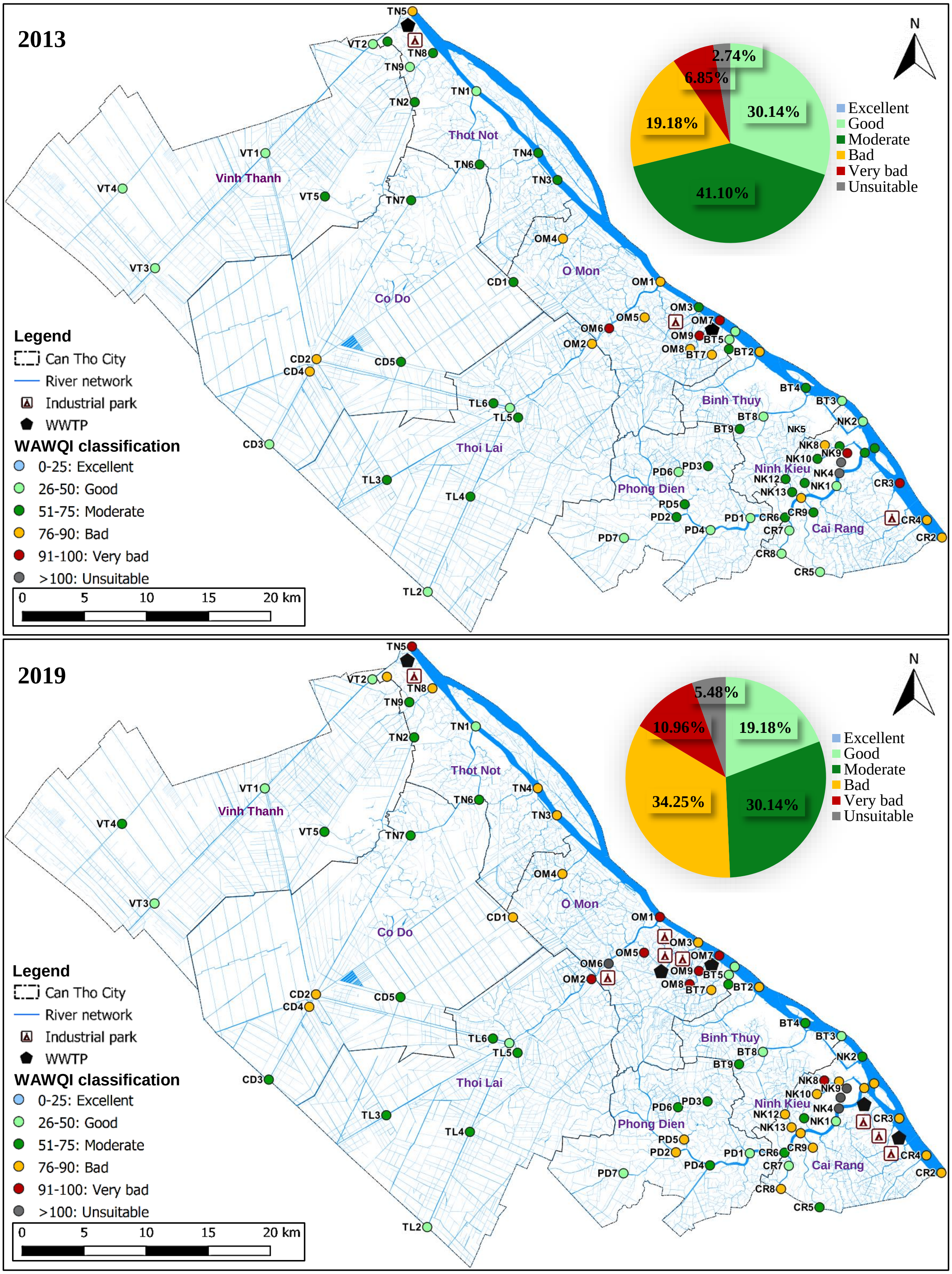


Figure 3.9 Temporal variation and statistical classifications of SWQ in 2013 and 2019

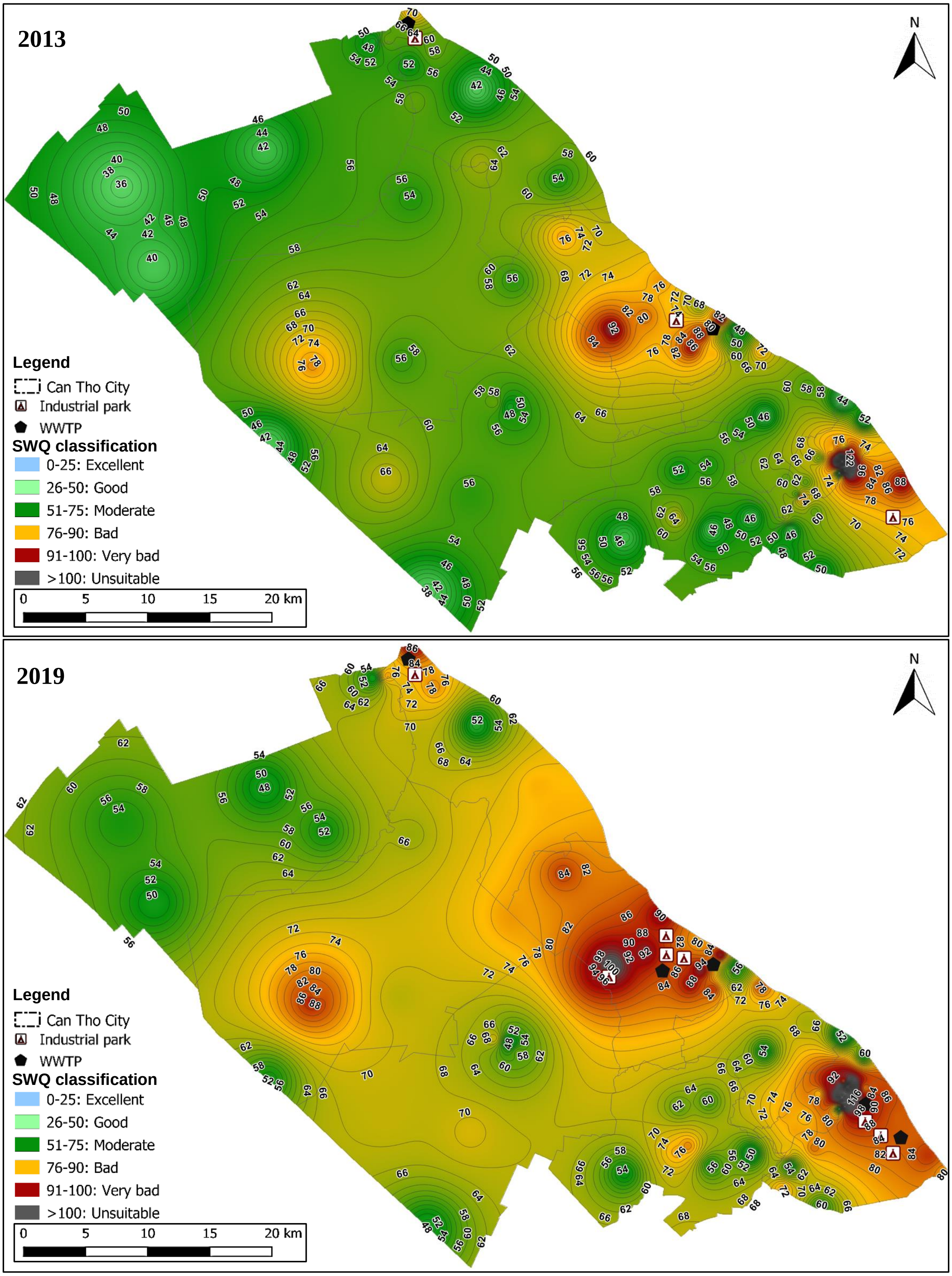


Figure 3.10 Spatiotemporal distributions of WAWQI values in 2013 and 2019

3.4.3.4 Temporal Variation in SWQ

Overall, compared to 2013, SWQ in 2019 indicated degradation, particularly in urban districts and along major rivers due to intensive industrial urbanization beginning in 2014. For clarity, the annual levels of the four most spatially discriminant SWQ parameters were analyzed (Figure 3.11). A negative correlation was found between COD and DO levels during the study period. Increasing trends occurred in COD levels, particularly from 2015 to 2019, and these trends were attributed to industrial urbanization beginning at the end of 2014. Notably, although a series of canal rehabilitation and industrial WWTP projects were conducted from mid-2013 to the end of 2016 in pollution hotspots (i.e., Tham Tuong, Cai Khe, Ngong, Sang Trang, and Cay Me canals), these projects were efficient only temporarily and locally around selected sites. In addition, 100-year droughts in 2015 and 2016 (Guo et al., 2017) contributed to increasing COD levels over this 4-year period.

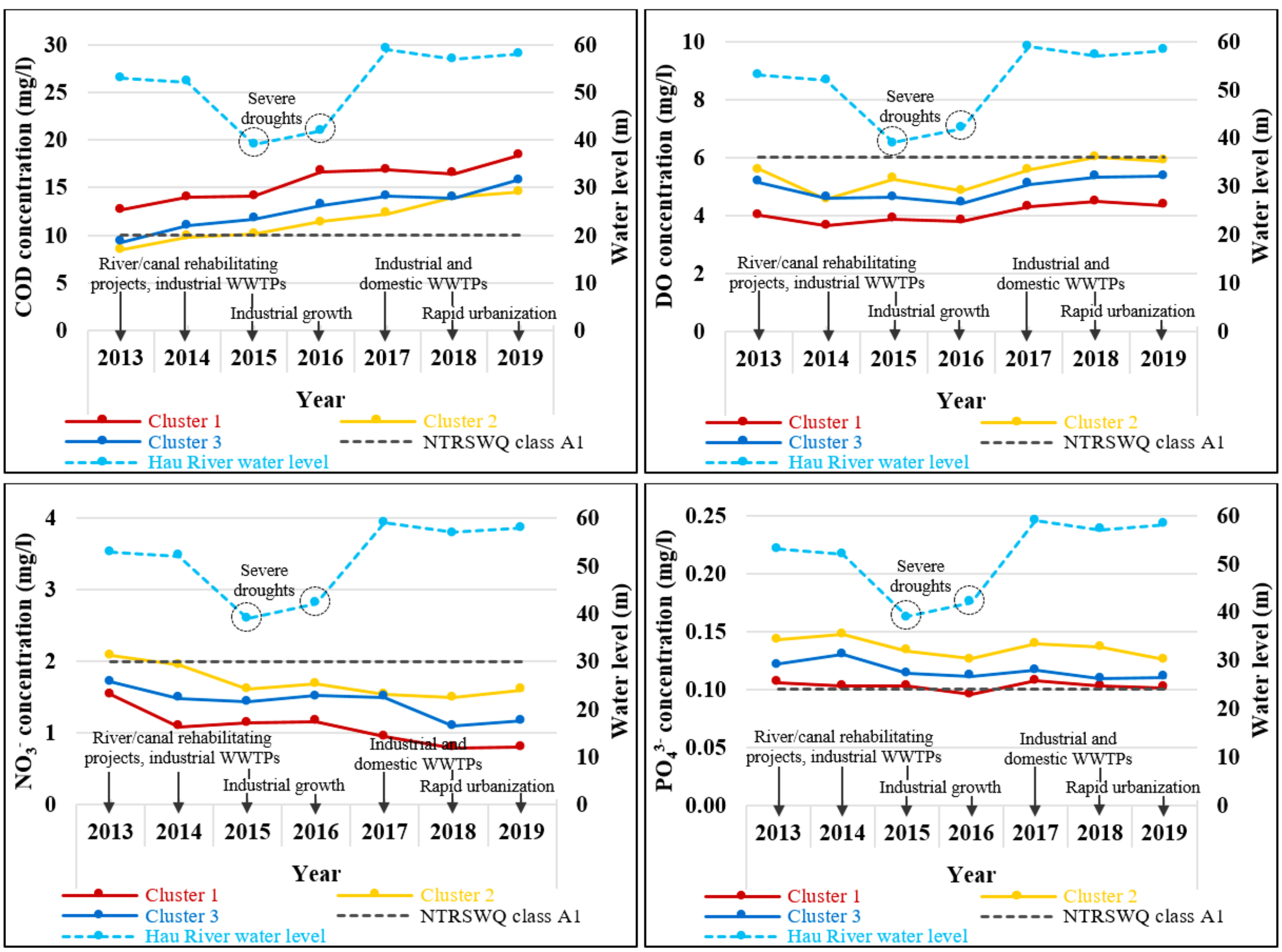


Figure 3.11 Variation in annual COD, DO, NO_3^-, and PO_4^{3-} levels in clusters over the study period

A very slight increase in 2017 followed by a decrease in 2018 was observed in the COD levels of Clusters 1 and 3. The success of recent projects (i.e., the first domestic and new industrial WWTPs in urban and industrial Thot Not, O Mon, and Cai Rang districts) in early 2018 was considered the key driver of this decline. However, the expansion of human settlement in rural areas caused the COD loading of Cluster 2 to increase slightly. Since 2018, inadequate wastewater management infrastructure and the rapid emergence of new trading centers, residential areas, and local markets have occurred (DONRE, 2019, 2020a; MONRE, 2020), driving increased COD pollution for all clusters in 2019. NO_3^- and PO_4^{3-} levels showed downward trends during the study period, driven by shrinking of agricultural land area in 2013–2016 and severe droughts in 2015–2016. The expansion of urbanized and industrialized areas was the main contributor to the reduction in agricultural land, thereby causing decreases in NO_3^- and PO_4^{3-} levels.

3.4.4 Correlation between SWQ and LULC Variation

Using RA, the correlated linkages between annual changes in WAWQI values and land-use areas were determined (Figure 3.13) to provide clear quantitative evidence of the key drivers of SWQ degradation in Can Tho City. The land-use dataset indicated the dominance of agricultural land, followed by built-up, water bodies, and fallow land (Figure 3.12). The average annual WAWQI values and areas of various land-use classes are summarized in Table B4 (CTCSO, 2020c; DONRE, 2020b). Upward trends were observed in the annual areas of built-up land and water bodies. Built-up land covered 182.21 km^2 in 2013, which soared to 217.68 km^2 in 2019, while water bodies experienced an increase from 75.13 to 86.44 km^2. While rapid industrialization (during 2014–2016) and urbanization (2018–2019) led to expansion of the built-up land area, rehabilitation of a series of canals and lakes (2013–2015) resulted in the growth of water bodies (CTCPC, 2016; CTODA, 2016a, 2016b). The opposite trends were observed for agricultural and fallow land, which decreased from 1,179.66 to 1,134.18 km^2 and from 1.96 to 0.66 km^2, respectively. Notably, paddy field area showed the largest decrease from 2013 to 2019, from 941.54 to 867.72 km^2, mainly due to urbanization of rural areas and severe droughts (2015–2016) (Sebastian et al., 2016; CTCSO, 2020b). Mean annual WAWQI values showed an increasing trend from 2013 to 2019, except for a slight drop in 2018, attributable to the introduction of new domestic and industrial WWTPs in early 2018.

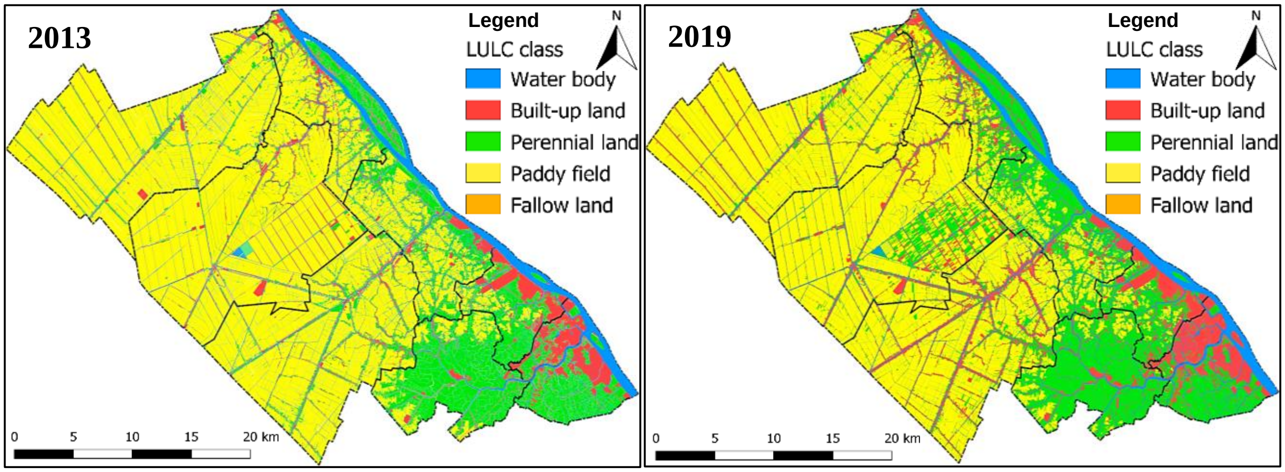


Figure 3.12 Land-use maps of the study area in 2013 and 2019

As shown in Table B4 and illustrated in Figure 3.13a, a strong positive correlation (R^2 = 0.92 and P = 0.001) between the average annual WAWQI values at 73 sampling sites throughout the city and built-up land area was observed during the research period of 2013–2019, revealing that as the city became increasingly urbanized and industrialized, its SWQ progressively worsened. By contrast, Figures 3.13b and 3.13d had respectively shown strong and moderate negative correlations between the average annual WAWQI values and agricultural and fallow land areas. These correlations indicate that as the areas of agricultural and fallow lands decreased, a corresponding increase in WAWQI was observed, indicating declining SWQ. From 2013 to 2019, large areas of agricultural (45.48 km^2) and fallow (1.3 km^2) lands along major rivers and canals were cleared to allow for industrial urbanization processes, which were noted above as key drivers of increasingly serious pollution and declining SWQ in the city.

The variation in the annual area of water bodies was positively correlated with changes in the average annual WAWQI values (Figure 3.13c), indicating that SWQ of the city was increasingly polluted despite an increase in water area between 2013 and 2019. However, the strength of this correlation was only moderate, with R^2 = 0.61 and P = 0.04. Although the expansion of water surface area mainly from 2013 (75.13 km^2) to 2015 (87.06 km^2) due to canal rehabilitation projects was temporarily and locally effective at improving SWQ in heavily polluted hotspots, particularly in 2017 and 2018, pollution of river water remains a concerning issue in many zones throughout the study area. These findings and interpretation are consistent with local environmental reports (CTCPC, 2016, 2019b; DONRE, 2020a). In general, our findings confirm that SWQ in the city is controlled by multiple driving forces, among which urbanization and industrialization are the main factors.

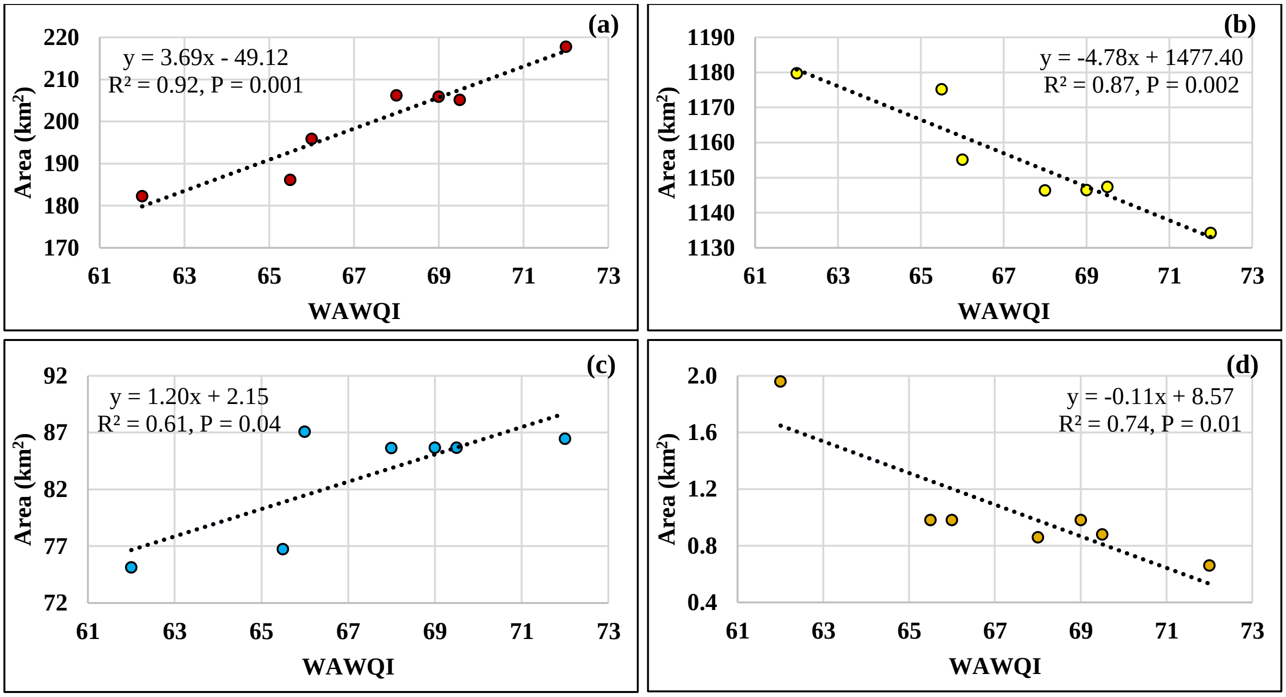


Figure 3.13 Correlated relationships between the average annual WAWQI values at the total of 73 sampling sites throughout the city and areas of built-up land (a), agricultural land (b), water bodies (c), and fallow land (d) in the research period

3.5 Conclusions and Next Work

In this chapter, using a multivariate analytical approach, the study had successfully obtained an overall picture of spatiotemporal variation in SWQ in Can Tho City under rapid land-use changes during the period of 2013–2019. The obtained findings indicated that the city's SWQ status was bad or unsuitable for domestic usage in most urban districts along Hau River. Compared to 2013, SWQ was clearly worse in 2019 mainly due to rapidly industrial urbanization and climate change. Therefore, the city needs timely and appropriate measures to deal with both its current and future SWQ pollution. Among existing measures, the city tends to focus on technical ones, mainly the WWTP application as proposed and prioritized in its master plans. However, the current and future effectiveness of these plants needs to be comprehensively assessed and predicted to provide timely policy-relevant scientific information supporting the city's policy-makers and technical staff to review the feasibility and sustainability of this technical measure, and hence make policy adjustments or propose alternative measures. These assessment and prediction have even become more urgent under the context of the city's rapid and sometimes uncontrolled development. Therefore, to meet this need, they were performed by applying computer-based mathematical models and tools, and the achieved results were presented in the next chapter.

Chapter 4

Scenario-Based Numerical Simulation to Predict the Future SWQ for Boosting Robust Water Management Plan in Can Tho City, Vietnam

4.1 Introduction

As proved in Chapter 2, Can Tho City is experiencing water stresses mainly related to water quality degradation. This situation can be seen as a warning sign for the city's government to develop a more robust and comprehensive water management plan for the future. For designing this plan, the identification of the current water pollution status as well as its key drivers play an important role. However, apart from water quality conditions today, the future ones that is intensively impacted by potential uncertainties such as socio-economic development, policy and institution changes, climate change, and others is also a crucial factor guiding this design. Noticeably, predicting and evaluating the future water quality status could be a challenging tasks without building possible future scenarios taking into thorough consideration of these uncertainties. Indeed, Kannel et al. (2007) and Mishra et al. (2017) also stated that the formulation of water quality management plans and strategies compulsorily requires an interdisciplinary analysis of various potential causes of water quality degradation as well as corresponding solutions.

With the above-mentioned facts, computer-based mathematical models have been developed since the 1980s to assess and predict the future water quality. In WRM, the favorable approaches vary from simplified conceptual, empirical to data-based ones. Most models can provide detailed insight into water quality conditions in a river system such as SWAT, QUAL2K, MIKE, etc. However, there has mostly been an absence of policy-setting issues in detail (Mishra et al., 2017; Kumar, 2019). Specifically, the IWRM model targets different components of water resource governance (socio-economic status, hydro-meteorological factors, agriculture, industries, wastewater, etc.) and thereby, integrate them for the policy- and decision-making processes (Blanco-Gutiérrez et al., 2013; Frija et al., 2015). Several IWRM numerical models like RIBASIM (River Basin Simulation Model), SWMM (Storm Water Management Model), VENSIM (The System Dynamic Model), WEAP, and WBalMo (Water Balance Model) have been developed and widely used to address water security issues (Sieber and Purkey, 2015; Kumar, 2018; Trung et al., 2019a). The application of an optimal water quality model depends on data availability, calculation time, and intended output variables.

Particularly, the WEAP model is not data-intensive and free of charge, and thus, it has been widely used in water quality modeling, especially in data-scarce developing countries (Slaughter et al., 2014; Sieber and Purkey, 2015). Besides, this integrated model has also been widely used to analyze the efficiency of different planned adaptation and mitigation measures for improving the water resources in the future (Kumar, 2018; Mirauda and Ostoich, 2018). Noticeably, despite the lack of detailed water quality variables like several other models, the WEAP model supports scenario formation functionalities. These scenarios can be built with the involvement of policy and strategic plans in this model, based on different variables such as population growth, industrialization and urbanization, climate change, LULC, the status of treatment plants and sewerage network, hydropower generation, etc. (Mishra et al., 2017; Kumar, 2018). Moreover, the WEAP hydrology module also allows the estimation of rainfall-runoff and pollutant travel from a catchment to water sources (Ingol-Blanco and McKinney, 2013).

With the aforementioned facts, based on the current SWQ conditions, the study included in this chapter aims to simulate and quantify the future outlook of SWQ for the year 2030 in Can Tho City with the case simulation of the Hau River water quality based on four possible scenarios. The first scenario is the BAU where the effects of all possible key factors (population growth, urbanization, and climate change) affecting the Hau River water quality are considered. The others are scenarios WMs, in which water treatment plants are considered as the mitigation measure for improving the river water environment. The second scenario denoted by "WM100" refers to an ideal situation considering 100% completion of the WWTPs of capacity planned in the cities' master plans, whereas the third scenario i.e., "WM75" refers to 75% completion of the planned WWTPs because of some delay in the project completion in the cities. Considering the existing gap to achieve the desired water quality with WM100, a fourth scenario named "WM_Opt." with the same characteristics and components as the MW100 scenario and the addition of river water treatment plants (RWTPs) at serious water pollution centers along the Hau River was applied.

4.2 Study Area

Being the main tributary of the Mekong River, the Hau River flows across the entire area of Can Tho City with a total length of nearly 60 km (Konings, 2012) (Figure 4.1). Compared to other rivers in the city's dense waterways, the Hau River was selected as the case study area due to its important role, unique characteristics, and especially diverse dataset of hydro-meteorological variables that are required for SWQ simulation and model setup. Remarkably, this river also borders the large parts of Dong Thap and Vinh Long Cities' areas (VLCSO, 2018; VNCSO, 2018; CTCPC, 2020; MOPI, 2020), and their relevant information and dataset were also collected and included in the processes of model setup. Therefore, in this study, the study area comprised of both Can Tho (North latitudes/East longitudes: 9°55'08"–10°19'38"/105°13'38"–105°50'35"), Dong Thap (10°07'59"–10°58'22"/105°12'00"–105°56'01") and Vinh Long (9°52'45"–10°19'50"/105°41'25"–106°17'00") Cities (CTCPC, 2020; MOPI, 2020) (Figure 4.1). The total areas of Dong Thap and Vinh Long Cities are approximately 3,384 km^2 (including two urban districts and ten rural ones) and 1,526 km^2 (one urban district and seven rural ones), respectively (VNCSO, 2018; VLCSO, 2018). Similarly to Can Tho City, both Dong Thap and Vinh Long are also considered populous cities in Vietnam with nearly 1.694 and 1.052 million people in 2018, respectively (VNCSO, 2018).

Together located in the middle of the Lower Mekong Basin, Dong Thap and Vinh Long Cities also lie in a tropical and monsoonal climate with rainy and dry seasons, annual humidity of 83%, and annual rainfall of 1,650 mm (Konings, 2012). Geographically, the northeast of Can Tho City and the southwest of Dong Thap and Vinh Long Cities are bordered by the Hau River. As previously mentioned, all five urban districts of Can Tho City are all located along the Hau River; while Lap Vo and Lai Vung districts of Dong Thap City as well as Binh Tan and Binh Minh districts of Vinh Long City are bordered by the Hau River (Figure 4.1). They are the nine most populous and crucial districts contributing to these cities' general development. Although the area of these nine districts only accounts for nearly 20% (1,156 km^2) of the total area of Can Tho, Dong Thap and, Vinh Long Cities; their population makes up nearly 34% (nearly 1.338 million people) of these cities' total population in 2018 (CTCSO, 2019). Table 4.1 shows the nine districts' area and population characteristics in the study area (VLCSO, 2018; VNCSO, 2018; CTCSO, 2019; UN DESA, 2019; MOPI, 2020).

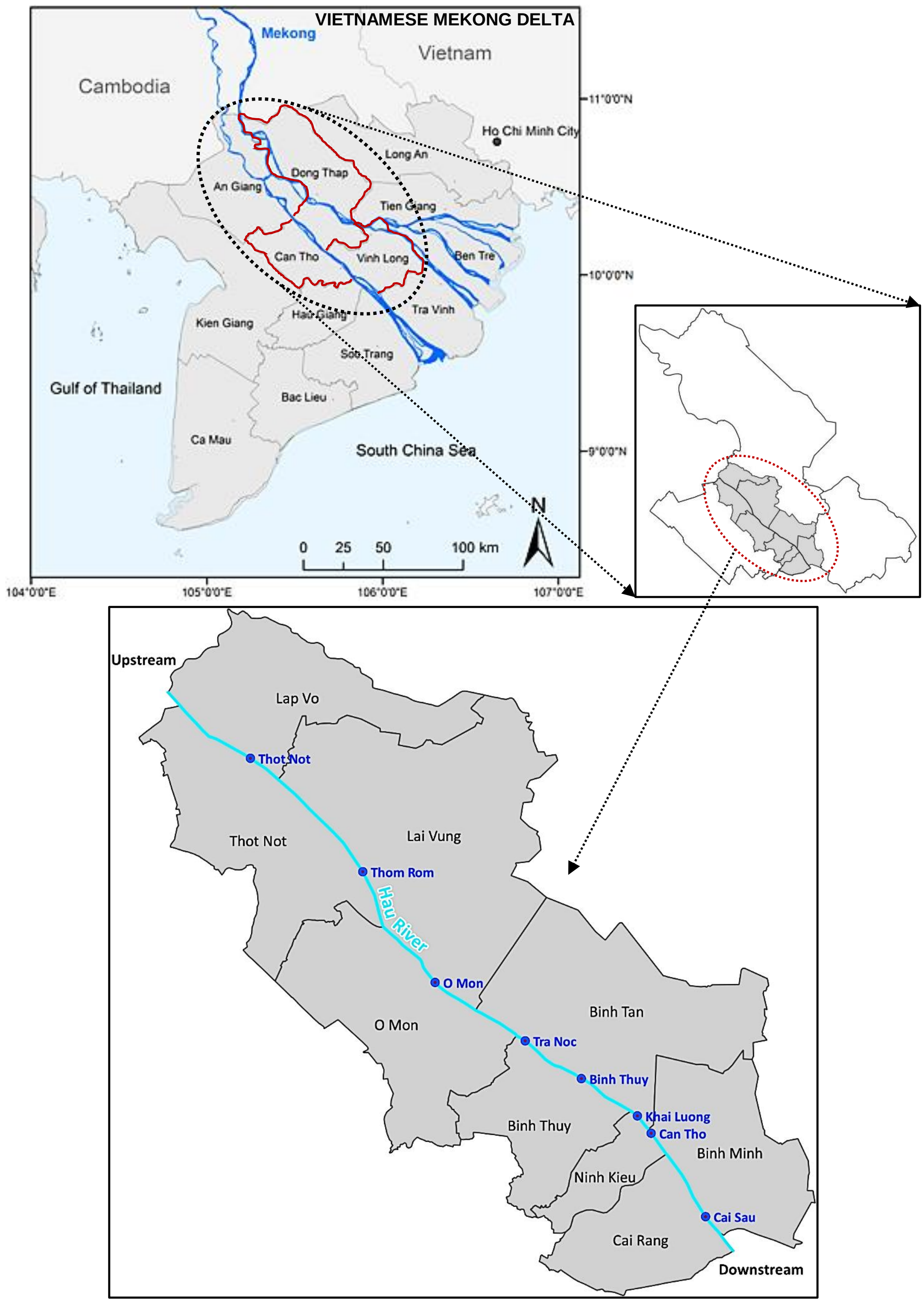


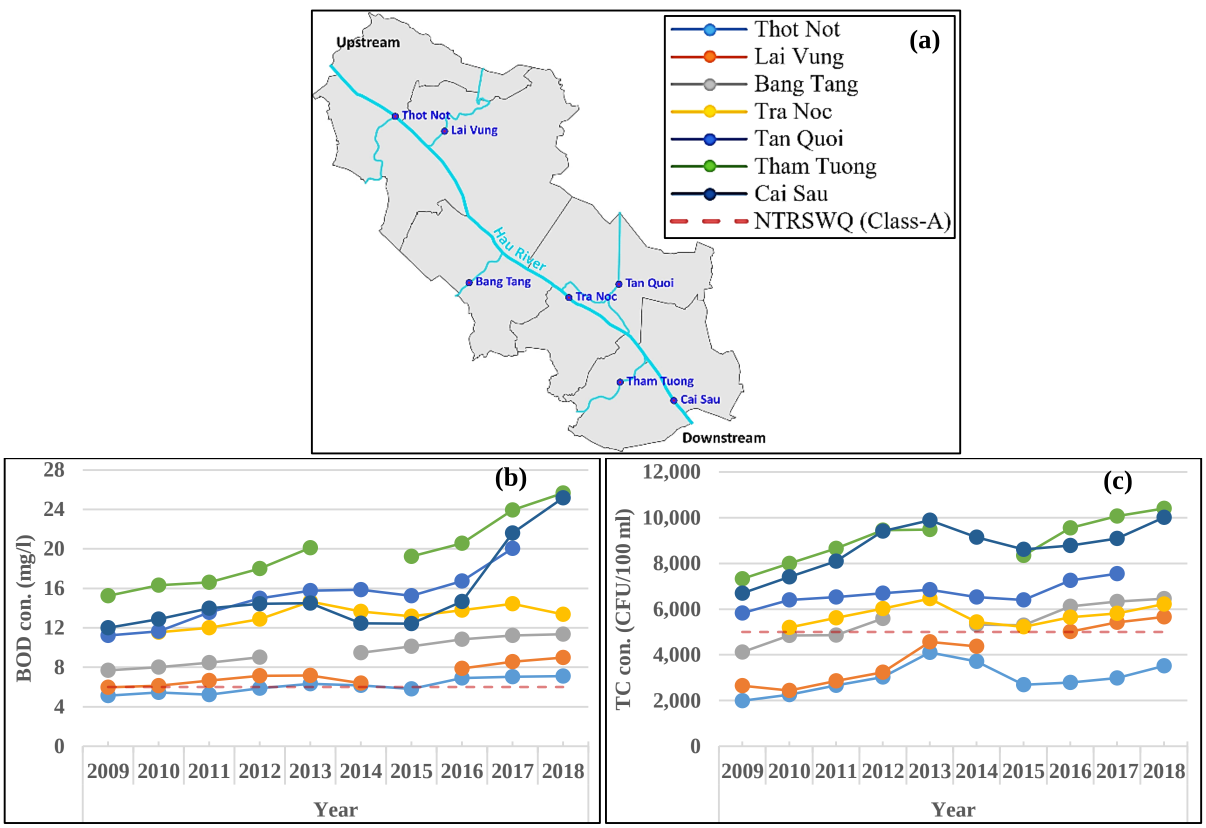
Figure 4.1 The location of the study area's nine districts along the Hau River (light blue) with several hydrological and water quality monitoring stations (dark blue) from upstream to downstream areas

Table 4.1 The nine districts' area and population characteristics in the study area

City	District considered for this study	Area (km^2)	Percentage of the city's total area (%)	Total population (people)		Percentage of the city's total population (%)
				2018	2030	
Can Tho	Thot Not	121	29.18	172,786	274,878	62.94
	O Mon	132		140,712	223,853	
	Binh Thuy	71		125,739	200,033	
	Ninh Kieu	29		269,541	428,802	
	Cai Rang	67		98,320	156,413	
Dong Thap	Lap Vo	246	14.30	180,266	234,586	20.33
	Lai Vung	238		163,912	213,304	
Vinh Long	Binh Tan	158	16.94	96,327	125,353	17.75
	Binh Minh	94		90,327	117,545	
Total		**1,156**	**19.99**	**1,337,931**	**1,974,767**	**33.67**

The surface water of the Hau River is the main water source supplied for all daily activities in these nine districts, while residents in the remaining rural districts mostly use groundwater for their water demand. Although there are abundant water resources available in the Hau River to cater to these nine districts' general demand, the growth of point and non-point pollution sources in recent years has increasingly become a matter of concern, especially for this river's water quality management. Therefore, the city's environmental reports since 2018 have clearly pointed out that converting the Hau River water quality from Class-B to A will be one of the leading policy priorities of the city's government in the next stages (CTCPC, 2016, 2019a; Long and Cheng, 2018). In the case of the Hau River, point wastewater sources generated by rapid population and industrial growth along two river banks (i.e., residential wastewater in Can Tho City; industrial runoff in both Can Tho, Dong Thap, and Vinh Long Cities; etc.) are considered the main reasons causing water pollution in this river (CTCPC, 2019b). To support this fact, seven monitoring stations and spatiotemporal trends in BOD, TC, NO_3^-, and PO_4^{3-} concentrations at an annual average for some monitoring stations across the study area in the period of 2009–2018 are shown in Figure 4.2.

As can be seen from Figures 4.2b, 2c, 2d, and 2e, all BOD, TC, NO_3^-, and PO_4^{3-} concentrations have mostly shown upward trends over these 10 years except for slight decreases from 2013 to 2015 thanks to a series of environmental projects (rehabilitating canal network, building an industrial WWTP, etc.) implemented during these three years (CTCPC, 2014; ODAPMU, 2016). However, these parameters' levels, especially BOD and TC, have significantly re-increased since 2016 due to the rapid urbanization, population growth, and land-use changes in recent years (CTCPC, 2019b). Noticeably, BOD and TC concentrations are much higher compared to Class-A of the NTRSWQ, while an opposite trend can be seen in NO_3^- and PO_4^{3-} levels that are within the permissible ones. It is noteworthy that the upward trends of NO_3^- and PO_4^{3-} levels are contradictory to that showing lightly downward trends in Figure 3.11 of Chapter 3. This opposite can be explained by that these two water quality parameters are mainly indicative of agricultural practices (i.e., inputs of inorganic fertilizers) and disturbed soil erosion, and the presence of them in the Hau River water is caused not only by farming runoff in these three cities but also by intensively agricultural activities and erosion of disturbed soil in the upstream regions (i.e., An Giang Province) especially in the flooding season (Figure 4.1). As shown in Figure 4.2, another thing to note is that the pollution status is more serious in the Hau River downstream areas, where the most populous districts of the study area are located with many residential zones, trading centers, and industrial parks.



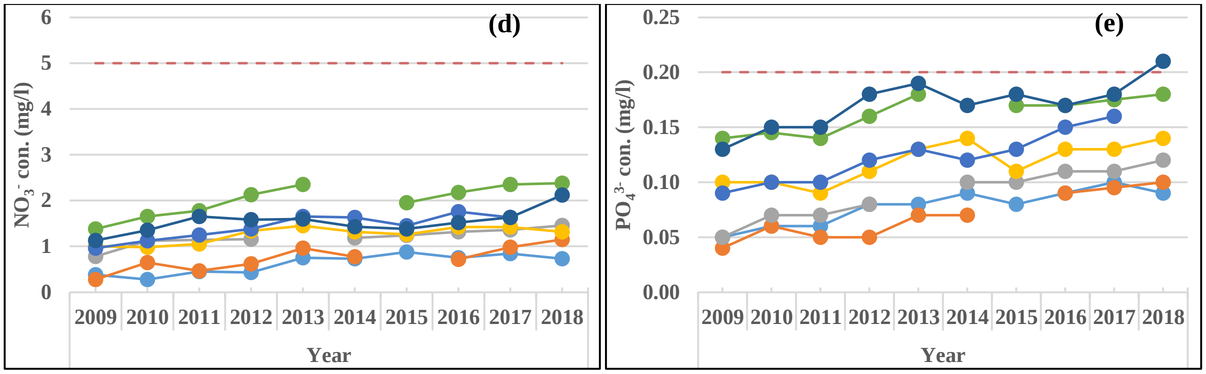


Figure 4.2 The BOD (b), TC (c), NO_3^- (d), and PO_4^{3-} (e) concentrations at a number of monitoring stations (a) across the study area in the 10-year period of 2009–2018

Noticeably, despite the reticulated water supplies system, there is a lack of sufficient WWTPs to handle both domestic and industrial wastewater generated in these heavily urbanized districts (CTCPC, 2019b). At present, only one domestic WWTP with a treatment capacity of 30,000 m^3 per day is functional in the study area. It accounts for only more than 25% of the study area's total daily discharged domestic wastewater (CTCPC, 2019b; DOC, 2019). Regarding industrial wastewater treatment, although the WWTPs for industrial parks in the study area are currently being operated, the existing treatment capacity and efficiency do not meet the increasing water demand for industrial activities along the Hau River (Trung et al., 2019b). According to CTCPC (2019b), only five centralized WWTPs are currently being used for industrial wastewater treatment with a total treatment capacity of 70,000 m^3 per day, accounting for nearly 64% of the total daily industrial wastewater generated in the study area. Consequently, the remaining domestic and industrial wastewater is discharged directly into the Hau River and its diversion network.

In the current cities' master plan, therefore, developing policies and strategies to sustain rapid urbanization, significant industrial development, economic activities while maintaining desired water resources for the future are prioritized in these three cities (Long and Cheng, 2018; MOPI, 2018a; DTCPC, 2020). One of the current priorities for these cities is to expand advanced centralized WWTPs (CTCPC, 2016; CTCPC, 2019a) to cater to all wastewater generated and achieve the ambient water quality of Class-A prescribed by the Vietnamese national standard (CTCPC, 2016).

4.3 Methodology

4.3.1 The WEAP Model

In this study, the WEAP model was used to simulate rainfall-runoff and water quality variables in different scenarios to assess water quality management and policy alternatives amidst the population growth, industrial extension, and climate change in the Hau River basin. Due to the Hau River's important role for many cities, transboundary characteristics, and adequacy of dataset required for the data-intensive WEAP model, this river was opted for this simulation. Spatiotemporal river pollution analyses were carried out in the scenario of wastewater increase and then proposed both new rehabilitated WWTPs and RWTPs. The flowchart for the research methodology is shown in Figure 4.3.

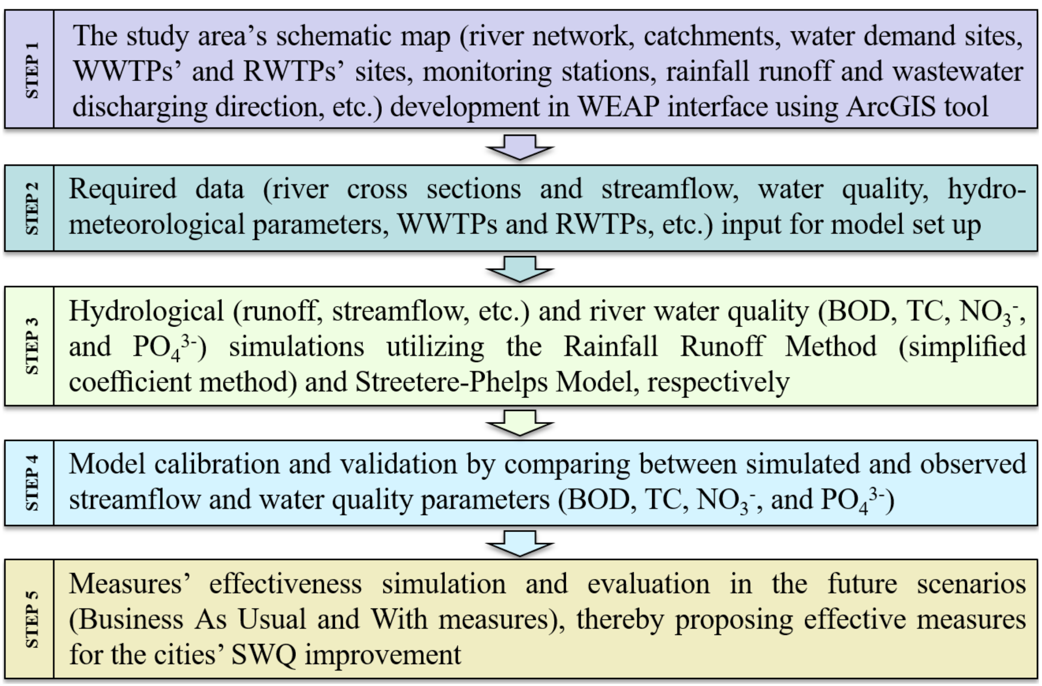


Figure 4.3 Flowchart for the research methodology

4.3.2 Hydrological/Catchment Simulation

With support from the Geographic Information System (GIS) and remote sensing (RS), the study area's schematic maps were generated in the WEAP interface (Figure 4.4). Based on the geographical, topographical, geomorphological, hydrological, and climatic features as well as confluence points, then, the study area was required to be divided into nine smaller catchments. These catchments will be one of the main components for the hydrological simulation in the WEAP model (Sieber and Purkey, 2015; Kumar, 2018).

Due to data availability, the Rainfall-Runoff method (simplified coefficient method) among five different methods available was applied for the catchment simulation in this research. This method can simulate different components of the hydrologic cycle, including the catchment's potential evapotranspiration (by using crop coefficients), surface runoff, and infiltration of rainfall. In more detail, the available precipitation for the potential evapotranspiration (PrecipAvailableForET) and the catchment's potential evapotranspiration (ETpotential) were calculated by equations based on the real precipitation (Precip), catchment's area (Area), effective precipitation (PrecipEffective), reference evapotranspiration (ETreference), and crop coefficients (K_c) (Eqs. (1) and (2)). The runoff to both groundwater (RunoffToGW) and surface water (RunoffToSurfaceWater) can be calculated with equations (3), (4), and (5) (Sieber and Purkey, 2015).

$$\mathrm{PrecipAvailableForET_{LC}} = \mathrm{Precip_{HU}} * \mathrm{Area_{LC}} * 10^{-5} * \mathrm{PrecipEffective_{LC}} \tag{1}$$

$$\mathrm{ETpotential_{LC}} = \mathrm{ETreference_{HU}} * \mathrm{Kc_{LC}} * \mathrm{Area_{LC}} * 10^{-5} \tag{2}$$

$$\mathrm{Runoff_{LC}} = \mathrm{Max}\ (0, \mathrm{PrecipAvailableForET_{LC}} - \mathrm{ETpotential_{LC}}) \tag{3}$$

$$\mathrm{RunoffToGW_{HU}} = \sum\nolimits_{\mathrm{LC}}(\mathrm{Runoff_{LC}} * \mathrm{RunoffToGWFraction_{LC}}) \tag{4}$$

$$\mathrm{RunoffToSurfaceWater_{HU}} = \sum\nolimits_{\mathrm{LC}}(\mathrm{Runoff_{LC}} * (1 - \mathrm{RunoffToGWFraction_{LC}})) \tag{5}$$

where, subscripts $_{LC}$ is land cover, and $_{HU}$ is hydro-unit.

Pollutant transport from a catchment accompanied by rainfall-runoff is enabled by ticking the water quality modeling option. The surface runoff takes the accumulated pollutants from the catchment surfaces during non-rainy days to the water bodies. The formula of the castaway catchment surface pollutants is by multiplying runoff volume and concentration (Sieber and Purkey, 2015). All parameters and datasets required for this hydrological/catchment simulation in this research were shown in Table 4.2.

4.3.3 Water Quality Simulation

Developed from the Streeter-Phelps model, the WEAP employs descriptive models of point source pollutant loadings that can simulate the impact of wastewater on receiving waters from demand sites and WWTPs. In terms of simulation of oxygen balance in a river, two processes are identified, which are consumption by decaying organic matter and reaeration induced by an oxygen deficit. The DO and BOD removal from water is a function of water temperature, settling velocity, and water depth (Eqs. (6), (7), (8), and (9)) (Sieber and Purkey, 2015).

$$BOD_{final}=BOD_{init}exp^{\frac{-k_{rBOD}L}{U}} \tag{6}$$

$$\text{where, } k_{rBOD} = k_{d20}^{1.047(T-20)} + \frac{v_s}{H} \tag{7}$$

BOD_{init}: The BOD concentration of the pollutant loading (mg/l) at the top of the reach, and BOD_{final}: The BOD concentration of the pollutant loading (mg/l) at the end of reach;

T: The water temperature (in degrees Celsius); H: The depth of the water (m); and L: The reach length (m), and U: The water velocity in the reach; and v_s: The settling velocity (m/s);

$k_r = 0.4$; $k_d = 0.4$ and $k_a = 0.95$: The re-aeration, decomposition, and reaction rates, respectively (1/time), and k_{d20}: The decomposition rate at a reference temperature of 20 degrees Celsius.

Oxygen concentration in the water is a function of water temperature, DO, and BOD:

$$\text{Oxygen saturation or } OS = 14.54 - (0.39T) + (0.01T^{2)} \tag{8}$$

$$O_{final} = OS - \left(\frac{k_d}{k_a - k_r}\right)\left(exp^{\frac{-k_r L/U}{U}} - exp^{\frac{-k_{ra} L/U}{U}}\right) BOD_{init} - [(OS - O_{init})exp^{\frac{-k_{ra} L/U}{U}}] \tag{9}$$

where, O_{init}: The oxygen concentration (mg/l) at the top of the reach, and O_{final}: The oxygen concentration (mg/l) at the end of the reach.

Even though these different parameters should be examined and measured in the individual research, most water quality parameters have been estimated from the secondary database due to the lack of time and funds (Bowie et al., 1985).

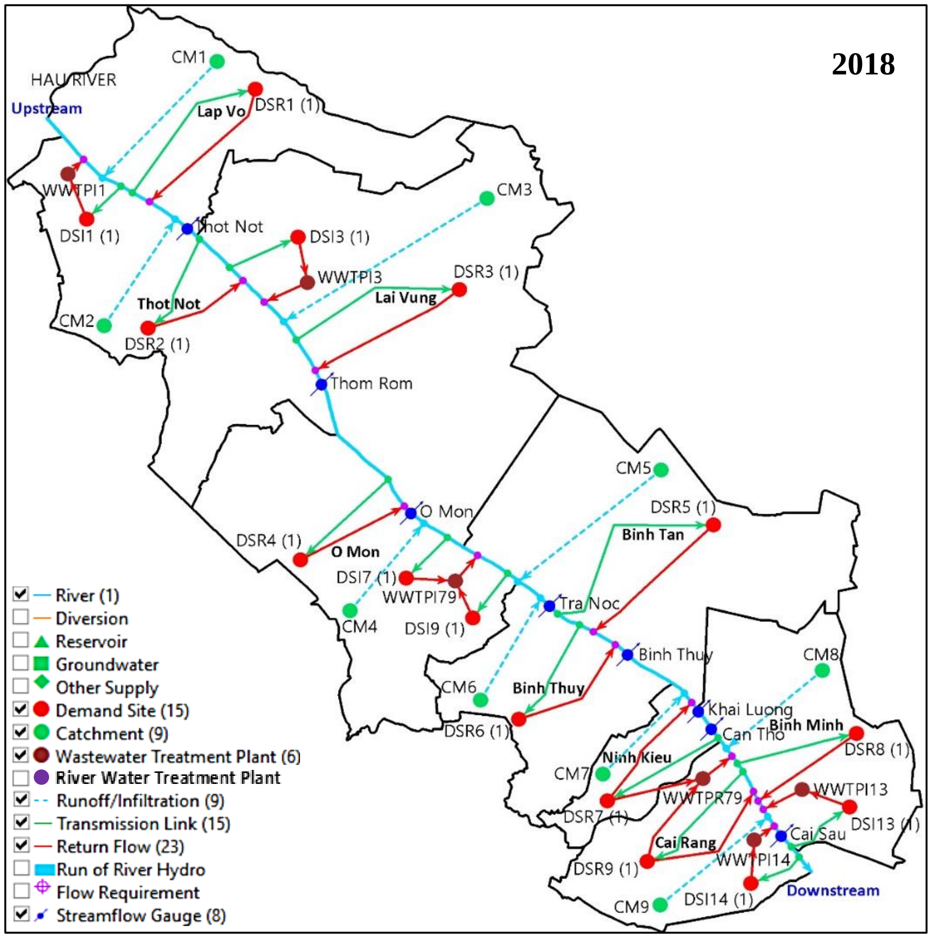
4.3.4 Data Requirement

To simulate the current status and predict the future for river water quality in the WEAP model, various input data were collected and its summary is shown in Table 4.2. The point pollution sources' locations and concentrations, past spatiotemporal water quality, WWTPs' and RWTPs' locations and capacities, past and projected population, water consumption, and current drainage networks were considered required datasets for the water quality simulation. The historical and future climate (rainfall, evaporation, temperatures, etc.), hydrological data (river flow-stage-width relationships, river length, surface water inflows, etc.), LULC, and catchments' areas and locations were utilized for hydrological simulation. Besides, the cities' documents (reports, master plans, etc.) were also collected for the scenario building and evaluation. Noticeably, the colors shown in Table 4.2 have corresponded to that presented in Figure 4.4, indicating the links between required datasets and their usages.

Table 4.2 The summary of required parameters and dataset as well as their sources and usage for the case study

No.	Dataset		Brief description	Scale	Type	Source	Usage					
							Model setup	Hydrological simulation	Water quality simulation	Calibration	Validation	Scenario building
1	Climate	Temperature	Data in the period 2013-2018 were collected	Monthly	Secondary	DOHM	✓	✓	-	-	-	-
		Evaporation					✓	✓	-	-	-	-
		Precipitation, effective rainfall	Data in the period 1979-2018 were collected				✓	✓	✓	✓	-	✓
2	Hydrology and LULC	River streamflow	Data in the period 2013-2018 were collected at the Hau Riverhead, Thot Not, Tra Noc, and Can Tho stations	Monthly	Secondary	DOHM, DONRE and DOC	✓	✓	✓	-	✓	-
		River cross-section and length		Yearly	Primary and secondary		✓	✓	✓	-	-	-
		Catchment area and slope	Data in the period 2013-2018 and 2030 were collected		Secondary		✓	✓	-	-	-	-
		LULC, runoff/infiltration ratio					✓	✓	-	✓	-	-
3	Population, industry and water use-related issues	Population growth	Data in the period of 2013-2030 were collected	Yearly	Secondary	Statistical Office and UN DESA	✓	-	✓	-	-	✓
		Industrial growth		5-yearly		Statistical Office and DOC	✓	-	✓	-	-	✓
		Water consumption		Daily		DONRE and DOC	✓	-	✓	-	-	✓
		Wastewater discharge			Primary and secondary		✓	-	✓	-	-	✓
4	Water quality	Surface water quality	BOD, TC, NO_3^-, and PO_4^{3-} levels in the period of 2013-2018 were collected at Thot Not, Thom Rom, O Mon, Tra Noc, Binh Thuy, Khai Luong, and Cai Sau stations	Quarterly	Secondary	DONRE	✓	-	-	-	✓	-
		Riverhead water quality	BOD, TC, NO_3^-, and PO_4^{3-} levels at the Hau Riverhead and from catchments' runoff in the period of 2013-2018 were collected	Yearly			✓	-	✓	✓	-	-
		Point sources of pollution	The current and future locations of these sources as well as their BOD, TC, NO_3^-, and PO_4^{3-} levels were collected	-			✓	-	✓	-	-	✓
5	WWTPs	Number and location	Historical, current, and future data were collected	-	Secondary	DONRE and DOC	✓	-	✓	-	-	✓
		Capacity		Daily			✓	-	✓	-	-	✓
		Technology and efficiency		-			✓	-	✓	-	-	✓
6	Drainage network	Location	Data in the period of 2013-2018 were collected	-	Secondary	DONRE and DOC	✓	-	✓	-	-	-
		Connection rate		-			✓	-	✓	-	-	-

To model water quality with WEAP, schematic diagrams (the virtual representation of the contributory elements of the water pollution in the study area) for both the current stage (the year 2018) and the target year (the year 2030) were prepared as shown in Figure 4.4. As mentioned earlier, the Hau River basin was also divided into nine smaller catchments (CMs) areas with inter-basin transfers. Water demand sites (red dots) for residential (DSRs) and industrial (DSIs) zones mainly give a schematic representation of current and future water consumption in the study area. Based on the study areas' population and industrial distribution, their areas and locations were identified in the catchments along the Hau River. Regarding WWTPs, in the cities, these plants are often built and placed inside or near industrial and residential zones. Thus, in this study, the locations of existing and planned WWTPs were also identified based on the cities' reports, master plans, and land-use planning maps; while proposed RWTPs' sites were located based on the simulated results of river water quality conditions from the model using the scenario WMs (WM100). Located along the Hau River, gauges (dark blue nodes) represent water quality and streamflow monitoring stations. For more details, water quality data were monthly measured at Thot Not, Thom Rom, O Mon, Tra Noc, Binh Thuy, Khai Luong, and Cai Sau stations, while streamflow data were monthly recorded at three stations, namely Thot Not, Tra Noc, and Can Tho.


2018
HAU RIVER
Upstream
Downstream
CM1
CM2
CM3
CM4
CM5
CM6
CM7
CM8
CM9
DSR1 (1)
DSR2 (1)
DSR3 (1)
DSR4 (1)
DSR5 (1)
DSR6 (1)
DSR7 (1)
DSR8 (1)
DSR9 (1)
DSI1 (1)
DSI3 (1)
DSI7 (1)
DSI9 (1)
DSI13 (1)
DSI14 (1)
WWTPI1
WWTPI3
WWTPI79
WWTPR79
WWTPI13
WWTPI14
Lap Vo
Thot Not
Lai Vung
O Mon
Binh Tan
Binh Thuy
Ninh Kieu
Binh Minh
Cai Rang
Thot Not
Thom Rom
O Mon
Tra Noc
Binh Thuy
Khai Luong
Can Tho
Cai Sau
River (1)
Diversion
Reservoir
Groundwater
Other Supply
Demand Site (15)
Catchment (9)
Wastewater Treatment Plant (6)
River Water Treatment Plant
Runoff/Infiltration (9)
Transmission Link (15)
Return Flow (23)
Run of River Hydro
Flow Requirement
Streamflow Gauge (8)

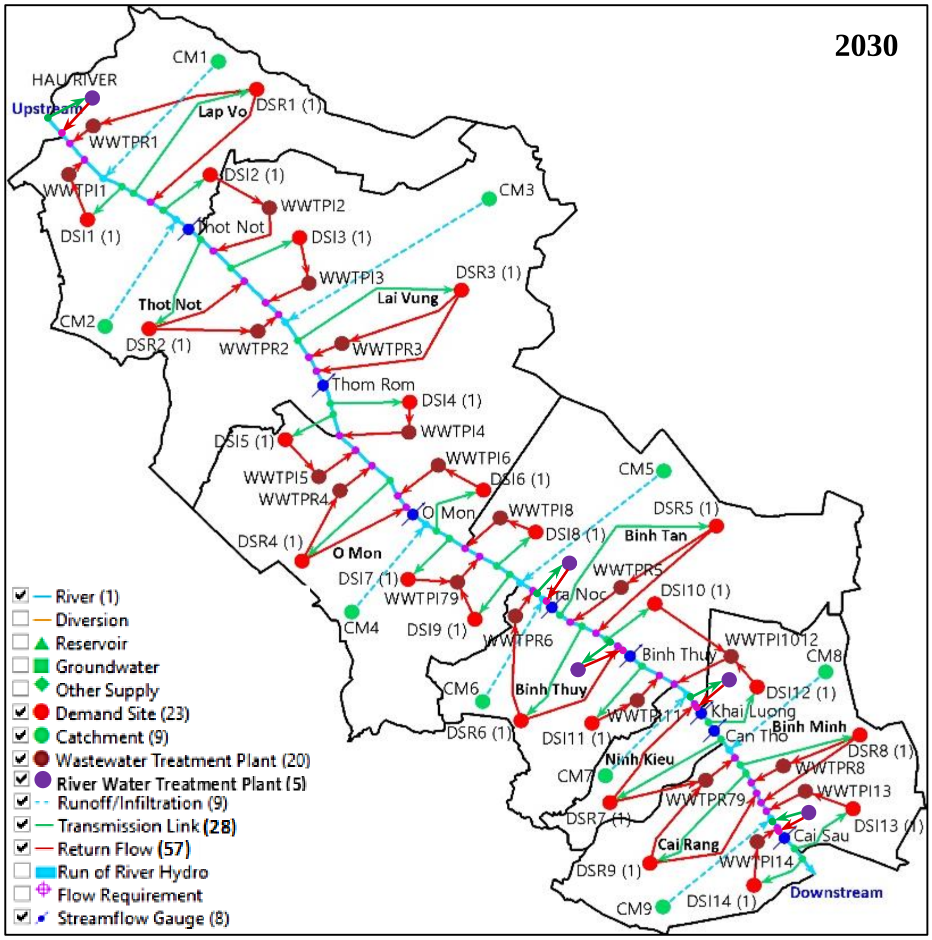


Figure 4.4 The current (2018) and future (2030) schematic maps in the WEAP interface showing key components utilized for the Hau River surface water quality modeling

Historical climatic data, including daily temperature, rainfall, and evaporation for the 40 years from 1979 to 2018, were collected from the Department of Hydro-Meteorology of the cities (DONRE, 2019). Instead of using rainfall from 2018, the 10-year average rainfall in the period of 2009–2018 from this study area was considered the current rainfall for setting up the model to reduce the bias influence of climate variability on simulated outcomes. For climate change impact on water quality analysis, the future prediction of precipitation was done using different Global Climate Models (GCMs), and Representative Concentration Pathway (RCP) output was used after downscaling and bias correction. Changes in average monthly precipitation were calculated as an indicator of climate change on river water quality. Statistical downscaling and trend analysis (a less demanding computation technique to reduce biases in the precipitation frequency and intensity) (Goyal and Ojha, 2011) were employed to get monthly climate variables. A historical rainfall analysis with monthly precipitation data of 25 years (1989 – 2013) was integrated. In the proposal of climate change mitigation strategies, understanding and examining the potential impacts of climate change are vital. Based on the above-mentioned historical rainfall analysis of 25 years, in this research, an assessment of the possible climate change (mainly rainfall change) in the study area over the period 2020–2044 was carried out by using MRICGCM3 and MIROC5 as GCMs with RCP4.5 and RCP8.5 emission scenarios.

Similarly, LULC and hydrological data used in this research were also collected from the cities' Department of Hydro-Meteorology (DOHM), Department of Construction (DOC), and Department of Natural Resources and Environment (DONRE). As mentioned above, Thot Not, Tra Noc, and Can Tho are streamflow monitoring stations in the study area (Figure 4.1). In which, monthly streamflow data have been measured in Thot Not and Tra Noc since 2013, while Can Tho station was established for monitoring since 2001 (DONRE, 2019; MRC, 2020). In this study, the collected data were applied for the calibration and validation processes by comparing them with the simulated values from the WEAP hydrology module simulation. In detail, average monthly streamflow values for the period of 2013–2018 at upstream stations namely Thot Not and Tra Noc were used for calibration, while validation was separately done at Can Tho station located at the downstream area because of observed data availability for a longer period. Parameters utilized for the calibration process are effective precipitation and runoff/infiltration ratio, and the steps used to achieve the best fit are shown in Table 4.3.

In this research, the Hau River water quality was assessed and simulated under the impact of wastewater discharged from industrial and domestic activities of cities' nine districts along the Hau River banks. Thus, these districts' population and industrial data in the period of 2013–2018 were collected from the cities' Statistical Offices (VNCSO, 2018; CTCSO, 2019). The DSRs mainly give a schematic representation of domestic water consumption (130, 150, and 180 liters/capita/day in 2013 – 2015 (DONRE, 2015; DOC, 2019), 2016 – 2025 (Trung et al., 2019b), and 2026–2030 periods (MOC, 2011; CTCPC, 2019b), respectively) and wastewater pollution loads (domestic discharge) per capita (DOC, 2019). In order to evaluate the impact of population growth on the future river water quality, the future population distribution at these DSRs was also calculated by ratio method using the United Nations Department of Economic and Affairs (UN DESA) projected growth rate (UN DESA, 2019). In terms of industry, the water consumption and demand of current DSIs were collected from the cities's current reports, while the ones of future DSIs were calculated and assumed based on new industrial parks' areas and functions that are planned and shown in the cities' future master plans (CTCPC, 2019b; WASSC, 2013, 2020)

For river water quality data, BOD, TC, NO_3^-, and PO_4^{3-} concentrations, which were monitored on a monthly basis for the period of 2013–2018 by the Can Tho Centre of Natural Resources and Environment, were used (DONRE, 2020a). This observed data of river water quality were seasonally compared with the simulated ones with the aim of calibrating and validating the WEAP water quality modeling component. In the calibration process, the seasonal values of BOD, TC, NO_3^-, and PO_4^{3-} concentrations in the wet (May to November) and dry (December to April) periods for the years 2013 – 2018 at four upstream stations namely Thot Not, Thom Rom, O Mon, and Tra Noc were used for calibration, while concentrations at Binh Thuy, Khai Luong and Cai Sau stations located in lower areas were utilized for validation. Table 4.3 shows the Hau Riverhead water quality parameters adjusted for the calibration process.

In the study area, the numbers of centralized WWTPs and RWTPs as wastewater and river water handling infrastructures considered for current and future scenarios were 6 (DOC, 2019) and 25 (Master Plans), respectively (Figure 4.4). In the scenarios with mitigation measures, the sewerage connection rates for households, industrial factories, and the Hau River were assumed as equals to the percentages of total wastewater and river water being transported to centralized WWTPs and RWTPs. In other words, clogging and leakage of sewerage pipelines were neglected. In this research, the sewerage pipeline systems for households and industrial factories were the only input sources of domestic and industrial wastewater into the Hau River and its tributaries, while the system used to collect polluted river water for treating was also applied for transporting river water only. In terms of technology, current WWTPs adopted in the model was of up-flow anaerobic sludge blanket reactor coupled with trickling filter (UASB-TF) type (Chernicharo and Nascimento, 2001; JICA, 2010) (with the filtering velocity: only 0.1 – 0.5 m/h) in wastewater treatment, and their average treatment efficiency for BOD, TC, NO_3^-, and PO_4^{3-} levels are calculated as 86.47%, 89.63%, 50.79%, and only 31.59% respectively (DOC, 2019). However, the key aim of the cities' master plans is to achieve Class-A of surface water quality (BOD $\leq$ 6 mg/l, TC $\leq$ 5,000 CFU/100 ml, $NO_3^- \leq$ 5 mg/l, and $PO_4^{3-} \leq$ 0.2 mg/l) (MONRE, 2015b) prescribed by Vietnamese national standard with all possible mitigation measures in the future (DOC, 2019). Therefore, more advanced treatment technology - the up-flow anaerobic sludge blanket reactor coupled with sequencing batch reactor (UASB-SBR) type (Khan et al., 2013; Kumar, 2018) will be adopted for both new WWTPs and RWTPs in the future scenarios of 2030 (CTCPC, 2016). Consequently, the average treatment efficiency of these new treatment plants for 2030 will be 97.26%, 99.72%, 75.55%, and 76.65% for the BOD, TC, NO_3^-, and PO_4^{3-} levels, respectively (DOC, 2019). For details, Table B5 indicated the characteristics of the existing and planned WWTPs as well as proposed RWTPs along the Hau River in the study area.

As mentioned earlier, the compulsory processes of the water quality simulation are the calibration and validation processes performed with river discharge and water quality parameters. Once satisfied statistically, numerical simulation using different future scenarios called BAU scenario and scenarios with mitigation measures (WM75, WM100, and WM_Opt. with WWTPs and RWTPs) will be applied.

Assumptions made: The following assumptions are made for this study.

(i) No consideration about the seasonal fluctuations of water consumption and wastewater discharge. Because the differences in water consumption and wastewater discharge between the wet and dry seasons in the city are insignificant (WASSC, 2020);

(ii) No consideration about the mixing of stormwater with domestic wastewater in the sewerage pipelines. Because, since 2017, domestic wastewater drainage pipelines have been operating independently in the city (DOC, 2019).

4.4 Results and Discussion

4.4.1 Future Pattern of Precipitation

To study the climate change impact on water quality, the change of rainfall pattern in the future was forecast using the GCMs (MRICGCM3 and MIROC5) and RCPs (RCP4.5 and RCP 8.5). Comparison of average monthly rainfall for current (i.e., 10-year average from 2009 to 2018 as previously mentioned) and future (i.e., 2030) years was shown in the line chart in Figure 4.5. Although it is evident that the differences between annual average rainfall for both the current and future simulated values are small, this study further investigates the impact of seasonal variation in rainfall patterns on water quality.

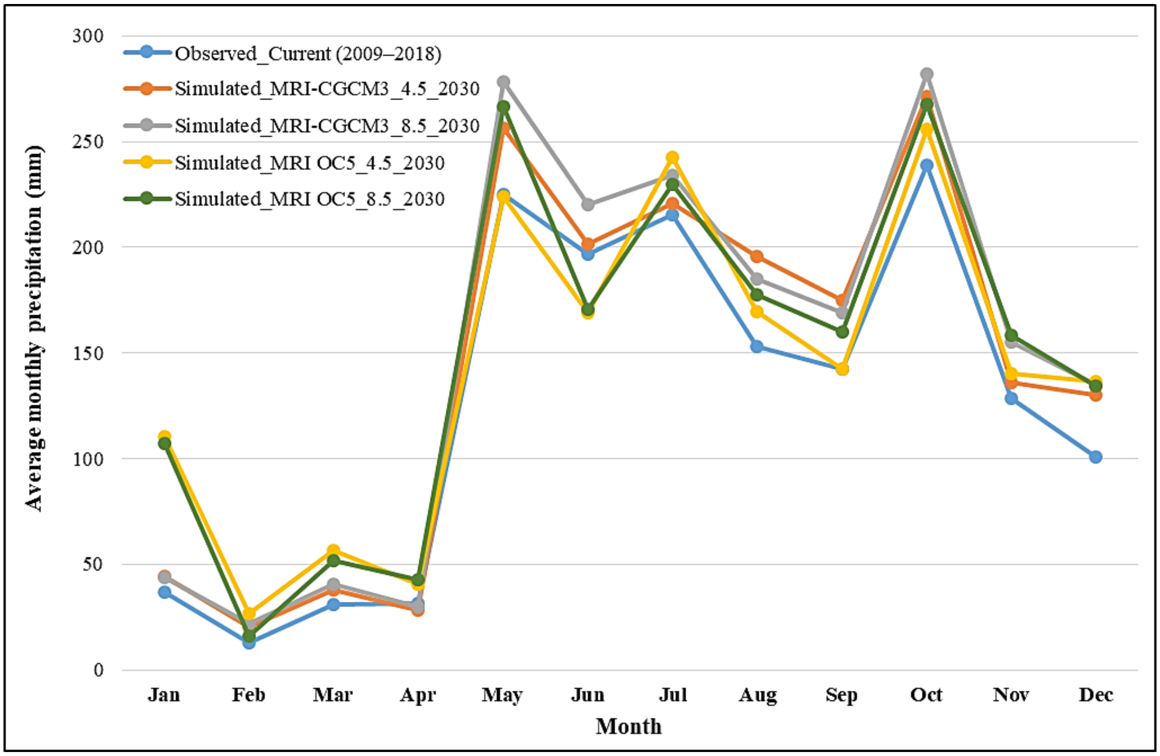


Figure 4.5 The current and future monthly precipitation at the Can Tho station

4.4.2 Population and Industrial Growth

In this study area, population growth and intensive industrialization were considered to have a potential threat to river water quality in the future. The current population of the study area in 2018 (base year) collected from the cities' Statistical Offices was 1,337,931 people (VNCSO, 2018; VLCSO, 2018). Based on the projected growth rates in the UN DESA's report (UN DESA, 2019), the ratio method was used for the study area's future population prediction (see Table B6 for projected population growth rates of the study area from 2018 to 2030). The current (2018) and future (2030) populations of each district/catchment as well as the total population of the study area were calculated and shown in Table 4.1. It is predicted that the estimated population in the target year 2030 (1,974,767 people) will be 47.6% higher than that in the base year 2018 (1,337,931 people). Remarkably, this increasing population has resulted in much higher water demand for domestic activities in the study area's residential areas in the future, from 73.25 million m^3 in 2018 to 130.33 million m^3 in 2030.Regarding industrial development in the future, based on the cities' reports and master plans, the used data are the number of new planned industrial parks; their locations and areas; and water demand (MOC, 2009; DONRE, 2015; VLCPC, 2018). Eight new planned industrial zones considered in the study area are HighTech Can Tho, O Mon, Bac O Mon, Song Hau 2, Song Hau 3, HighTech Lai Vung, Dong Binh, and Binh Tan. The total area and daily water consumption of these planned industrial zones were 3,090 ha and 299.3 million m^3, respectively (MOC, 2011; MOPI, 2018a; DTCPC, 2015, 2020). Figure 4.6 indicates the study area's comparative water demands of residents and industry between 2018 and 2030. In the absence of precise information, the amount of wastewater being generated from both domestic and industrial sites for the WEAP modeling was calculated based on the actual demand. For example, in the case of the domestic sector, wastewater generated was roughly 80% of the total water being consumed (DOC, 2019), whereas for the industrial sector it was 75% (JICA, 2017; CTCCP, 2019b; WASSC, 2020).

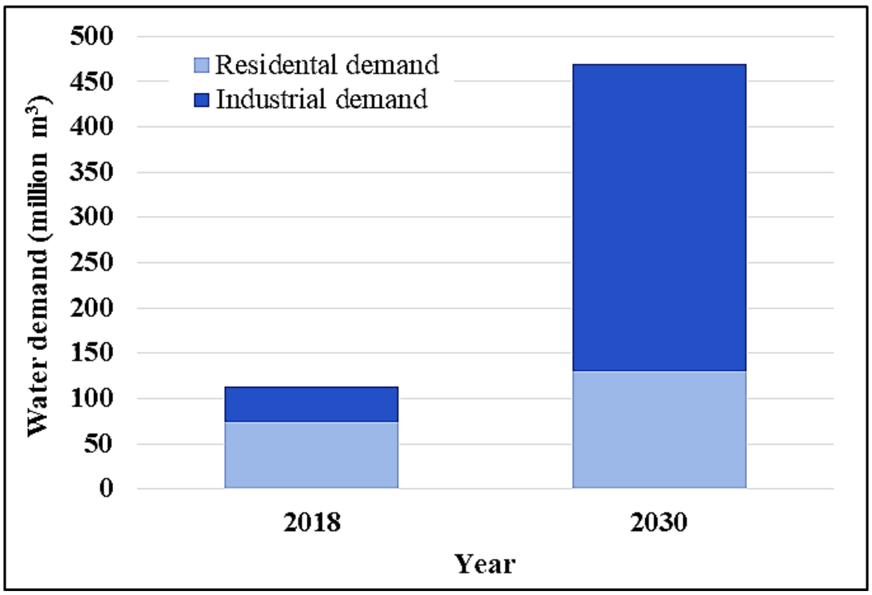


Figure 4.6 The comparative water demands of residents and industry activities in the study area between 2018 and 2030

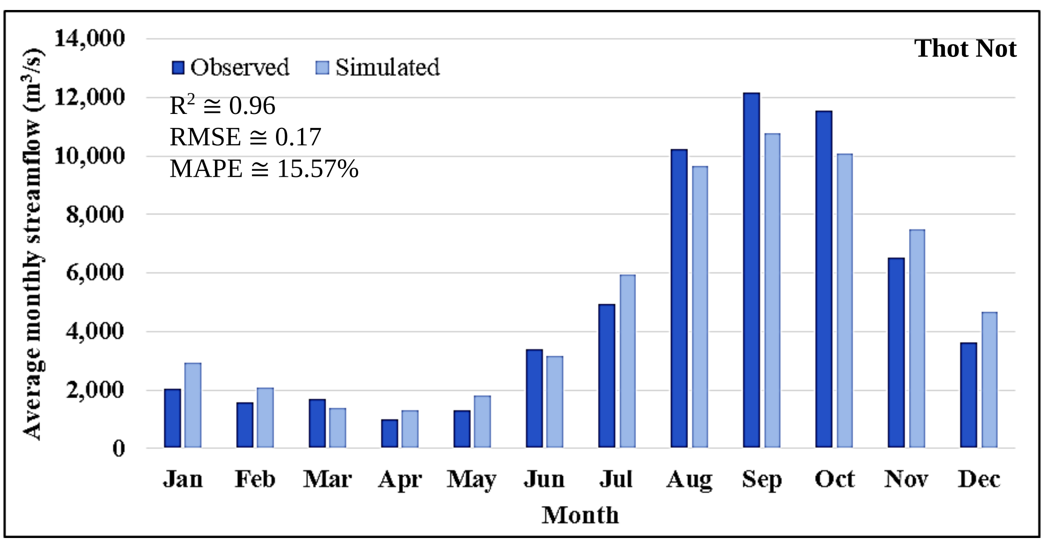
4.4.3 Water Quality Simulation

4.4.3.1 Model Performance Evaluation

For streamflow and water quality calibration processes, effective precipitation, runoff/infiltration ratio, and the Hau Riverhead water quality parameters (with their best-fit values shown in Table 4.3) were adjusted using the trial-and-error method. These processes aim to obtain simulated results having a high association with observed values. The association level is represented by correlation coefficients R-squared (R^2), root mean square error (RMSE), and mean absolute percentage error (MAPE). The calibration and validation results of hydrological components through comparative results between the average monthly observed and simulated streamflow for the year 2013 – 2018 at three hydraulic stations (namely Thot Not, Tra Noc, and Can Tho) in the Hau River were shown in Figure 4.7. Basically, both simulated and observed streamflow for both Thot Not, Tra Noc, and Can Tho stations have shown high associations supported by $R^2 \cong 0.96$, RMSE ≅ 0.17, and MAPE ≅ 15.57%; $R^2 \cong 0.99$, RMSE ≅ 0.10, and MAPE ≅ 6.06%; and $R^2 \cong 0.99$, RMSE ≅ 0.11, and MAPE ≅ 5.73%, respectively.

Table 4.3 Summary of parameters and steps used for streamflow and water quality calibration processes

Parameter	Initial value	Best-fit value	Step
Streamflow calibration			
Effective precipitation (%)	100	98	±0.5
Runoff/infiltration ratio (%)	50/50	40/60	±5/5
Water quality calibration			
Riverhead's BOD (mg/l)	8	5	±0.5
Riverhead's TC (CFU/100 ml)	500	650	±25
Riverhead's NO_3^- (mg/l)	1	0.5	±0.1
Riverhead's PO_4^{3-} (mg/l)	0.07	0.055	±0.005



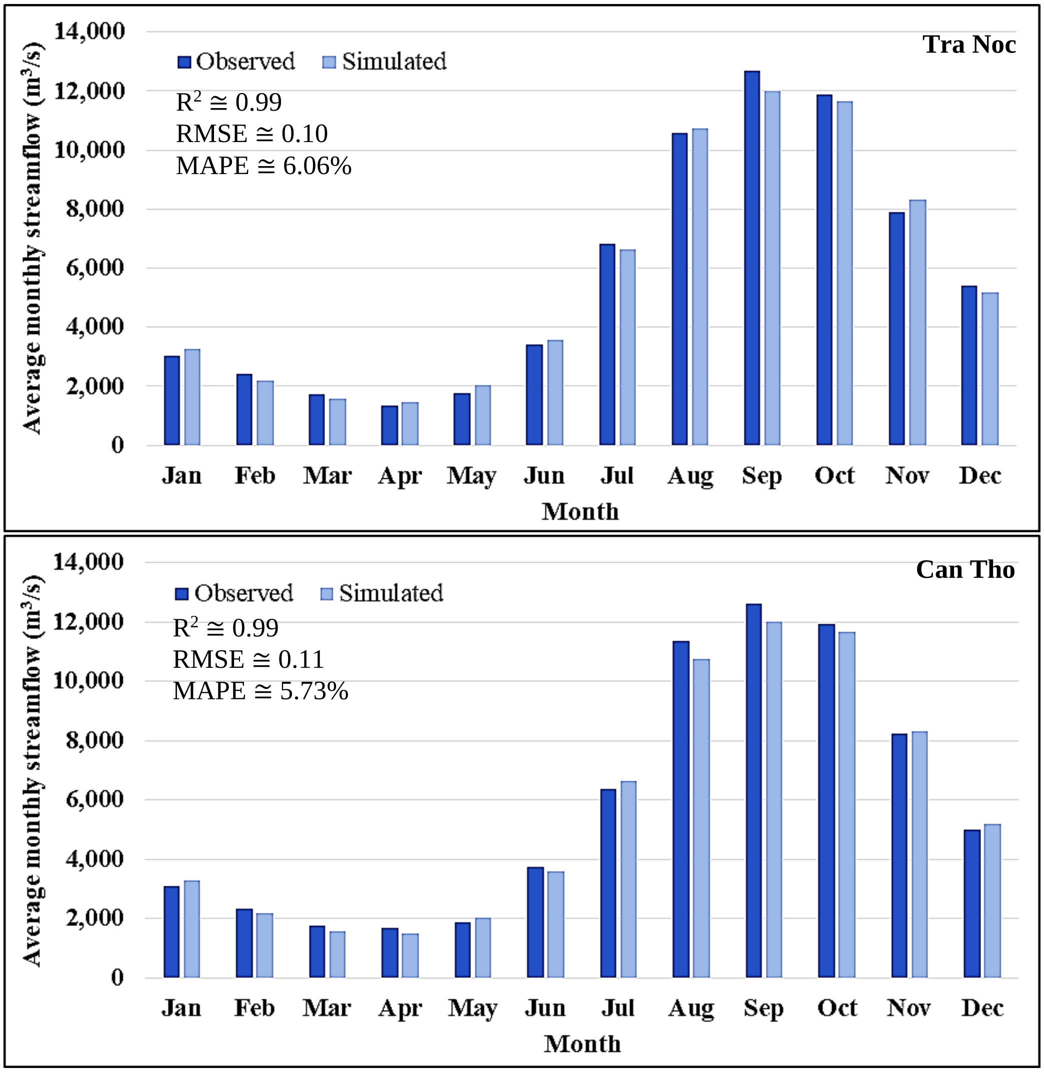
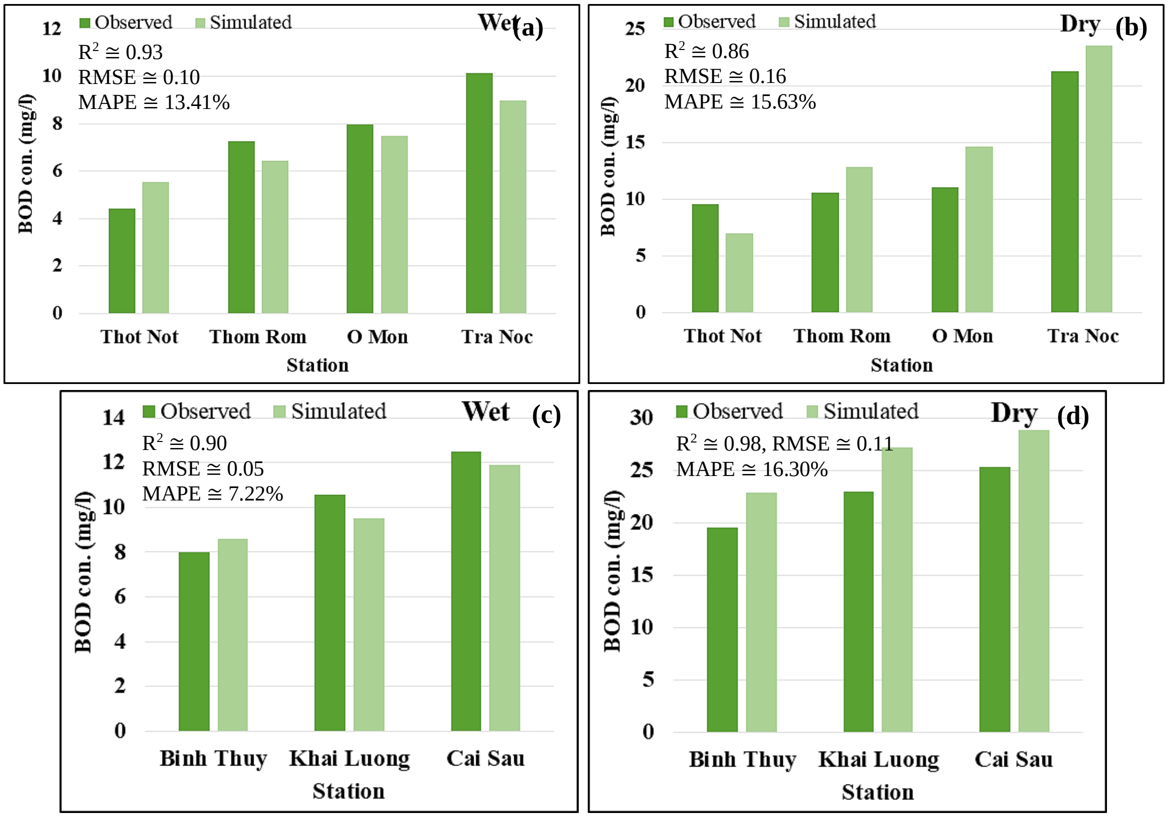
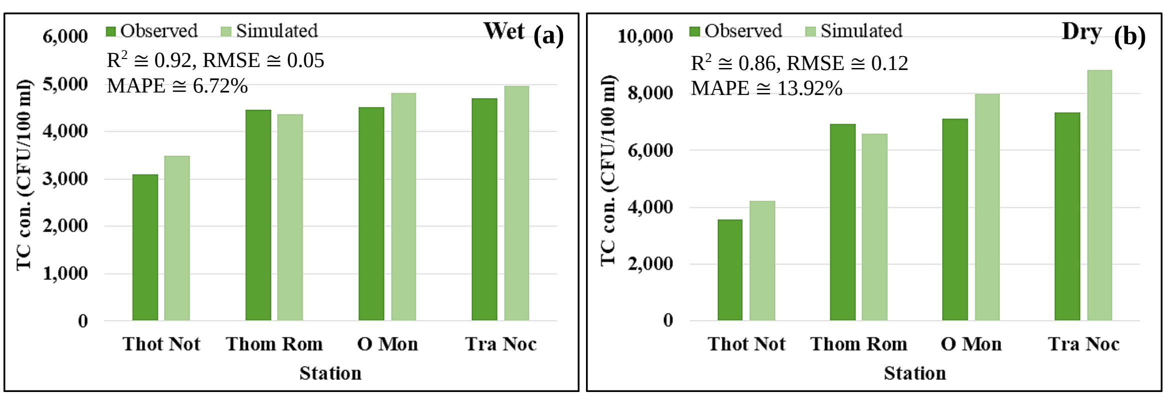


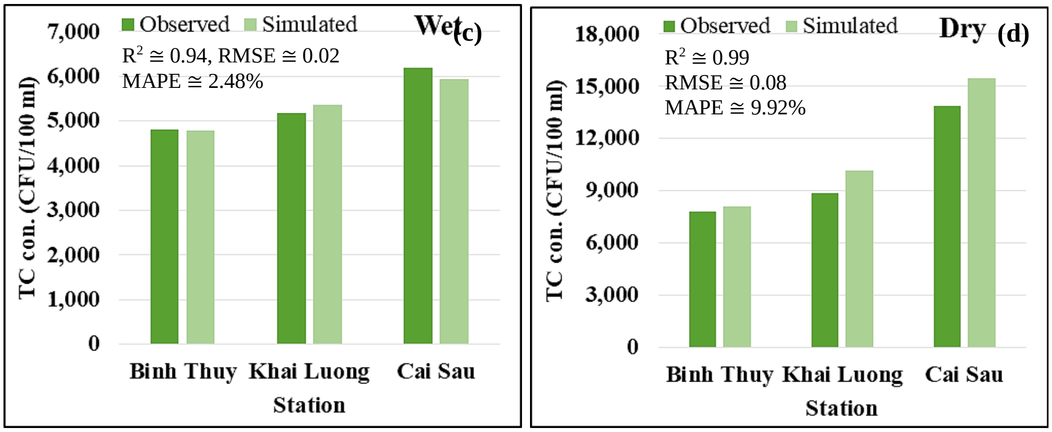
Figure 4.7 The comparative values of average monthly observed and simulated streamflow for the year 2013 – 2018 for calibration (Thot Not and Tra Noc stations) and validation (Can Tho station) processes in the Hau River

Results for calibration and validation processes in case of water quality parameters i.e., BOD, TC, NO_3^-, and PO_4^{3-} were shown through the comparison between average seasonally observed and simulated concentrations for the year 2013 – 2018 at seven stations, namely Thot Not, Thom Rom, O Mon, Tra Noc (selected for calibration), Binh Thuy, Khai Luong, and Cai Sau (used for validation). As Figures 4.8, 4.9, 4.10, and 4.11 show, significant associations were also found between observed and simulated average seasonally BOD, TC, NO_3^-, and PO_4^{3-} levels in both the wet and dry periods at selected stations. These matches were expressed through the fluctuations of $R^2 \cong 0.76 – 0.99$, RMSE ≅ 0.02 – 0.16, and MAPE ≅ 2.48 – 16.61% for the comparison of these four parameters. Thus, the calibration and validation results for both streamflow and water quality parameters of the Hau River had demonstrated high reliability and suitability of the model performance for both hydrological and water quality modeling.

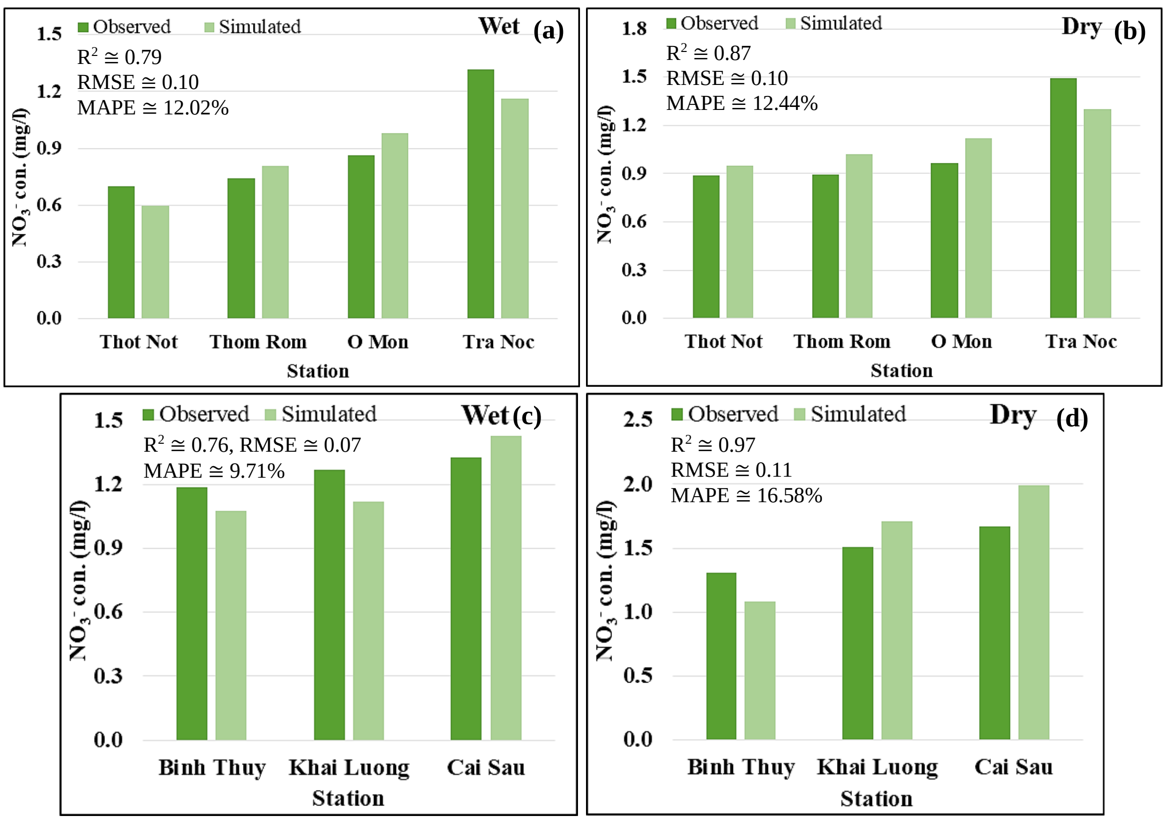


Figures 4.8 The comparative values of average seasonally observed and simulated BOD levels in the period of 2013 – 2018 utilized in the calibration (a and b) and validation (c and d) processes

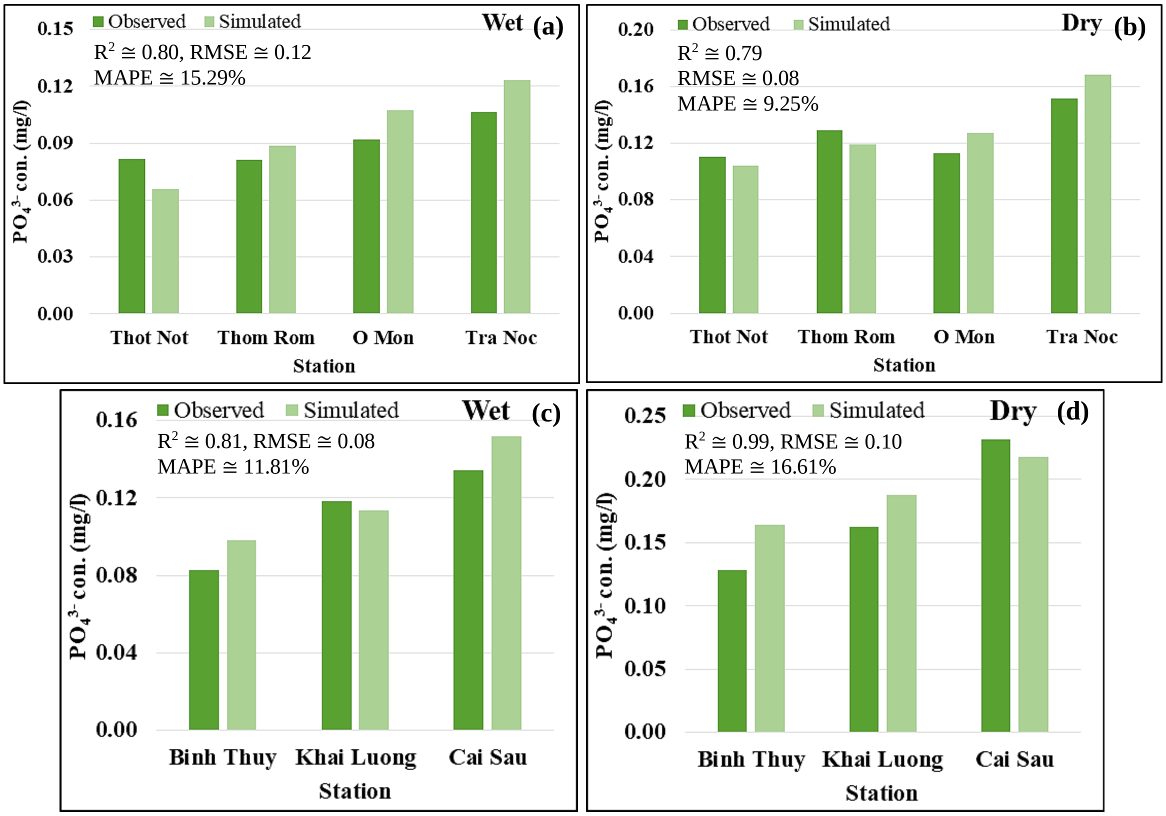




Figures 4.9 The comparative values of average seasonally observed and simulated TC levels in the period of 2013 – 2018 utilized in the calibration (a and b) and validation (c and d) processes



Figures 4.10 The comparative values of average seasonally observed and simulated NO_3^- levels in the period of 2013 – 2018 used in the calibration (a and b) and validation (c and d) processes



Figures 4.11 The comparative values of average seasonally observed and simulated PO_4^{3-} levels in the period of 2013 – 2018 used in the calibration (a and b) and validation (c and d) processes

4.4.3.2 Predicting Future Water Quality Using Scenario Analyses

Scenario analysis was done to predict possible future water quality status in both the wet and dry seasons and evaluate the effectiveness of the proposed countermeasures in water pollution mitigation. In this study, the future changes in BOD, TC, NO_3^-, and PO_4^{3-} concentrations were simulated and analyzed under four different future scenarios. While the scenario with BAU employs key drivers to water quality influence such as population growth, industrial development, and climate change (mainly rainfall changes); countermeasures i.e., wastewater treatment policy change (WWTPs' and RWTPs' application) will be included in other scenarios. Noticeably, the study area's government has often faced a number of difficulties related to the financial limitation, technology changes, and policy barriers that lead to the delayed completion of WRM projects in recent years (listed in Table 4.4). Therefore, future scenarios with mitigation measures had been built based on the study area's more realistic conditions in recent years.

Currently, to solve the current and future Hau River water pollution, the study areas' government is planning to build from 11 to 14 new centralized WWTPs with the national budget and the Japanese Official Development Assistance (ODA) loan. The major target of this investment is to collect and treat 75% to 100% of the total domestic and industrial wastewater discharged from the study areas' point pollution sources by 2030 (CTCPC, 2016). Based on the cities' current condition and future strategies, therefore, two future mitigation measures (with centralized WWTPs applied for treating 100% (WM100) and only 75% (WM75) of total wastewater, respectively) were assumed and analyzed. In addition, to achieve the ambient water quality of Class-A prescribed by the Vietnamese national standard (CTCPC, 2016) in case the WM100 scenario is unable to bring about the expected effectiveness, an optimistic scenario (WM_Opt.) has been also built. This additional scenario possesses similar components as the WM100 scenario but with the addition of five RWTPs for treating surface water at seriously polluted locations along the Hau River in 2030 (Figure 4.4). As previously mentioned, sites of planned WWTPs were identified based on the cities' reports and master plans, while proposed RWTPs' sites were located based on the pollution status of the Hau River water quality, which was simulated from the model. One thing to note is that according to CTCPC (2019b) and MOC (2020), in the study area, the total average costs investing for a water treatment plant (treatment capacity: 30,000 m^3 per day) with the technology of UASB-TF and UASB-SBR are nearly 22.69 and 24.25 million USD, respectively. All scenarios used in the study as well as their key characteristics, components, and estimated costs were briefly indicated in Table 4.5.

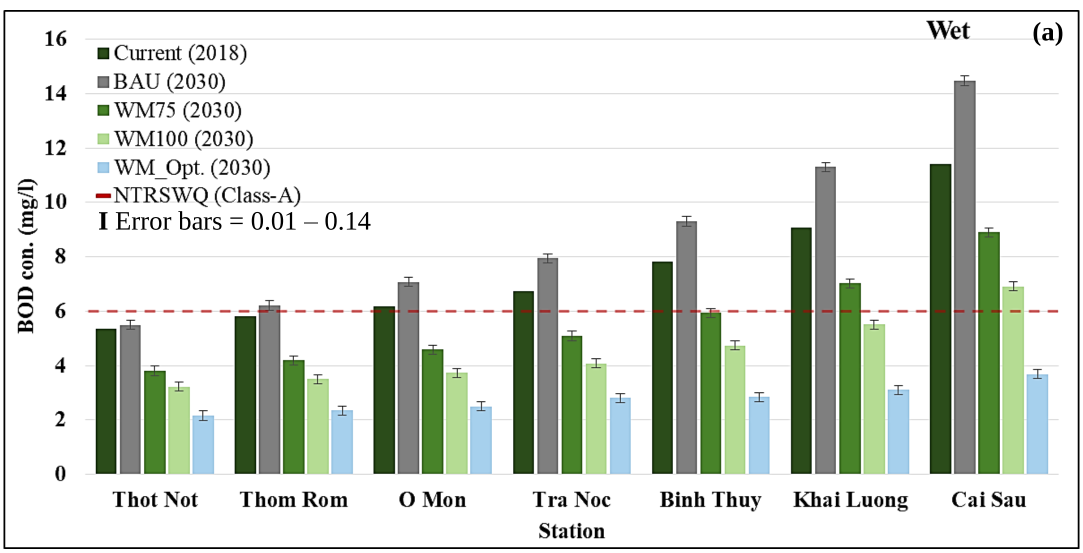
Table 4.4 The implementation progress of WRM projects in the study area in recent years

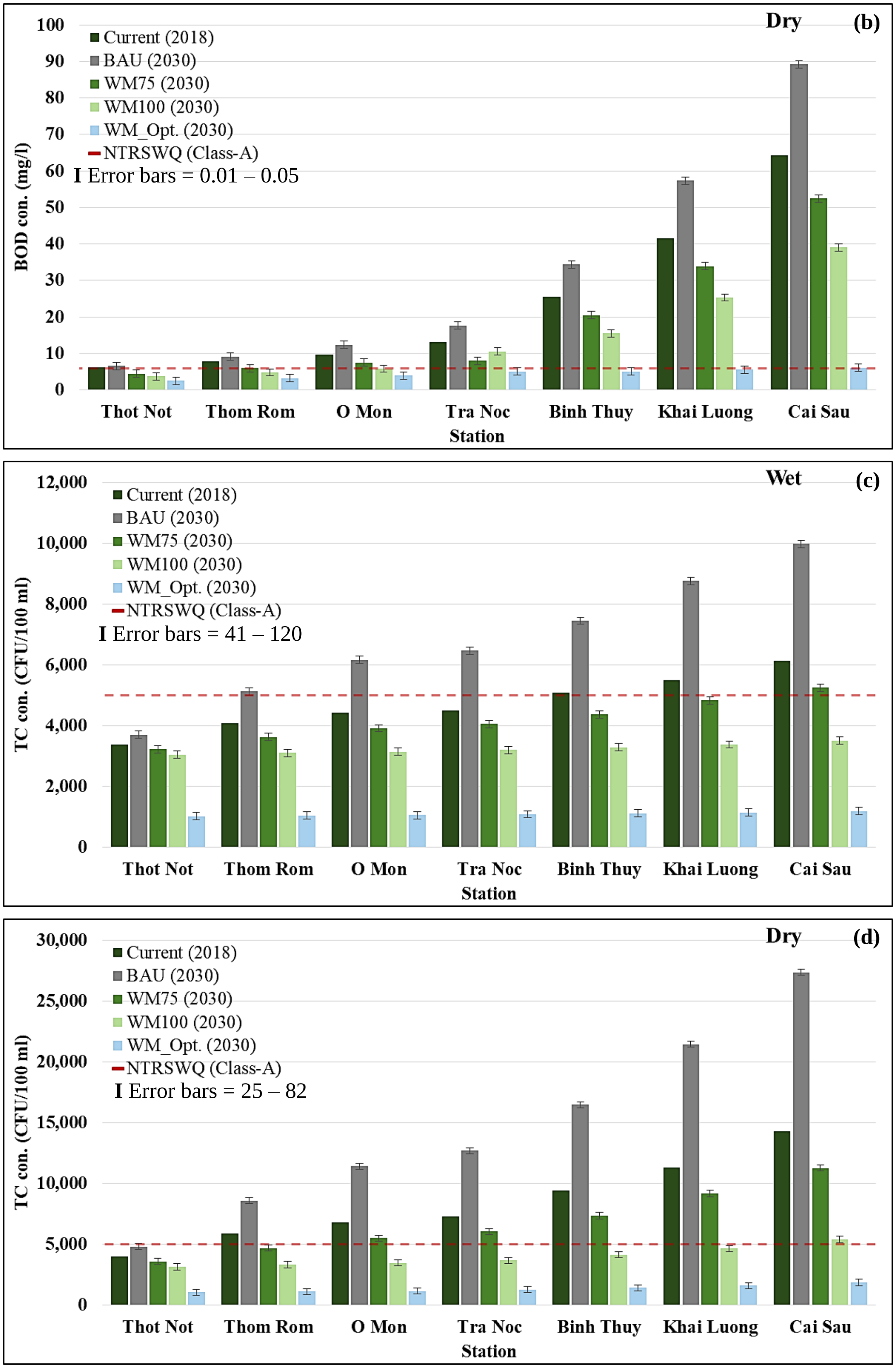
Project	**Quantity**	**Capacity(m^3/day)/ Technology**	**Cost (million USD)**	**Planned year**	**Targeted year**	**Finished year**	**Delayed gap**	**Main reasons**
Domestic WWTP	1	30/UASB-TF	21.03	2003	2006	2017	11 years	Financial shortage, changes in technology, policy barriers, etc.
Industrial WWTPs	5	70/UASB-TF	56.79	2008	2010	2016	6 years	

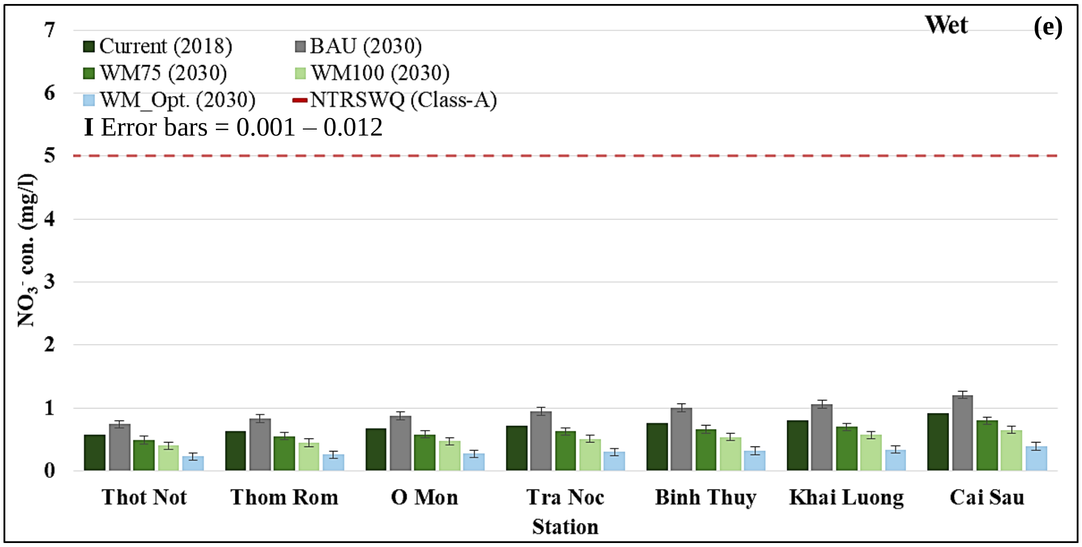
Table 4.5 The summary of key components of four different scenarios used for the future water quality simulation

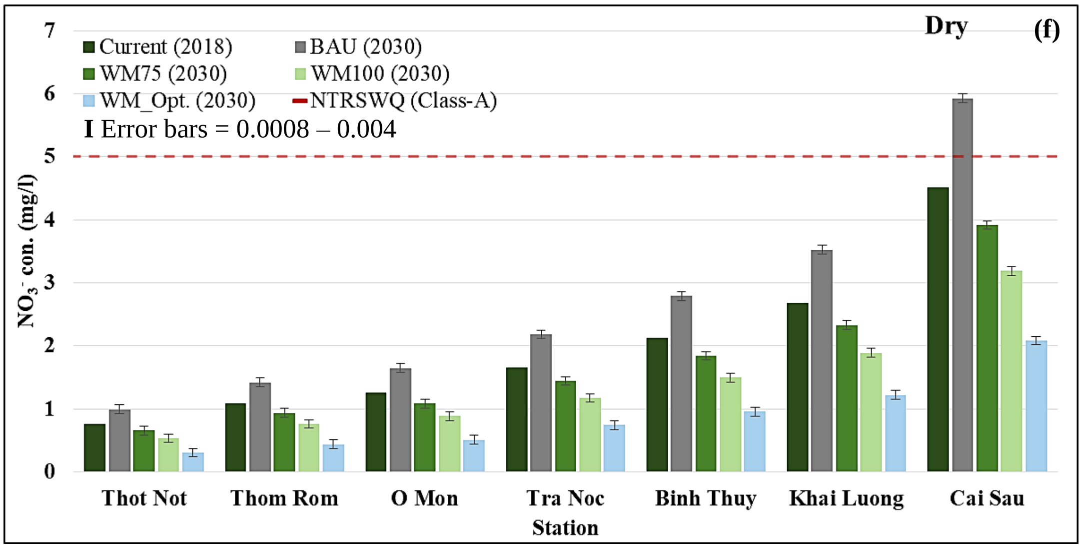
Future scenarios	Population growth	Industrial growth	Climate change	WWTPs' and RWTP's application/treatment capacity	Estimated cost (million USD)
Business as Usual (BAU)	☑	☑	☑	☑ (6 WWTPs: 100,000 m^3/day)	-
With measures_75% (WM75)	☑	☑	☑	☑ (15 WWTPs: 1,117,500 m^3/day)	☑822.48
With measures_100% (WM100)	☑	☑	☑	☑ (20 WWTPs: 1,490,000 m^3/day)	☑1,123.58
With optimistic measures (WM_Opt.)	☑	☑	☑	☑ (20 WWTPs: 1,490,000 m^3/day; 5 RWTPs: 775.000 m^3/day)	☑1,750.04

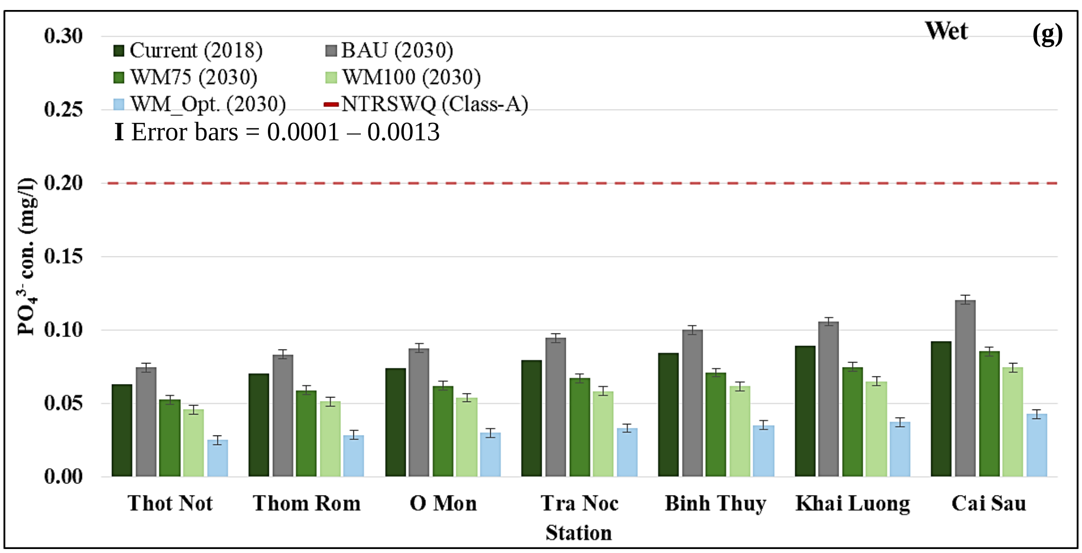
In the four considered scenarios, the BOD, TC, NO_3^-, and PO_4^{3-} concentrations of the Hau River surface water were simulated on a seasonal basis for the year 2030. After establishing proposed scenarios, the Hau River water quality simulations were modeled, and obtained results were shown in the bar charts and maps in Figure 4.12. In addition, these simulated results were also illustrated at the spatial scale in Figures 4.13 and 4.14. The differences in simulated parameters' concentrations caused by rainfall changes from the GCMs with RCP4.5 and RCP8.5 emission scenarios were shown by small bars on the top of bar charts. It can be noticed that the impacts of rainfall changes on BOD, TC, NO_3^-, and PO_4^{3-} concentrations of the Hau River water in both wet and dry seasons were negligible. This might be explained by the insignificant difference between the increased volume of rainfall in the future (as shown in Figure 4.5) and the Hau River streamflow.




Dry
(b)
Current (2018)
BAU (2030)
WM75 (2030)
WM100 (2030)
WM_Opt. (2030)
NTRSWQ (Class-A)
I Error bars = 0.01 – 0.05
BOD con. (mg/l)
100
90
80
70
60
50
40
30
20
10
0
Thot Not
Thom Rom
O Mon
Tra Noc
Binh Thuy
Khai Luong
Cai Sau
Station
Wet
(c)
Current (2018)
BAU (2030)
WM75 (2030)
WM100 (2030)
WM_Opt. (2030)
NTRSWQ (Class-A)
I Error bars = 41 – 120
TC con. (CFU/100 ml)
12,000
10,000
8,000
6,000
4,000
2,000
0
Thot Not
Thom Rom
O Mon
Tra Noc
Binh Thuy
Khai Luong
Cai Sau
Station
Dry
(d)
Current (2018)
BAU (2030)
WM75 (2030)
WM100 (2030)
WM_Opt. (2030)
NTRSWQ (Class-A)
I Error bars = 25 – 82
TC con. (CFU/100 ml)
30,000
25,000
20,000
15,000
10,000
5,000
0
Thot Not
Thom Rom
O Mon
Tra Noc
Binh Thuy
Khai Luong
Cai Sau
Station


Wet
(e)
Current (2018)
BAU (2030)
WM75 (2030)
WM100 (2030)
WM_Opt. (2030)
NTRSWQ (Class-A)
I Error bars = 0.001 – 0.012
NO3- con. (mg/l)
Thot Not
Thom Rom
O Mon
Tra Noc
Binh Thuy
Khai Luong
Cai Sau
Station


Dry
(f)
Current (2018)
BAU (2030)
WM75 (2030)
WM100 (2030)
WM_Opt. (2030)
NTRSWQ (Class-A)
I Error bars = 0.0008 – 0.004
NO3- con. (mg/l)
Thot Not
Thom Rom
O Mon
Tra Noc
Binh Thuy
Khai Luong
Cai Sau
Station


Wet
(g)
Current (2018)
BAU (2030)
WM75 (2030)
WM100 (2030)
WM_Opt. (2030)
NTRSWQ (Class-A)
I Error bars = 0.0001 – 0.0013
PO43- con. (mg/l)
Thot Not
Thom Rom
O Mon
Tra Noc
Binh Thuy
Khai Luong
Cai Sau
Station

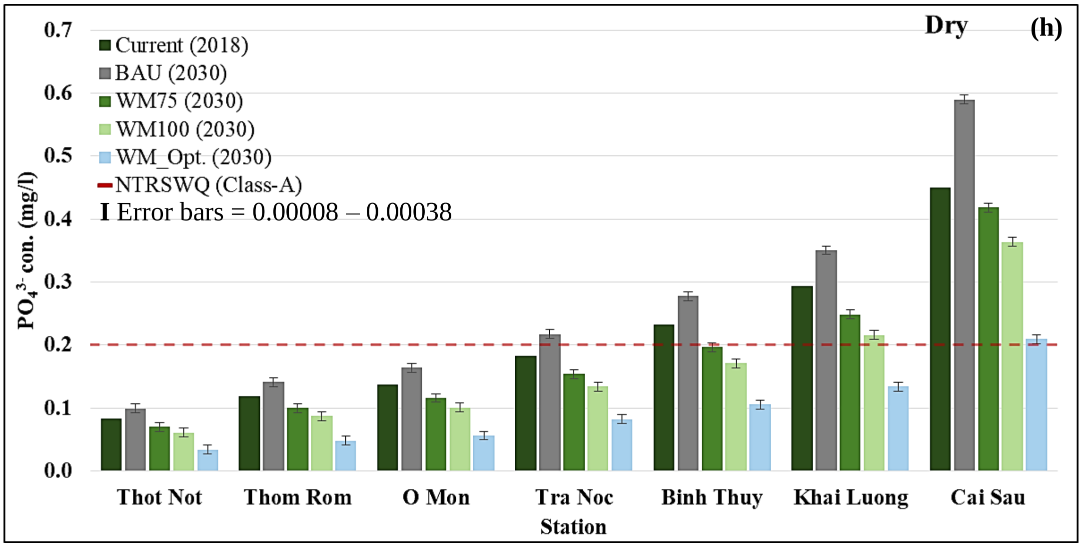


Figure 4.12 The average seasonally comparative results of simulated BOD (a and b), TC (c and d), NO_3^- (e and f), and PO_4^{3-} (g and h) levels for the current status and future scenarios. The error bars show differences in simulated levels caused by rainfall changes from the GCMs with RCP4.5 and RCP8.5 emission scenarios

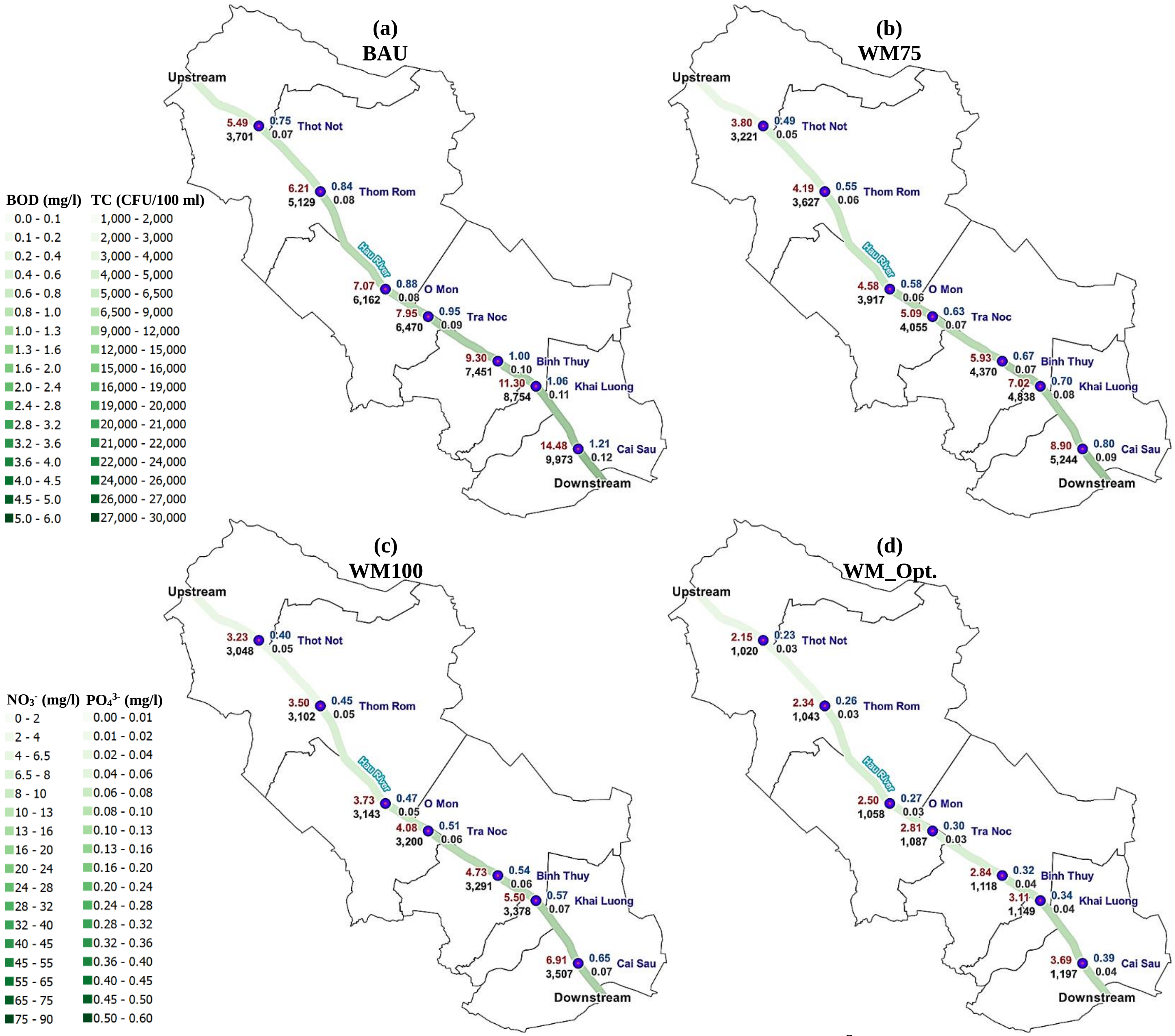


Figure 4.13 The spatial variations of BOD (red numbers), TC (black), NO_3^- (blue), and PO_4^{3-} (grey) levels simulated in scenarios in the wet season

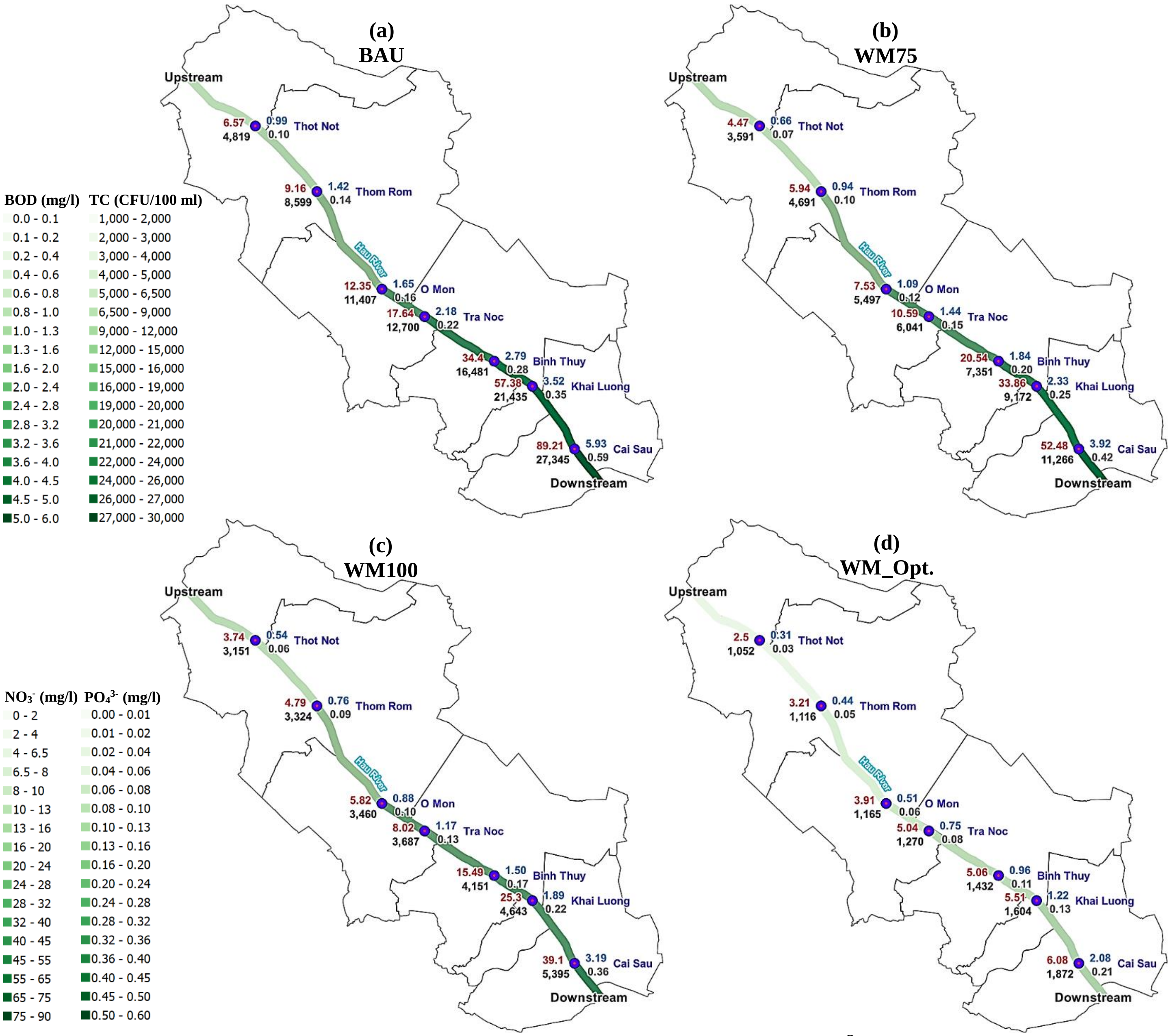


Figure 4.14 The spatial variations of BOD (red numbers), TC (black), NO_3^- (blue), and PO_4^{3-} (grey) levels simulated in scenarios in the dry season

In the current year, as can be seen from Figure 4.12, simulated BOD, TC, NO_3^-, and PO_4^{3-} concentrations from most monitoring stations, except for some ones in the Hau River downstream areas, in the wet season were not too high, fluctuating from 5.36 to 11.42 mg/l, from 3,391 to 6,127 CFU/100 ml, from 0.57 – 0.93 mg/l, and only from 0.06 – 0.09 mg/l respectively. Compared to Class-A of the NTRSWQ, the Hau River surface water quality in the wet season of 2018 was relatively polluted in terms of BOD and TC at Binh Thuy, Khai Luong, and Cai Sau stations despite this river's large discharge during the rainy period (Figures 4.12a and 4.12c). Noticeably, regarding NO_3^- and PO_4^{3-}, these parameters' current levels were much lower compared to the permissible ones of Class-A (Figures 4.12e and 4.12g). For the BAU scenario, consequently, the BOD and TC pollution has increasingly become more serious in 2030 under the impacts of intensive population and industry growths, and rainfall change without any appropriate mitigating measure applied, while NO_3^- and PO_4^{3-} concentrations are still within the desired limits of Class-A. In this scenario, it can be seen that the BOD and TC levels in the wet season at four downstream stations of the Hau River basin have sharply increased and are much higher compared to Class-A, ranging from 7.95 to 14.48 mg/l and from 6,470 to 9,973 CFU/100 ml, respectively (Figures 4.12a, 4.12c, and 4.13a). Because of the key drivers (population growth, industrial development, and climatic changes), the average levels of BOD, TC, NO_3^-, and PO_4^{3-} in the wet season will be increased by 16.01%, 40.85%, 30.49%, and 20.22%, respectively by 2030 compared to 2018 (Table 4.6).

In the dry season, the Hau River water pollution has intensively become more serious in both the current (2018) and the coming years (2030). Simulated BOD, TC, and PO_4^{3-} levels at most stations, especially for the ones downstream, in 2018 were much higher compared to Class-A of the NTRSWQ, fluctuating from 6.22 to 64.34 mg/l, from 4,024 to 14,306 CFU/100 ml, and 0.08 – 0.45 mg/l, respectively (Figures 4.12b, 4.12d, and 4.12h). Noticeably, simulated BOD, TC, and PO_4^{3-} levels at four downstream stations in 2030 for the BAU scenario will further deteriorate in comparison with these levels in the current year, ranging from 17.64 to 89.21 mg/l, from 12,700 to 27,345 CFU/100 ml, and from 0.22 to 0.59 mg/l, respectively (Figure 4.14a). These significantly high levels are mostly due to untreated wastewater discharged from future domestic and industrial activities as well as low discharge and severe droughts in the Hau River during the dry period. Regarding NO_3^- level in the BAU scenario, only the nitrogenous pollution at Cai Sau station should be noted and solved in the future (Figure 4.12f). Table 4.6 also shows the average increased percentages of future BOD, TC, NO_3^-, and PO_4^{3-} levels in the dry season as compared to these levels in 2018. From simulated results, it can be clear that these parameters' current and future concentrations at all monitoring stations along the Hau River in the dry season are much higher than those in the wet one. For the year 2030, without any measures applied, indeed, the average BOD, TC, NO_3^-, and PO_4^{3-} levels in the dry season are from two to threefold as much as those in the wet one. Remarkably, the highest difference in TC level can be seen at Cai Sau station, at 9,973 CFU/100 ml in the wet season as opposed to 27,345 CFU/100 ml in a dry one (Figures 4.13a and 4.14a). For BOD, this difference has amounted to more than six-fold, at 14.48 mg/l as compared to 89.21 mg/l (Figures 4.13a and 4.14a). In terms of NO_3^- and PO_4^{3-} levels, the highest differences are also noted at the lowest monitoring station, at 1.21 mg/l as compared to 5.93 mg/l and 0.12 mg/l as opposed to 0.59 mg/l respectively (Figures 4.13a and 4.14a). Key factors responsible for the differences in river water pollution levels between the wet and dry seasons in the study area are seasonal changes in rainfall and especially the Hau River discharge.

With the aim of generating more detailed and practical use of this result to support the cities' policymakers and master plans, the seasonal impact of each considered driver on the Hau River water quality was separated and assessed individually and the result was shown in Table 4.6. There is an insignificant difference in contribution rates between the two seasons. For BOD concentration, industrial growth has accounted for the highest percentage of contribution, fluctuating from 98.74% to 98.81%, whereas the opposite is true of rainfall change and population growths (only 0.11% – 0.16% and 1.08% – 1.10%, respectively). This is due to the fact that the typical average BOD concentration of industrial wastewater was nearly thirteen-fold higher than that of residential wastewater, at 1,000 mg/l as opposed to 80 mg/l for the latter (JICA, 2017; CTCPC, 2019b; DOC, 2019). Moreover, the increased volume of industrial wastewater of the study area in 2030 considered in this model will be very large in comparison to that of domestic wastewater (Figure 4.6). Regarding the increased TC level in 2030, the industrial expansion and population growth have shared similarly high rates of contribution to TC pollution in both the wet and dry seasons, ranging from 43.44% – 43.66% and 55.51% – 55.74%, respectively. This similarity can be explained by the converse TC level in domestic and industrial sewages. Specifically, although the volume of the forecast wastewater from domestic activities in 2030 is only about one-fifth of the industrial wastewater (57.08 million m^3 versus 299.03 million m^3), the average recorded TC level of the former is much higher than that of the latter, (8.8 million CFU/100 ml versus 1 million CFU/100 ml) (Phung et al., 2015; Nga et al., 2018; DOC, 2019). Noticeably, the contribution through the change in future rainfall trend and volume is also relatively small (only 0.82% – 0.83%). This result is consistent with the statement mentioned earlier in the future rainfall forecast.

In terms of NO_3^- and PO_4^{3-} increases, the contribution rates of industrial development in both the wet and dry seasons fluctuate around 60%, while around 34% are contributed by population growth. These were due to that although typical average NO_3^- and PO_4^{3-} levels of domestic wastewater in the study area were higher than those of industrial wastewater (at NO_3^-: 19 mg/l and PO_4^{3-}: 1.5 mg/l as opposed to NO_3^-: 5 mg/l and PO_4^{3-}: 0.4 mg/l for the latter (JICA, 2017; CTCPC, 2019b; DOC, 2019)), the volume of the predicted wastewater from residential activities is much lower compared to the industrial waste. One thing to note is that the precipitation changes in the future have accounted for worth-noting percentages of contribution on the increases in both NO_3^- and PO_4^{3-} levels, fluctuating from more than 5% to nearly 7%. This can be explained that urban runoffs and especially agricultural runoffs with quite high input of inorganic nitrogenous and phosphorus fertilizers and manures (Kumar et al., 2010, 2019; Minh et al., 2020) in the study area are also considered remarkable contributors of NO_3^- and PO_4^{3-} concentrations to the Hau River.

Table 4.6 The average increases and key components' contribution rates on seasonal BOD, TC, NO_3^-, and PO_4^{3-} concentrations of the Hau River water in the BAU scenario

Parameter	Average increase with BAU scenario (2018 – 2030) (%)		Rate of contribution (%)					
			Population growth		Industrial growth		Rainfall change	
	Season							
	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry
BOD	16.01	27.80	1.08	1.10	98.81	98.74	0.11	0.16
TC	40.85	65.94	55.74	55.51	43.44	43.66	0.82	0.83
NO_3^-	30.49	31.05	34.86	34.30	59.24	60.73	5.23	5.62
PO_4^{3-}	20.22	20.64	33.98	33.66	59.15	59.77	6.48	6.98

Under the negative impacts from inevitable drivers (population and industrial growths) and pressure (climate change) on the Hau River water quality in the future, the WEAP model was used to evaluate the effectiveness of potentially structural measures in the study area. In three scenarios WMs, building WWTPs (with the total treatment capacities of nearly 1.118 and 1.49 million m^3 per day) and RWTPs (0.775 million m^3 per day) with advanced treatment technology UASB-SBR for treating

75% and 100% wastewater discharged from residential and industrial zones as well as the polluted Hau River water in the future was considered. These water treatment plants' effectiveness was simulated, assessed, and also illustrated in Figures 4.12, 4.13, and 4.14.

In both scenarios with mitigation measures (WM75 and WM100), as shown from these figures, the application of WWTPs led to the considerable decline in the average BOD, TC, NO_3^-, and PO_4^{3-} levels in the wet season of 2030, by 35.28% (for WM75)/47.68% (WM100), 35.65% (MW75)/48.39% (WM100), 33.80% (MW75)/46.09% (WM100), and 29.10% (MW75)/38.03% (WM100) respectively compared to those in the BAU scenario. Noticeably, the simulated values of four these parameters' levels in the wet season at all stations will meet the desired water quality of Class-A (BOD $\leq$ 6 mg/l, TC $\leq$ 5,000 CFU/100 ml, $NO_3^- \leq 5$ mg/l, and $PO_4^{3-} \leq 0.2$ mg/l) (MONRE 2015b) of the NTRSWQ except for BOD levels at Cai Sau station. The average BOD concentrations at this station for WM75 and WM100 were only 8.90 and 6.91 mg/ml, which were just over that in Class-A (Figures 4.12a, 4.13b, and 4.13c). Regarding water quality in the dry season, however, the simulated concentrations of both BOD, TC, and PO_4^{3-} for both scenarios WM75 and WM100 indicated that the application of WWTPs has given high effectiveness for river water quality improvement at the upstream stations only. At the remaining stations in lower areas, including Tra Noc, Binh Thuy, Khai Luong, and Cai Sau; TC, PO_4^{3-} and especially BOD levels were still much higher compared to Class-A, ranging from 6,041 to 11,266 CFU/100 ml, from 0.13 to 0.42 mg/l, and from 8.02 to 52.48 mg/l, respectively (Figures 4.12d, 4.12f, 4.12b, 4.14b, and 4.14c). In the WM100, however, TC levels in the dry season at most stations along the Hau River were quite low and meet the desired level of Class-A (Figure 4.12d). It is also noteworthy that the study area's NO_3^- pollution in the dry season is not a concerning matter in 2030.

Based on simulated outcomes, it can be seen that the BOD, TC, NO_3^-, and PO_4^{3-} pollution of the Hau River water in the study area was significantly improved in the wet season by adopting WWTPs with advanced technology treatment of UASB-SBR. In the dry season, however, the pollution of BOD and PO_4^{3-} had not been completely resolved in this river downstream areas (Figures 4.12b and 4.12h). The key reasons responsible for this issue are that (i) the residual concentrations of pollutants after wastewater treatment in the upstream area will be enhanced in the downstream regions by accumulative effects, (ii) being located at the downstream regions of the study area, the most populous and industrialized districts, namely O Mon, Binh Thuy, Ninh Kieu, Cai Rang, and Binh

Minh, hence release a higher amount of wastewater, and (iii) the Hau River streamflow is very low in the dry months. Therefore, in the optimistic scenario (WM_Opt.), the application of RWTPs with the optimal and possible lowest treatment capacity has been proposed with the aim of thoroughly solving the water quality pollution of the entire Hau River in general and its downstream areas in particular. As shown in Figures 4.12 and 4.13, thanks to the application of five RWTPs (with a total treatment capacity of 775,000 m^3 per day) at key locations along the Hau River, the BOD and PO_4^{3-} levels at downstream stations have significantly decreased. Indeed, the BOD and PO_4^{3-} levels at Tra Noc, Binh Thuy, Khai Luong, and Cai Sau stations in the dry season have only ranged from 5.04 to 6.08 mg/l and from 0.08 to 0.21 mg/l, respectively (Figures 4.12b, 4.12h, and 4.14d). It is also noteworthy that the water quality improvement in the dry season is much higher than that in the wet season. This is because the difference between the total treatment capacity of proposed plants and the Hau River discharge in the dry season is much lower compared to that in the wet period.

4.4.4 Merits and Demerits of Proposed Measures

Although the application of WWPTs has proven its effectiveness on river water pollution mitigation, it cannot be considered as a standalone solution for improving water quality to reach a desirable value of BOD and PO_4^{3-} under Class-A without an additional support of RWTPs. Reason for selection and application of RWTPs within the WM_Opt. scenario proposed for achieving the desired SWQ of the city are appended below.

First of all, based on the simulated results from W100, it was found that even if 100% of future wastewater was collected and treated, the Hau River water with the BOD and PO_4^{3-} pollution in the dry season could not be thoroughly resolved in downstream areas. Also, treatment efficiency of the applied WWTPs under W100 scenarios were equipped with most cutting-edge one technology. So, there is no scope of either increasing the capacity of WWPTs or their treatment efficiency. Apart of rapid industrial urbanization, the issues remain here is the accumulation of pollutants in river downstream area, especially in the dry months, which is a concerning driver leading to this river water quality degradation. An Giang, an upstream city (Figure 4.1), is also one of the prominent agro-industrial cities in Vietnam, hence the quality of river water flowing from this city to the study area can also be considered under the wastewater management and treatment plans. Moreover, according to the current and future master plans, the cities' governments are investing in environmental projects to improve the future river water quality by mainly using structural measures, especially applying more advanced wastewater treatment plants. The national budget and international grants are the main financial sources of these projects. With the aforementioned facts, considering the existing gap to achieve the desired 2030 water quality with WM100, RWTPs at serious water pollution locations along the Hau River were considered to apply in WM_Opt.

However, implementation of proposed structural measures might have some negative issues as well like financial burden for building supporting structures like pipelines, land appropriation in urbanized centers, disturbances to the local ecosystems, etc. For example, the estimated costs for investing and building water treatment plants in proposed scenarios were relatively high, ranging from 822.48 to 1,750.04 million USD. Therefore, the local authorities should not consider the application of these plants as the sole solution for the city.

4.5 Conclusions and Next Work

Based on the current conditions of SWQ and using the scenario-based analysis, the study in this chapter had presented an overview of the future SWQ in the wet and dry seasons of the Hau River to identify key drivers of water pollution and to aware the local policymakers. In general, with the additional combination of RWTPs, the application of WWTPs along Hau River can deal with the water pollution in this river by 2030. However, their high investment cost and potential impacts on local ecosystems should be taken into careful consideration. Thus, a robust and comprehensive IWRM that can be considered a long-term and more sustainable solution supporting these plants to completely solve the SWQ pollution is also an urgent need for the city. Nevertheless, IWRM in developing cities like Can Tho often faces many complex challenges, and hence it needs to be comprehensively examined and effectively improved. Specifically, the IWRM-related issues mainly such as water policies, institutions, and especially governance (also including water quality governance) need to be systematically reviewed and hence propose appropriate improvement solutions. However, WG studies in a developing country like Vietnam is still very limited, leading to a lack of information and data needed to review and assess. Therefore, with these essential needs as well as limitation, a study was conducted to reflect the WG-related issues and challenges in Asia where the majority of countries including Vietnam are the less developed or developing ones and facing mounting water challenges. From the reviewed findings shown in the next chapter, an optimal WG framework was proposed for Vietnam in general and its developing Can Tho City in particular to improve their water quality management and achieve their more robust and comprehensive IWRM as well as the SDGs.

Chapter 5

Systematic Review to Assess the Role of Governance for IWRM in the Asian Developing Regions with Special Focus on Can Tho City, Vietnam

5.1 Introduction

Currently, an increasing number of countries particularly in developing regions are facing mounting challenges in the complex implementation of IWRM. And as aforementioned, to achieve robust and comprehensive IWRM as well as the SDGs in these developing countries, an effective WG is primarily fundamental. Indeed, over the last two decades, WG has emerged as an important topic in the international arena and is currently acknowledged to be a widely accepted framework to globally orient IWRM towards achieving diverse SDGs (Tropp, 2007; Gain and Schwab, 2012; Zinzani and Bichsel, 2018; Jiménez et al., 2020). Although much work and diverse entry points and views have been developed regarding the meaning of the term "water governance", there is still not enough clarity about the practical meaning of this term and how to work with it (Araral and Yu, 2012, 2013; Araral and Ratra, 2016; Özerol et al., 2018; Jiménez et al., 2020). For instance, there is no consensus on scope and definition of WG, principles of good governance, concepts or elements required for effective governance framework, etc.; leading to disputations by practitioners and researchers alike. Different schools of thought have adopted and interpreted governance from different perspectives, and international forums and platforms have also understood and used this term with different interests, and sometimes with conflicting objectives. WG has been referred to both as a process and as an outcome, which gives rise to different usage of the term. Moreover, although the number of studies in WG is increasing in recent years, a synthesis of these studies especially reflecting WG regimes in developing regions is still very rare. Similarly, little synthetic reflection has been conducted on the diverse elements of WG frameworks and their temporal evolution, the most-concerned WG-related issues, the spatiotemporal growth of scholarly attention towards WG concepts in scientific disclosures, the performance indicators used to assess WG effectiveness, the current and potential WG challenges and opportunities, etc. in these developing regions.

With the economies of most countries (30 out of 47 ones including Vietnam) characterized as less developed and developing, Asia is considered one of the developing regions globally (UN, 2020, 2022a; Britannica, 2022; O'Neill, 2022). These 47 independent countries are located across five Asian regions including SEA (11 countries), South Asia (SA: 8), East Asia (EA: 5), Central Asia (CAs: 5), and West Asia (WA: 18) (Figure 5.1 and Table B7). Noticeably, Asia is considered the Earth's largest continent, covering the total area of 44,579,000 km^2. Considered the most populous continent with 4.7 billion people, this continent is the home to approximately 60% of the world's population (Kataoka, 2005; Douglass, 2013; Wikipedia, 2022; Worlddata, 2022). Noticeably, although the annual absolute volume of water resources in this continent is 13,500 km^3 or 32% of world's freshwater resources which is larger than any other continent of the world, it has less fresh water per capita than any others (Chellaney, 2007; Douglass, 2013; Wikipedia, 2022) mainly due to high water demand for its burgeoning population, urbanization process, industrial growth, and agricultural production. Therefore, the situation is likely to deteriorate in the future especially in these developed and developing Asian countries like Vietnam unless appropriate action is taken in a timely manner to have a better governance for managing this precious resource.

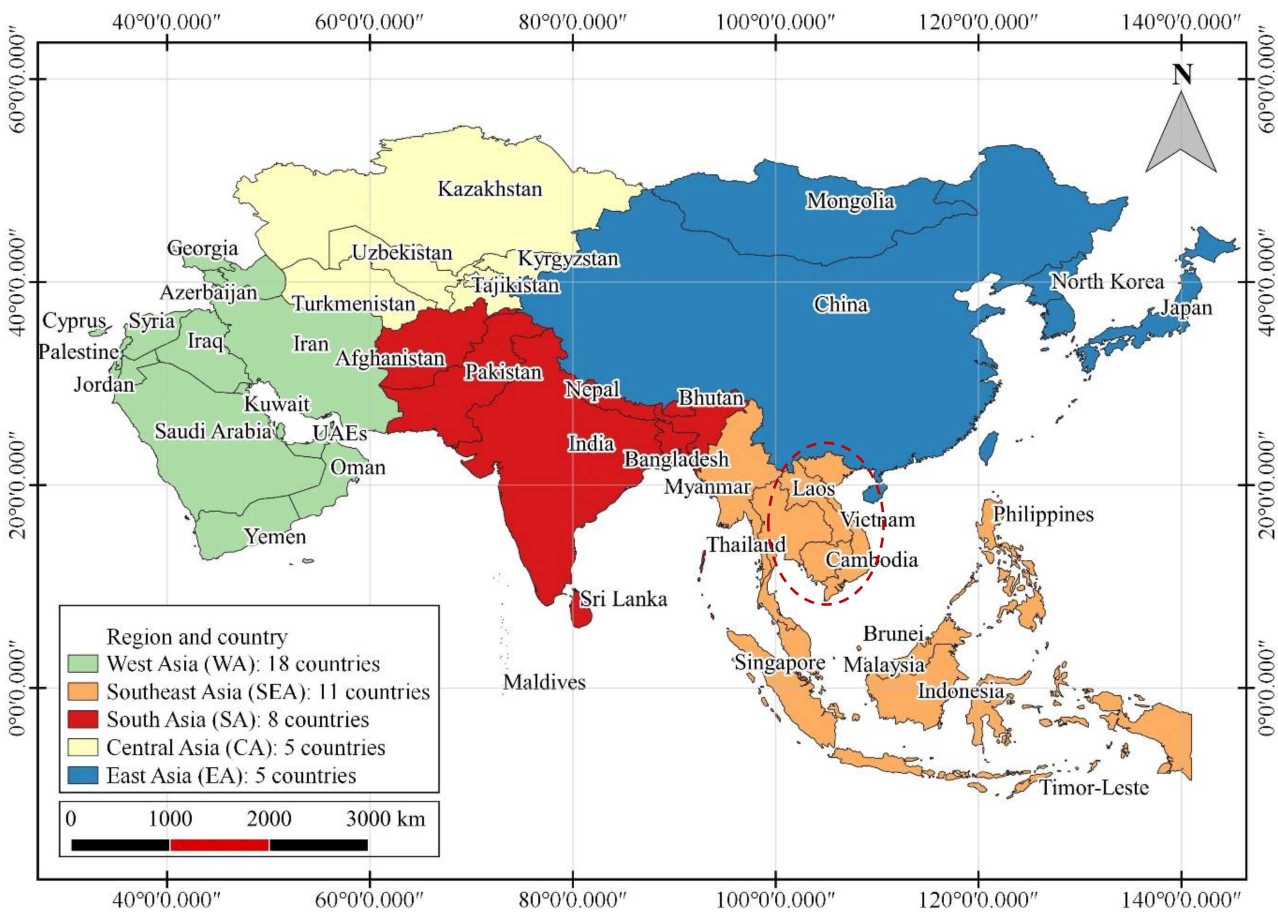


Figure 5.1 Map of Asia with its regions and countries including Vietnam (red circle)

Geographically, Asia is home to 57 of the 263 globally international river basins (Figure 5.2), which account for 39% of the continent's land surface (Mfodwo, 2010; Rieu-Clarke et al., 2012; Chen et al., 2013; Douglass, 2013; Dixit, 2018). Noticeably, at least 40 major cross-border rivers and lakes are in this continent, totaling more than 16 million km^2 of land area in the basins surrounding these bodies of water. Among the largest and most well-known are the Amur River Basin, Aral Sea-Central Asia River Basin (ASCARB), Ganges-Brahmaputra-Meghan River Basin (GBMRB), Indus River Basin (IRB), Irrawaddy River Basin, Mekong River Basin, and Tarim River Basin, each of which covers from 700,000 to nearly 3 million km^2 (UNEP 2008; Douglass, 2013). This high availability of water has enabled the region to become one of the world's largest hydropower as well as most productively agricultural producers (Rahaman and Varis, 2008; Baran and Myschowoda, 2009; MRC 2010; Keskinen et al., 2016; Hanasz, 2017b; Lebel et al., 2020; Pahl-Wostl et al., 2021). In the case of Vietnam, this country is characterized by a dense system of rivers with 17 major basins (Figures 5.2 and 5.3) (Hanh and Dong, 2010; Ha et al., 2013; Do et al., 2018). These basins account for more than 80% of the country area, and many of them are international water bodies (Hanh and Dong, 2010; Ha et al., 2013). Out of the total 1,167,000 km^2 basin area of local and trans-boundary rivers in Vietnam, only 329,570 km^2 (28.2%) is located within the country (Ha et al., 2013). Major rivers such as the Mekong (also called the Cuu Long in Vietnam (red circle in Figure 5.3), which flows through the VMD including Can Tho City), Red, and Ca Rivers have their headwaters located in other countries. Only middle and small-scale rivers are found locally. Some of the tributaries of the Mekong River originate in Vietnam, flow through Lao or Cambodia (i.e., Se San and Srepok Rivers), join the Mekong, and then return to Vietnam (Hanh and Dong, 2010; Ha et al., 2013).

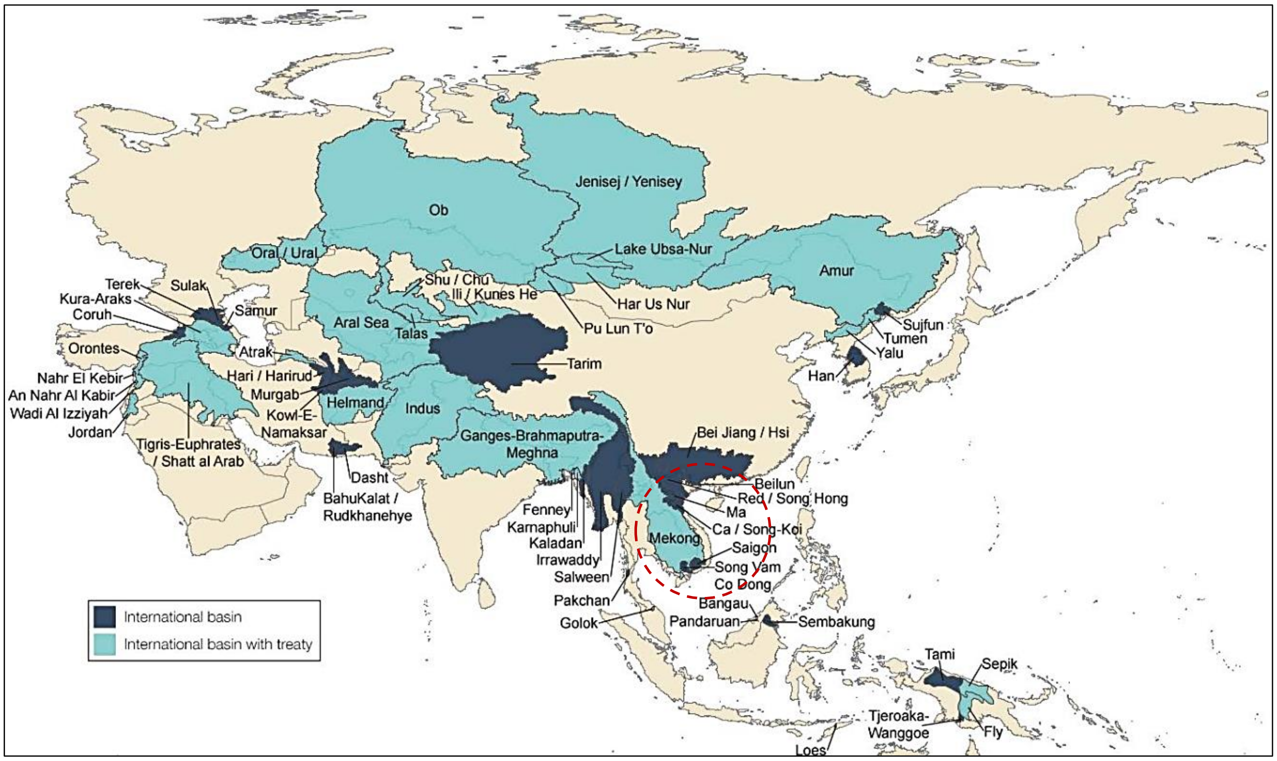


Figure 5.2 Main cross-border river basins of Asia and Vietnam (red circle, including the Mekong River Basin) (OSU, 2009; Rieu-Clarke et al., 2012; Douglass, 2013)

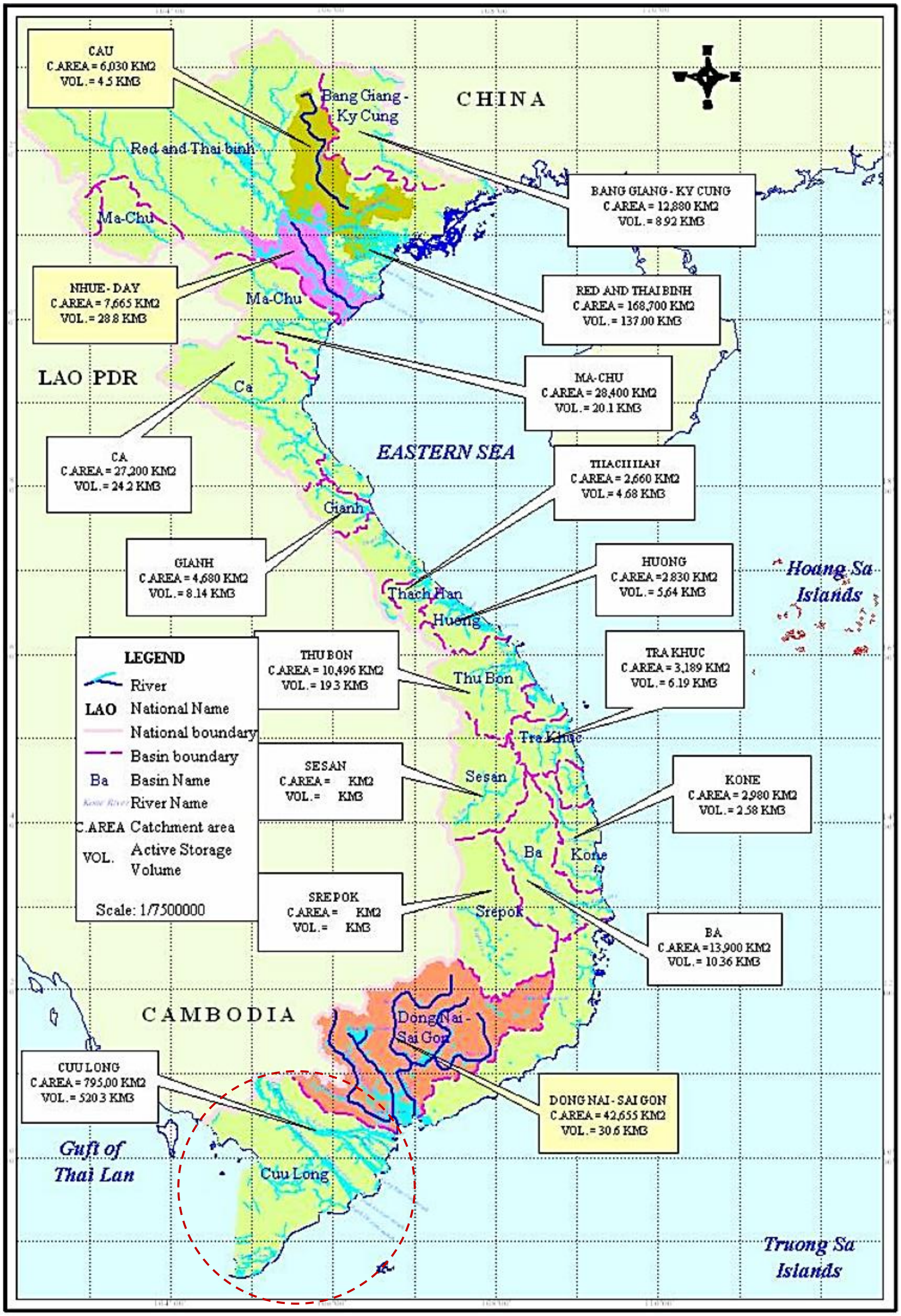


Figure 5.3 Map of major river basins in Vietnam and their main characteristics (Ha et al., 2013)

However, according to Rieu-Clarke et al. (2012) and Chen et al. (2013), only 25 transboundary river basins in this continent are fully (10 basins) or partially (15) covered by basin agreements, while 32 remaining ones are not managed by any joint agreement. Also, in Vietnam, only two cross-border river basins are fully supervised by basin agreements (Hanh and Dong, 2010; Ha et al., 2013). Therefore, various issues are there in terms of transboundary political challenges. In addition, although Asian riparian systems are immense, the region is a global hot spot for water insecurity (ADB, 2016). With more than 60% of the world's population and half of the world's poorest people, Asia has the least fresh water per capita and the largest number of people with no access to clean water and basic sanitation (Batchelor, 2007; Douglass, 2013; ADB, 2016). Moreover, this region is one of the most climate-related hazard and disaster prone regions (ADB, 2016; OXFAM, 2020). In 2017, natural disasters caused more than $48 billion worth of agricultural damage in Asia (FAO, 2018). Especially, flood- and drought-induced loss and damage in South Asia (SA) can cost $215 billion a year by 2030. The severity and frequency of many such climate-related hazards is on the rise resulting in large scale economic, environmental and social disruptions across Asia. For example, the devastating SA floods of 2017 affected more than 40 million people across Nepal, India and Bangladesh. Riverine communities in the GBMRB were the worst affected (OXFAM, 2020).

In general, although Asia is changing rapidly and becoming a new global economic center with the increasing importance of the private sectors in the development sphere, many poor and developing countries including Vietnam in this continent often suffer from the problem of bad hydrology such as more frequent floods and droughts, higher levels of uncertainties, dependency on agriculture and hence irrigation, rapid growth in population and industrial urbanization and hence water demand and pollution, small endowments of water infrastructure, fragile institutions and face more uncertainties arising from climate change (Araral and Yu, 2012; OXFAM, 2020). The result is more water insecurity and more conflicts within and between countries particularly in poor and developing ones (Briscoe 2009; Araral and Yu, 2012). Consequently, it is acknowledged that the problem of WG is actually acute in many the Asian countries, hence the role of understanding and improving governance there is more vital than anywhere else. An effective WG-related activities will be an integrated part of both the regionally and globally sustainable economies, providing livelihoods, renewable energy, and food security for billions of people (MRC 2010; Keskinen et al., 2016).

To bridge knowledge gaps and provide more comprehensive understandings of WG mainly in the Asian developing regions including Vietnam and its rapidly growing Can Tho City, the study in this chapter presents a systematic review analyzing, assessing, and reflecting on how WG is defined, conceptualized, performed, evolved, and challenged in the Asian countries' diverse contexts during the last 20 years from 2000 to 2020. Based on the reviewed information, an optimal WG framework will be proposed for Vietnam in general and Can Tho City in particular to achieve more robust and effective IWRM as well as SDGs at later stage. Specifically, the following key research questions were sought to answer:

1. How is WG defined and conceptualized temporally? What is an effective WG?

2. How is the scholarly attention to WG in Asia and Vietnam developed spatiotemporally in scientific disclosures?

3. What are the frameworks and their key elements popularly used to analyze WG and its related issues in Asia and Vietnam?

4. What is the optimal framework utilized for current and future WG in Asia, especially in developing countries as well as Vietnam and its urban centers like Can Tho City? What are governance difficulties and challenges of this framework application?

5.2 Methodology

Systematic reviews are useful for synthesizing trends and abstracting findings from large bodies of information (Petticrew and Roberts, 2006; Özerol et al., 2018; Di Vaio et al., 2021; Paudel et al., 2021). Thus, this study employed a systematic literature review to provide a comprehensive insight into WG in Asia including Vietnam between 2000 and 2020, following the PRISMA guidelines to document literature review process (Moher et al., 2009). To collect relevant peer-reviewed literature, the Scopus database (http://www.scopus.com/, accessed on December 2021) was mainly used. More publications were also searched manually on Google Scholar and other relevant global reports (grey literature). The implementation process of this study consisted of four key steps (Figure 5.4) as follows.

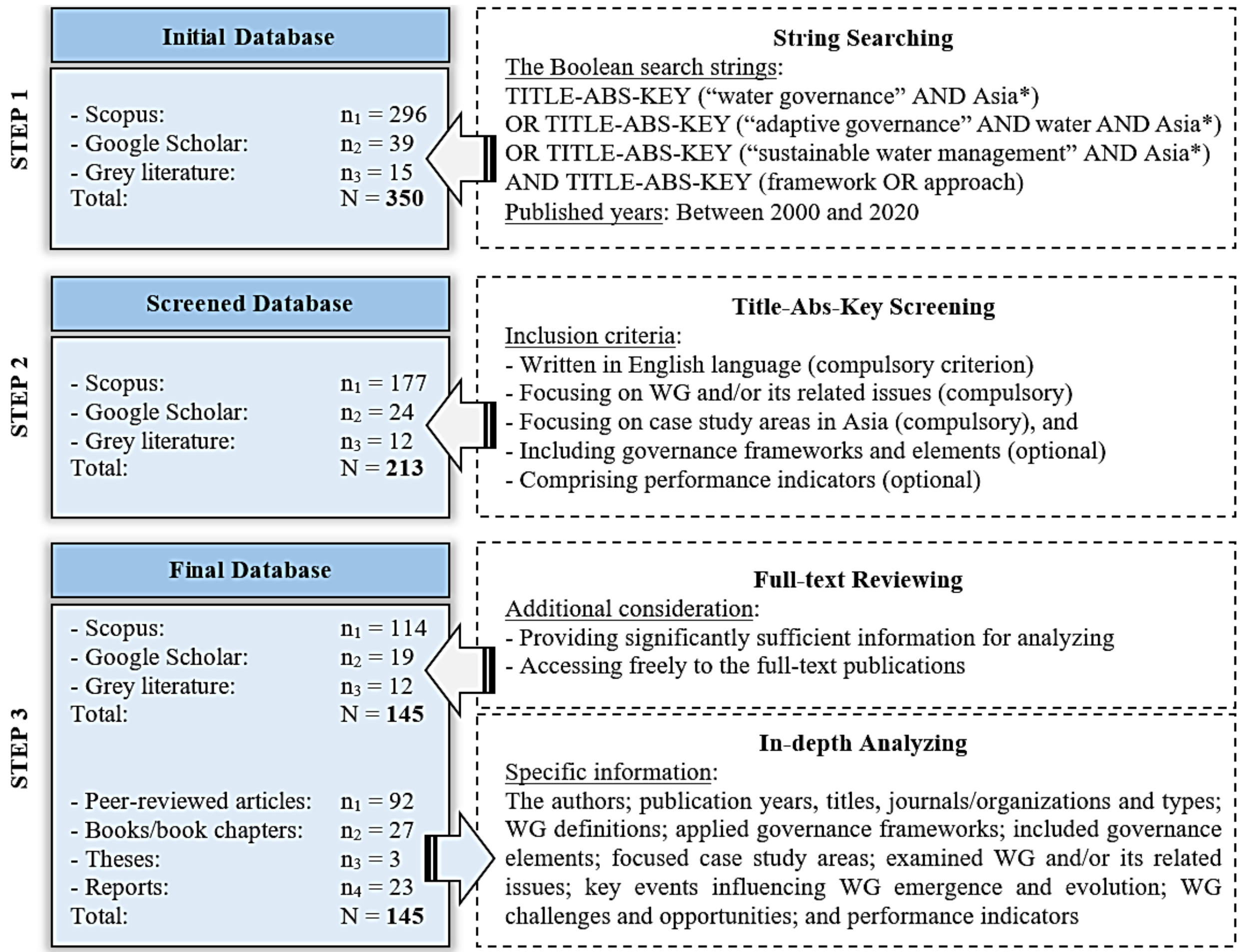


Figure 5.4 Flowchart of the systematic review methodology

In the first step, the study performed a keyword search in major scientific databases. As the search query for the Scopus database, the following Boolean string was used: (TITLE-ABS-KEY ("water governance" AND Asia*) OR TITLE-ABS-KEY ("adaptive governance" AND water AND Asia*) OR TITLE-ABS-KEY ("sustainable water management" AND Asia*)) AND TITLE-ABS-KEY (framework OR approach). The search was restricted by publication period from 2000 (when the millennium development goals (MDGs) were approved at the UN Millennium Summit (Mfodwo, 2010; UNDP, 2013; Chan et al., 2016) to 2020. The search yielded 296 publications mostly including articles, books, book chapters, and conference proceedings from Scopus. Next, to extend the study to relevant publications published in non-indexed journals, a manual search in Google Scholar targeting the first 250 results was applied. This search obtained 39 publications more, mainly comprising reports, dissertations, policy documents, and newspaper articles. Moreover, 15 professional publications was added into the study's database by manually searching in repositories of the Global

Water Partnership (GWP) (https://www.gwp.org/en/GWP-CEE/WE-ACT/publications/), Organization for Economic Co-operation and Development (OECD) (https://www.oecd-ilibrary.org/), International Union for Conservation of Nature (IUCN) (https://www.iucn.org/resources/libraries), United Nations Development Programme (UNDP) (https://www.un-ilibrary.org/), and Asian Development Bank (ADB) (https://www.adb.org/publications). A total of 350 publications were initially retrieved by using the study's defined search query.

The next step was the process of database screening to obtain only relevant publications for inclusion in the full-text review. A quick screening of title, abstract, and keywords (or even full-text screening if these three areas included insufficient information for screening and making decision) of each publication was conducted. During this process, the following five inclusion criteria were thoroughly examined for each retrieved publication: The publication (i) had the full-text written in English language (compulsory criterion), (ii) focused on WG and/or its related issues (compulsory), (iii) included frameworks and elements applied for analyzing WG and/or these issues (optional), (iv) focused on case study areas (regions, countries, cities, etc.) in Asia (compulsory), and (v) comprised indicators utilized for assessing WG performance (optional). After screening and eliminating duplicate publications, a total of 213 ones were found to be matching the defined inclusion criteria. A quick random examination of the full-text of the publications left out showed that these five criteria were robust in capturing relevant publications.

In the last step, the full-text review was manually applied for each of these 213 publications to retain only the ones significantly effective for in-depth analysis. The reviewed information was mainly how the case study areas were selected, methodology was applied, database was collected and analyzed, analytical frameworks and their elements were built and applied, etc. Besides, free accessibility to the full-text publications was also included in this step. Consequently, this review process had narrowed the number of eligible publications to 145 ones comprising 92 peer-reviewed articles, 27 books/book chapters, three theses, and 23 reports. For the process of in-depth analysis, these publications' specific information such as the authors; publication years, titles, journals/organizations and types; WG definitions; performed governance frameworks; included governance elements; focused case study areas; examined WG and/or its related issues; key events influencing WG emergence and evolution; WG challenges and opportunities; and performance indicators were collected and summarized in Table B8 for analyzing.

5.3 Results and Discussions

5.3.1 Spatiotemporal Distribution of the Available Literature on WG

5.3.1.1 Temporal Distribution

Figure 5.5 shows the progression in the annual numbers of qualifying publications focusing on WG and its related issues in Asia and published between 2000 and 2020. Overall, these numbers showed an upward trend, originating from 2001 and especially after 2015 with almost 50% of them (72 publications) being published. Specifically, starting with a very low baseline of 0–3 publications per year from the early 2000s until 2007 (totaling only 12), the annual number of published ones increased slightly from 2008 to 2014, with fluctuations of 6–10 (totaling 50 publications), and picked up significantly during the latter period. The published publications were 11 in 2015, then rapidly rose and peaked at 19 in 2020 except for declining down to around 10 in 2017 and 2018. Similarly, an upward trend could be also observed in the annual numbers of publications focusing on WG-related issues in Vietnam after 2005 and especially since 2015 with nearly 54% of published studies (Figure 5.6). These upward trends indicated a growing global attention towards the issues of WG in both Asia and Vietnam after the 1990s and especially in recent years. Noticeably, this growing attention was possibly due to the emergence of the MDGs, SDGs, and following specific events occurred over the last two decades.

According to OECD (2011), the attention to WG followed a general shift in focus on the sector during the 1990s. In fact, after the establishment of the "Dublin Principles" in 1992, which was considered a milestone in global consciousness of the importance of water resources and urged all governments to translate these principles into urgent action programs, a global effort was mounted to promote a set of universal principles for good WG and sustainable development (Huyen, 2007; Rahaman and Varis, 2008; OECD, 2011). Moreover, following the creation of the World Water Council in 1996, the first (1997) and second World Water Forum (2000) considered WG to be a main issue for water-related problems and continued to call for ensuring good WG (Rahaman and Varis, 2008; Gain and Schwab, 2012; Wajjwalku, 2019; WWC, 2022). Noticeably, in the Millennium Summit 2000, a list of 8 MDGs including eradicating extreme poverty and hunger and ensuring environmental sustainability was adopted by world leaders as an international development agenda until 2015. Related to water, the MDGs included a specific target to halve by 2015 the world population without access to safe drinking water and basic sanitation (Mfodwo, 2010; Chan et al., 2016). Then, subsequent international meetings from 2000 to 2005 such as the Hague Ministerial Declaration in 2000 (WWF, 2000), United Nations Millennium Assembly in 2000 (UN, 2000; Aminova and Abdullayev, 2009), Bonn Freshwater Conference in 2001 (WWF, 2000; Aminova and Abdullayev, 2009), World Summit on Sustainable Development in 2002 (Gain and Schwab, 2012), 3rd World Water Forum in 2003 (Chan, 2009), and Commission on Sustainable Development in 2005 (Gain and Schwab, 2012) had all seen improved governance in the water sector to be an overarching concern for meeting the water-related MDGs (Tropp, 2007; Gain and Schwab, 2012). These key events also identified WG as the first area for priority action (WWF, 2000) and called all localities, nations, and regions including Asia for governing water wisely to ensure good governance so that the involvement of the public and interests of all stakeholders were included in the management of water resources (UN, 2000; WWF, 2000; Aminova and Abdullayev, 2009; Chan, 2009; Gain and Schwab, 2012).

Another event to note was that an official definition of IWRM was presented by the Global Water Partnership (GWP) in 2002 at the World Summit on Sustainable Development. In the concept of IWRM, a better WG focusing on technical and scientific aspects was recognized as a key condition for holistic water management (Huyen, 2007; Rahaman and Varis, 2008; OECD, 2011) as well as one of the key components for achieving sustainable development (Huyen, 2007; Otsuka, 2019b). In addition, United Nations Water (UN-Water) was established in 2003 and proclaimed the "Water for Life" International Decade for Action (a campaign to meet the 2000–2015 MDGs' sanitation target and end open defecation) (UN, 2022b). Also in 2003, WG had been firstly defined by GWP as "the range of political, social, economics, and administrative systems that are in place to develop and manage water resources, and the delivery of water services, at different levels of society" (Rogers and Hall, 2003).

It was acknowledged that WG issues had become a centerpiece of high level political agenda of the early 2000s. However, although there was a growing recognition of the importance of WG issues, surprisingly there was a lack of theoretical analysis and debate over WG in this period of time (Franks and Cleaver, 2007; Aminova and Abdullayev, 2009). Until the 4th World Water Forum in Mexico in 2006 and especially the 5th one in Istanbul in 2009, the WG concept was more widely discussed with the focus on a supportive legal and institutional framework that was considered one of the central elements of WG (OECD, 2011). Consequently, the number of WG studies in both the globe, Asia, and Vietnam gradually increased from the end 2000s to early 2010s. For instance, according to Hanasz (2017b), some international organizations such as the World Bank and Asian Development Bank (ADB) began to intervene in the WG-related issues (especially transboundary water management) in SA and SEA (including Vietnam) from 2006, and the South Asia Water Initiative was the most ambitious of these organizations' initiatives in this regard. Solanes and Gonzalez (1999); Swyngedouw (1997, 2004); Allan (2003), and Zinzani and Bichsel (2018) also stated that social scientists had increasingly begun to debate and analyze the political nature of water and processes of its governance, leading to the increasing emergence of WG studies globally. Even, in the early 2010s, the terms "sustainable water management" and "IWRM", the most prevalent paradigms of the water sector in the 2000s, had been suggested to replace by the term "water governance" (Biswas and Tortajada 2010; Gain and Schwab, 2012). Another action plan recorded as a key factor contributing to the attention growth towards WG issues in the early 2010s was the Strategic Plan for Biodiversity. This plan included 20 Aichi Biodiversity Targets for the 2011–2020 period, supporting the MDGs' implementation by providing an effort to protect and conserve the biodiversity that underpins global food security, health, and clean water (CBD, 2020).

As previously mentioned, most WG publications in both Asia and Vietnam have been published since 2015. According to Pahl-Wostl (2015), this year was also considered a milestone remarking a rapid growth of debates on WG globally. In fact, since 2000, substantial progress has been made towards achieving the MDGs, but as of 2015 many of the targets, including water related targets, has not been fully achieved (e.g., globally one in ten people lack access to safe water) (WHO and UNICEF, 2015). Thus, in 2015, the UN presented the SDGs as a unifying global vision to continue the progress made under the MDGs over the course of the next 15 years. The SDGs' core content covers 17 global goals and 169 associated targets covering the three aspects of sustainable development – economy, social affairs, and environment (Chan et al., 2016; Osti, 2018; GWP and UNEP-DHI, 2020). In the case of Vietnam, 115 nationally sustainable development targets had been set closely based on these 17 global SDGs; and the period from 2015 to 2017 was recognized as the remarkable milestone of starting to actively engage in the implementation process of the global SDGs in this Asian developing country (MOPI, 2018b).

Among the SDGs, specific to WG, Goal 6 (to ensure availability and sustainable management of water and sanitation for all) globally calls for robust and effective WG by implementing IWRM across multiple scales of WG – local, regional and beyond (Mcdonnell, 2008; Chan et al., 2016; Osti, 2018; GWP and UNEP-DHI, 2020; WWC, 2022). This inclusion of WG had represented a formal recognition that comprehensive achievement of the IWRM as well as SDGs cannot be realized without taking WG into consideration. Therefore, the announcement of SDGs (especially SDG 6) had been actually acknowledged as key driver of publishing more WG publications since 2015. For instance, since the end of 2016, the GWP has partnered with the UN Environment Programme (UNEP), UNEP-DHI Centre, and Cap-Net in the SDG 6 IWRM Support Programme to assist governments in promoting and accelerating more programs, projects, and studies towards SDG indicator 6.5.1 – the degree of implementation of IWRM and WG. In Asian region, leaders of the Asia-Pacific region including Vietnam declared their determination in the Third Asia-Pacific Water Summit 2017 to facilitate the implementation of IWRM including WG-related issues at all levels, strongly focusing on transboundary water management in the region (GWP and UNEP-DHI, 2020). In India, a study of Ahmed and Arara (2019) measured improvement in WG in eight Indian states after the announcement of SDGs. The findings suggested that WG in these states as well as WG studies in this Asian country had significantly improved after 2015, and good WG was the key for the realization of SDGs and particularly SDG 6.

Moreover, apart from the SDGs, the adoptions of Sendai Framework 2015–2030 (including seven global targets of reducing disaster risk) (ADB, 2016, 2020) and Climate Change Strategic Framework (agreed at the Climate Change Conference of the Parties (COP) 21 in 2015 and being at the center of negotiations for COP22 in 2016) (UN, 2016; Osti, 2018) emphasized higher priorities in water and climate change adaptation and mitigation. These frameworks were also recognized key drivers promoting better WG, and hence boosting WG studies in the whole Asia in general and its developing countries in particular. In general, this study's findings are likely reflective of the fact that although WG concept has been emerged since the 2000s, this concept itself is still a fairly young field and needs further research. Thus, it is expected that there will be more emphasis on studying WG across different settings in the coming years.

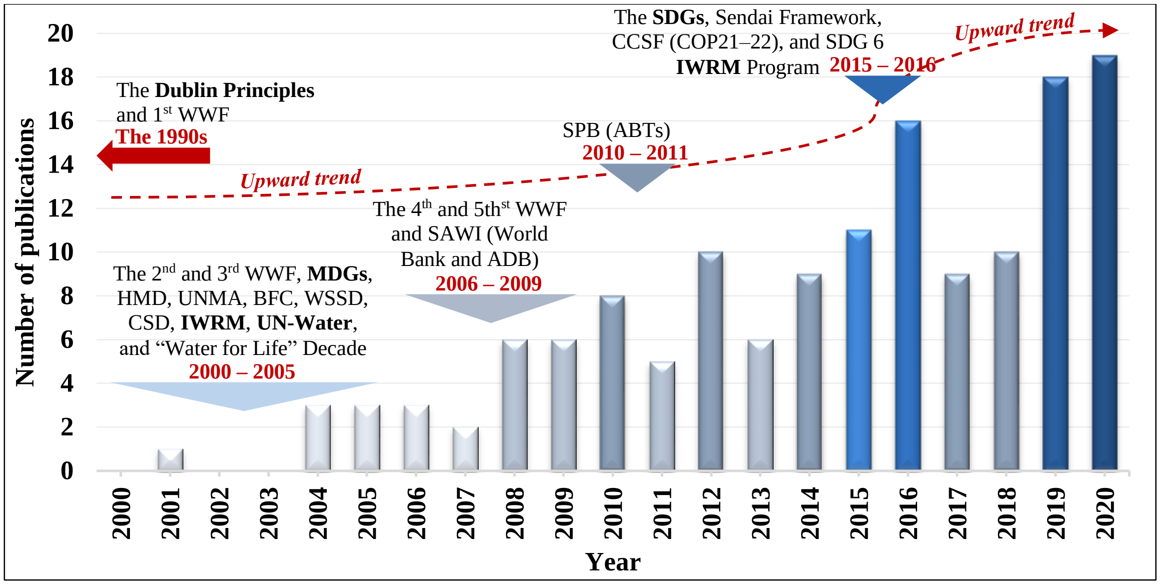


Figure 5.5 Temporal distribution of the available literature on WG in Asia by publication dates (Notes: WWF - World Water Forum, HMD - Hague Ministerial Declaration, UNMA - United Nations Millennium Assembly, BFC - Bonn Freshwater Conference, WSSD - World Summit on Sustainable Development, CSD - Commission on Sustainable Development, SAWI - South Asia Water Initiative, SPB - Strategic Plan for Biodiversity, ABTs - Aichi Biodiversity Targets, and CCSF - Climate Change Strategic Framework)

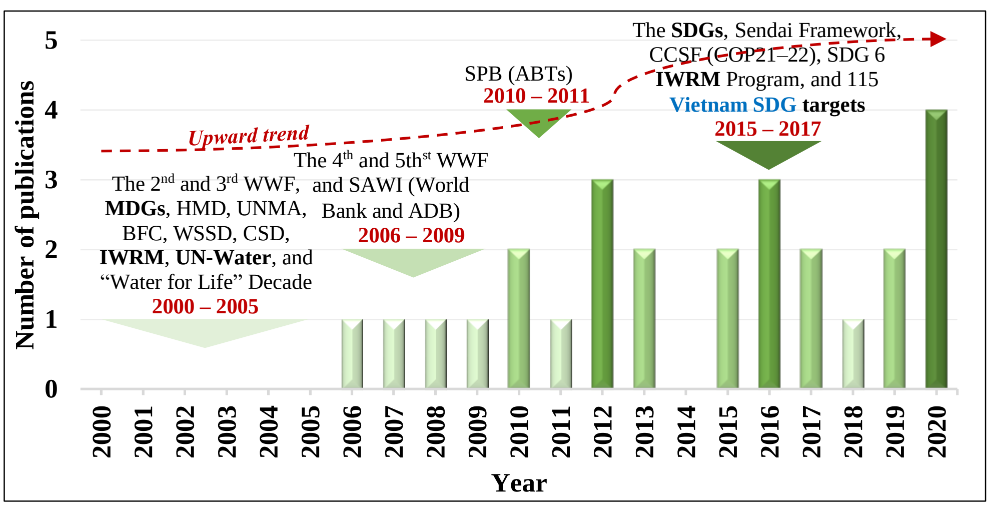


Figure 5.6 Temporal distribution of the available literature on WG in Vietnam by publication dates (Notes: Specific events occurred over the last two decades are similar to that shown in Figure 5.5)

5.3.1.2 Spatial Distribution

With regards to the geographic focus of the publications, 80% (n = 116 publications) selected specific Asian countries (i.e., China, India, Vietnam, etc.) as study locations, while the remaining 20% (n = 29) focused on the Asia's wider regions (i.e., CAs, SA, SEA, etc.) as study areas. Out of these 116 publications, more than 68% (n = 79) included only one country (study area), while the percentages of publications covering two, three, four and five study areas were around 14 (n = 16), 5 (n = 6), 2 (n = 2), and 3% (n = 3) respectively. The remaining publications (nearly 9%, n = 10) included more than five Asian countries as their study locations. Noticeably, there were some well-known WG studies including high numbers of the Asian case study areas such as Dinar and Saleth (2005) (with 16 Asian countries included), Araral and Yu (2012, 2013) (18 and 17 countries respectively), and ADB (2020) and OECD (2020) (30 countries each). Generally, the scope and number of case study areas included in publications varied widely. This variation can be explained by the diversity in (i) typical characteristics of watersheds (i.e., national or international), (ii) types and specific objectives of studies (i.e., analytical, assessment, or comparative studies), and even (iii) database availability. To enhance the visualization of study locations, their spatial distribution is shown in Table B7 and plotted on the Asian map in Figure 5.7.

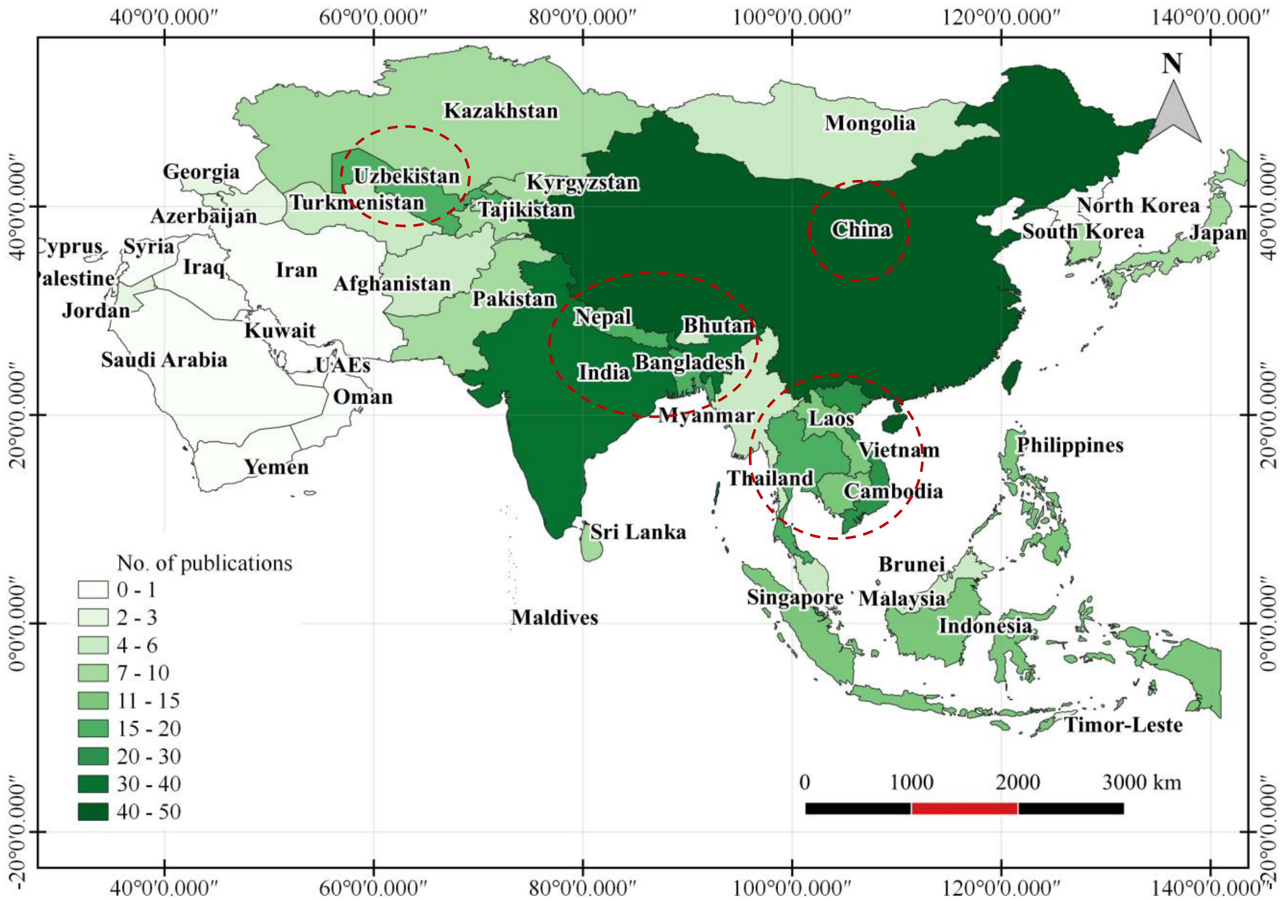


Figure 5.7 Spatial distribution of the available literature on WG by study locations (countries)

As shown, the study locations are unevenly distributed across Asia; and this pattern reflects the uneven distribution of global resources, including within the research community. In Asia, it was found that the majority of the publications focused on WG issues in Southern, Eastern, and Southeastern regions. In SA, India was the most-studied countries (with n = 32 cases), followed by Bangladesh (n = 17) and Nepal (n = 16). Noticeably, China was considered the hotspot of WG studies not only in EA but also in the whole Asia, accounting for the highest number of cases (n = 44). It was also noteworthy that the SEA countries, especially Vietnam (n = 26) and Thailand (n = 19), occupied nearly one-third of the total number of case study locations (111 out of 334) in Asia (Table B7). Apart from these countries, scholars also had great interest in WG issues of Uzbekistan. This CAs country had become the case study area in 18 publications. The predominance of WG study in all the above-mentioned regions and countries, especially SEA and its most-studied nation of Vietnam, was due to their abundant water resources as well as typical WG-related challenges. Indeed, the Asian largest cross-border river basins are mostly located in these countries and regions (Figure 5.2), such as the

GBMRB (mainly crossing India, China, Nepal, and Bangladesh (Douglass, 2013; Hanasz, 2015)), IRB (Afghanistan, China, India, Nepal, and Pakistan (Douglass, 2013)), Mekong River Basin (China, Myanmar, Thailand, Laos, Cambodia, and Vietnam (Lebel et al., 2005; Kranz et al., 2010); Vietnam is the lowest country in this basin, and the VMD (40,500 km^2) including Can Tho City is the region where the Mekong River approaches and empties into the sea through a network of distributaries (Figure 5.8)), Red River Basin (China, Vietnam, and Laos (Douglass, 2013)), ASCARB (Uzbekistan, Kazakhstan, Tajikistan, Kyrgyzstan, and Turkmenistan (Douglass, 2013; Droogers and Bouma, 2014)), etc. Besides, complex transboundary water management, water-food-energy-climate nexus, water conflict and cooperation, legal and institutional arrangements, and climate change were considered popular WG-related challenges in these locations, leading to high attention of global scholars.

Moreover, although the high concentrations of WG studies in some nations like China and India can be also explained by their large size as well as high number of water-related scientists and experts, Vietnam constituted an exception, given its relatively small area but a dense waterway network. In fact, as previously mentioned, this SEA developing country has a complex river system with 2,360 perennial rivers longer than 10 km (Ha et al., 2013), and noticeably, most of its large river systems linked (Figure 5.3 and 5.8) (Hanh and Dong, 2010; Do et al., 2018). Compared to the country's major river basins including the Bang Giang-Ky Cung, Thai Binh, Ma, Ca, Vu Gia-Thu Bon, Ba, Sesan, Srepok, and Dong Nai Basins, the Red and Mekong Rivers Basins have the largest areas (155,000 and 795,000 km^2, respectively) as well as the highest total volume of water flow (Hanh and Dong, 2010; Ha et al., 2013). Noticeably, these two national largest basins are characterized with both diversely national and international WG-related challenges. These challenges are mainly related to agricultural (mainly irrigation and fishery) and industrial productions, hydropower generation, surface and ground water pollution, extreme weather events (floods, droughts, and saline intrusion), and ecological degradation (Ha et al., 2013; Do et al., 2018). Particularly, up to 13 out of 26 reviewed publications examining the Vietnamese WG-related issues had focused on international water conflicts between nations in the Mekong River Basins (n = 8) and local WG in the Vietnamese Mekong Delta (n = 5) where Can Tho City is located in.

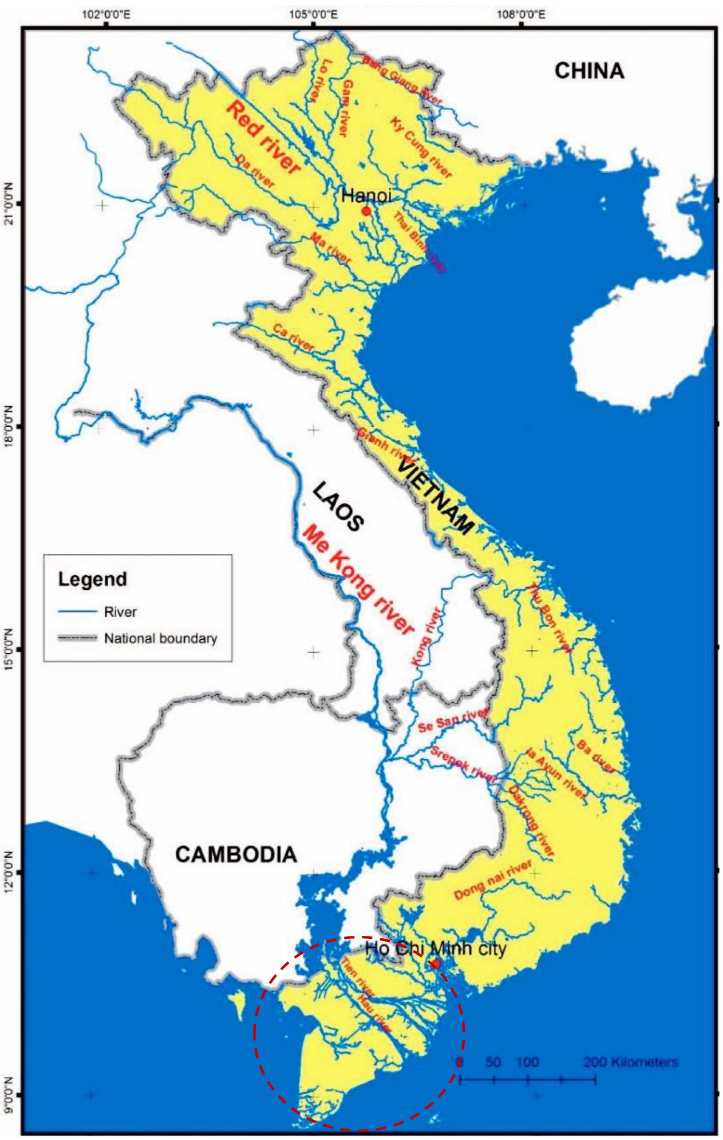


Figure 5.8 Major river systems in Vietnam (including the Mekong River Basins and its VMD (red circle)) and their complex linkage (Do et al., 2018)

Regarding 29 publications focusing on WG issues in the Asia's wider regions, each of them opted from one to four regions for case study areas. As shown in Figure 5.9, SEA accounted for the largest rate with more than 39% (n = 18 out of 46 cases), followed by CAs with nearly 24% (n = 11). EA and SA shared a same level of percentage, at more than 17% each (n = 8 each). Remarkably, only one case covered the whole Asia as study location, while there was no case covering WA. These findings were also consistent with ones shown in Figure 5.7, indicating the overrepresentation of Southeastern nations including Vietnam in WG studies. Conversely, very few studies focused on Western countries, mainly due to the various obstacles regarding the lack of trust and official cooperation in water management, absence of participatory data collection, hard accessibility to required information, limitation in research capacity, and socio-economic and political instability in and between these water- and data-deficient nations.

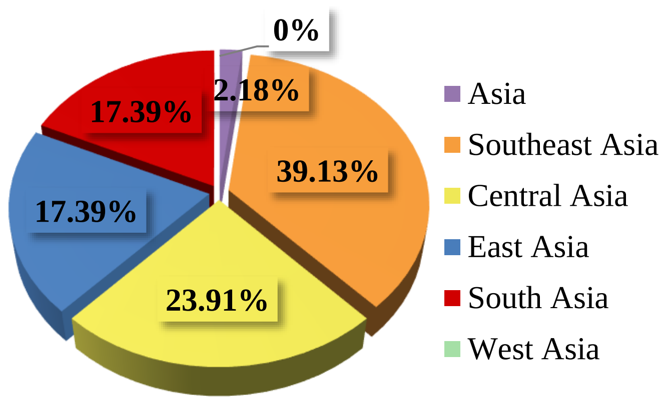


Figure 5.9 Spatial distribution of the available literature on WG by study locations (regions)

5.3.2 International Perspectives on WG Definitions

With 145 reviewed publications, the questions "how is WG defined and conceptualized temporally?" and "what is an effective WG?" were examined to provide comprehensive perspectives on this complex WG concept. As reviewed, only 33 publications provided definitions of WG, while the number of publications representing the concepts of good/effective WG was 20. Each of these 33 publications mentioned one or more different definitions. The GWP's WG definition, which was issued in 2003 and considered the first official definition, had been the most-mentioned one in the reviewed publications (n = 31). The WG definitions of Araral and Yu (2013) and the OECD (2015) were provided in 4 and 2 publications, respectively. The remaining definitions generated by Moench in 2003 (Moench et al., 2003), the Water Governance Facility (WGF) in 2005 (Wajjwalku, 2019), the Department for International Development (DFID) in 2006 (Aminova and Abdullayev, 2009; Pahl-Wostl et al., 2012), etc. were included in only one publication each. Noticeably, only three publications of Moench et al. (2003), Pahl-Wostl et al. (2012), and Araral and Yu (2013) proposed their own definition of WG. For more insight of the WG concept, diverse perspectives on its definitions, scopes, and aspects were analyzed and discussed as follows.

In 1997, the UN defined governance as "the exercise of political, economic, and administrative authority in the management of a country's affairs at all levels". However, this statement did not specify which institutional arrangements can enable the achievement of the defined objectives and targets. Based on this UN's perspective, since early 2000s, many international organizations, forums, and scholars have provided the definitions and scopes of WG. However, over the last two decades, there is no consensus on these definitions and scopes. In fact, the concept of WG was firstly mentioned by the UNDP in 2000 (UNDP, 2004; Batchelor, 2007; Pahl-Wostl, 2009; Baumgartner and Pahl-Wostl, 2013), and then the GWP officially defined it in 2003 as "the range of political, social, economic, and administrative systems that are in place to develop and manage water resources, and the delivery of water services, at different levels of society". In addition, WG "embraces the formal and informal institutions by which authority is exercised" (Rogers and Hall, 2003; Otsuka, 2019b). These perspectives elaborated that the notion of WG includes the ability to design public policy and an institutional framework that are socially accepted and mobilize social resources to support them. Importantly, WG focuses not only on "internal governance" (traditional management) within the water sector that often emphasizes economic and technical solutions but also on "external governance" outside the water sector, which involves processes more social and political in nature.

In 2005, the WGF also shared a similar (but more nuanced and concrete) definition, referring to WG as "the political, social, economic and administrative systems in place that influence water's use and management, essentially who gets what water, when and how, and who has the right to water and related services, and their benefits" (Wajjwalku, 2019; SIWI, 2022). In 2006, the DFID described WG as "encompassing all the mechanisms, processes, relationships and institutions through which citizens and groups articulate their interests and exercise their rights and obligations" (DFID, 2006; Aminova and Abdullayev, 2009). Compared to the GWP's perspectives, both the WGF's and DFID's definitions had emphasized one more crucial WG element, being the clarification of the roles and responsibilities of stakeholders engaged in water resources and services.

Although the above-mentioned definitions are helpful in reminding WG scholars to pay more attention to the broader aspects of water issues, including both social, economic, and political factors; they fall short in terms of diagnostic and prescriptive utility. It is argued that for research on WG to be useful, it should diagnose and tackle incentive problems beyond statements of general principles. Thus, Tropp (2007) referred to WG in terms of the "evolution of formal and informal networks, partnerships, joint-decision making processes including dialogue and negotiated outcomes as mechanisms for steering water governance". Wiek and Larson (2012) summarized key features of WG as "a systemic perspective, a governance focus on social actors, a transparent and accessible discourse on values and goals, and a comprehensive perspective on water sustainability". Hirsch (2006) argued that catchment governance, in this case in the Mekong, should be understood as "an arena for negotiating more sustainable, equitable, and productive use and management of water at multiple scales". Others such as Kashyap (2004) mentioned WG as "the ability to develop adaptive capacity" and Godden et al. (2011) as "adaptive and sustainable water management" in the context of climate change. Some scholars take a more behavioral approach. For instance, Pahl-Wostl et al. (2008) defined the term as "the development and implementation of norms, principles, rules, incentives, informative tools, and infrastructure to promote a change in the behavior of actors at the global level in the area of water governance". This definition, however, suffered the same fate as the GWP's, WGF's, and DFID's ones. Thus, Pahl-Wostl et al. (2012) updated their WG definition as a system with "structural features and transient processes at both rule making and operational levels", that "takes into account the different actors and networks that help formulate and implement water policy".

Noticeably, in recent years, some studies found that the majority of previous statements of WG, especially the GWP's definition, seemed to present a "one-size-fits-all" concept (Araral and Yu, 2013; OECD, 2015, 2018a; Rola et al., 2015b; Otsuka, 2019b). Thus, it is difficult for applying the same WG strategy to developing as to developed countries, since developing countries (including many ones in Asia) frequently have poorer capacity in administration, democratic institutions, social service provision, and other factors. Moreover, these statements are too broad and does not provide mechanisms for developing and managing water resources. According to Araral and Yu (2013), the mechanisms to develop and manage water resources are often not well specified, and thus their operational implications for research and governance reform are unclear. Therefore, in 2013, these two authors provided an alternative operational definition of WG in terms of "various dimensions of water law, policies, and administration that have been commonly regarded in the literature as important determinants of performance". These include water rights, pricing, decentralization, accountability, integration, private sector participation, user group participation, and organizational basis of water management among others (Araral and Yu, 2013; Rola et al., 2015b; Maharjan, 2018).

In 2015, through discussions among member states as well as multi-stakeholder participants including public, private, and nonprofit sectors, the OECD listed its 12 WG principles that provided a framework to understand whether WG systems are performing optimally and help to adjust them where necessary. Under these principles, three main elements were emphasized, namely, enhancing the effectiveness, efficiency, and trust and engagement in WG (OECD, 2015). Noticeably, many WG scholars acknowledge that the OECD's WG perspective has developed "on the premise that there is no one-size-fits-all solution to water challenge worldwide", that "water policies need to be tailored to different water resources and places", and that "governance responses have to adapt to changing circumstances" (OECD, 2015; Otsuka, 2019b; Wajjwalku, 2019). Furthermore, Jiménez et al. (2020) proposed a practical WG definition depicting the concept into "what" (the functions), "how" (the attributes), and "what for" (the outcomes): "Water governance is a combination of functions, performed with certain attributes, to achieve one or more desired outcomes, all shaped by the values and aspirations of individuals and organizations". This perspective on WG can contribute to improved understanding of WG through its future use: (i) to understand how in practice (at national and local level) different functions are linked to certain attributes for achieving desired outcomes, basing the analysis on the proposed framework; (ii) to understand how countries self-assess their weaknesses in relation to the framework, and extract general common trends; (iii) to improve governance intervention design as a result of increased understanding of the WG pathway.

Recently, the concept of "effective water governance" has become a more regularly discussed issue by many WG scholars and organizations. However, unlike the case of the WG definition, there is a relative consensus of perspectives on this concept. For instance, the GWP stated that effective WG means governance that permits effective formation and implementation of water policy and enables application of IWRM to develop, allocate, and manage water use "equitably and efficiently and ensuring environmental sustainability" (Otsuka, 2019b). According to Rogers and Hall (2003), effective WG should include open, transparent, inclusive, communicative, coherent, integrative, equitable, and ethical approaches. Its performance and operation should be accountable, efficient, responsive, and sustainable. Within perspectives of the OECD's and UN-Water; effective WG enables people to participate in decisions affecting their lives; and to ensure this, accountability mechanisms need to be in place (UN-Water, 2014; Otsuka, 2019b). Also, both Aminova and Abdullayev (2009) and Biswas and Tortajada (2010) referred to effective governance as a strong and effective state that is accountable to its people, governed by a constitutional rule of law and able to provide a stable political environment. Moreover, to the DFID (2006) and UNDP (2006a), effective governance is responsive, participatory, transparent, equitable, accountable, consensus oriented, effective, and efficient, and directed towards strategic vision.

Several following conclusions can be drawn from systematically reviewing WG definitions. Generally, the WG concept embraces the full complexity of political, social, economic, and administrative dimensions as well as their interaction. This is reflected in diverse perspectives on WG over the last two decades, indicating no common approach to defining WG. This situation is partially due to diverse usages of the WG concept by practitioners and scholars in planning different WG projects or studying its various scopes, aspects, and norms (such as the role of different actors, laws and policies, institutions, mechanisms, politics, etc.) in WRM, rather than a broad, encompassing definition of WG. Noticeably, although there are increasingly more specific definitions of WG introduced; the GWP's one, due to covering the general characteristics of WG, is still mentioned frequently in the WG studies and considered the basis for other concepts to be studied, generated, and applied. Regarding the effective WG concept, however, it has been conceptualized with relatively similar perspectives. Generally, with its key elements such as efficiency, transparency, equity, accountability, sustainability, responsiveness, and participatory, effective WG requires the participation of both government, civil society and the private sectors to ensure the balance of competing interests and social equity.

5.3.3 Focus Point Addressed Using WG

The focus points examined using WG in this study can be considered water- (indirect) and WG-related (direct) issues. By reviewing 145 selected publications, these main issues in Asia, especially in this continent's developing countries, were identified and analyzed. Each of these publications focused on one or more direct and indirect issues, and Table 5.1 shows a long list of them. As shown, the most-concerned water-related issue in Asia was "transboundary water management", examined in one-third of the total publications (n = 48). Noticeably, "agriculture" (mainly including irrigation management) (n = 41) and "water quality" (n = 31) were also important issues in the Asian developing regions, which appealed to the attention of WG practitioners and scholars. Besides, they also frequently investigated renewable energy-related issues in Asia such as "hydropower energy" and "the water-energy-food nexus". These two issues were investigated in the total of 31 publications (n = 25 and 6, respectively). Remarkably, "climate change" and "urban water services" shared a similar level of attention, studied in 21 publications each. Related to the issue of urban water services, “water technology and infrastructure management” (mostly managing water supply and drainage, wastewater treatment, and flooding prevention systems in the Asian developing urban areas) was also highlighted in the reviewed studies (n = 16). It is noteworthy that “sustainable development and the SDGs” has also become a hot topic of study in the whole Asia in recent years (n = 20). While only 7 out of 20 these studies was published before 2015 and focused on general sustainable development, the majority of them (n = 13) have been published since 2015 and mostly centered on the specific SDGs including goals 11 (sustainable cities, n = 1), 16 (effective institutions at all levels, n = 4), and especially 6 (clean water and sanitation for all, n = 9). In addition, the following climatic hazard-related issues were examined in the total of 26 publications: “water scarcity and drought” and “flood risk management”. Moreover, “river basin management” (n = 18) and “water security” (n = 13) were also considered popularly discussed topics. The remaining issues (e.g., groundwater management, ecological water needs, environmental protection, etc.) all contained between one and 11 publications.

Among WG-related issues in Asia, “legal and institutional arrangements” was the most common topic of discussion (n = 116). Especially, up to 26 out of these 116 publications referred to legal and institutional reforms as key drivers of improving WG in the Asian developing regions. The issues related to “coordination and cooperation” (n = 50) and “stakeholder engagement” (n = 27) in WG were considered the second and third most-discussed ones in the reviewed publications, followed closely by “politics and power” (n = 26). Other issues that were also frequently examined (n = 10 each) included “adaptive governance” and “capacity development”. Noticeably, these issues were mostly discussed in the reviewed publications focusing on examining WG in the Asian less developed or developing countries. The remaining sub-issues (e.g., knowledge and data sharing, polycentric governance, etc.) were mentioned in the varying numbers of publications, ranging from one to five.

Regarding the situation of Vietnam, based on data collected from reviewing 26 publications focusing on this country’s WG, “transboundary water management” (n = 10), “river basin management” (n = 7), “water quality” (n = 7), “agriculture” (n = 6), “hydropower energy” (n = 6), and “urban water services” (n = 4) were the most-discussed water-related issues. Remarkably, exactly like the whole Asia’s context, “legal and institutional arrangements” (n = 18), “coordination and cooperation” (n = 6), and “stakeholder engagement” (n = 4), “politics and power” (n = 2), and “adaptive governance” (n = 2) were also the most-highlighted WG-related issues in Vietnam. Other water- and WG-related issues in this country were mostly examined in only one publication. It is also noteworthy that as aforementioned, Can Tho is one of the most rapidly developing cities in Vietnam. Besides, it also has a crucial location in the middle of VMD that is the lowest part of the Mekong River Basin and has been regularly selected as the main case study area in the most of 26 reviewed publications focusing on WG in Vietnam. Therefore, the above-mentioned water- and WG-related issues can be considered the most-concerned ones not only in Vietnam but also in Can Tho City.

Table 5.1 Summary of the main water- and WG-related issues not only in Asia but also in Vietnam and its developing Can Tho City

Water-related issue	**No. of publications**	**WG-related issue**	**No. of publications**
Transboundary water management	48	Legal and institutional arrangements	116
Agriculture	41	Coordination and cooperation	50
Water quality	31	Stakeholder engagement	27
Hydropower and energy	25	Politics and power	26
Climate change	21	Adaptive governance	10
Urban water services	21	Capacity development	10
Sustainable development and the SDGs	20	Knowledge and data sharing	5
River basin management	18	Polycentric governance	2
Water technology and infrastructure management	16	Innovative governance	1
Water scarcity and drought	13	Multi-level and multi-scale governance	1
Flood risk management	13		
Water security	13		
Groundwater management	11		
Ecological water needs	9		
Environmental protection	7		
The water-energy-food nexus	6		
Watershed management	6		
Rural water services	5		
Water commodification and market	4		
Tourism and navigation	2		
Coastal zone management	2		
Industry	1		
Poverty reduction	1		

Notes:

"*Hydropower and energy*" also includes dam management; "*Urban water services*" mainly includes water supply and drainage, sanitation, and wastewater management; "*River basin management*" also includes reservoir and lake management; "*Coordination and cooperation*" also includes water conflicts and negotiation; "*Legal and institutional arrangements*" also includes policy and institutional reform; "*Politics and power*" also includes geopolitics and hydropolitics

From the obtained findings, several following observations can be made. Only 10 out of 57 cross-border river basins in Asia and 2 out of 17 major river basins in Vietnam are fully covered by basin agreements (Rieu-Clarke et al., 2012; Chen et al., 2013). This situation has partially explained why "transboundary water management" has become one of the most concerning issues in the whole Asia in general and Vietnam in particular. In fact, the Asian continent and this SEA downstream country face many various challenges related to sharing and governing water resources between upstream and downstream nations. For instance, these key cross-border challenges in the GBMRB (SA) and Mekong River Basin (SEA) are water conflicts caused by hydropower dam-operating and building activities, poor regional cooperation in water allocation for irrigation, lack of joint strategies for mitigating climate change (mainly floods and droughts) and addressing its risks, absence of effective legal frameworks and institutional arrangements for governing regional water resources towards achieving the SDGs, etc. (Douglass, 2013; Xing, 2017; Maharjan, 2018; Parven and Hasan, 2018; Bourdais et al., 2021). Also, the IRB (SA) and ASCARB (CAs) have faced core challenges such as water shortages in Pakistan due to diverting rivers for irrigation in India, weak agreements for controlling transboundary water pollution and serious saline intrusion in the Aral Sea region, food and electricity shortages in Tajikistan, Turkmenistan, and Kyrgyzstan due to unprecedentedly low water level in reservoirs, etc. (Droogers and Bouma, 2014; Williams, 2018; Bourdais et al., 2021).

The above-mentioned information has confirmed the fact that transboundary management, irrigation management, water quality control, hydropower generation, climate change adaptation and risk mitigation, and the achievement of SDGs are the most-discussed issues in the reviewed publications focusing WG in Asia and Vietnam. Moreover, this finding can be also more supported by the following interpretation. Nearly two-thirds of the total Asian nations including Vietnam are less developed and developing ones (UN, 2020, 2022a; Britannica, 2022; O'Neill, 2022). Therefore, rapid industrial urbanization, intensification of primary production for export, global economic integration, increasing scales of projects such as very large dams, global warming, and privatization of water infrastructure and services have been set as priorities for socio-economic growth in these countries, leading to spatiotemporally extensive interactions and impacts on the general WG in Asia comprising Vietnam.

In terms of directly WG-related issues, "legal and institutional arrangements" was the most-highlighted one. The main reason behind this can be explained as follows. The concept of governance has strongly referred to laws, policies, regulations, and institutional arrangements set up to govern. Thus, legal and institutional arrangements should be considered the core factors in the WG system. Many reviewed publications had also confirmed this. They argued that reforming WG is considered a key solution to complex water-related challenges in the Asian less developed and developing countries including Vietnam; and in the case of these countries, this reform should firstly focus on the improvement of their poor legal and institutional structures. For instance, most recently, Jiang et al. (2020) analyzed two policy trends of WG in China – "state control" and "marketization", and argued that instead of contradicting or supplanting each other, these two policy trends of WG should be complementary, collectively contributing to a distinctive governance institution that serves broader political, economic, and water security goals. Also, Pahl-Wostl (2009) and Otsuka (2019a) recognized that top-down governance has limitations in supporting WG policies enforced in both China and Vietnam, hence it should be replaced by or incorporate a bottom-up mechanism into new WG systems. For the WG mechanism in Philippines, Rola et al. (2015a, 2016) concluded that nationally, water use across sectors is governed by too complex and numerous institutions that are disjointed organizations, thus the national highest priority should be reform of institutional structures that could support the more formal, more scientific basis for water-use decisions.

Another thing to note is that "coordination and cooperation", "stakeholder engagement", "politics and power", "adaptive governance", and "capacity development" were also frequently studied. Their outstanding emergence in the reviewed publications has been reflected by the following situation. Apart from weak legal accountability (Araral and Yu, 2012) and poor institutional framework (Delavari and Abdi, 2018), WG in the Asian developing nations like Vietnam is often characterized by limited stakeholder involvement and public participation, inadequate governance capabilities (especially institutional adaptive capacity) (Chen et al., 2013; Bettini et al., 2015; Wu and Leong, 2016; Delavari and Abdi, 2018; Otsuka, 2019b), ineffective coordination and cooperation at both national and international scales (mainly including data and information sharing, the balance of interests, collaborative research, mutual trust, and conflict negotiation) (Dore and Lebel, 2010; Xing, 2017; Bourdais et al., 2021), unequal power and unstable political regime (especially including both transboundary geopolitics and hydropolitics) (Williams, 2018; Zinzani and Bichsel, 2018; Hussein, 2019; Sehring, 2020; Bourdais et al., 2021), and restricted funding (Araral and Yu, 2012; Delavari and Abdi, 2018). These characteristics reflect an urgent need of promoting effective cooperation and stakeholder involvement, building up political confidence and power justice, and enhancing governance capacity to boost more robust and comprehensive WG regimes in the Asian countries including Vietnam. This urgent need is strongly consistent with the study's findings pointing out the WG-related issues in Asia in general and its specific regions in particular.

5.3.4 Frameworks Used to Define WG

A framework for assessing and working with WG or its related issues is the crucial part in the studies of WG. A well-designed WG framework includes a set of diverse elements and their interactions that need to be examined in implementing theoretical or empirical studies of a particular type of phenomenon (Ostrom, 1990, 2005; Clement, 2010; McGinnis and Ostrom, 2014), which can help scholars and policymakers to evaluate more comprehensively the general status of WG or its specific related issues, and hence to identify and overcome WG challenges and gaps. In the reviewed studies, a wide range of new and existing frameworks were utilized for performing (Table 5.2). Based on the reviewed information and referring the WG framework studies (Özerol et al., 2018; Di Vaio et al., 2021), they were classified into "applied" (application of existing frameworks), "developed" (development of new frameworks based on existing theory), and "generated" (generation of new frameworks based on own theory) frameworks. As shown in Table 5.2, over three-thirds of the studies (n = 114) were implemented by utilizing analytical frameworks, while the remaining ones (n = 31) were conducted with no or unclear frameworks. Remarkably, almost half of these 114 publications (n = 56) had applied existing frameworks for analyzing WG and its relevant issues in their Asian study locations, while the number of studies using "developed" frameworks was 36. Generating new own frameworks was also popular, accounting for nearly 20% of the total publications (n = 22).

Table 5.2 Summary of the popular WG frameworks utilized in the reviewed publications

Popular framework	No. of publications
Legal and institutional framework (LIF)	18
Institutional Decomposition and Analysis (IDA) framework	10
Adaptive and integrated water management (AIWM) framework	7
OECD Water Governance Indicator and Measurement framework (WGIMF)	5
Institutional Analysis and Development (IAD) framework	4
OECD Multi-level Governance framework	3
Heuristic framework	3

Hydro-Hegemony framework (HHF)	2
Management and Transition framework (MTF)	2
Transboundary Water Interaction Nexus (TWINS) framework	2
Water Framework Directive (WFD)	2
Other	58
No or unclear framework used	31
Total	**145**
Note: More detailed information on other frameworks used in the reviewed publications is shown in Table B8	

There are some critical points that a more detailed review can observe. Among 55 publications using existing frameworks, 18 applied the LIFs that are relatively simple and mainly comprise a range of laws, regulations, policies, decisions, and organizations in place to develop and govern water resources. Together with being used in the Asian WG studies, this framework has been also popularly applied by many Asian developing countries' governments to govern and sustain their water resources. Noticeably, Vietnam is also currently using the LIF for governing, analyzing, and assessing both its surface and ground water resources (Figure 5.10 and 5.11). For instance, using the LIF, Loan (2010) and Vo et al. (2017) assessed the Vietnamese WG status (mainly in agricultural sector) by analyzing the implementation process of policy; and hence identified policy contradictions and gaps as well as countermeasures for reforming policies and institutional structures towards sustainable development. In the study of Molle et al. (2009), this framework was applied to analyze the Mekong River Commission's institutional structure in transboundary water management (mainly focusing on hydropower and irrigation cooperation between Thailand, Laos, Cambodia, and Vietnam) and brings to light the institutional dissonances between regional and national decision-making landscapes in the Lower Mekong Basin. Ho (2019a, 2019b) compared the national-level water LIFs in China and India across dimensions including institutional and bureaucratic structures, laws, policies, and regulations that govern these two nations' urban water sector. Huy et al. (2015) also applied the LIF to analyze and discuss about institutional challenges for peri-urban water supply in Can Tho City, Vietnam. Noticeably, a few other frameworks examined in this study can be also worked as the LIF. The "Four Systems" framework, which is considered the Chinese institutional one, provides another example of this (He et al., 2020b). Generally, as performed in the reviewed studies, the LIF was mostly utilized to focus on examining and understanding specific case- or place-based WG issues in the Asian less developed and developing countries comprising Vietnam.

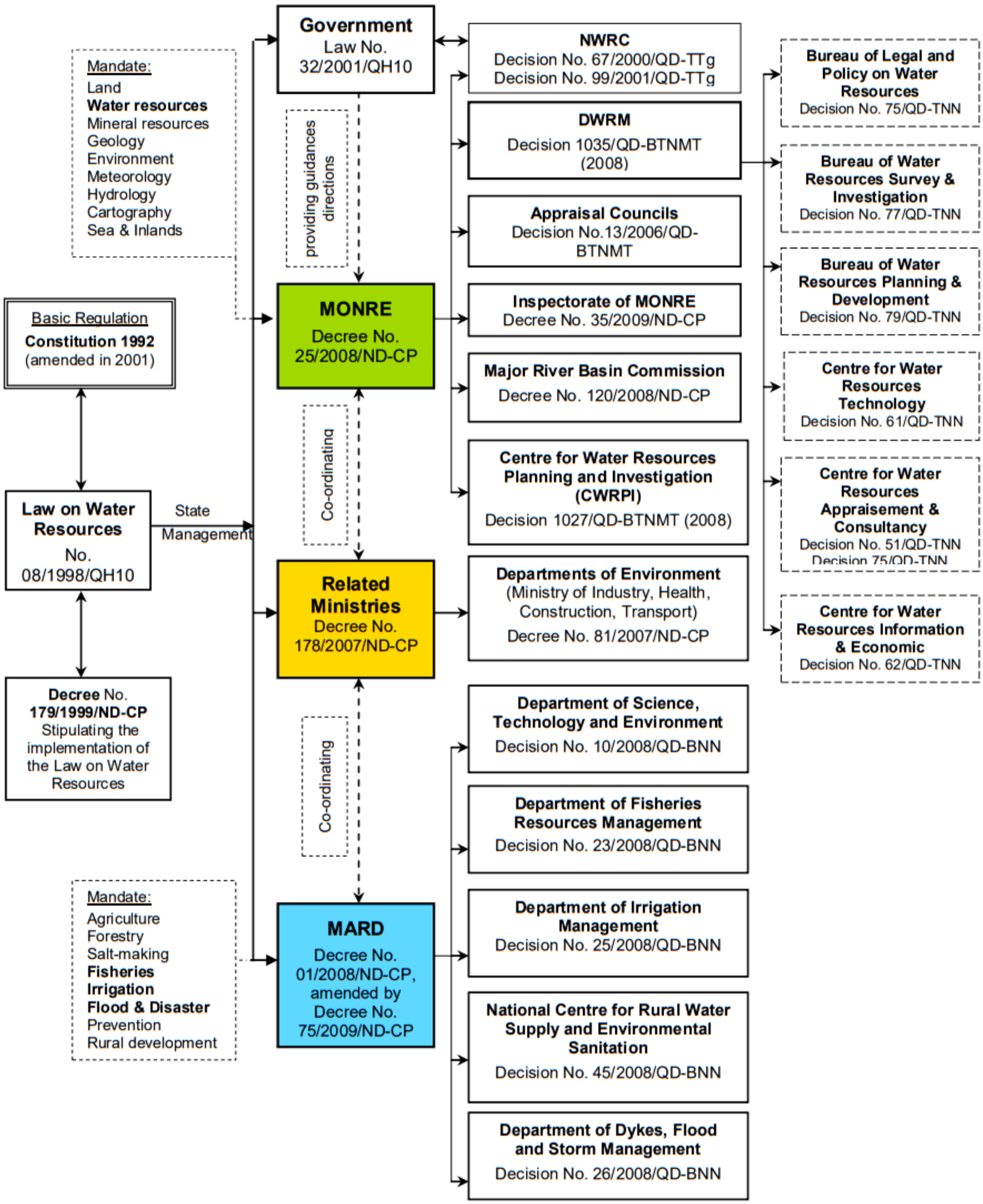


Figure 5.10 The legal and institutional framework for WG in Vietnam at national scale (Loan, 2010, 2012; Waibel et al., 2012; Vo et al., 2017) (Notes: MONRE - Ministry of Natural Resources and Environment, MARD - Ministry of Agriculture and Rural Development, NWRC - National Water Resources Council, and DWRM - Department of Water Resources Management)

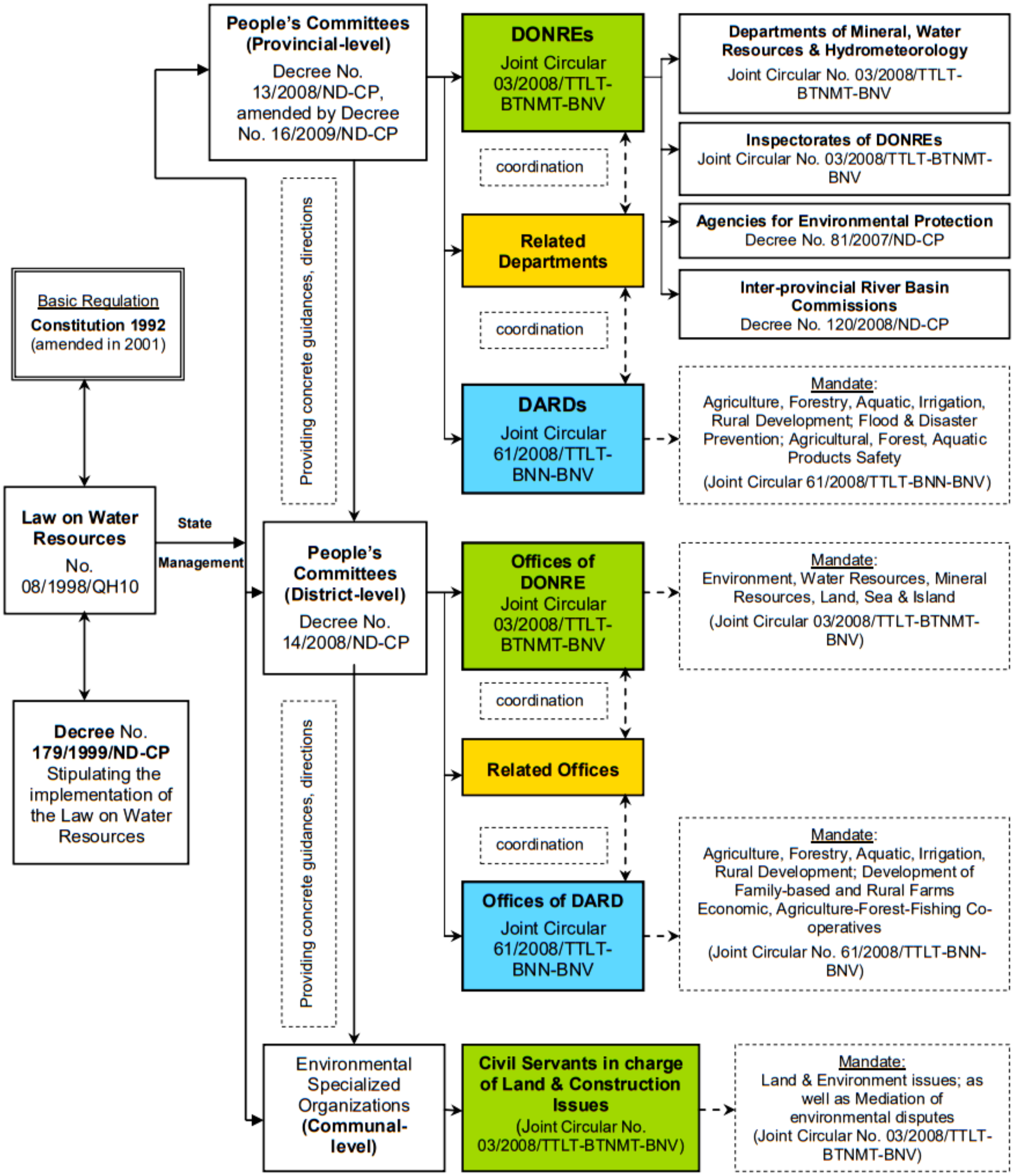


Figure 5.11 The legal and institutional framework for WG in Vietnam at local scale (e.g., at Can Tho City) (Loan, 2010, 2012; Waibel et al., 2012; Vo et al., 2017) (Notes: DONRE – Department of Natural Resources and Environment, DARD - Department of Agriculture and Rural Development)

Noticeably, the frameworks generated or developed by adopting the Ostrom's theory of the common pool resources (CPRs) management were significantly emerged in the studies. They are mainly the SES, AIWM, MTF, and especially IDA and IAD frameworks. Among these frameworks, the IAD was generated by Ostrom in 1994 and considered one of the most distinguished and tested framework in the field of policy sciences (Clement, 2010; Ostrom, 2011; Shrestha and Ojha, 2017). The focal level of this framework consists of an action arena, composed of actors and affected by a set of external variables including biophysical conditions (i.e. the physical state of the environment where actors evolve), the attributes of the community, and the rules-in-use. They represent nature, society and the rules that govern nature-society interaction (Ostrom, 2005; Clement, 2010; Shrestha and Ojha, 2017). Among the reviewed studies, the IAD framework was directly utilized for performing four studies, and especially was referred to or modified by many scholars to develop various frameworks and apply in other 31 studies. For instance, in the study of Araral and Wu (2016), the IAD framework was modified and used as a systematically analytic tool to conduct a comparative study of WG between China and India, mainly analyzing and comparing the large number of micro-institutional variables in three areas: water laws, policies and administration. Bhargava (2019) and Bruns (2017) also applied the IAD framework to understand both the interactive and polycentric WG process in India and Philippines, focusing on investigating physical, institutional, and community factors and their linkages, and then developing a database of WG assessment based on a social-ecological system approach.

Especially, in 2004, rooted in the IAD framework, Saleth and Dinar developed the IDA framework for the larger purpose of analytically demonstrating and empirically evaluating the institutional linkages and their performance implications within water sector (Saleth and Dinar, 2004; Dinar and Saleth, 2005). This framework was performed in ten Asian WG studies. In 2004 and 2005, applying the institutional decomposition approach from the IDA framework, Saleth and Dinar developed the Water Institution Health Index, based on a set of legal, policy, and organizational variables to capture aspects: accountability, political stability, corruption, credit worthiness, competitiveness, institutional performance, and governance effectiveness. Then, this index was used to evaluates and compares the relative health of water institutions and their components across 43 countries including 16 SA and SEA ones, and demonstrates the linkage and consistency of this index with other economic, social and governance indicators (Saleth and Dinar, 2004; Dinar and Saleth, 2005). Later, between 2012 and 2019, a series of studies mainly such as Araral and Yu (2012, 2013); Araral and Ratra (2016); Rola et al. (2015a, 2016); Ahmed and Araral (2019); and Singh et al. (2019)

also applied the IDA framework to explore key variations in WG of China, India, and other 17 nations across Asia by measuring 20 diverse WG indicators related to water law, policy, and administration.

Moreover, also based on the Ostrom's theory, the Pahl-Wostl's AIWM framework was developed in 2005 and frequently performed in the publications (n = 7) to analyze water policy and institution reforms towards more adaptive WG and management in the Asian developing countries. Particularly, Ha et al. (2018) and Mishra et al. (2020) utilized this framework to assess the linkages between adaptive governance capacities and integrated freshwater management (in Vietnam) and water security (in India) improvement focusing on legal and institutional reforms. Knieper and Pahl-Wostl (2016) explored potential links between WG, IRWM, and environmental performance in light of different context factors between the African and Asian river basins. In addition, the Ostrom's theory-based various frameworks (i.e., the IWRM's conceptually normative (Herrfahrdt et al., 2006), SES developed (Mfodwo, 2010), MTF (Kranz et al., 2010), and CPRs governance (Yu et al., 2015) frameworks, respectively developed in 2006, 2007, 2010, and 2016) were also performed in the reviewed publications.

Recently, the OCED's frameworks, namely the OECD Multi-level Governance framework (generated in 2011) and OECD Water Governance Indicator and Measurement framework (WGIMF) (upgraded from 2015 to 2018), have been popularly performed in the reviewed publications (n = 8) to govern, analyze, and evaluate WG-related issues especially in the Asian developing regions. Specifically, the WGIMF includes 12 principles enhancing three main element: effectiveness, efficiency, and trust and engagement in WG. This framework is applicable across governance scales (local, basin, national, etc.) for assessing the state of play of WG policy frameworks (what), institutions (who) and instruments (how), and their needed improvements over time (OECD, 2018a, 2018b). For example, considered this framework as a tool to engage multi-stakeholder into dialogues on the performance of WG systems, Wajjwalku (2019) applied it successfully to clarify the interaction and coordination between local NGOs and government authorities in water allocation and flood prevention in Chiang Rai (Thailand), focusing on participatory opportunities and negotiation capacity. In the reports of ADB (2016, 2020) and OECD (2020), the OECD surveyed 48 Asia-Pacific members using the WGIMF's 12 OECD principles to shed some light on the governance gaps in the region and make policy recommendations on the roles of stakeholder engagement, integrity, trade-offs, and monitoring and evaluation in WG systems towards sustaining regional water security.

Moreover, a wide range of other frameworks were reviewed in this study. The majority of them were "applied" and "developed" frameworks and performed in only one publication each. However, these frameworks can be clustered into groups according to the specific WG-related issues analyzed. For example, the Transboundary Water Interaction Nexus (TWINS) (Hanasz, 2017b), Track II Dialogue (Hanasz, 2017a), heuristic (Dore et al., 2012), transboundary nexus (Keskinen et al., 2016), water-energy-food (Lebel et al., 2020), and effective cross-border governance (Douglass, 2013) frameworks focus on analyzing issues related to transboundary water management; the Hydro-Hegemony (Hussein, 2019; Bourdais Park et al., 2021), "politics of scale" analytical (Neef, 2008), and actor-oriented political ecological (Maharjan, 2018) frameworks focus on discussing about impacts of political and power factor on both national and regional WG.

Overall, there was significant diversity in the frameworks used after generation, modification or adaptation. It is acknowledged that the influence of Ostrom's theory on frameworks performed in the Asian WG studies is very significant. This acknowledgement is also relatively consistent with the obtained results of the previous studies such as Özerol et al. (2018) and Di Vaio et al. (2021). As reviewed, it is noteworthy that compared to the LIF that is currently used in Vietnam and mostly applied for analyzing and exploring specific case- or place-based WG issues in Asia, the Ostrom's theory-based frameworks (especially such as the IAD, IDA, AIWM, MTF, and SES frameworks) often tend to assess the more general status of WG systems in Asia, specially focusing on law, policy, and administration areas. The WG scholars applying these broad frameworks in a systematic manner for their studies have a tendency to focus on building databases, abstracting obtained findings, and giving more scientific evidence-based statements on WG or its related issues. The reviewed studies using the OECD's WGIMF also provide another example of this tendency. Noticeably, with the aim of achieving more effective, efficient, and inclusive governance especially in developing regions, and of understanding better who does what, at which level, how, and why with respect to water-related policies, the WGIMF has been generated and used in the WG studies including many Asian developing nations as study areas. Generally, the application of these frameworks has met the need for a next generation research agenda on the developing regions' WG that is required to become more theoretically coherent, analytically robust, empirically grounded, and policy relevant.

5.3.5 Elements Included in WG Frameworks and Their Evolution

5.3.5.1 Inclusion of Key WG Elements

For an effective WG, a well-designed framework including a thorough set of governance elements plays a crucial role. The obtained results indicated that these elements were significantly diverse, and being differently used in WG frameworks and for specific analytical purposes. Even these elements' practical meaning, application, and the names/phrases of use can be also spatiotemporally different. Thus, to fully identify these elements as well as unify their diverse name/phrase of use, the results obtained by reviewing 145 publications were compared to the others referred from the studies of Rogers and Hall (2003); OECD (2018a, 2018b), and Jiménez et al. (2020). These three studies focused on analyzing the WG frameworks' elements and principles, and well recognized in the research community. For some unusual, unclear, or difficult-to-unify elements, they were deeply discussed by all team members to be identified. As a result, this study identified a wide range of key elements and listed them in Table 5.3. The following observations regarding the WG frameworks' elements applied in the Asia WG studies can be found.

Table 5.3 Summary of the key elements of frameworks applied in the reviewed publications for governing water resources in the Asian regions

Element	No. of publications
Legislation, regulation, instrument, and policy	93
Management arrangement	92
Stakeholder engagement	90
Cooperation and coordination	78
Monitoring and evaluation	68
Clear role and responsibility	50
Appropriate scales within basin system	49
Integrity and transparency	45
Data, information, and knowledge sharing	41
Capacity development	33
Trade-offs across users, areas, and generations	13
Financial capacity	12

Planning and preparedness	12
Innovative governance	9
Notes: "Management arrangement" mainly refers to the combination of organizational, managerial and institutional arrangements	

Among the identified governance elements, "legislation, regulation, instrument, and policy" (n = 93), "management arrangement" (n = 92), "stakeholder engagement" (n = 90), and "cooperation and coordination" (n = 78) were the four most-included elements in the WG frameworks used to analyze the Asian WG issues. Noticeably, the LIF currently applied for WG in Vietnam as well as Can Tho City (Figure 5.10 and 5.11) also mainly includes the first three elements such as (i) water regulations, laws, decrees, and decisions; (ii) management arrangement comprising relevant organizations (e.g., MONRE, DONRE, MARD, DARD, NWRC, DWRM, etc.); and (iii) stakeholder involvement showing roles and links between these organizations in the WG framework. Apart from the first two elements that are widely considered the core ones in the WG framework and need to be firstly reformed in many Asian less developed and developing nations, "stakeholder engagement" and "cooperation and coordination" have been also frequently included. These two elements often comprise the processes, mechanisms, instruments, and platforms that promote multi-level, multi-sectorial, and multi-stakeholder cooperation among all actors. They entail information sharing, dialogue and collaborative decision-making, linked to policy making and planning. At the transboundary scale, they often fall under the umbrella of water diplomacy and can have far reaching impacts beyond the water sector, e.g., geopolitical and hydropolitical security. Noticeably, their frequent emergence in the reviewed studies is strongly consistent with the previously obtained results that mentioned stakeholder engagement, cooperation, coordination, and especially transboundary water management as the most-discussed water- and WG-related challenges in Asia. In fact, most frameworks applied in the reviewed publications to analyze the transboundary water management issue in the Asian regions included "stakeholder engagement" and "cooperation and coordination" as compulsory elements and emphasized their crucial roles.

Importantly, for successfully engaging stakeholders and then sustaining their effective cooperation and coordination, it should be started by considering whether the roles and responsibilities not only of all actors but also for policy making, policy implementation, operational management, and regulation are clearly allocated. Besides, the process of investigating whether made policies are fitted to places and take account of multi-level dynamics across the regional, national, federal/state, basin, and local levels, and whether there are cooperation and coordination challenges between the different scales is also vital for ensuring the effective coordination and sustainable cooperation between stakeholders. More importantly, monitoring and evaluating water policies, institutions, cooperation, and governance where appropriate; and then sharing the evaluation results with the public and making adjustments when needed must be implemented regularly, timely, and transparently. Noticeably, as previously discussed, many Asian countries, especially less developed and developing are increasingly facing difficulties in implementing the above-mentioned requirements. However, these difficulties can also explain why “monitoring and evaluation”, “clear role and responsibility”, and “appropriate scales within basin system” were also highlighted as key elements of WG frameworks applied for analyzing WG in these Asian nations, reflected in the high numbers of reviewed publications (n = 68, 50, and 49, respectively) focusing on them.

The next popular elements were “integrity and transparency” and “data, information, and knowledge sharing”. These elements require governments, organizations, and individuals to facilitate all means for citizens to understand the decisions that may affect them; and they require the information to be usable through open data, that is accurate, available, complete, conformant, consistent, credible, processable, relevant, and timely. Specially, they are vital to the underlying trust in a transboundary relationship, where access to data can be strategically withheld or manipulated to strengthen the negotiating positions of one or more countries. The popularity of these elements in Asia WG studies is partly due to the follows. The WG system in many Asian developing countries (e.g., China, Vietnam, Laos, Cambodia, India, Bangladesh, etc.) is characterized by a lack of integrity and transparency in openness and public access to information so that stakeholders cannot understand the decision-making processes that affect them, and are not knowledgeable about the standards to expect from public officials. The reviewed publications also confirmed this characteristic. Chang et al. (2020) evaluated the performance of the IWRM in the Chinese major cities and concluded that information, data, and policy-making transparency are one of the most complex challenges for the future IWRM improvement in these cities. Islam et al. (2020) assessed the status of WG institutions in Bangladesh and stated that the significant integrity and transparency gaps between national water departments were key drivers of poor quality of WG work in this nation. Consequently, these two elements were included in many frameworks and frequently discussed in the Asian WG studies.

Respectively mentioned in 33 publications, “capacity development” also become WG element of attention in the Asian regions, particularly in developing ones. According to UNDP (2009), UNISDR (2009), and Jiménez et al. (2020), capability development refers to the processes by which all WG stakeholders systematically stimulate, develop, and strengthen their capabilities over time to be able to govern water resources sustainably. This could be through knowledge development, awareness building, training and skills development, and improving systems and processes. As reviewed, the main reason behind the attention of “capacity development” is clear. As previously mentioned, inadequate governance capability is considered one of the common WG-related challenges in many Asian developing countries including Vietnam. Therefore, developing WG capacities is vital in this continent in general and its developing nations in particular. In fact, many studies focused on this Asian challenge and gave solutions to address it. Li et al. (2021) analyzed how the key actors involved in the WG in Hong Kong play their role, especially focusing on their capacity to capture signals, implement policies, and adapt to external changes; and then found out capacity limitations needing to be addressed. Waibel et al. (2012), Singh et al. (2019), and Chang et al. (2020) assessed governance capacity in Vietnam, China, and India, focusing on institutional and policy implementation capacities; and then identified relevant obstacles and challenges as well as proposed countermeasures. Also, Wu and Leong (2016) stated that the institutional capacity was the key point leading to the difference in the river basin governance quality between China and India; and Wajjwalku (2019) discussed about role of civil society in flooding warning systems in Northern Thailand, focusing on negotiation capacity and solutions. Regarding “trade-offs across users, areas, and generations” (n = 13), “financial capacity” (n = 12), “planning and preparedness” (n = 12), and “innovative governance” (n = 9), they were considered less common elements of analytical frameworks used in the reviewed studies.

5.3.5.2 Evolution of WG Elements

The study recognized that there was the temporal variation in the number of elements in the WG frameworks over the research period of 2000–2020. To identify the evolution process of these elements in the Asian WG studies, this variation was analyzed by reviewing 145 selected publications. The average number of main WG elements and their frequency in the applied frameworks were identified for every 5-year period. The obtained results are shown in Table 5.4 and Figure 5.12, and then discussed as the follows.

Table 5.4 The average number of key governance elements and their frequency in the applied WG frameworks for the 5-year periods

Element	No. of publications				
	2000–2005	2006–2010	2011–2015	2016–2020	Total
Legislation, regulation, instrument, and policy	**5**	**22**	**38**	**28**	93
Management arrangement	**6**	**22**	**36**	**28**	92
Stakeholder engagement	**5**	**21**	**37**	**27**	90
Cooperation and coordination	**5**	**12**	**20**	**41**	78
Monitoring and evaluation	**4**	**19**	**17**	**28**	68
Clear role and responsibility	1	**12**	**15**	**22**	50
Appropriate scales within basin system	**4**	6	**13**	**26**	49
Integrity and transparency	2	6	9	**28**	45
Data, information, and knowledge sharing	2	**8**	**15**	**16**	41
Capacity development	2	5	7	**19**	33
Trade-offs across users, areas, and generations	1	0	2	10	13
Financial capacity	0	2	5	5	12
Planning and preparedness	0	2	1	9	12
Innovative governance	1	0	1	7	9
The average number of included elements	**6**	**7**	**8**	**10**	**14**

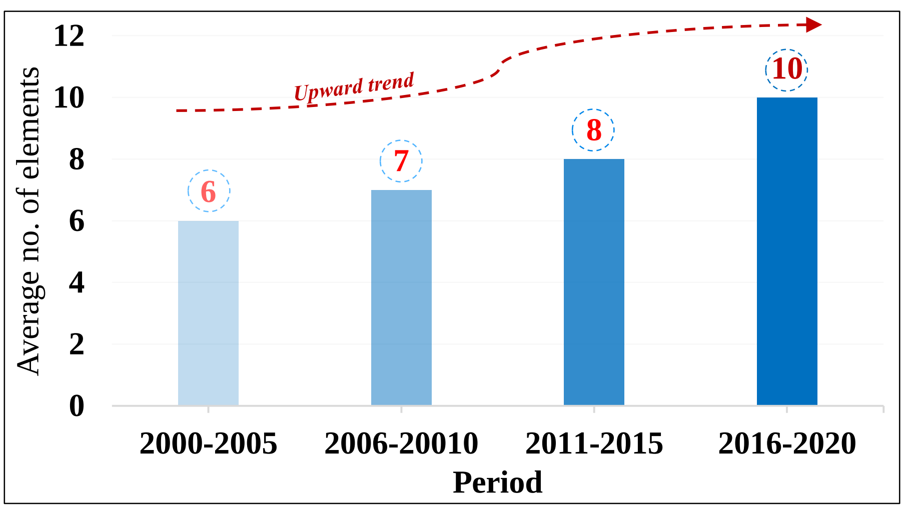


Figure 5.12 The evolution of the average number of key governance elements included in the applied WG frameworks over the research period

In the Asian WG studies conducted between 2000 and 2005 (n = 7 (Figure 5.5)), the average number of governance elements in analytical frameworks was only six. As examined, these elements were "legislation, regulation, instrument, and policy", "management arrangement", "stakeholder engagement", "cooperation and coordination", "monitoring and evaluation", and "appropriate scales within basin system". It can be seen that together with the legal framework and institutional arrangements, the involvement of all actors and their cooperation were referred to as integral components of the Asian WG systems in the early emergence period of the WG concept. Besides, regularly examining and assessing the effectiveness of policies, institutions, cooperation, and coordination were also required to take into consideration. In the next period, two more elements of "clear role and responsibility" and "data, information, and knowledge sharing" began to be concerned by water scholars and added to the applied frameworks. They were even more concerned than the "appropriate scales within basin system" element. Noticeably, this period was recorded with a higher number of Asian WG publications (n = 25). By frequently including these two elements in the analytical frameworks applied, these publications showed the important role of not only effectively engaging stakeholders but also clearly allocating their roles and responsibilities as well as timely sharing needed information between them in the implementation process of WG in Asia.

The average number of elements mentioned in the 2010–2015 Asian WG studies was eight. Compared to the last period, there was no significant change in the category of elements, except for the increase in the number of studies published (n = 41). However, from 2015 to 2020, the frameworks performed in the reviewed studies mostly were the combination of ten various governance elements. Even, some frameworks including more than 10 elements were mentioned or applied in the publications, such as the Van Rijswick's framework (11 elements) (Van Rijswick et al., 2014), Pahl-Wostl's modified AIWM framework (11) (Ha et al., 2018), OECD's framework (12) (Otsuka, 2019b; Wajjwalku, 2019; OECD, 2020), etc. In this prominent period of WG studies in Asia (n = 72), integrity and transparency practices across water policies, institutions, and governance frameworks for greater accountability and trust especially in decision making had been better appreciated, reflected through 28 studies focusing on them. Moreover, in this continent of limited WG capacity, building competencies of responsible authorities to be able to effectively carry out their duties as well as to address complex WG challenges was also well noted after 2015. In Vietnam, the currently applying WG framework, namely the LIF, includes only three key governance elements, namely "legislation, regulation, instrument, and policy", "management arrangement", and "stakeholder engagement" as previously reviewed and discussed in the part 5.3.5.1. Noticeably, to govern its water resources in the last periods, this developing country also applied this kind of framework with no significant change in the number of key governance elements included. In fact, comparing the LIFs for WG in Vietnam between these 5-year periods, only the change in the number of water laws applied and organizations involved as well as their roles and linkages can be observed. Overall, over the last two decades, there was an upward trend in the number of elements included in the WG frameworks in Asia, except for some countries like Vietnam. This trend can be partially explained by the constantly changing perception of the WG concept around the globe as well as the increasingly challenging status quo of WG in many Asian regions.

5.3.6 Proposed WG Framework and Common Challenges

5.3.6.1 Proposed WG Framework

Based on the reviewed results of the current WG frameworks, elements, characteristics, problems, and limitations in Asia including Vietnam and its developing urban center, the study has proposed an analytical framework including 13 key elements for the robust WG in Asian perspective as well as this SEA country (Figure 5.13). Specifically, together with 10 elements frequently used in the 2015–2020 WG frameworks, three others, namely "planning and preparedness", "financial capacity", and "innovative governance", are also suggested for the proposed framework.

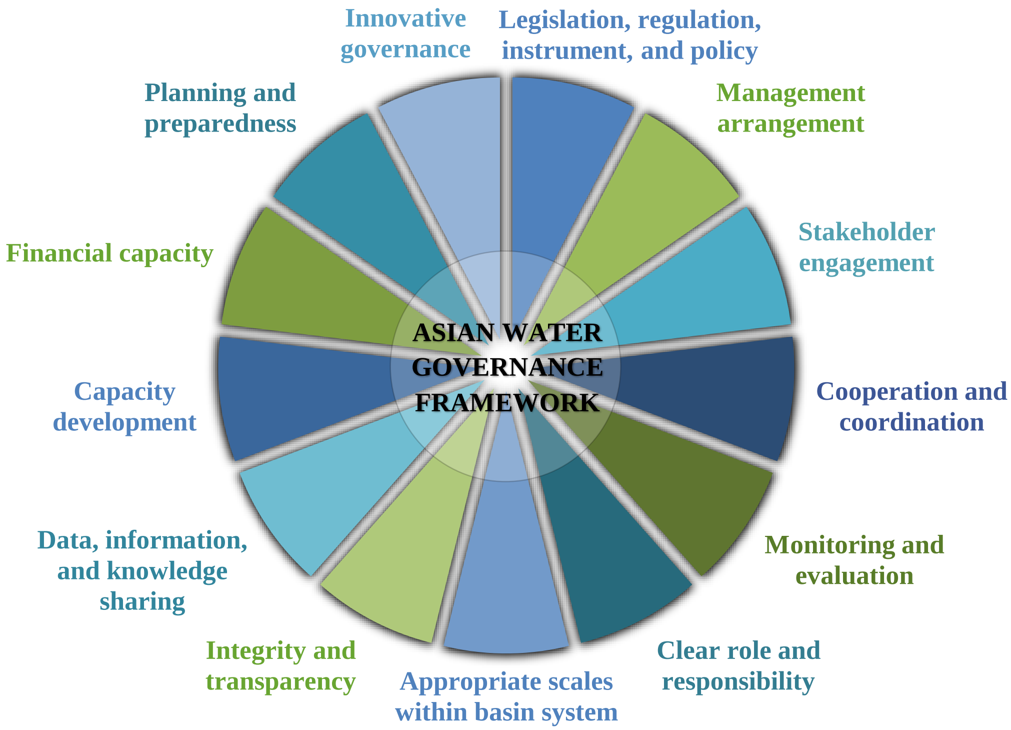


Figure 5.13 The proposed framework and its key elements for WG in the Asian developing regions including Vietnam and its urban cities like Can Tho

Planning is the process of data collection and analysis, formulation of actionable plans, and estimation of costs; while preparedness refers to the arrangements, capacities, and knowledge developed by responsible authorities to help all actors to be able to respond effectively to potential or current water- and WG-related challenges. At a regional scale, the process of planning and preparedness may be also broadened to encompass international agreements that govern the joint development and management of institutions (e.g., River Basin Organizations). This process can establish and maintain important channels of communication for countries that need to work together on basic issues related to regional WG within a shared basin.

Especially, an effective and timely "planning and preparedness" can significantly support to implement successfully the functions of the "financial capacity" element, and hence these two element will together contribute to a more effective WG. Indeed, the planning and preparedness process produces time-bound roadmaps with estimations of human and financial resources needed for effectively implementing all WG activities as well as elements. Based on these produced estimations, financial raising – one of the key functions of "financial capacity" element – will be implemented to call needed funds from different funding sources to cover these activities and elements. Furthermore, financial capacity also includes forecasting – i.e., the ability to project the costs under different scenarios that are also generated through the process of planning and preparedness – and budgeting – i.e., the ability to plan expenditure within a certain time horizon. Therefore, with the useful functions as well as clear benefits of the "planning and preparedness" and "financial capacity" elements, they are really essential to be included in the proposed framework that can be used as an orientation tool for the WG implementation in many Asian regions, especially less developed and developing ones including Vietnam and its developing cities like Can Tho, where deficient planning and restricted funding are often considered chronic governance challenges (Araral and Yu, 2012; Delavari Edalat and Abdi, 2018).

In the case of Asia in general and Vietnam in particular, they own unique characteristics in terms of water resources, climate, socio-economic mechanisms, and political contexts that frequently affect the WG quality. Besides, this quality in many Asian developing nations including Vietnam are also increasingly facing diverse gaps such as policy gap (lack of effective policy coherence across sectors), capacity gap (lack of knowledge and technologies for implementing effective policies), and information gap (lack of sufficient information and technical systems for transferring scientific findings to practices). Thus, the "innovative governance" element should be also taken in consideration for these Asian countries' WG framework. This element's function is promoting pilot experiments and tests on WG, drawing own lessons from successes and failures, and scaling up replicable practices. Based on these pilot experiments and tests as well as lessons learned, the negative impact of these unique characteristics on WG quality will be gradually mitigated and then thoroughly addressed. Besides, this element promotes social learning to facilitate dialogue and consensus-building, for example through networking platforms, social media, information and communication technologies, and user-friendly interfaces. In addition, it also focuses on building innovative ways to co-operate, pool resources and capacity, build synergies across sectors, and search for efficiency gains; and promoting a strong and user-friendly science-policy interface to contribute to better WG and bridge the divide between scientific findings and WG practices. Thus, this element can actively contribute to addressing the existing gaps related to policy implementation, policy coherence, information sharing, and capacity development in Asia in general and Vietnam in particular.

Overall, with the Vietnam's as well as Can Tho City's current WG context, due to facing diverse and complex challenges mainly such as poor legal and institutional framework, inadequate stakeholder and public participation, weak governance capabilities, ineffective coordination and cooperation at both national and local scales, unequal power regime, and limited funding, applying this proposed framework in this country can be considered an appropriate solution to effectively respond to these WG challenges towards achieving a more robust and comprehensive IWRM as well as SDGs in the country, especially in its rapidly developing urban centers like Can Tho. However, to successfully apply this framework in developing regions, there are some difficulties and challenges that occur during the implementation of the framework and need to be identified and addressed. These main difficulties and challenges are identified and discussed below.

5.3.6.2 Common Challenges

Based on the reviewed findings, it is acknowledged that an increasing number of the Asian countries are facing mounting challenges during their implementation process of this proposed WG framework. The following common governance challenges in these countries are summarized to serve as the basis for giving appropriate recommendations to respond to these challenges towards realizing a more effective WG in this continent and especially its developing regions in the future.

The challenges of legal and institutional arrangements: While improved and reformed legal and institutional arrangements have been initiated in many Asian regions, there are still challenges that need to be addressed. These challenges mainly relate to institutional and territorial fragmentation of water laws, regulations, and policies across multiple actors, lack of effective legal coherence across sectors, absence of the sufficient process of translating laws and policies into action, etc. Besides, in many Asian developing nations, especially in SEA and SA ones (i.e., Vietnam, Laos, Cambodia, Philippines, India, Bangladesh, Nepal, etc.) water use across sectors is governed by dense network of institutions that are disjointed organizations, do not have flow of information horizontally, and have roles and responsibilities overlapped.

The challenges of stakeholder engagement, cooperation, and coordination: In most Asian developing nations, particularly Vietnam, there are many challenges for stakeholder engagement and cooperation at all levels mainly due to the dense and complex network of institutions and organized stakeholders, restricting the WG improvement. In fact, there are overlaps in responsibilities and tasks of various ministries and agencies, resulting in indefinite and vague accountability assigned to any of the agencies, and even leading to unexpected conflicts between and among them. Besides, there is weak collaboration and coordination among sectors and the various administrative layers, especially in the CAs, WA, and SEA countries (ADB, 2020) hence the implementation of policies, schemes and programs is ineffective. Participation of communities and affected stakeholders is also limited and there is generally poor awareness regarding WG and management issues amongst both communities and government officials. Noticeably, many countries in Asia (mainly in SA (India, Bangladesh, Pakistan, etc.) and SEA regions (Vietnam, Thailand, Cambodia, Laos, Philippines, etc.)) are characterized as that provinces have a relatively large autonomy that sometimes result in sub-optimal solutions at the larger scale. Moreover, human resources in these countries' WG are relatively poorly developed compared to the countries' standard, both quantitatively and qualitatively.

Noticeably, at the transboundary scale – one of the most-concerned scale in the Asian WG – stakeholder engagement and cooperation challenges in this continent are often caused by missing institutions for promoting joint management of shared water resources. Where they do exist, they often remain ad-hoc, disparate, and underfinanced. Among other challenges are a lack of common global platforms to advance joint management of transboundary water and a lack of coordinated approaches among development partners. Especially, financing for appropriate institutional development and joint management in the Asian developing regions is significantly lacking, and in yet other contexts, underfinancing of much-needed infrastructural development to meet increased climate variability and change prevails. Moreover, notwithstanding contemporary challenges, there are also new challenges emerging in Asia, which need to be addressed – preferably in a cooperative manner. While national institutions and legislative bodies provide mechanisms for addressing conflicting demands within a country, there are no equivalent institutional mechanisms to respond to transboundary problems. Without such mechanisms, competition for water might lead to disruptive conflicts.

The challenges of monitoring, evaluation, information sharing, and transparency: Some common WG challenges regarding these issues in Asia are ineffective stakeholder engagement and public participation for inclusive and transparent decision making (also mainly in CAs, WA, and especially SEA including Vietnam); lack of or not regular use of monitoring, evaluation, and enforcement mechanisms (in all Asian regions); insufficient or incomplete water information systems in support of decision makers; and lack of mutual trust and transparency in water benefit sharing, conflict negotiation, and governance cooperation, especially transboundary cooperation.

The challenges of capacity development: In most Asian less developed and developing countries, lack of knowledge, experience, human capital, technology, funding, and others are acknowledged as the key challenges for effectively and sustainably implementing all WG activities, also including financial raising and planning work.

5.4 Conclusion and Next Work

In this chapter, the study conducted a systematic review of the WG-related issues in Asia, particularly Vietnam and its rapidly developing cities like Can Tho, over the last two decades, focusing on the scholarly attention and perspectives, concerned issues, applied frameworks and elements, proposed framework, and potential challenges. In general, complex transboundary water management, water quality control, irrigation and hydropower management, and climate change were the most-concerned governance issues in the Asian developing countries including Vietnam. Besides, inadequate legal and institutional arrangements, coordination and cooperation, and stakeholder engagement were also considered the key challenges restraining effective WG systems in these countries. Thus, by providing scientific evidence-based knowledge and information as well as proposing an advanced WG framework and its potential implementation challenges, this study had recalled the need for more effective, efficient, and inclusive WG and more specifically for a better understanding of who does what, at which level, how, and why with respect to water-related policies and institutions in Asia as well as Vietnam and its Can Tho City. In addition, the study also significantly contributed to supporting water, policy makers, managers, and scholars to formulate, implement, evaluate, and adjust WG policies and institutions towards a robust and comprehensive IWRM as well as the SDG achievement. For the next work, based on the obtained results, the study suggests that recommendations for dealing with the above-mentioned common governance challenges should be carefully considered and timely and appropriately given first; and then pilot studies on WG at all local, national, and regional scales in Asia, particularly in Vietnam and its urban centers like Can Tho City, need to be carried out, evaluated, and adjusted, thereby widely applied not only to these studied areas but also to others where are facing limitations in their implementation process of WG.

Chapter 6

Challenges, Opportunities, and Mitigation and Adaptive Measures to Achieve Robust and Comprehensive SWQ management and IWRM

6.1 Highlights of Main Results

The studies in this research have successfully assessed both the Can Tho City's past, current, and future SWQ conditions complexly impacted by multiple factors and systematically reviewed the current status of IWRM focusing on water governance (WG) in the Asian countries including Vietnam and its developing cities like Can Tho. Based on these studies' key findings, the main conclusions are obtained and summarized as follows.

Regarding the Can Tho City's SWQ status between 2013 and 2019, BOD, COD, DO, TC, turbidity, TSS, and PO_4^{3-} levels exceeded the permissible values for the SWQ standard of Class-A and the water was unacceptable for residential use. Based on CA, the city's SWQ and river network can be divided into two seasonal clusters (dry season from December to April and wet one from May to November) and three spatial zones (urban-industrial, agricultural, and mixed urban-rural zones), and PCA successfully identified key SWQ pollution sources for these groups, including point (industrial and household activities), non-point (surface runoff from agricultural fields), and mixed sources (industrial, household and agricultural runoff). According to DA, COD, DO, PO_4^{3-}, NO_3^-, and turbidity were the most important SWQ parameters for discriminating both among spatial zones and between seasonal clusters. The city's river water was markedly more polluted during the dry season, with higher concentrations of COD, BOD, and TC, while the opposite trend was found in the wet season, with higher levels of turbidity, TSS, PO_4^{3-}, and NO_3^-. Spatially, SWQ status was bad or unsuitable for domestic usage in most urban districts, while rural districts generally showed moderate or good levels, indicating usable water. Temporally, SWQ was clearly worse in 2019 than in 2013, mainly due to increased built-up land area and severe droughts. The greatest negative changes in SWQ were observed in five urban districts along the Hau River and its major diversions. For countermeasures against its current and future SWQ pollution, the city is currently focusing on applying structural solutions, mainly the application of WWTPs as emphasized in its master plans.

Regarding the future SWQ condition in the city, the Hau River water quality with typical SWQ parameters such as BOD, TC, PO_4^{3-}, and NO_3^- was selected as a representational case to be predicted and assessed. Under the BAU scenario with the anticipated population growth, rapid industrialization, and rainfall change, the river water quality will be further deteriorated, especially in the dry season and in downstream areas. Noticeably, industrial development is considered the main driver compared to the other ones i.e., population growth and climate change. In the scenarios WMs, the implementation of WWTPs in the residential and industrial areas can potentially deal with the water pollution problem in the wet season by 2030. However, water quality, especially BOD and PO_4^{3-} pollution, will still be a matter of concern when looking into the downstream water quality in the dry period. In order to combat this issue, the additional combination of RWTPs for treating river water at a number of key locations of pollution was successfully applied.

It can be seen that both the city's current and future SWQ have been impacted by multiple drivers specifically industrial urbanization, population growth, land-use changes, climate change (mainly low water level in dry season), and especially policy changes (mainly wastewater management policies). Existing and planned water treatment plants can effectively support the city to control the acceptable status of SWQ in the future. However, given the relatively high investment costs for developing countries like Vietnam and potentially negative impacts on the local ecosystems for the application of these plants, the city's governments should consider and propose other more effective and sustainable solutions (i.e., a robust and comprehensive IWRM mainly including an effective WG) to the future water pollution. However, the number of WG studies in a developing country like Vietnam is still very limited, leading to a lack of information and data needed to review, improve, and achieve a more effective WG in this country including Can Tho City. Thus, selected as the main case study, WG in the developing Asian continent including Vietnam was systematically reviewed to explore its governance-related challenges, hence to propose potential measures to improve WG as well as IWRM including water quality pollution management in this continent's developing countries and Vietnam comprising its growing cities like Can Tho.

The reviewed results shown that there is a growing global attention towards WG in Asia since the early 2000s and especially after the announcement of SDGs in 2015. This finding is likely reflective of the fact that WG itself is still a fairly young field of study. Geographically, the countries in SEA (especially Vietnam, Thailand, Laos, and Cambodia), SA (India and Bangladesh), and EA

(China) regions were the main hotspots for studying WG and its related issues. This is mainly due to these regions' and countries' unique characteristics within Asia such as the largest areas with the highest population, abundant water resources with the largest cross-border river basins, and complex WG issues (i.e., transboundary water, water quality, and irrigation managements). Regarding the WG definitions, there was no consensus on these definitions over the last two decades mainly due to diverse usages of the WG concept by scholars in studying its various scopes, aspects, and norms, rather than a broad, encompassing definition of WG. However, effective WG concept was conceptualized with similar perspectives, requiring actively engagement of relevant actors and ensuring efficiency, transparency, accountability, sustainability, and responsiveness during the implementation process of WG.

Among diverse water-related issues in the Asian countries, particularly Vietnam, transboundary water management, irrigation management, water quality control, hydropower generation, and climate change were the most prevalent ones, considered key drivers of challenging WG in these nations. This is mainly explained by lack of joint agreements in the most of cross-border river basins there. Moreover, inadequate legal and institutional framework, limited stakeholder engagement, poor coordination and cooperation, unstable politics and power, and weak governance capabilities – the most common WG-related issues in Asia and Vietnam – could be also considered the main reasons behind the complexity and ineffectiveness of WG in this continent's countries as well as between them. To analyze these issues, significantly diverse frameworks were developed or modified and then used. The relatively simple framework, namely the LIF, was regularly used for analyzing and assessing WG in many reviewed publications. This kind of framework is being currently applied for governing water resources in Vietnam and other Asian developing countries. Noticeably, many scholars had used analytical frameworks rooted in the Ostrom's work. Besides, the OCED's framework has been also frequently utilized in recent years. Beyond this, there was little consistency in the frameworks applied, which can be explained by the diversity of disciplinary backgrounds as well as research objectives of the WG researchers. Generally, the frameworks performed in the reviewed studies can fall into two categories within the research community, including (1) the frameworks (i.e., the LIF and Four Systems) used to focus on examining and understanding specific case- or place-based WG issues only, and (2) the broader others (i.e., the IAD, AIWM, MTF, and SES) applied to assess the more general status of WG systems (mainly focusing on law, policy, and administration areas). Especially, the studies applying these broader frameworks had a tendency to build databases, abstract obtained findings, and give scientific evidence-based statements on WG.

Noticeably, the diversity in the frameworks used had consequently led to a wide range of governance elements included and discussed. Among them, legal framework, institutional arrangement, stakeholder engagement, cooperation and coordination, and monitoring and evaluation were respectively the most popular elements included in the Asian WG framework. These popular elements are widely considered core ones in the WG frameworks as well as the key drivers of effectively implementing water policies, institutions, and governance. In the case of Asia in general and Vietnam in particular, these elements' emphasis had significantly reflected the fact that inadequate legal and institutional framework, poor involvement of and cooperation between stakeholders, and ineffective monitoring and evaluation were chronic governance challenges in this developing continent and country, hence they were frequently included in frameworks for analyzing and discussing. It was also recognized that there was a temporal evolution of the number of elements included in the Asian WG frameworks, except for the WG framework (the LIF) applied in Vietnam, increasing from six in the early 2000s to ten after 2015. This is partially due to the constant change in the WG perspectives globally as well as the WG status in Asia over the last 20 years. Based on the reviewed information, an optimal framework for WG in the Asian regions comprising Vietnam had been proposed, comprising 13 elements matching to the current WG status in these regions and country; and the common governance challenges often occurred during the implementation process of this proposed framework were given.

It is also noteworthy that the Asian countries as well as Vietnam own unique characteristics regarding water resources, climate, socio-economic mechanisms, power and political contexts, etc. This leads to differences in WG-related issues as well as WG regimes (e.g., frameworks used, elements included, regulations and policies applied, solutions given, etc.) applied to respond to these issues between the countries. Some of these regimes are advanced and robust and have been effectively performed for WG in several Asian nations, especially developed ones such as Japan, Singapore, China (Taiwan), etc. However, it is significantly difficult for Vietnam to successfully imitate and apply these regime for governing its water resources. Therefore, based on the findings obtained from systematically reviewing the Asian WG, the country can considers, selects, modifies, and applies the most appropriate regime for its WG at both local, national, and international scales.

6.2 Countermeasures and Recommendations

6.2.1 Specific Countermeasures against SWQ Pollution in Can Tho City

The obtained results have indicated that the Can Tho City's SWQ, especially in urban districts, polluted by diverse pollution sources, is not suitable for human consumption with upward trends in both annual WAWQIs and concentrations of most SWQ parameters over the research periods. These concentrations are constantly higher than the permissible limits of Class-A prescribed as a key target in the city's master plans. Therefore, some specific solutions are proposed as follows for the city to response this situation.

Firstly, the identification of water resource with poor quality in the city should be entailed with the estimation of specific pollutant loads discharged into the city's water bodies from various possible sources. This provides the Can Tho policy-makers guidance to design optimal solutions toward achieving the SWQ Class-A in particular and improving IWRM in general. A reliable science-based tool (well adopted in different locations around the world) (Zaidi and deMonsabert, 2015; Vallero, 2016; Camacho et al., 2018; Sang-Cheol and Jihyung, 2018; MDEP, 2022), the total maximum daily load (TMDL) approach should be applied. The TMDL will calculate the highest load of each pollutant (discharged from either point or nonpoint pollution sources in the city) that a water body can assimilate and still meet the city's SWQ of Class-A (Camacho et al., 2018; Sang-Cheol and Jihyung, 2018). Noticeably, seasonal variation in pollutant loads in the city can be also calculated (AMTC, 2017; MDEP, 2022). According to Vallero (2016), AMTC (2017), and MDEP (2022), five steps should be implemented in the TMDL process in the city: (1) selection of pollutants (i.e., eight polluted SWQ parameters (Table 3.4)) in need of consideration, (2) estimation of the water body assimilative capacity (i.e., permissible limits set by Class-A (Table 3.4)), (3) estimation of the each parameter's loading from all pollution sources to the water body, (4) analysis of the each parameter's current load and determination of needed reductions to meet permissible limits of Class-A, and (5) allocation, including a margin of safety, of the allowable load among the different pollution sources in a manner that SWQ of Class-A will be achieved. TMDL estimation's inputs include land use, SWQ parameters, modeling techniques, calculation methods, and other relevant evidence (i.e., outcomes obtained from the studies in this research) (AMTC, 2017).

In the city, five urban districts along the Hau River should be prioritized to be a pilot for

TMDL estimation, since their SWQ recorded at many sampling sites of Cluster 1 has shown the most extreme degradation due to cumulative effects from more drivers (population growth, industrial urbanization, upstream flows, climate change, and even policy changes) than that in other areas of the city. Moreover, Vietnam in general and Can Tho City in particular are characterized by poor stakeholder engagement in their WG (Trung et al., 2019; Duc et al., 2021), so an active public involvement is strongly advisable. Locals are typically more aware of their water usage and watershed than state agencies, hence their involvement will be valuable for the successful TMDL implementation in the city. Specifically, their activities include providing data and information to the state agencies, giving feedback on the impaired water list, reviewing and giving comments on draft reports, and assisting the general development of TMDL.

Secondly, based on TMDL generated results, advanced hydrological models should be applied to predict fate and transport of different pollutants and identify technological measures for achieving SWQ of Class-A. Thus, based on the city's SWQ characteristics, some following advanced models are suggested: SWMM (applied for assessing SWQ pollution caused by flood and urban drainage in four urban and flooded districts Ninh Kieu, Cai Rang, Binh Thuy, and O Mon), VENSIM (for identifying effects of population, water demand, and wastewater growth on SWQ in the whole city), WEAP (for evaluating effectiveness of the current and planned water treatment plants not only along the Hau River as presented in Chapter 4 but also along its major diversions in the city, hence proposing more cutting-edge treatment technology and optimal treatment capacity for these plants), and an integrated hydrological model SWAT-MODFLOW (for examining agricultural impacts on both groundwater and SWQ in the city's intensively agricultural districts Vinh Thanh, Co Do, and Thoi Lai where groundwater overexploitation is very prominent).

Moreover, due to the highly accurate capability to capture the spatiotemporal variations in the hydro-meteorological variables and represent the dynamics of the hydrologic processes in large water bodies like Can Tho City's river network (Kumar and Reshmidevi, 2013; García et al., 2016; Wang and Xie, 2018; GWSP, 2019), remote sensing (RS) techniques with the support of a geographic information system (GIS) are strongly proposed as a practical tool to improve the SWQ in the city. According to Kumar and Reshmidevi (2013) and INBO and IOwater (2018), these techniques have significantly changed the SWQ assessment and management methodologies by providing complementary data needed to confront key water-related challenges. Specifically, all eight polluted

SWQ parameters in the city can be assessed and estimated by near real-time monitoring and measuring variations in the optical properties of water caused by the presence of the contaminants (Kumar and Reshmidevi, 2013). Furthermore, the repercussions of management policies, land-use practices, point and non-point source pollution, upstream flow, and climate change (i.e., flood and drought events) that are characterized as threats to the city's SWQ can be visualized and assessed by RS and GIS application (Kumar and Reshmidevi, 2013; INBO and IOwater, 2018; Wang and Xie, 2018; GWSP, 2019). Especially, integrated use of these state–of–the–art models, techniques, and approaches for estimating dynamics of SWQ evolution will be significantly useful in supporting the city to achieve its target SWQ of Class-A.

Thirdly, technocratic approaches are still prominent practice in Can Tho City's SWQ management with an emphasis on structural solutions such as canal/lake rehabilitation and water treatment plant application (CTCPC, 2019b; Trung et al., 2019; CTCSO, 2020a; Duc et al., 2021). These approaches may work in times but expose unintended consequences in the long run. Thus, these should be combined with socio-hydrology, an integrated approach to managing and allocating water resources by involving all actors and stakeholders, and considering how water resources link different sectors of society (Di Baldassarre et al., 2015, 2019; Pande and Savenije, 2016; Kumar et al., 2020). It can develop a generalizable understanding of the interaction and feedback between technical, natural, and social processes (Di Baldassarre et al., 2019; Kumar et al., 2020), which can effectively improve SWQ management practice for the longer term. Therefore, this combination of an advanced socio-hydrology approach and the implementation of short-term technological solutions (i.e., the application of models, techniques, approaches, and water treatment plants) will not only assist the city to comprehensively address SWQ-related problems in achieving ambient SWQ of Class-A but also maintain it in the distant future. Additionally, stakeholders should be strongly involved in making and implementing other water policies, strategies, and master plans in the city thanks to the application of the science-policy interface and participatory approaches as mentioned in the previous parts of Chapters 1 and 5.

6.2.2 General Countermeasures against SWQ Pollution in Can Tho City

As aforementioned, in the city, the canal/lake rehabilitation and WWTP application are currently prioritized solutions for dealing with both the current and future SWQ pollution. Moreover, in Chapter 4, the additional application of RWTPs was also proposed. However, apart from these structural measures' benefits regarding SWQ improvement, their potentially negative repercussions related to financial burden, land appropriation in urbanized centers, and disturbance to local ecosystems' health should be also taken into careful consideration. Therefore, the city's government should not consider the application of these structural measures as a standalone one for resolving SWQ pollution in the city to reach the desirable Class-A rating in the future while undergoing rapid industrial urbanization. For instance, proposing a hybrid solution, where along with building these water treatment plants, other options especially green infrastructures or nature-based solutions viz. constructed wetlands, rain gardens, vegetated swales and median strips, bioswales, porous pavement, enhancement of riparian buffers and floodplains, etc. should be also considered for managing industrial wastewater, which can be more environmentally sustainable and cost-effective.

In addition, based on the estimated contribution rates (as shown in Chapter 4) to the water pollution, industrial growth was attributed as the biggest driver of the city's future SWQ pollution compared to the other inevitable drivers i.e., urbanization, population growth and climate change. Thus, stricter but technically feasible policies and regulations should be issued to restrict both effluent concentration and volume of wastewater discharged from industrial plants into river bodies. These policies and regulations can focus on main requirements ranging from promoting decentralized WWTPs, adopting industrial symbiosis and sustainability-oriented hybrid solutions, and applying onsite green technologies (e.g. absorbent gardens, green rooftops, roadside plantings, storm water tree trenches, etc.) for wastewater treatment and sustainable resource management. Furthermore, concepts of circular economy, sustainable cleaner production, and Industry 4.0 standards should also be considered by the city's government in the future. Indeed, circular economy practices are being considered one of the most important factors for increasing sustainability performance in manufacturing, followed by the practices of cleaner production and Industry 4.0. Supply chain traceability and information, reuse and recycling infrastructure, natural and clean environment, etc. are globally being the potential practices identified for manufacturing organizations in particular and cities, in general, aiming to enhance sustainability. However, before prioritizing and practicing these concepts at the local level, a robust scientific understanding about their economic and environmental benefits, must be there.

6.2.3 Recommendations Responding to Governance Challenges in Asia and Vietnam

The follows are key guiding recommendations proposed for responding to the common governance challenges in the Asian countries including Vietnam. These recommendations focuses on the challenges of legal and institutional arrangements, stakeholder engagement, cooperation and coordination, monitoring and evaluation, information sharing, integrity and transparency, capacity development, financial capacity, and planning work identified previously in Chapter 5.

For the challenges of legal and institutional arrangements: To respond to these challenges, firstly, legal coherence should be improved through effective cross-sectorial coordination mechanisms. These mechanisms will facilitate coherent laws, regulations, and policies across ministries, public agencies, and levels of government, including cross-sectorial plans. One of the key functions of these mechanisms is developing coordinated management of the use, protection, and clean-up of water resources, taking into account coordinated policies that affect water availability, quality, and demand at and across all relevant water use sectors (e.g., agriculture, industry, energy, fisheries, ecology, transportation, and navigation in the case of most Asian countries, particularly Vietnam). Importantly, based on these mechanisms, identifying and addressing the barriers to legal coherence from practices, policies, and regulations within and beyond the water sector are also required to implement by using monitoring, reporting, and reviews. In addition, it is essential to provide incentives and regulations to mitigate conflicts among sectorial strategies, bring these strategies into line with WG and management needs, and find solutions that fit with local governance and norms. In terms of institutional arrangement, there is an urgent need to specify the allocation of roles and responsibilities across all levels of government and water-related institutions in regard to water as well as to identify and address gaps, overlaps, and conflicts of interest between these institutions through effective and comprehensive coordination.

For the challenges of stakeholder engagement, cooperation, and coordination: To boost the involvement of stakeholders as well as their cooperation, it is crucial to (i) clearly map public, private and non-profit actors who have a stake in the outcome or who are likely to be affected by water-related decisions, as well as their responsibilities, core motivations, and interactions, (ii) mitigate power imbalances and risks of consultation capture from over-represented or overly vocal categories, as well as between expert and non-expert voices, (iii) encourage capacity development of relevant stakeholders as well as accurate, timely, and reliable information systems, as appropriate, (iv) assess the process and outcomes of stakeholder engagement to learn, adjust, and improve accordingly, and (v) customize the type and level of stakeholder engagement to the needs and keeping the process flexible to adapt to changing circumstances.

Noticeably, in response to the transboundary challenges, there is a range of ways. A key insight is to understand the various actors at play in the transboundary arena. An improved understanding of this context is crucial for those wanting to better understand and efficiently engage in transboundary water management. To have this better understanding, it is imperative to make a thorough analysis of the power structures prior to any engagement in the support of transboundary water management. Without recognizing the power structure dynamic, resulting policy measures may be misguided and unintentionally result in favor of the stronger party – thus entrenching a status quo that in the long run may be disruptive for effective, just, and sustainable cooperation. It is important to strengthen the weaker parties in a region so that all actors can interact on equal terms with each other when negotiating the governance of a shared resource such as water. In this way, creating an equilibrium between all riparians within a basin means establishing the enabling environment necessary to achieve higher levels of cooperation and coordination.

To address the financial scare in most Asian developing countries including Vietnam, developing WG plans, activities, and projects with clear outcomes and timeline is critical for calling financial support from international donors such as the ADB and World Bank who are largely interested in the WG issues in this continent and its developing nations. In general, generating WG cooperation in transboundary basins largely consists of promoting a process of building collaborative structures and institutions, commonly at both national and regional levels. This process is inevitably time- and money-consuming, and often means taking two steps forward and one step back. For a development partner to engage in building such cooperative structures in a shared river basin, patience is prerequisite.

For the challenges of monitoring, evaluation, information sharing, and transparency: The following main recommendations can be considered the key countermeasures for addressing the challenges of monitoring and evaluation process: Insisting on establishing dedicated monitoring and evaluation institutions, which are competent and independent as well as equipped with effective instruments; establishing reliable mechanisms to monitor and report to aid decision-making; and ensuring timely and transparent sharing of the evaluation results and adapting strategies as new information become available. For improving transparency practices across all WG activities, the most-prioritized solutions should be (i) establishing legal frameworks to hold all stakeholders accountable, such as the right to information as well as independent authorities to investigate water-related issues and enforce the law; (ii) developing clear accountability and control mechanisms for transparency (especially for transparent water policy making, implementation, monitoring, and assessment); and (iii) applying multi-stakeholder approaches, dedicated tools, and action plans that can effectively support the these developed frameworks and mechanisms towards gaining greater accountability and trust for the Asian WG, particularly for the CAs, WA, and SEA ones.

Regarding data and information sharing, the Asian countries like Vietnam should develop requirements for cost-effective methods, encourage effective coordination, and learn practical experience for effective sharing of water-related data and information. For transboundary scale, it is necessary to design agreement frameworks, platforms, and mechanisms for data sharing. A good example from six SEA countries could be seen and learned. One year after the SDG announcement in 2015, these countries China, Cambodia, Laos, Myanmar, Thailand, and Vietnam had jointly established a Lancang-Mekong Cooperation Framework for Sustainable Development. A data sharing mechanism was signed in the agreements for transboundary management in Lancang-Mekong River. This transboundary agreement was established to promote sharing of data, information, experiences, research outcomes, and others to narrow the development gap between these countries towards achieving their SDGs.

For the challenges of capacity development: To respond to these challenges, firstly, it is required to review the specific capacity constraints that are existing at all levels of the institutional structure and also in all specific tasks (e.g., planning, policy-making and implementation, project management, planning, finance, budgeting, data collection and monitoring, risk management and evaluation, etc.) Then, aligning the technical, financial, and institutional capacity of WG systems with the nature of problems and needs as well as encouraging adaptive and evolving assignment of competences upon demonstration of capacity should be implemented. Besides, activities such as education, training, and knowledge-sharing of water professionals to strengthen the capacity of water institutions as well as stakeholders at large must be regularly and timely promoted at both local, national, and regional levels. Last but not least, the Asian countries, especially developing ones as Vietnam, should be actively get involved in international organizations, associations, and committees to seek potential opportunities for sharing experiences, learning knowledge, as well as calling for funding to support and facilitate their WG implementation.

6.3 Limitations and Future Work

There are some limitations of the research, which should be improved in future research. The first limitation is that in the future SWQ simulation by using WEAP, there was no adequate consideration about non-point pollution sources because of the unavailability of this dataset in Can Tho City. However, if the data are available, the WEAP model can handle simulation of non-point source pollutants like pollutants from directly agricultural runoff and others. For example, if we would like to consider the simulation of pollutants directly coming from agricultural runoff, apart from the area of agricultural fields that is available in the city's agricultural reports, we need to know, chemical composition and amount of fertilizers used, amount of irrigation water used, etc., then we have an empirical formula to calculate the pollutant generated from runoff. Specifically, according to USEPA (2001), Sieber and Purkey (2015), and Kipyego et al. (2018), the non-point sources' load contribution from each land-use type at catchment level is estimated using the simple and export coefficient methods based on the data availability and applicability on a watershed. In these methods, the following equation is used for the estimation of constituents such as total suspended solids (TSS), BOD, NO_x (nitrate and nitrite), ammonia, fecal coliforms, etc.

$L_p = \sum_p (L_{PU} * A_U)$, where, L_p: Pollutant load (kg/year); L_{PU}: Pollutant export coefficient for each land use (kg/hectare/year); A_U: Area by certain land use (hectare);

The second limitation of this research is related to the first one. The CA in Chapter 3 implied that the number of SWQ monitoring sites in three identified clusters is not mutually balanced. The number of sites belonging to Cluster 2 (located in agricultural areas) is limited (only 5), while Cluster 1 and 3 have possessed a large number of sites (mostly located in urban and peri-urban areas), in which some of them have been spatially overlapped. However, due to some limitations in research time, budget, and the widespread of the Covid-19 epidemic globally, there is no more addition and measurement of monitoring sites in the city's agricultural areas for Cluster 2. However, the obtained evidence also offer an opportunity to design a more cost-effective water monitoring program and a better spatial assessment of the whole network's SWQ in Can Tho City by logically rearranging or reducing the number of monitoring sites in Cluster 1 and 3 as well as adding more monitoring sites for Cluster 2. Besides, the monitoring and assessing programs on non-point pollution sources (especially agricultural runoff) in the city should be also developed with the aim of achieving a more comprehensive assessment of future river water pollution.

The next limitation is that a number of green and nature-based measures such as constructed wetlands, rain gardens, vegetated swales and median strips, bioswales, porous pavement, floodplains, green rooftops, storm water tree trenches, and hybrid solution were proposed in the research. Nevertheless, doing technical, economical, and socio-ecological evaluation of these green infrastructures is beyond the scope of this research. Because as mentioned before, this research aims to (i) assess the past, current, and future SWQ statuses, (ii) evaluate the operational efficiency of water treatment plants proposed in current master plans, (iii) review WG-related issues, thereby (iv) support the city's policymakers in reviewing these plans and WG regime as well as proposing more environmentally resilience approaches towards achieving better IWRM and the SDGs. Therefore, there would be the research gap with the application of these green measures for future studies.

For the last limitation, the systematically review in Chapter 5 was conducted with a systematic review of only 145 publications captured based on the above-mentioned searched keywords and reviewed criteria. As a result, specific items may have been missed during the searching and screening steps. However, the selection process of these keywords and criteria was thoroughly considered. In addition, as mentioned above, the examination of the excluded publications during the screening process was randomly carried out. Therefore, it can be guaranteed that this study allows practitioners and scholars to gain valuable insights.

6.4 Conclusion

In overall, the research presents an overall picture of SWQ as well as its complex variations caused by multifactorial dynamics in the fast-growing Can Tho City. Based on this, a number of solutions were proposed to respond to these variations towards achieving not only better SWQ but also more robust and comprehensive IWRM in the city as well as Vietnam in the future. Among these solutions, an effective WG regime can be considered the most important one. Therefore, an overall and systematic assessment of WG regime not only in Vietnam but also in the Asian developing countries was effectively performed. Regarding the obtained findings, an optimal governance framework with a range of important elements included was proposed for WG in Vietnam and its rapidly developing cities as Can Tho. However, to effectively apply, this framework and its elements should be reviewed and modified to suit the current context, status, and characteristics of Vietnam's and Can Tho City's water resources before being adopted.

With the above-mentioned key findings, this research has provided useful information for local policy planners and technical staff to thoroughly review all the Vietnam's as well as Can Tho City's water-related institutions, policies, strategies, and master plans and then consider and adjust the currently applied measures or propose alternative ones in a timely and appropriate manner towards achieving the city's desired SWQ standard in particular and a more robust and comprehensive IWRM in general. Besides, the research also provides useful information and knowledge for these planners and technical staff to enhance their capacity and understanding of applying advanced approaches and tools such as multivariate analytical techniques and computer-based mathematical models for monitoring, simulating, and evaluating water quality at their respective watershed levels. Furthermore, the results obtained in this research will also aid the city's policymakers in designing relevant management policies and strategies in a timely manner to achieve the SDGs, particularly SDGs 6 (clean water and sanitation), 3 (human well-being), 11 (sustainable cities), 12 (effective natural resource consumption), 13 (climate change mitigation), and 14 (river ecosystem conservation), allowing those policymakers to be actively involved in helping their regions reach these global targets. The last but not least, the key findings acquired from the case of developing Can Tho can be considered and widely applied not only to other cities in Vietnam but also to other international ones where are facing difficulties and challenges in their IWRM, especially urban SWQ management.

Appendices

Appendix A

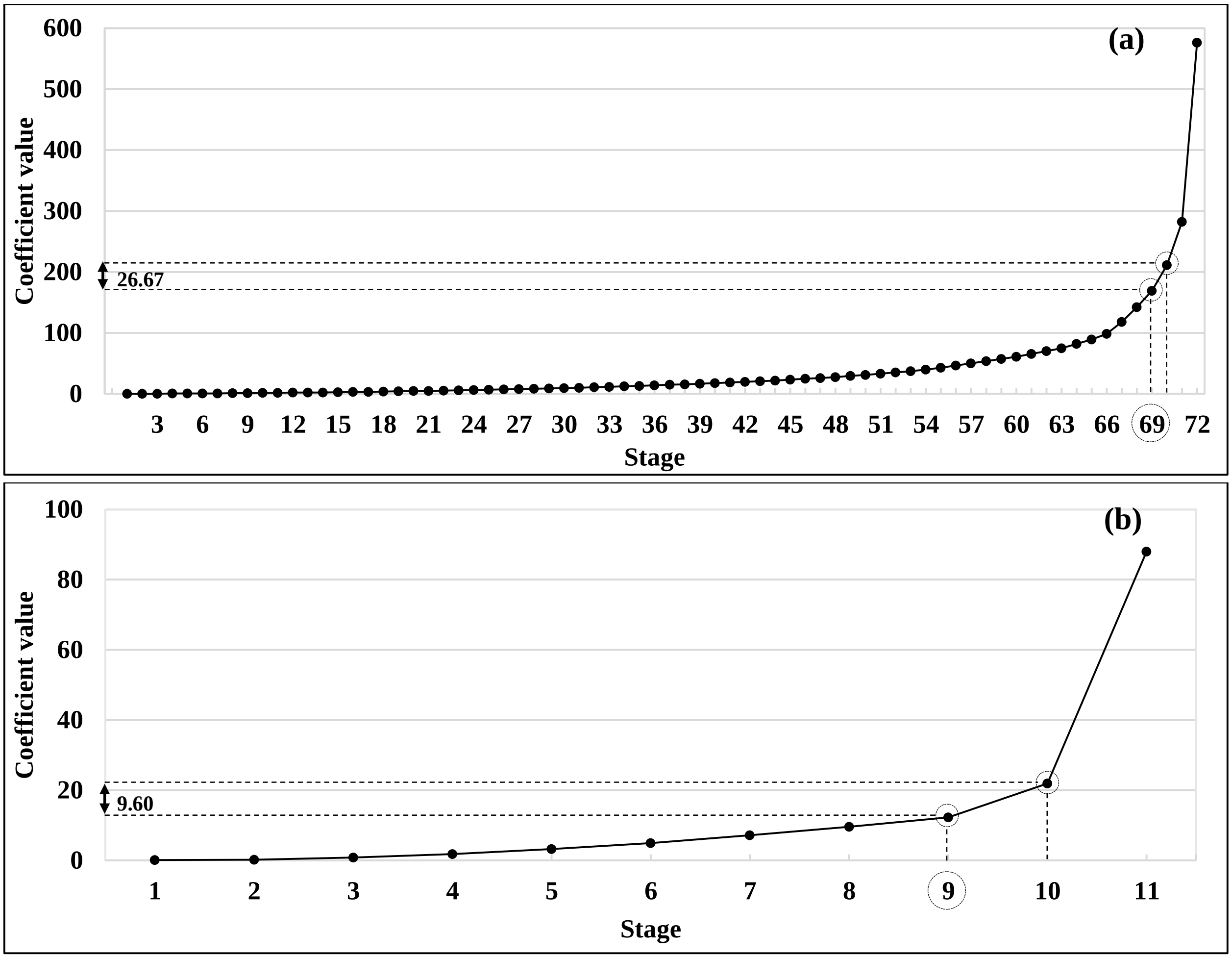


Figure A1 The change of agglomeration coefficient values during the stages of the spatial and seasonal CA processes. The clustering was ideally stopped after the 69th (for spatial CA) and 9th (for seasonal CA) stages that showed the first noticeable increase in coefficient values of 26.67 and 9.60, respectively. Therefore, the optimal number of spatial and seasonal clusters were three (72nd stage – 69th stage = 3) and two (11th stage – 9th stage = 2), respectively

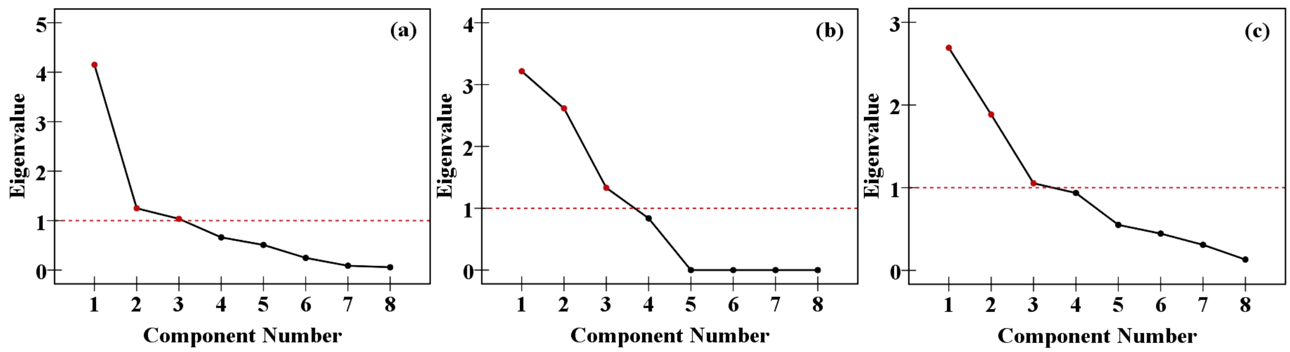


Figure A2 The Scree plots showing eigenvalues (> 1) for Clusters 1 (a), 2 (b), and 3 (c)

Appendix B

Table B1 The F and Wilks' lambda values calculated for testing in the entering and removing models of DA to explore the most spatial and seasonal discriminant SWQ variables

Step	Variables	F to Enter/ Remove	Wilks' lambda	Step	Variables	F to Enter/ Remove	Wilks' lambda
Spatial variables							
Entering model							
0	BOD_5 (20^{o}C)	49.077	0.416	2	BOD (20^{o}C)	7.829	0.033
	COD	29.577	0.542		**COD**	**13.428**	**0.029**
	DO	**187.722**	**0.157**		TC	0.228	0.040
	TC	24.403	0.589		Turbidity	0.116	0.041
	Turbidity	22.020	0.614		TSS	0.653	0.040
	TSS	54.536	0.391		PO_4^{3-}	4.704	0.036
	NO_3^-	184.494	0.159	3	BOD (20^{o}C)	0.849	0.028
	PO_4^{3-}	13.969	0.715		TC	2.536	0.027
1	BOD (20^{o}C)	4.179	0.140		Turbidity	0.117	0.029
	COD	8.881	0.125		TSS	0.918	0.028
	TC	1.459	0.151		**PO_4^{3-}**	**5.190**	**0.025**
	Turbidity	0.211	0.156	4	BOD (20^{o}C)	0.739	0.025
	TSS	0.775	0.154		TC	2.110	0.024
	NO_3^-	**98.892**	**0.041**		Turbidity	0.414	0.025
	PO_4^{3-}	21.060	0.098		TSS	0.549	0.025

Removing model							
1	DO	187.722	-	4	DO	122.119	0.117
2	DO	100.854	0.159		NO_3^-	70.739	0.078
	NO_3^-	98.892	0.157		COD	13.911	0.036
3	DO	105.444	0.119		PO_4^{3-}	5.190	0.029
	NO_3^-	111.836	0.125				
	COD	13.428	0.041				
Seasonal variables							
Entering model							
0	BOD_5 (20ºC)	56.991	0.149	2	BOD (20ºC)	0.531	0.004
	COD	649.239	0.015		COD	0.095	0.004
	DO	**1244.243**	**0.008**		TC	0.107	0.004
	TC	20.198	0.331		TSS	0.011	0.004
	Turbidity	24.448	0.290		NO_3^-	0.082	0.004
	TSS	215.741	0.044		**PO_4^{3-}**	**4.492**	**0.003**
	NO_3^-	29.523	0.253	3	BOD (20ºC)	0.046	0.002
	PO_4^{3-}	1.131	0.898		**COD**	**4.255**	**0.002**
1	BOD (20ºC)	0.926	0.007		TC	0.039	0.002
	COD	2.136	0.006		TSS	1.440	0.002
	TC	1.315	0.007		NO_3^-	1.462	0.002
	Turbidity	**9.347**	**0.004**	4	BOD (20ºC)	1.809	0.001
	TSS	0.672	0.007		TC	0.030	0.002
	NO_3^-	6.505	0.005		TSS	1.139	0.001
	PO_4^{3-}	1.428	0.007		NO_3^-	0.045	0.002
Removing model							
1	DO	1244.243	-	4	DO	17.346	0.005
2	DO	659.013	0.290		Turbidity	6.365	0.003
	Turbidity	9.347	0.008		PO_4^{3-}	10.368	0.004
3	DO	839.356	0.265		COD	4.255	0.003
	Turbidity	13.979	0.007				
	PO_4^{3-}	4.492	0.004				

Table B2 The average concentration of critical SWQ parameters for the period of 2013–2019 according to spatially different clusters

No.	Parameter	Unit	Mean concentration		
			Cluster 1	Cluster 2	Cluster 3
1	BOD_5 (20°C)	mg/l	10.10	6.13	7.10
2	TC	CFU/100 ml	3,740	2,000	2,697
3	Turbidity	NTU	43.65	29.47	35.22
4	TSS	mg/l	56.49	38.56	44.67

Table B3 The calculated annual WAWQI values at 73 sampling sites throughout the study area during the research period of 2013–2019

No.	Code	Year							No.	Code	Year						
		2013	2014	2015	2016	2017	2018	2019			2013	2014	2015	2016	2017	2018	2019
1	TN1	37	89	80	58	50	69	45	38	NK10	61	173	78	105	107	96	76
2	TN2	59	82	74	92	76	68	68	39	NK11	59	63	76	94	69	74	74
3	TN3	52	46	69	50	98	100	76	40	NK12	59	73	52	79	51	68	77
4	TN4	62	52	67	76	76	79	76	41	NK13	57	54	61	102	40	59	77
5	TN5	76	60	49	99	77	61	92	42	CR1	80	72	54	56	77	80	77
6	TN6	65	90	54	54	51	53	72	43	CR2	76	54	77	73	75	82	79
7	TN7	53	46	66	54	51	45	65	44	CR3	92	51	76	106	76	68	83
8	TN8	59	54	29	83	85	80	79	45	CR4	76	51	64	72	51	53	86
9	TN9	49	52	34	35	87	80	73	46	CR5	45	31	72	79	60	50	53
10	TN10	59	39	45	77	71	76	77	47	CR6	63	35	41	47	73	79	74
11	OM1	78	78	75	91	94	98	92	48	CR7	41	46	39	54	89	80	47
12	OM2	85	76	101	106	92	98	91	49	CR8	44	41	71	52	85	81	77
13	OM3	64	42	56	69	54	62	78	50	CR9	59	70	40	39	88	82	81
14	OM4	77	58	61	53	56	80	85	51	VT1	40	32	60	54	74	64	47
15	OM5	81	46	60	68	95	82	94	52	VT2	47	74	42	47	72	58	48
16	OM6	96	147	81	139	107	98	107	53	VT3	38	32	55	28	49	55	48
17	OM7	96	53	75	50	73	90	93	54	VT4	35	30	42	32	33	36	52
18	OM8	90	88	73	54	64	75	91	55	VT5	55	49	30	43	49	33	51
19	OM9	91	141	62	60	79	72	95	56	CD1	54	130	52	64	51	49	78
20	BT1	37	61	53	59	60	58	46	57	CD2	76	46	75	84	88	68	82
21	BT2	76	52	95	74	76	70	84	58	CD3	38	44	75	77	47	55	51

22	BT3	30	64	195	66	76	71	34	59	CD4	79	56	33	64	64	60	89
23	BT4	57	64	109	58	80	71	66	60	CD5	55	31	61	38	31	32	68
24	BT5	43	78	77	132	88	91	46	61	TL1	47	54	68	51	54	51	44
25	BT6	57	58	65	93	91	94	61	62	TL2	37	64	63	55	42	39	47
26	BT7	76	44	67	79	68	78	86	63	TL3	68	45	62	57	45	52	69
27	BT8	40	55	54	49	60	55	47	64	TL4	54	131	41	33	77	55	71
28	BT9	52	47	33	76	51	54	63	65	TL5	53	39	71	46	74	52	59
29	NK1	36	53	71	71	58	60	44	66	TL6	59	54	33	40	72	67	69
30	NK2	40	55	74	70	60	68	51	67	PD1	41	29	41	64	51	47	41
31	NK3	73	49	81	48	62	64	82	68	PD2	67	39	42	62	51	45	77
32	NK4	126	89	84	131	126	98	122	69	PD3	52	31	51	55	73	61	56
33	NK5	153	185	80	99	104	96	128	70	PD4	40	39	59	64	51	55	52
34	NK6	74	108	57	67	84	80	84	71	PD5	58	36	36	51	73	63	79
35	NK7	72	106	130	110	84	80	85	72	PD6	49	57	55	54	51	57	59
36	NK8	76	120	111	103	68	95	92	73	PD7	41	31	64	38	33	34	49
37	NK9	91	177	156	114	89	84	151	**Mean**		**62**	**65.5**	**66**	**69**	**69.5**	**68**	**72**

Table B4 The average annual WAWQI values for all sampling sites and areas of four different land-use categories between 2013 and 2019 in the study area

LULC (Category)	**Area (km^2)**							**Overall trend/ Difference in area (%)**
	2013	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	
Built-up land	182.21	186.09	195.86	205.89	205.07	206.15	217.68	Increased/+19.47
Agricultural land	1,179.66	1,175.16	1,155.06	1,146.42	1,147.34	1,146.31	1,134.18	Decreased/-3.86
Water bodies	75.13	76.73	87.06	85.67	85.67	85.64	86.44	Increased/+15.05
Fallow land	1.96	0.98	0.98	0.98	0.88	0.86	0.66	Decreased/-66.32
Total	**1438.96**	**1438.96**	**1438.96**	**1438.96**	**1438.96**	**1438.96**	**1438.96**	Unchanged/0
WAWQI	**Value**							**Overall trend/ Difference in value (%)**
All sampling sites	62	65.5	66	69	69.5	68	72	Increased/+16.13

Table B5 The treatment characteristics of existing and new WWTPs and RWTPs located in the study area

WWTPs	**Location (district)**	**Capacity (thousand m^3/day)**		**Efficiency (%)/ Discharged concentration (BOD, NO_3^-, and PO_4^{3-}: mg/l; TC CFU/100 ml)**							
				BOD	**TC**	**NO_3^-**	**PO_4^{3-}**	**BOD**	**TC**	**NO_3^-**	**PO_4^{3-}**
		2018 (current standard)	**2030 (designed standard)**	**2018 (current standard)**				**2030 (designed standard)**			

Domestic WWTPs											
Can Tho	Ninh Kieu	30	110	87.83/ 9.74	89.75/ 902,422	51.58/ 9.2	30.67/ 1.04	97.5/≤2	99.74/ ≤22,500	75.65/ ≤5	76.8/ ≤0.35
Thot Not	Thot Not	-	50	-	-	-	-	97.5/≤2	99.74/ ≤22,500	75.65/ ≤5	76.8/ ≤0.35
O Mon	O Mon	-	40	-	-	-	-	97.5/≤2	99.74/ ≤22,500	75.65/ ≤5	76.8/ ≤0.35
Binh Thuy	Binh Thuy	-	35	-	-	-	-	97.5/≤2	99.74/ ≤22,500	75.65/ ≤5	76.8/ ≤0.35
Lap Vo	Lap Vo	-	40	-	-	-	-	97.5/≤2	99.74/ ≤22,500	75.65/ ≤5	76.8/ ≤0.35
Lai Vung	Lai Vung	-	40	-	-	-	-	97.5/≤2	99.74/ ≤22,500	75.65/ ≤5	76.8/ ≤0.35
Binh Tan	Binh Tan	-	25	-	-	-	-	97.5/≤2	99.74/ ≤22,500	75.65/ ≤5	76.8/ ≤0.35
Binh Minh	Binh Minh	-	20	-	-	-	-	97.5/≤2	99.74/ ≤22,500	75.65/ ≤5	76.8/ ≤0.35
Total		**30 (1 plant)**	**360 (8 plants)**								
Industrial WWTPs											
Thot Not Industry	Thot Not	10	150	85.1/ 149	89.5/ 104,980	50/2.5	32.5/ 0.27	97.01/ ≤30	99.7/ ≤3,000	75.45/ ≤1.25	75.3/ ≤0.1
Tra Noc	O Mon	30	80	85.1/ 149	89.5/ 104,980	50/2.5	32.5/ 0.27	97.01/ ≤30	99.7/ ≤3,000	75.45/ ≤1.25	75.3/ ≤0.1
Bac O Mon	O Mon	-	70	-	-	-	-	97.01/ ≤30	99.7/ ≤3,000	75.45/ ≤1.25	75.3/ ≤0.1
Hung Phu	Cai Rang	10	90	85.1/ 149	89.5/ 104,980	50/2.5	32.5/ 0.27	97.01/ ≤30	99.7/ ≤3,000	75.45/ ≤1.25	75.3/ ≤0.1
HighTech Can Tho	Ninh Kieu	-	110	-	-	-	-	97.01/ ≤30	99.7/ ≤3,000	75.45/ ≤1.25	75.3/ ≤0.1
Song Hau 1	Lai Vung	10	130	85.1/ 149	89.5/ 104,980	50/2.5	32.5/ 0.27	97.01/ ≤30	99.7/ ≤3,000	75.45/ ≤1.25	75.3/ ≤0.1
Song Hau 2, 3, and HighTech Lai Vung	Lai Vung	-	70, 110, and 80	-	-	-	-	97.01/ ≤30	99.7/ ≤3,000	75.45/ ≤1.25	75.3/ ≤0.1
Binh Minh Industry	Binh Minh	10	60	85.1/ 149	89.5/ 104,980	50/2.5	32.5/ 0.27	97.01/ ≤30	99.7/ ≤3,000	75.45/ ≤1.25	75.3/ ≤0.1
Dong Binh	Binh Minh	-	100	-	-	-	-	97.01/ ≤30	99.7/ ≤3,000	75.45/ ≤1.25	75.3/ ≤0.1
Binh Tan	Binh Tan	-	80	-	-	-	-	97.01/ ≤30	99.7/ ≤3,000	75.45/ ≤1.25	75.3/ ≤0.1
Total		**70 (5 plants)**	**1,130 (12 plants)**								
RWTPs											
Hau Riverhead	Lap Vo	-	155	-	-	-	-	97.26/ ≤0.5	99.72/ ≤50	75.55/ ≤0.4	75.65/ ≤0.05
Binh Tan	Binh Tan	-	155	-	-	-	-	97.26/ ≤0.5	99.72/ ≤50	75.55/ ≤0.4	75.65/ ≤0.05
Binh Thuy	Binh Thuy	-	155	-	-	-	-	97.26/ ≤0.5	99.72/ ≤50	75.55/ ≤0.4	75.65/ ≤0.05
Binh Minh	Binh Minh	-	155	-	-	-	-	97.26/ ≤0.5	99.72/ ≤50	75.55/ ≤0.4	75.65/ ≤0.05
Cai Sau	Binh Minh	-	155	-	-	-	-	97.26/ ≤0.5	99.72/ ≤50	75.55/ ≤0.4	75.65/ ≤0.05
Total		**0 (0 plant)**	**775 (5 plants)**								

Table B6 The UN DESA's projected population growth rate of the study area from 2018 to 2030

Cities	Population growth rate (%)		
	2018 – 2020	**2021 – 2025**	**2026 – 2030**
Can Tho	6.24	4.32	2.67
Dong Thap and Vinh Long	2.24	2.14	2.29

Table B7 Summary of the Asian regions and countries opted as the case studies in the reviewed publications

Region and Country	No. of case studies/pub.	Country	No. of case studies/pub.
Southeast Asia (11 countries)	**111**	China (People's Republic of China)	44
Vietnam	26	India	32
Thailand	19	Vietnam	26
Cambodia	12	Thailand	19
Indonesia	11	Uzbekistan	18
Laos (Lao LDR)	11	Bangladesh	17
Philippines	11	Nepal	16
Malaysia	6	Cambodia	12
Singapore	5	Indonesia	11
Myanmar	4	Laos (Lao LDR)	11
Brunei	3	Philippines	11
Timor-Leste	3	Pakistan	10
South Asia (8 countries)	**96**	Kyrgyzstan	9
India	32	South Korea	9
Bangladesh	17	Japan	8
Nepal	16	Kazakhstan	8
Pakistan	10	Sri Lanka	8
Sri Lanka	8	Tajikistan	7
Bhutan	6	Bhutan	6
Afghanistan	4	Malaysia	6
Maldives	3	Mongolia	6
East Asia (5 countries)	**67**	Singapore	5
China (People's Republic of China)	44	Turkmenistan	5

South Korea	9	Afghanistan	4
Japan	8	Myanmar	4
Mongolia	6	Armenia	3
North Korea	0	Azerbaijan	3
Central Asia (5 countries)	**47**	Brunei	3
Uzbekistan	18	Georgia	3
Kyrgyzstan	9	Maldives	3
Kazakhstan	8	Timor-Leste	3
Tajikistan	7	Jordan	2
Turkmenistan	5	Iran	1
West Asia (18 countries)	**13**	UAE	1
Armenia	3	Bahrain	0
Azerbaijan	3	Cyprus	0
Georgia	3	Iraq	0
Jordan	2	Israel	0
Iran	1	Kuwait	0
United Arab Emirates (UAEs)	1	Lebanon	0
Bahrain	0	North Korea	0
Cyprus	0	Oman	0
Iraq	0	Palestine	0
Israel	0	Qatar	0
Kuwait	0	Saudi Arabia	0
Lebanon	0	Syria	0
Oman	0	Yemen	0
Palestine	0	**Total**	**334**
Qatar	0	Note: In this study, the total number of the Chinese case study areas also includes the ones in both China, Taiwan, Macau, and Hong Kong	
Saudi Arabia	0		
Syria	0		
Yemen	0		
Total (47 countries)	**334**		

Table B8 Main WG-related information classified and collected from 145 publications for systematic review

No.	Author(s)	Year	Title	Category	Journal/ Publisher	Analytical/ theoretical/ conceptual framework used	Framework category	Governance element/concept included	Asian country/region studied	Point focused
1	2	3	4	5	6	7	8	9	10	11
1	Ashim Das Gupta	2001	Challenges and opportunities for water resources management in Southeast Asia	Article	Hydrological Sciences Journal	x	x	Appropriate scales within basin system Capacity development Data, information, and knowledge sharing Legislation, regulation, instrument, and policy Management arrangement Stakeholder engagement	Thailand	Water scarcity and drought, and water technology and infrastructure management Legal and institutional arrangements
2	Rathinasamy Maria Saleth and Ariel Dinar	2004	The institutional economics of water: a cross-country analysis of institutions and performance	Book	The World Bank, USA	The Institutional Decomposition and Analysis framework	Developing	Appropriate scales within basin system Cooperation and coordination Integrity and transparency Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	16 countries	Legal and institutional arrangements
3	Ben Iii Sobong Malayang	2004	A model of water governance in the Philippines	Book chapter	Philippine Institute for Development Studies	The three-dimensional framework	Original	Appropriate scales within basin system Cooperation and coordination Legislation, regulation, instrument, and policy Management arrangement Stakeholder engagement Trade-offs across users, areas, and generations	Philippines	Watershed management Legal and institutional arrangements, and stakeholder engagement
4	Dulce D. Elazegui	2004	Water resource governance: realities and challenges in the Philippines	Book chapter	Philippine Institute for Development Studies	The legal and institutional framework	Applying	Clear role and responsibility Cooperation and coordination Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	Philippines	Coordination and cooperation, legal and institutional arrangements, and stakeholder engagement
5	Louis Lebel, Po Garden, and Masao Imamura	2005	The politics of scale, position, and place in the governance of water resources in the Mekong Region	Article	Ecology and Society	The water-related resource political framework	Original	Capacity development Cooperation and coordination Data, information, and knowledge sharing Integrity and transparency Management arrangement Monitoring and evaluation	EA and SEA	Transboundary water management Legal and institutional arrangements, and politics and power
6	Ariel Dinar and Rathinasamy Maria Saleth	2005	Can water institutions be cured? A water institutions health index	Article	Water Science and Technology	The Institutional Decomposition and Analysis framework	Developing	Appropriate scales within basin system Cooperation and coordination Integrity and transparency Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	16 countries	Legal and institutional arrangements
7	François Molle	2005	Irrigation and water policies in the Mekong Region:	Report	The International Water	x	x	Legislation, regulation, instrument, and policy	EA and SEA	Agriculture and river basin management

			current discourses and practices		Management Institute, Sri Lanka					Legal and institutional arrangements
8	Philip Hirsch, Kurt Mørck Jensen, Ben Boer, Naomi Carrard, Stephen FitzGerald, and Rosemary Lyster	2006	National interests and transboundary water governance in the Mekong	Report	Australian Mekong Resource Centre, Australia	The legal and institutional framework	Applying	Appropriate scales within basin system Clear role and responsibility Cooperation and coordination Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	Cambodia, China, Laos, Thailand, and Vietnam	Agriculture, hydropower and energy, transboundary water management, and river basin management Coordination and cooperation, legal and institutional arrangements, and stakeholder engagement
9	Philip Hirsch	2006	Water governance reform and catchment management in the Mekong Region	Article	The Journal of Environment and Development	x	x	Clear role and responsibility Cooperation and coordination Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	EA and SEA	Transboundary water management, and river basin management Legal and institutional arrangements
10	Herrfahrdt Elke, Kipping Martin, Pickardt Tanja, Polak Mathias, Rohrer Caroline, and Wolff Carl Felix	2006	Water governance in the Kyrgyz agricultural sector: on its way to integrated water resource management?	Report	Deutsches Institut für Entwicklungspolitik, Germany	The conceptually normative framework of IWRM	Developing	Cooperation and coordination Integrity and transparency Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	Kyrgyzstan	Agriculture, ecological water needs, transboundary water management, and water quality Coordination and cooperation, and legal and institutional arrangements
11	Do Thi Thanh Huyen	2007	When global water policy goes local: mainstream versus everyday water governance in Vietnam	Thesis	The University of Auckland, New Zealand	x	x	Clear role and responsibility Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	Vietnam	Water commodification and market Legal and institutional arrangements
12	Edsel E. Sajor and Rutmanee Ongsakul	2007	Mixed land use and equity in water governance in peri-urban Bangkok	Article	International Journal of Urban and Regional Research	The legal and institutional framework	Applying	Clear role and responsibility Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	Thailand	Agriculture, environmental protection, and water quality Legal and institutional arrangements
13	IRC International Water and Sanitation Centre (IRC WASH)	2008	Andhra Pradesh: shift to adaptive managing water demand needed	Report	IRC International Water and Sanitation Centre, the Netherlands	The water governance analytical framework	Developing	Capacity development Clear role and responsibility Data, information, and knowledge sharing Legislation, regulation, instrument, and policy Monitoring and evaluation Stakeholder engagement	India	Urban water services Adaptive governance, and legal and institutional arrangements
14	Patrick Huntjens, Claudia Pahl-Wostl, Benoit Rihoux, Zsuzsanna Flachner, Susana Neto, Romana Koskova, Maja Schlüter, Isah	2008	The role of adaptive and integrated water management (AIWM) in developing climate change adaptation strategies for dealing with floods and droughts – A formal comparative analysis	Report	Institute of Environmental Systems Research, Osnabrück University, Germany	The adaptive and integrated water management framework	Developing	Capacity development Cooperation and coordination Data, information, and knowledge sharing Financial capacity Legislation, regulation, instrument, and policy Management arrangement Stakeholder engagement	Uzbekistan	Climate change, flood risk management, river basin management, and water scarcity and drought Adaptive governance, and legal and institutional arrangements

	Nabide Kiti, and Chris Dickens		of eight water management regimes in Europe, Asia, and Africa							
15	Oliver Hensengerth	2008	Vietnam's objectives in Mekong Basin governance	Article	Journal of Vietnamese Studies	x	x	x	Vietnam	Agriculture, environmental protection, hydropower and energy, transboundary water management, and river basin management Coordination and cooperation, and legal and institutional arrangements
16	Muhammad Mizanur Rahaman and Olli Varis	2008	Central Asian waters: social, economic, environmental and governance puzzle	Book	Helsinki University of Technology, Finland	The Transboundary Water Interaction Nexus framework	Applying	Appropriate scales within basin system Capacity development Clear role and responsibility Cooperation and coordination Data, information, and knowledge sharing Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	Afghanistan, Kazakhstan, Kyrgyzstan, and Uzbekistan	Agriculture, transboundary water management, river basin management, and water scarcity and drought Coordination and cooperation, and politics and power
17	Vishwa Ballabh	2008	Governance of water: institutional alternatives and political economy	Book	SAGE Publications New Delhi, India	The Institutional Analysis and Development framework	Applying	Appropriate scales within basin system Cooperation and coordination Integrity and transparency Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	China and India	Groundwater management, river basin management, water scarcity and drought, watershed management, water security, water technology and infrastructure management, and water-energy-food nexus Coordination and cooperation, and legal and institutional arrangements
18	Andreas Neef	2008	Lost in translation: the participatory imperative and local water governance in North Thailand and Southwest Germany	Article	Water Alternatives	The Water Framework Directive	Applying	Appropriate scales within basin system Capacity development Clear role and responsibility Cooperation and coordination Data, information, and knowledge sharing Integrity and transparency Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	Thailand	River basin management Stakeholder engagement
19	Sarah Turner, Ganesh Pangare, and Robert Julian Mather	2009	Water governance: a situational analysis of Cambodia, Lao PDR and Vietnam	Report	International Union for Conservation of Nature, Gland, Switzerland	x	x	Clear role and responsibility Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	Cambodia, Lao, and Vietnam	Agriculture, industry, hydropower and energy, tourism and navigation, transboundary water management, and urban water services Legal and institutional arrangements
20	Ngai Weng Chan	2009	Issues and challenges in water governance in Malaysia	Article	Iranian Journal of Environmental Health Science	x	x	Integrity and transparency Legislation, regulation, instrument, and policy Management arrangement Stakeholder engagement	Malaysia	Legal and institutional arrangements, politics and power, and stakeholder engagement

					and Engineering					
21	Jenniver Sehring	2009	Path dependencies and institutional bricolage in post-soviet water governance	Article	Water Alternatives	The Institutional Decomposition and Analysis framework	Applying	Appropriate scales within basin system Cooperation and coordination Integrity and transparency Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	Kyrgyzstan and Tajikistan	Agriculture Legal and institutional arrangements
22	Teresita Cruz-Del Rosario	2009	Risky riparianism: cooperative water governance in Central Asia	Article	Australian Journal of International Affairs	The reflexive governance framework (including the Type II governance model)	Applying	Outcomes and impact Uncertainty Context for risk materialization	CAs	Transboundary water management and river basin management Coordination and cooperation
23	François Molle, Tira Foran, and Mira Käkönen	2009	Contested waterscapes in the Mekong Region: hydropower, livelihoods, and governance	Book	Earthscan	The legal and institutional framework	Applying	Appropriate scales within basin system Clear role and responsibility Cooperation and coordination Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	SEA	Agriculture, hydropower and energy, transboundary water management, and river basin management Legal and institutional arrangements
24	Munira Aminova and Iskandar Abdullayev	2009	Water management in a state-centered environment: water governance analysis of Uzbekistan	Article	Sustainability	The practical governance analytical framework	Developing	Clear role and responsibility Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Planning and preparedness Stakeholder engagement	Uzbekistan	Agriculture Legal and institutional arrangements, and stakeholder engagement
25	Kwame Mfodwo	2010	Water governance in developing countries: a policy and interdisciplinary introduction	Book	International Water Centre, Brisbane, Australia	The Water Social-Ecological System framework	Applying	Social, economic, and political settings Resource systems Governance systems Resource units Users Interactions and outcomes Related ecosystems	China and India	Climate change, groundwater management, hydropower and energy, transboundary water management, river basin management, and water quality Legal and institutional arrangements
26	Nguyen Thi Phuong Loan	2010	Legal framework of the water sector in Vietnam	Report	The University of Bonn, Germany	The legal and institutional framework	Applying	Clear role and responsibility Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	Vietnam	Legal and institutional arrangements
27	Nicole Kranz, Timo Menniken, and Jochen Hinkel	2010	Climate change adaptation strategies in the Mekong and Orange-Senqu Basins: what determines the state-of-play?	Article	Environmental Science and Policy	The Management and Transition framework	Developing	Data, information, and knowledge sharing Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	EA and SEA	Climate change and transboundary water management Adaptive governance, and legal and institutional arrangements
28	Floriane Clement	2010	Analyzing decentralized natural	Article	Policy Sciences	The politicized Institutional	Developing	Appropriate scales within basin system Cooperation and coordination	Vietnam	Legal and institutional arrangements, and politics and power

			resource governance: proposition for a "politicized" institutional analysis and development framework			Analysis and Development framework		Integrity and transparency Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement		
29	United Nations Development Programme (UNDP)	2010	UNDP GoAL WaSH programme: governance, advocacy and leadership for water, sanitation and hygiene	Report	The United Nations Development Programme, USA	The water governance framework	Original	Capacity development Cooperation and coordination Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Planning and preparedness	Tajikistan	Urban water services
30	Maja Schlu¨ter, Darya Hirsch, and Claudia Pahl-Wostl	2010	Coping with change: responses of the Uzbek water management regime to socio-economic transition and global change	Article	Environmental Science and Policy	The Management and Transition framework	Applying	Data, information, and knowledge sharing Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	Uzbekistan	Climate change and ecological water needs Adaptive governance, and legal and institutional arrangements
31	Christine Werthmann	2010	Water management in seasonal floodplains of the Mekong Delta: a case study from four villages in Cambodia and Vietnam	Article	The journal of Sustainable Development	x	x	Clear role and responsibility Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	Cambodia and Vietnam	Legal and institutional arrangements
32	John Dore and Louis Lebel	2010	Deliberation and scale in Mekong Region water governance	Article	Environmental Management	x	x	x	SEA	Hydropower and energy, poverty transboundary water management, and river basin management Coordination and cooperation, and stakeholder engagement
33	Claire Charbit	2011	Governance of public policies in decentralized contexts: the multi-level approach	Report	The Organisation for Economic Co-operation and Development, France	The OECD Multi-level Governance framework	Original	Capacity development Clear role and responsibility Data, information, and knowledge sharing Financial capacity Integrity and transparency Legislation, regulation, instrument, and policy Management arrangement Stakeholder engagement	Korea and Japan	Legal and institutional arrangements
34	The Organisation for Economic Co-operation and Development (OECD)	2011	Water governance in OECD countries: a multi-level approach	Report	The Organisation for Economic Co-operation and Development, France	The OECD Multi-level Governance framework	Original	Capacity development Clear role and responsibility Data, information, and knowledge sharing Financial capacity Integrity and transparency Legislation, regulation, instrument, and policy Management arrangement Stakeholder engagement	Korea and Japan	Legal and institutional arrangements

35	Patrick Huntjens, Claudia Pahl-Wostl, Benoit Rihoux, Maja Schlüter, Zsuzsanna Flachner, Susana Neto, Romana Koskova, Chris Dickens, and Isah Nabide Kiti	2011	Adaptive water management and policy learning in a changing climate: a formal comparative analysis of eight water management regimes in Europe, Africa and Asia	Article	Environmental Policy and Governance	The adaptive and integrated water management framework	Developing	Capacity development Cooperation and coordination Data, information, and knowledge sharing Financial capacity Legislation, regulation, instrument, and policy Management arrangement Stakeholder engagement	Uzbekistan	Climate change, flood risk management, river basin management, and water scarcity and drought Legal and institutional arrangements, and multipolitics and power
36	Marco Gemmer, Andreas Wilkes, and Lucie M. Vaucel	2011	Governing climate change adaptation in the EU and China: an analysis of formal institutions	Article	Advances in Climate Change Research	The heuristic framework	Original	Legislation, regulation, instrument, and policy Management arrangement	China	Climate change Legal and institutional arrangements
37	Narendra Kumar Tripathi	2011	Scarcity dilemma as security dilemma: geopolitics of water governance in South Asia	Article	Economic and Political Weekly	x	x	x	Bangladesh, India, Nepal, and Pakistan	Agriculture, climate change, flood risk management, hydropower and energy, transboundary water management, river basin management, water scarcity and drought, watershed management, and water technology and infrastructure management
38	Eduardo Araral and David Yu	2012	Water governance: critique, theory and evidence from Asia	Article	Water Policy	The Institutional Decomposition and Analysis framework	Applying	Appropriate scales within basin system Cooperation and coordination Integrity and transparency Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	18 countries	Legal and institutional arrangements
39	Animesh Kumar Gain and Maria Schwab	2012	An assessment of water governance trends: the case of Bangladesh	Article	Water Policy	The Institutional Decomposition and Analysis framework	Developing	Appropriate scales within basin system Cooperation and coordination Integrity and transparency Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	Bangladesh	Legal and institutional arrangements, and politics and power
40	Claudia Pahl-Wostl, Louis Lebel, Christian Knieper, and Elena Nikitina	2012	From applying panaceas to mastering complexity: toward adaptive water governance in river basins	Article	Environmental Science and Policy	The analytical framework	Original	Cooperation and coordination Data, information, and knowledge sharing Legislation, regulation, instrument, and policy Management arrangement	7 countries	Adaptive governance, coordination and cooperation, knowledge and data sharing, legal and institutional arrangements, polycentric governance, and stakeholder engagement
41	John Dore, Louis Lebel, and Francois Molle	2012	A framework for analyzing transboundary water governance complexes,	Article	Journal of Hydrology	The heuristic framework	Original	Appropriate scales within basin system Clear role and responsibility Cooperation and coordination Integrity and transparency Legislation, regulation, instrument, and policy Management arrangement	EA and SEA	Agriculture, climate change, hydropower and energy, transboundary water management, and river basin management

			illustrated in the Mekong Region					Monitoring and evaluation Stakeholder engagement		
42	Nguyen Thi Phuong Loan	2012	Legal framework of the water sector in Vietnam: achievements and challenges	Article	Journal of Vietnamese Environment	The legal and institutional framework	Applying	Clear role and responsibility Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	Vietnam	Environmental protection Coordination and cooperation, and legal and institutional arrangements
43	Gabi Waibel, Simon Benedikter, Nadine Reis, Sven Genschick, Loan Nguyen, Pham Cong Huu, and Tran Thanh Be	2012	Water governance under renovation? concepts and practices of IWRM in the Mekong Delta, Vietnam	Book chapter	Springer	The legal and institutional framework	Applying	Clear role and responsibility Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	Vietnam	Rural water services, and water technology and infrastructure Legal and institutional arrangements
44	Helle Munk Ravnborg, Rocio Bustamante, Abdoulaye Cissé, Signe M. Cold-Ravnkilde, Vladimir Cossio, Moussa Djiré, Mikkel Funder, Ligia I. Gómez, Phuong Le, Carol Mweemba, Imasiku Nyambe, Tania Paz, Huong Pham, Roberto Rivas, Thomas SkielboeS, and Nguyen T.B Yen	2012	Challenges of local water governance: the extent, nature and intensity of local water-related conflict and cooperation	Article	Water Policy	The conceptual and methodological framework	Developing	Cooperation and coordination	Vietnam	Coordination and cooperation
45	Iskandar Abdullaev, Shavkat Rakhmatullaev, Alexander Platonov, and Denis Sorokin	2012	Improving water governance in Central Asia through application of data management tools	Article	International Journal of Environmental Studies	The data management framework	Original	Principles Data Hardware Software Style of data management Style of governance participation	Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan	Agriculture, transboundary water management, river basin management, and water technology and infrastructure management Knowledge and data sharing
46	Diana Suhardiman, Mark Giordano, and François Molle	2012	Scalar disconnect: the logic of transboundary water governance in the Mekong	Article	Society and Natural Resources	The legal and institutional framework	Applying	Appropriate scales within basin system Clear role and responsibility Cooperation and coordination Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	SEA	Transboundary water management and river basin management Coordination and cooperation, and legal and institutional arrangements
47	Anna Zimmer and Patrick Sakdapolrak	2012	The social practices of governing: analyzing waste	Article	Environment and	x	x	x	India	Urban water services and water quality

			water governance in a Delhi Slum		Urbanization ASIA				Legal and institutional arrangements, and politics and power
48	Louis Lebel, Elena Nikitina, Claudia Pahl-Wostl, and Christian Knieper	2013	Institutional fit and river basin governance: a new approach using multiple composite measures	Article	Ecology and Society	The institutional capacity framework	Original	Cooperation and coordination Stakeholder engagement	7 countries	Adaptive governance, and legal and institutional arrangements
49	Mike Douglass	2013	Cross-border water governance in Asia	Book chapter	United Nations	The effective cross-border governance framework	Original	Capacity development Cooperation and coordination Data, information, and knowledge sharing Integrity and transparency Legislation, regulation, instrument, and policy Management arrangement Stakeholder engagement	CAs, EA, SA, and SEA	Climate change, hydropower and energy, and transboundary water management Coordination and cooperation
50	Eduardo Araral and David Yu	2013	Comparative water law, policies, and administration in Asia: evidence from 17 countries	Article	Water Resources Research	The Institutional Decomposition and Analysis framework	Applying	Appropriate scales within basin system Cooperation and coordination Integrity and transparency Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	17 countries	Legal and institutional arrangements, and politics and power
51	Xiaoxi Wanga, Ilona M. Ottoa, and Lu Yu	2013	How physical and social factors affect village-level irrigation: an institutional analysis of water governance in northern China	Article	Agricultural Water Management	The Institutions of Sustainability Framework	Developing	Cooperation and coordination Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	China	Agriculture and groundwater management Legal and institutional arrangements
52	Cheryl de Boer, Joanne Vinke-de Kruijf, Gül Özerol, and Hans Bressers	2013	Water governance, policy and knowledge transfer international studies on contextual water management	Book	Routledge	The legal and institutional framework	Applying	Appropriate scales within basin system Clear role and responsibility Cooperation and coordination Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	Kazakhstan and Vietnam	Agriculture, transboundary water management, river basin management, urban water services, and water quality Legal and institutional arrangements
53	Sulan Chen, John C. Pernetta, and Alfred M. Duda	2013	Towards a new paradigm for transboundary water governance: implementing regional frameworks through local actions	Article	Ocean and Coastal Management	The adaptive and integrated water management framework	Applying	Capacity development Cooperation and coordination Data, information, and knowledge sharing Financial capacity Legislation, regulation, instrument, and policy Management arrangement Stakeholder engagement	Cambodia, China, Indonesia, Philippines, Thailand, and Vietnam	Coastal zone management, transboundary water management, and river basin management Adaptive governance, capacity development, and legal and institutional arrangements
54	Marleen van Rijswicka, Jurian Edelenbosb, Petra Hellegersc, Matthijs Kokd, and Stefan Kuks	2014	Ten building blocks for sustainable water governance: an integrated method to assess the governance of water	Article	Water International	The interdisciplinary assessment framework	Original	Clear role and responsibility Cooperation and coordination Data, information, and knowledge sharing Financial capacity Innovative governance Integrity and transparency Legislation, regulation, instrument, and policy	Indonesia	Flood risk management, water quality, and water scarcity and drought

								Management arrangement Monitoring and evaluation Stakeholder engagement Trade-offs across users, areas, and generations		
55	Barbara Janusz-Pawletta	2014	Current legal challenges to governance of transboundary water resources in Central Asia and joint management arrangements	Article	Bulletin of Abay Kazakh National Pedagogical University, Kazakhstan	The legal and institutional framework	Applying	Appropriate scales within basin system Clear role and responsibility Cooperation and coordination Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	CAs	Transboundary water management and river basin management Coordination and cooperation, and legal and institutional arrangements
56	K.J. Joy, Seema Kulkarni, Dik Roth, and Margreet Zwarteveen	2014	Re-politicising water governance: exploring water re-allocations in terms of justice	Article	Local Environment	x	x	x	India	Coordination and cooperation, legal and institutional arrangements, and politics and power
57	Peter Droogersa and Johan Bouma	2014	Simulation modelling for water governance in basins	Article	International Journal of Water Resources Development	The science-policy-stakeholder interface framework	Developing	Data, information, and knowledge sharing Stakeholder engagement	CAs	Agriculture, climate change, river basin management, water quality, and water technology and infrastructure management Legal and institutional arrangements, and stakeholder engagement
58	Maryam Nastar	2014	What drives the urban water regime? An analysis of water governance arrangements in Hyderabad, India	Article	Ecology and Society	The multi-level perspective framework	Developing	Legislation, regulation, instrument, and policy Management arrangement	India	Urban water services Legal and institutional arrangements, and stakeholder engagement
59	Priyam Das	2014	Women's participation in community-level water governance in urban India: the gap between motivation and ability	Article	World Development	The institutional framework evaluating women's participation	Original	Motivating factors Constraining factors Form of participation	India	Urban water services Capacity development and stakeholder engagement
60	Rajendra Poddar, M. Ejaz Qureshi, and Tian Shi	2014	A comparison of water policies for sustainable irrigation management: the case of India and Australia	Article	Water Resources Management	Unnamed	Developing	Management arrangement Stakeholder engagement	India	Agriculture, groundwater management, and water commodification and market
61	Mohamad Ali Fulazzaky	2014	Challenges of integrated water resources management in Indonesia	Article	Water	x	x	x	Indonesia	Flood risk management, sustainable development and the SDGs, water quality, water scarcity and drought, and watershed management Capacity development, and legal and institutional arrangements

62	Global Water Partnership (GWP)	2014	Integrated water resources management in Central Asia: The challenges of managing large transboundary rivers	Report	The Global Water Partnership, Sweden	The legal and institutional framework	Applying	Capacity development Data, information, and knowledge sharing Integrity and transparency Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Planning and preparedness Stakeholder engagement	CAs	Agriculture, ecological water needs, hydropower and energy, transboundary water management, and river basin management Coordination and cooperation, legal and institutional arrangements, and stakeholder engagement
63	Carl Middletona and John Dore	2015	Transboundary water and electricity governance in mainland Southeast Asia: linkages, disjunctures and implications	Article	International Journal of Water Governance	The heuristic framework	Applying	Appropriate scales within basin system Clear role and responsibility Cooperation and coordination Integrity and transparency Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	Thailand and Vietnam	Hydropower and energy, transboundary water management, and river basin management
64	Nodir Djanibekov, Kristof Van Assche, and Vladislav Valentinov	2015	Water governance in Central Asia: a luhmannian perspective	Article	Society and Natural Resources	x	x	x	CAs	Hydropower and energy, transboundary water management, and river basin management Coordination and cooperation
65	Nguyen Ngoc Huy, Tran Van Giai Phong, and Stephen Tyler	2015	Institutional challenges for peri-urban water supply in Can Tho, Vietnam	Report	The International Institute for Environment and Development, United Kingdom	The legal and institutional framework	Applying	Clear role and responsibility Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	Vietnam	Rural water services, urban water services, and water quality Legal and institutional arrangements
66	Agnes C. Rola, Juan M. Pulhin, Guillermo Q. Tabios III, Joy C. Lizada, and Maria Helen F. Dayo	2015	Challenges of water governance in the Philippines	Article	Philippine Journal of Science	The multi-dimensional governance framework	Developing	Appropriate scales within basin system Clear role and responsibility Cooperation and coordination Data, information, and knowledge sharing Integrity and transparency Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement Trade-offs across users, areas, and generations	Philippines	Urban water services and water quality Legal and institutional arrangements
67	Agnes C. Rola, Corazon L. Abansi, Rosalie Arcala-Hall, Joy C. Lizada, Ida M.L. Siason, and Eduardo K. Araral Jr	2015	Drivers of water governance reforms in the Philippines	Article	International Journal of Water Resources Development	The legal and institutional framework	Applying	Clear role and responsibility Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	Philippines	Legal and institutional arrangements

68	Cornelis J van Leeuwen, Nguyen Phuoc Dan, and Carel Dieperink	2015	The challenges of water governance in Ho Chi Minh City	Article	Integrated Environmental Assessment and Management	The OECD Multi-level Governance framework	Applying	Capacity development Clear role and responsibility Data, information, and knowledge sharing Financial capacity Integrity and transparency Legislation, regulation, instrument, and policy Management arrangement Stakeholder engagement	Vietnam	Ecological water needs, urban water services, and water quality
69	Paula Hanasz	2015	The politics of water governance in the Ganges-Brahmaputra-Meghna Basin	Article	Observer Research Foundation, India	x	x	x	India	Transboundary water management and river basin management Coordination and cooperation, and politics and power
70	David Benson, Animesh K. Gain, and Josselin J. Rouillard	2015	Water governance in a comparative perspective: from IWRM to a 'nexus' approach?	Article	Water Alternatives	The Water Framework Directive	Applying	Appropriate scales within basin system Capacity development Clear role and responsibility Cooperation and coordination Data, information, and knowledge sharing Integrity and transparency Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	Bangladesh	Agriculture, sustainable development and the SDGs, and water-energy-food nexus Legal and institutional arrangements
71	Haiyan Helen Yu, Mike Edmunds, Anna Lora-Wainwright, and David Thomas	2015	Governance of the irrigation commons under integrated water resources management – a comparative study in contemporary rural China	Article	Environmental Science and Policy	Unnamed	Applying	Clear role and responsibility Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation	China	Agriculture and river basin management Legal and institutional arrangements
72	Ahmad Hamidov, Andreas Thiel, and Dimitrios Zikos	2015	Institutional design in transformation: a comparative study of local irrigation governance in Uzbekistan	Article	Environmental Science and Policy	Unnamed	Developing	Cooperation and coordination Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	Uzbekistan	Agriculture Legal and institutional arrangements
73	Barbara Janusz-Pawletta and Mara Gubaidullina	2015	Transboundary water management in Central Asia: legal framework to strengthen interstate cooperation and increase regional security	Article	Cahiers d'Asie Centrale	x	x	Cooperation and coordination Legislation, regulation, instrument, and policy	CAs	Hydropower and energy, transboundary water management, and river basin management Coordination and cooperation, and legal and institutional arrangements
74	Christian Knieper and Claudia Pahl-Wostl	2016	A comparative analysis of water governance, water management, and environmental	Article	Water Resources Management	The adaptive and integrated water management framework	Developing	Capacity development Cooperation and coordination Data, information, and knowledge sharing Financial capacity Legislation, regulation, instrument, and policy	Bhutan	Environmental protection and river basin management

			performance in river basins					Management arrangement Stakeholder engagement		
75	Asian Development Bank (ADB)	2016	Asian water development outlook 2016: strengthening water security in Asia and the Pacific	Report	Asian Development Bank, Philippines	The Water Governance Indicator and Measurement framework	Applying	Appropriate scales within basin system Capacity development Clear role and responsibility Data, information, and knowledge sharing Financial capacity Innovative governance Integrity and transparency Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement Trade-offs across users, areas, and generations	30 countries	Water security
76	Eduardo Araral and Xun Wu	2016	Comparing water resources management in China and India: policy design, institutional structure and governance	Article	Water Policy	The modified Institutional Analysis and Development framework	Developing	Appropriate scales within basin system Cooperation and coordination Integrity and transparency Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	China and India	Legal and institutional arrangements
77	Eduardo Araral and Shivani Ratra	2016	Water governance in India and China: comparison of water law, policy and administration	Article	Water Policy	The Institutional Decomposition and Analysis framework	Applying	Appropriate scales within basin system Cooperation and coordination Integrity and transparency Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	China and India	Legal and institutional arrangements, and politics and power
78	Du Le Thuy Tien, Bui Du Duong, Quach Thi Xuan, and Lisa Robins	2016	Water governance in a changing era: perspectives on Vietnam	Book chapter	Strategic Information and Research Development Centre	The approach and conceptual framework	Applying	Clear role and responsibility Cooperation and coordination Integrity and transparency Legislation, regulation, instrument, and policy Planning and preparedness Stakeholder engagement	Vietnam	Legal and institutional arrangements, and stakeholder engagement
79	Agnes C. Rola, Corazon L. Abansi, Rosalie Arcala-Hall, and Joy C. Lizada	2016	Characterizing local water governance structure in the Philippines: results of the water managers' 2013 survey	Article	Water International	The Institutional Decomposition and Analysis framework	Applying	Appropriate scales within basin system Cooperation and coordination Integrity and transparency Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	Philippines	Legal and institutional arrangements
80	Rob Swinkels, Ekaterina Romanova, and Evgeny Kochkin	2016	Exploratory assessment of factors that influence quality of local irrigation water governance in Uzbekistan	Report	The World Bank, United States	The analytical framework	Developing	Appropriate scales within basin system Clear role and responsibility Cooperation and coordination Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement Trade-offs across users, areas, and generations	Uzbekistan	Agriculture Coordination and cooperation, and legal and institutional arrangements

81	Peter Emmanuel Cookey, Rotchanatch Darnsawasdi, and Chatchai Ratanachai	2016	Performance evaluation of lake basin water governance using composite index	Article	Ecological Indicators	The Lake Basin Water Governance Performance Composite Index framework	Developing	Capacity development Cooperation and coordination Data, information, and knowledge sharing Integrity and transparency Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Planning and preparedness Stakeholder engagement	Thailand	River basin management and rural water quality Legal and institutional arrangements
82	Ngai Weng Chan, Ranjan Roy, and Brian C. Chaffin	2016	Water governance in Bangladesh: an evaluation of institutional and political context	Article	Water	x	x	Clear role and responsibility Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement Planning and preparedness	Bangladesh	Climate change, flood risk management, sustainable development and the SDGs, and water scarcity and drought Legal and institutional arrangements, and politics and power
83	André Silveira, Sandra Junier, Frank Hüesker, Fan Qunfang, and Andreas Rondorf	2016	Organizing cross-sectoral collaboration in river basin management: case studies from the Rhine and the Zhujiang (Pearl River) Basins	Article	International Journal of River Basin Management	The collaboration impact framework	Developing	Cooperation and coordination Data, information, and knowledge sharing Integrity and transparency Legislation, regulation, instrument, and policy Management arrangement Stakeholder engagement	China	River basin management and water quality Coordination and cooperation, legal and institutional arrangements, and stakeholder engagement
84	Yahua Wang, Maitreyee Mukherjee, Dan Wu, and Xun Wu	2016	Combating river pollution in China and India: policy measures and governance challenges	Article	Water Policy	The legal and institutional framework	Applying	Legislation, regulation, instrument, and policy Management arrangement Stakeholder engagement	China and India	River basin management and water quality Coordination and cooperation, and legal and institutional arrangements
85	Marko Keskinen, Joseph H. A. Guillaume, Mirja Kattelus, Miina Porkka, Timo A. Räsänen, and Olli Varis	2016	The water-energy-food nexus and the transboundary context: insights from large Asian rivers	Article	Water	The transboundary nexus framework	Developing	Cooperation and coordination Legislation, regulation, instrument, and policy Stakeholder engagement	CAs, SA, and SEA	Transboundary water management, river basin management, and water-energy-food nexus Coordination and cooperation, legal and institutional arrangements, and politics and power
86	Haiyan Yu	2016	Can water users' associations improve water governance in China? A tale of two villages in the Shiyang River Basin	Article	Water International	The common pool resources governance framework	Developing	Appropriate scales within basin system Cooperation and coordination Integrity and transparency Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	China	Agriculture Legal and institutional arrangements, politics and power, and stakeholder engagement
87	Huijuan Wu and Ching Leong	2016	A composite framework of river sustainability: integration across time, space and interests in the	Article	Water Policy	The process analysis method sustainability assessment framework	Applying	The impact of the river system on 3 domains of sustainability Activities that have impacts on river sustainability Consequences are described by sustainability indicators	China and India	Sustainable development and the SDGs, and river basin management Capacity development

			Yellow River and Ganges River							
88	Ying Chai	2016	Institutions and government efficiency: decentralized irrigation management in China	Article	International Journal of the Commons	The institutional incentives and coordination framework	Developing	Cooperation and coordination Monitoring and evaluation	China	Agriculture Coordination and cooperation, and legal and institutional arrangements
89	Carl Middleton and Jeremy Allouche	2016	Watershed or powershed? critical hydropolitics, China and the 'Lancang-Mekong Cooperation Framework'	Article	The International Spectator	The 'Lancang-Mekong Cooperation' framework	Applying	Political and security issues Economic and sustainable development Social, cultural, and people-to-people exchanges	China, Thailand, and Vietnam	Agriculture, hydropower and energy, transboundary water management, river basin management, and watershed management Coordination and cooperation, and legal and institutional arrangements
90	Bryan Bruns	2017	Challenges of polycentric water governance in Southeast Asia: awkward facts, missing mechanisms, and working with institutional diversity	Book chapter	Elsevier	The Institutional Analysis and Development framework	Applying	Appropriate scales within basin system Cooperation and coordination Integrity and transparency Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	SEA	Agriculture Legal and institutional arrangements, and polycentric governance
91	Vo Tat Thang, Thong Tran, and Duy Luong	2017	Water governance for sustainable development: international practices and implications for the Mekong Delta region	Article	Journal of Economic Development	The legal and institutional framework	Developing	Appropriate scales within basin system Clear role and responsibility Cooperation and coordination Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	Vietnam	Agriculture, and sustainable development and the SDGs Legal and institutional arrangements
92	Phung Thi Ha, Carel Dieperink, Van Pham Dang Tri, Henriëtte Otter, and Piet Hoekstra	2017	Governance Conditions for adaptive freshwater management in the Vietnamese Mekong Delta	Article	Journal of Hydrology	The adaptive and integrated water management framework	Developing	Appropriate scales within basin system Capacity development Clear role and responsibility Cooperation and coordination Data, information, and knowledge sharing Financial capacity Integrity and transparency Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Planning and preparedness Stakeholder engagement	Vietnam	Agriculture, climate change, groundwater management, and water quality Adaptive governance
93	Paula Maria Hanasz	2017	A little less conversation? Track II Dialogue and transboundary water governance	Article	Asia and the Pacific Policy Studies	The Track II Dialogue framework	Applying	Cooperation and coordination Data, information, and knowledge sharing Integrity and transparency Stakeholder engagement	SA	Transboundary water management and river basin management Coordination and cooperation
94	Paula Maria Hanasz	2017	An examination of the South Asia Water	Thesis	Australian National	The Transboundary	Applying	Cooperation and coordination	SA	Agriculture, climate change, , flood risk management, hydropower and energy,

			Initiative and associated donor-led processes in the transboundary water governance of the Ganges-Brahmaputra problemshed		University, Australia	Water Interaction Nexus framework				sustainable development and the SDGs, transboundary water management, river basin management, water scarcity and drought, and water security Coordination and cooperation, and stakeholder engagement
95	Douglas J. Merrey, Anjal Prakash, Larry Swatuk, Inga Jacobs, and Vishal Narain	2017	Water governance futures in South Asia and Southern Africa: déjà vu all over again?	Book chapter	Springer	Unnamed	Developing	Appropriate scales within basin system Cooperation and coordination Legislation, regulation, instrument, and policy Management arrangement Stakeholder engagement	CAs and SA	Transboundary water management and river basin management Coordination and cooperation, and legal and institutional arrangements
96	Chitresh Saraswat, Binaya Kumar Mishra, and Pankaj Kumar	2017	Integrated urban water management scenario modeling for sustainable water governance in Kathmandu Valley, Nepal	Article	Sustainability Science	Unnamed	Original	Identified problems Driving forces Associated governance factors Future impacts	Nepal	Climate change, sustainable development and the SDGs, urban water services, water quality, and water security Legal and institutional arrangements
97	Xing Wei	2017	Lancang-Mekong River cooperation and trans-boundary water governance: a Chinese perspective	Article	China Quarterly of International Strategic Studies	x	x	x	EA and SEA	Hydropower and energy, sustainable development and the SDGs, transboundary water management, river basin management, and water security Coordination and cooperation
98	Xu Jianchu, Muhammad Asad Salim, Ed Grumbine, Su Yufang, Robert Zomer, Arjumand Nizami, Bikram Rana, Sailesh Ranjitkar, Jawad Ali, Mona Sherpa, and Rabin Raj Niraula	2017	Building effective water governance in the Asian highlands: living with risks and building resilience in water governance	Report	Centre for Mountain Ecosystem Studies, China	Unnamed	Applying	Capacity development Clear role and responsibility Cooperation and coordination Data, information, and knowledge sharing Integrity and transparency Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Planning and preparedness Stakeholder engagement Trade-offs across users, areas, and generations	Nepal, Pakistan, and China	Climate change Capacity development, coordination and cooperation, legal and institutional arrangements, and stakeholder engagement
99	Farideh Delavari Edalat and M. Reza Abdi	2018	Adaptive water management: concepts, principles and applications for sustainable development	Book	Springer	The adaptive and integrated water management framework	Applying	Capacity development Cooperation and coordination Data, information, and knowledge sharing Financial capacity Legislation, regulation, instrument, and policy Management arrangement Stakeholder engagement	Iran	Adaptive governance, and legal and institutional arrangements
100	Ilkhom Soliev, Kai Wegerich, Indira Akramova,	2018	Balancing the discussion of benefit sharing in transboundary water	Article	International Journal of Water Governance	The reductionist and integrative approaching framework	Applying	x	Kyrgyzstan and Uzbekistan	Agriculture, transboundary water management, and river basin management

	and Nozilakhon Mukhamedova		governance: stressing the long-term costs in an empirical example from Central Asia						Coordination and cooperation
101	Andrea Zinzani and Christine Bichsel	2018	IWRM and the politics of scale: rescaling water governance in Uzbekistan	Article	Water	The "politics of scale" analytical framework	Original	Socio-spatial practices State and non-state regulations and politics Power interactions Social struggles	Uzbekistan	Transboundary water management and river basin management Legal and institutional arrangements
102	Kiran Maharjan	2018	Political Ecology of water governance in South Asia: a case study of the Koshi River communities	Thesis	The University of Sydney, Australia	The actor-oriented political ecological framework	Developing	Appropriate scales within basin system Clear role and responsibility Cooperation and coordination Data, information, and knowledge sharing Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	Nepal and India	Agriculture, flood risk management, hydropower and energy, transboundary water management, river basin management, water quality, and water scarcity and drought Coordination and cooperation, and politics and power
103	Afshana Parven and Md.Shahidul Hasan	2018	Trans-boundary water conflicts between Bangladesh and India: water governance practice for conflict resolution	Article	International Journal of Agricultural Research, Innovation and Technology	x	x	x	Bangladesh and India	Transboundary water management, and river basin management Coordination and cooperation, and legal and institutional arrangements
104	Ajaya Dixit	2018	Trans-boundary water governance in South Asia: the beginning of a new journey	Book chapter	Springer	x	x	x	SA	Flood risk management, hydropower and energy, transboundary water management, and river basin management Legal and institutional arrangements, and politics and power
105	Paramita Rahayu, Johan Woltjer, and Tommy Firman	2018	Water governance in decentralizing urban Indonesia	Article	Urban Studies	The conceptually institutional capacity framework	Applying	Capacity development Cooperation and coordination Data, information, and knowledge sharing Innovative governance Stakeholder engagement	Indonesia	Urban water services and water quality Capacity development, and coordination and cooperation
106	Hussam Hussein	2018	Yarmouk, Jordan, and Disi Basins: examining the impact of the discourse of water scarcity in Jordan on transboundary water governance	Article	Mediterranean Politics	The Hydro-Hegemony framework	Applying	Geographical position Three dimensions of power (hard, bargaining, and ideational power) Exploitation potential	Jordan	Transboundary water management, river basin management, and water security Coordination and cooperation, and politics and power
107	Asian Development Bank (ADB)	2018	Managing water resources for sustainable socioeconomic development: a	Report	Asian Development Bank, Philippines	The water resources management strategic framework	Applying	Capacity development Clear role and responsibility Cooperation and coordination Data, information, and knowledge sharing Integrity and transparency	China	Climate change, ecological water needs, flood risk management, hydropower and energy, poverty reduction, sustainable development and the SDGs, rural water services, urban

			country water assessment for the People's Republic of China					Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Planning and preparedness Stakeholder engagement		water services, water quality, water scarcity and drought, water security, water technology and infrastructure management, and water-energy-food nexus Capacity development, coordination and cooperation, and legal and institutional arrangements
108	Jessica M. Williams	2018	Stagnant Rivers: transboundary water security in South and Southeast Asia	Article	Water	x	x	x	SA and SEA	Transboundary water management, river basin management, water security, and water technology and infrastructure management Coordination and cooperation, legal and institutional arrangements, and politics and power
109	Jacqueline Storey	2019	Policy influence and outcomes of the Mekong Inclusion Project	Report	Mekong Regional Water Governance Program, Oxfam	x	x	x	SEA	Agriculture, hydropower and energy, and transboundary water management Legal and institutional arrangements
110	Masood Ahmed and Eduardo Araral	2019	Water governance in India: evidence on water law, policy, and administration from eight Indian states	Article	Water	The Institutional Decomposition and Analysis framework	Applying	Appropriate scales within basin system Cooperation and coordination Integrity and transparency Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	India	Sustainable development and the SDGs Legal and institutional arrangements
111	Asian Development Bank Institute (ADBI)	2019	Water insecurity and sanitation in Asia	Book	Asian Development Bank Institute, Japan	The legal and institutional framework	Applying	Appropriate scales within basin system Clear role and responsibility Cooperation and coordination Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	Bangladesh, Korea, Malaysia, Nepal, and India	Urban water services, water quality, and water security Legal and institutional arrangements
112	Kenji Otsuka	2019	Interactive perspectives on water governance in Asia	Book chapter	Springer	The Water Governance Indicator and Measurement framework	Applying	Appropriate scales within basin system Capacity development Clear role and responsibility Data, information, and knowledge sharing Financial capacity Innovative governance Integrity and transparency Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement Trade-offs across users, areas, and generations	Asia	River basin management Legal and institutional arrangements
113	Kenji Otsuka	2019	Interactive governance of water	Book chapter	Springer	x	x	x	China	River basin management and water quality

			environment in Taihu Lake Basin: a challenge of legitimacy under the authoritarian regime in China							Legal and institutional arrangements, and stakeholder engagement
114	Siriporn Wajjwalku	2019	Civil society and water governance in Northern Thailand: local NGOs and management of Mekong's Tributaries in Chiang Rai	Book chapter	Springer	The Water Governance Indicator and Measurement framework	Applying	Appropriate scales within basin system Capacity development Clear role and responsibility Cooperation and coordination Data, information, and knowledge sharing Financial capacity Innovative governance Integrity and transparency Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Planning and preparedness Stakeholder engagement Trade-offs across users, areas, and generations	Thailand	Flood risk management Capacity development, coordination and cooperation, legal and institutional arrangements, and stakeholder engagement
115	Tadayoshi Masuda	2019	Interactive governance for sustainable resource use and environmental management: a case study of Yaman ng Lawa Initiative in the Laguna Lake Watershed, Philippines	Book chapter	Springer	The Institutional Analysis and Development framework	Developing	Appropriate scales within basin system Cooperation and coordination Legislation, regulation, instrument, and policy Management arrangement Stakeholder engagement Trade-offs across users, areas, and generations	Philippines	Environmental protection and watershed management Coordination and cooperation and stakeholder engagement
116	Mansee Bhargava	2019	Interactive governance at Anasagar Lake Management in India: analyzing using institutional analysis and development framework	Book chapter	Springer	The Institutional Analysis and Development framework	Applying	Appropriate scales within basin system Cooperation and coordination Integrity and transparency Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	India	Sustainable development and the SDGs, and watershed management Coordination and cooperation, legal and institutional arrangements, and stakeholder engagement
117	Mart Stewart and Peter Coclanis	2019	Water and power: environmental governance and strategies for sustainability in the Lower Mekong Basin	Book	Springer	The international trust analytical framework	Original	Capacity development Cooperation and coordination Data, information, and knowledge sharing Integrity and transparency Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	SEA	Agriculture, climate change, hydropower and energy, transboundary water management, river basin management, urban water services, water commodification and market, water quality, and water technology and infrastructure management

										Coordination and cooperation, legal and institutional arrangements, and stakeholder engagement
118	Xiaofeng Liu, Nicholas J. Souter, Raymond Yu Wang, and Derek Vollmer	2019	Aligning the freshwater health index indicator system against the transboundary water governance framework of Southeast Asia's Sesan, Srepok, and Sekong River Basin	Article	Water	x	x	Appropriate scales within basin system Clear role and responsibility Cooperation and coordination Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	Cambodia, Laos, and Vietnam	Climate change, ecological water needs, hydropower and energy, transboundary water management, river basin management, and water quality Legal and institutional arrangements
119	Himanshu Thakkar	2019	Challenges in water governance: a story of missed opportunities	Report	Economic and Political Weekly	x	x		India	Groundwater management and river basin management
120	Yahua Wang and Xiangning Chen	2019	River chief system as a collaborative water governance approach in China	Article	International Journal of Water Resources Development	The analytical framework of river chief system	Developing	Cooperation and coordination Data, information, and knowledge sharing Legislation, regulation, instrument, and policy Management arrangement Stakeholder engagement	China	Coordination and cooperation, and legal and institutional arrangements
121	R. Quentin Grafton, Dustin Garrick, Ana Manero, and Thang Nam Do	2019	The water governance reform framework: overview and applications to Australia, Mexico, Tanzania, U.S.A and Vietnam	Article	Water	The water governance reform framework	Original	Capacity development Data, information, and knowledge sharing Innovative governance Integrity and transparency Legislation, regulation, instrument, and policy Management arrangement Planning and preparedness Trade-offs across users, areas, and generations	Vietnam	Water quality and water security Legal and institutional arrangements
122	Imad Antoine Ibrahim	2019	Water governance in the Mekong after the Watercourses Convention 35th ratification: Multilateral or bilateral approach?	Article	International Journal of Water Resources Development	x	x	Appropriate scales within basin system Clear role and responsibility Cooperation and coordination Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	SEA	Transboundary water management and river basin management Legal and institutional arrangements
123	Selina Ho	2019	Comparing China's and India's water institutional frameworks	Book chapter	Cambridge University, the United Kingdom	The legal and institutional framework	Applying	Appropriate scales within basin system Clear role and responsibility Cooperation and coordination Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	China and India	Urban water services Legal and institutional arrangements
124	Amarjit Singh, Dipankar Saha, and Avinash C. Tyagi	2019	Water governance: challenges and prospects	Book	Springer	The Institutional Decomposition and Analysis framework	Applying	Appropriate scales within basin system Capacity development Cooperation and coordination Financial capacity Integrity and transparency Legislation, regulation, instrument, and policy	India	Agriculture, environmental protection, flood risk management, groundwater management, hydropower and energy, rural water services, urban water services, water quality, and water security

								Management arrangement Monitoring and evaluation Stakeholder engagement		Capacity development and stakeholder engagement
125	The UNESCO International Centre for Water Security and Sustainable Management (UNESCO i-WSSM)	2019	Global water security issues case studies: water security and the sustainable development goals	Report	The UNESCO International Centre for Water Security and Sustainable Management, Republic of Korea	Harmonisation framework	Applying	Appropriate scales within basin system Capacity development Clear role and responsibility Cooperation and coordination Data, information, and knowledge sharing Innovative governance Integrity and transparency Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	Jordan	Agriculture, climate change, environmental protection, groundwater management , hydropower and energy, sustainable development and the SDGs, transboundary water management, river basin management, water scarcity and drought, water security, and water technology and infrastructure management Capacity development, knowledge and data sharing, and legal and institutional arrangements
126	Michelle Kooy and Carolin T. Walter	2019	Towards a situated urban political ecology analysis of packaged drinking water supply	Article	Water	The situated Urban Political Ecology framework	Developing	x	Indonesia	Sustainable development and the SDGs, urban water services, water quality, and water technology and infrastructure management Politics and power
127	Wanxin Li, David von Eiff, and Alicia Kyoungjin An	2020	Analyzing the effects of institutional capacity on sustainable water governance	Article	Sustainability Science	The analytical framework	Original	Capacities to pick up signals Balance interests Implement policies Learn and adapt socio-economic and environmental changes	Hong Kong	Sustainable development and the SDGs, and water quality Legal and institutional arrangements
128	Louis Lebel, Andrea Haefner, Claudia Pahl-Wostl, and Anik Baduri	2020	Governance of the water-energy-food nexus: insights from four infrastructure projects in the Lower Mekong Basin	Article	Sustainability Science	The water-energy-food framework	Original	Cooperation and coordination Integrity and transparency	Laos and Thailand	Agriculture, hydropower and energy, transboundary water management, water technology and infrastructure management, and water-energy-food nexus Coordination and cooperation, and legal and institutional arrangements
129	Claudia Pahl-Wostl, Philipp Gorris, Nicolas Jager, Larissa Koch, Louis Lebel, Christian Stein, Sandra Venghaus, and Sisira Withanachchi	2020	Scale-related governance challenges in the water-energy-food nexus: toward a diagnostic approach	Article	Sustainability Science	The diagnostic framework	Original	Appropriate scales within basin system Clear role and responsibility Cooperation and coordination Integrity and transparency Legislation, regulation, instrument, and policy Management arrangement Stakeholder engagement	SA and SEA	Transboundary water management and water-energy-food nexus Multi-level and multi-scale governance
130	Global Water Partnership (GWP) and UNEP-DHI	2020	Progress on integrated water resources management in the Asia-Pacific Region:	Report	The Global Water Partnership, Sweden	The holistic framework	Original	Capacity development Cooperation and coordination Data, information, and knowledge sharing Legislation, regulation, instrument, and policy Management arrangement	16 countries	Sustainable development and the SDGs, and transboundary water

			learning exchange on monitoring and implementation towards SDG 6.5.1					Monitoring and evaluation Planning and preparedness Stakeholder engagement		Coordination and cooperation, legal and institutional arrangements, and stakeholder engagement
131	Vishwa Ranjan Sinha and Kathryn Bimson	2020	Nature-based solutions in the Ganges Brahmaputra Meghna River Basin: case studies and lessons learned	Report	International Union for Conservation of Nature, Asia Regional Office, Thailand	x	x	Capacity development Stakeholder engagement	Bangladesh, India, and Nepal	Agriculture, ecological water needs, flood risk management, and water quality Capacity development and stakeholder engagement
132	Asian Development Bank (ADB)	2020	Asian water development outlook 2020: strengthening water security in Asia and the Pacific	Report	Asian Development Bank, Philippines	The Water Governance Indicator and Measurement framework	Applying	Appropriate scales within basin system Capacity development Clear role and responsibility Data, information, and knowledge sharing Financial capacity Innovative governance Integrity and transparency Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement Trade-offs across users, areas, and generations	30 countries	Water security
133	Jenniver Sehring	2020	Unequal distribution: Academic knowledge production on water governance in Central Asia	Article	Water Security	x	x	x	CAs	Transboundary water management, and river basin management Coordination and cooperation, capacity development, and knowledge and data sharing
134	The Organisation for Economic Co-operation and Development (OECD)	2020	Water governance in Asia-Pacific	Report	The Organisation for Economic Co-operation and Development, France	The Water Governance Indicator and Measurement framework	Applying	Appropriate scales within basin system Capacity development Clear role and responsibility Data, information, and knowledge sharing Financial capacity Innovative governance Integrity and transparency Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement Trade-offs across users, areas, and generations	30 countries	Water security
135	Thomas Hamer, Carel Dieperink, Van Pham Dang Tri, Henriëtte S. Otter, and Piet Hoekstra	2020	The rationality of groundwater governance in the Vietnamese Mekong Delta's coastal zone	Article	International Journal of Water Resources Development	The rational groundwater governance framework	Developing	Appropriate scales within basin system Capacity development Clear role and responsibility Cooperation and coordination Data, information, and knowledge sharing Integrity and transparency Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation	Vietnam	Coastal zone management and groundwater management Legal and institutional arrangements, and stakeholder engagement

								Stakeholder engagement Trade-offs across users, areas, and generations		
136	Min Jianga, Michael Webbera, Jon Barnetta, Sarah Rogersb, Ian Rutherfurda, Mark Wanga, and Brian Finlayson	2020	Beyond contradiction: The state and the market in contemporary Chinese water governance	Article	Geoforum	x	x	x	China	Water commodification and market, and water technology and infrastructure management Legal and institutional arrangements
137	JeongWon Bourdais Park Aigul Adibayeva, and Danial Saari	2020	Contestation and collaboration for water resources: comparing the emerging regional water governance of the Aral Sea, Irtysh River, and Mekong River	Article	Journal of Asian and African Studies	The Hydro-Hegemony framework	Applying	Geographical position Three dimensions of power (hard, bargaining, and ideational power) Exploitation potential	EA, CAs, and SEA	Ecological water needs, transboundary water management, and river basin management Coordination and cooperation, and politics and power
138	Yuqing Geng, Mukasar Maimaituerxun, and Han Zhang	2020	Coupling coordination of water governance and tourism: measurement and prediction	Article	Discrete Dynamics in Nature and Society	The composite and aggregated evaluation framework	Original	Water governance pressure Water governance state Water governance response Tourism performance Tourism scale	China	Tourism and navigation, and water quality
139	Linda Shi, Sonia Ahmad, Prakriti Shukla, and Sauvanithi Yupho	2020	Shared injustice, splintered solidarity: Water governance across urban-rural divides	Article	Global Environmental Change	x	x	x	Bangladesh, India, Philippines, and Thailand	Climate change, flood risk management, rural water services, and urban water services Coordination and cooperation
140	Binaya Kumar Mishra, Shamik Chakraborty, Pankaj Kumar, and Chitresh Saraswat	2020	Urban water governance: concept and pathway	Book chapter	Springer	The adaptive and integrated water management framework	Developing	Capacity development Data, information, and knowledge sharing Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	India	Sustainable development and the SDGs, and urban water services Adaptive governance, capacity development, and legal and institutional arrangements
141	Fan He, Yongnan Zhu, and Shan Jiang	2020	An exploration of China's practices in water conservation and water resources management	Book chapter	Elsevier	The "Four Systems" framework	Applying	The total water consumption control system The water use efficiency improvement system The system on pollution carrying capacity in water functional zones The accountability and appraisal supporting system	China	Legal and institutional arrangements
142	Chansheng He, Carol P. Harden, and Yanxu Liu	2020	Comparison of water resources management between China and the United States	Article	Geography and Sustainability	x	x	National authority Water works and water supply Water quality Ecosystem use	China	Ecological water needs, sustainable development and the SDGs, urban water services, water commodification and market, water quality, and water technology and infrastructure management Legal and institutional arrangements

143	I-Shin Chang, Mengdie Zhao, Yilin Chen, Xiaomin Guo, Ying Zhu, Jing Wu, and Tao Yuan	2020	Evaluation on the integrated water resources management in China's major cities – based on City Blueprint Approach	Article	Journal of Cleaner Production	The Trends and Pressures, City Blueprint, and Governance Capacity Frameworks	Developing	Capacity development Data, information, and knowledge sharing Financial capacity Stakeholder engagement	China	Climate change, urban water services, water quality, and water technology and infrastructure management Capacity development, knowledge and data sharing, and stakeholder engagement
144	Abdulrahman S. Alsharhan and Zeinelabidin E. Rizk	2020	Water resources and integrated management of the United Arab Emirates	Book	Springer	The legal and institutional framework	Applying	Appropriate scales within basin system Clear role and responsibility Cooperation and coordination Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Stakeholder engagement	The United Arab Emirates	Agriculture, climate change, groundwater management, water quality, and water technology and infrastructure management Coordination and cooperation, and legal and institutional arrangements
145	Md. Razzaqul Islam, Chowdhury Sarwar Jahan, Md. Ferozur Rahaman, and Quamrul Hasan Mazumder	2020	Governance status in water management institutions in Barind Tract, Northwest Bangladesh: an assessment based on stakeholder's perception	Article	Sustainable Water Resources Management	The water governance assessment framework	Developing	Appropriate scales within basin system Capacity development Clear role and responsibility Cooperation and coordination Integrity and transparency Legislation, regulation, instrument, and policy Management arrangement Monitoring and evaluation Planning and preparedness Stakeholder engagement Trade-offs across users, areas, and generations	Bangladesh	Groundwater management, and sustainable development and the SDGs Capacity development, coordination and cooperation, and stakeholder engagement

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