Harmonizing multi-sectorial water management with minimum flow requirements in an anthropogenically impacted river basin

The case of Vu Gia – Thu Bon, Central Viet Nam

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Abstract

The low flow phenomenon is significantly concerned since it severely impacts socio economic activities. During low flow periods, diminished freshwater resources are often unable to provide adequate water for crop production, hydropower generation and urban water supply, as well as to maintain water quality of freshwater bodies due to high concentration of pollutants and saltwater intrusion. Accordingly, determining the required minimum flows in rivers during low flow periods is important to reduce the impact of saltwater intrusion and maintain a sustainable water supply for different water users such as agriculture, domestic use and industries.

Located in the central coastal zone of Viet Nam, the Vu Gia – Thu Bon river basin experiences drought during the dry season along with salt intrusion due to low flow. The region was chosen as an in-depth case study since it provides crucial information regarding the low flow phenomenon and drought situation during the period 1976 - 2014. This research aims to develop a generally applicable methodology to assess minimum flow requirements in the rivers. The goal of this thesis is (1) to analyze the low flow phenomenon and minimum flow requirements; (2) to quantify the potential water demand from the different user categories; (3) to assess the performance of the existing irrigation system in regards to water supply availability and water demand; (4) to determine the required minimum flow to prevent salt intrusion and satisfy the water demand from different activities during low flow periods; and (5) to derive a generally applicable methodology to assess minimum flow requirements in multi-sectorial water management scenarios.

Firstly, statistical analysis was conducted to examine trends in precipitation and flow during the study period. Thereafter, a flow duration curve and SPEI index were calculated to understand the flow pattern and drought events in the region. The potential water demand was quantified for the agricultural sector, as well as domestic and industrial uses to map the water utilization pattern. The Penman – Monteith equation was applied to calculate the potential evapotranspiration using

the data from the dry year 2005. Furthermore, the performance of the irrigation system was accessed by analyzing the two indicators of Relative Water Supply and Relative Irrigation Supply. Finally, a calculation of the minimum flow requirement was carried out by applying the hydrodynamic model MIKE 11. The model was run for different upstream discharge datasets to test the response of the salt concentration, and then define where the salt concentration remains under threshold values at chosen measurement points. Six different scenarios were developed to predict the minimum flow requirements toward the changes in potential water use, sea level rise and water use efficiency.

In general, the analysis of precipitation and flow revealed strong increasing trends, however these were mostly seen in rainy season. On the other hand, the SPEI index showed a decrease of drought events in the years post 2000. The yearly potential demand of the Vu Gia -Thu Bon Delta was calculated as 309 million m^3, of which 203 million m^3 is for agriculture, 89 million m^3 is for domestic use, and only 17 million m^3 is for industry. Furthermore, the analysis of Relative Water Supply and Relative Irrigation Supply revealed the constraints of the irrigation system to supply sufficient water for the crops, especially from February to June. Finally, the results of the six scenarios were mapped presenting the spatial and temporal extents of the minimum flow requirements in the Vu Gia – Thu Bon river basin.

The described methodology includes transferable state-of-the-art techniques, making it an applicable approach to determine the minimum flow requirement in an anthropogenically influenced river basin. This methodology has been successfully tested in the Vu Gia - Thu Bon river basin and can be extrapolated to similar river basins.

Zusammenfassung

Das Phänomen des geringen Durchflusses ist besorgniserregend, da es die sozioökonomischen Aktivitäten stark beeinträchtigt. Während einer Periode mit geringem Durchfluss sind die verringerten Süßwasserressourcen des Flusses nicht in der Lage ausreichend Wasser für die Pflanzenproduktion, die Wasserkrafterzeugung und die städtische Wasserversorgung bereitzustellen sowie die Wasserqualität von Gewässern aufgrund des Eindringens von Salzwasser aufrechtzuerhalten. Dementsprechend ist die Bestimmung der erforderlichen Mindestflüsse in Flüssen während Perioden mit geringem Durchfluss eine wichtige Notwendigkeit, um die Auswirkungen des Eindringens von Salzwasser zu verringern und eine nachhaltige Wasserversorgung für verschiedene Wassernutzer wie Landwirtschaft, Haushalt und Industrie aufrechtzuerhalten.

Das in der zentralen Küstenzone Vietnams gelegene Einzugsgebiet des Flusses Vu Gia - Thu Bon, in dem sich das Untersuchungsgebiet befindet, leidet während der Trockenzeit unter Trockenheit und Salzintrusionen aufgrund geringer Durchflussmengen. Die Region wurde analysiert und lieferte die entscheidenden Informationen zum Phänomen des geringen Durchflusses und zur Dürre im Zeitraum 1976 - 2014. Diese Forschung zielt darauf ab, eine allgemein anwendbare Methodik zur Bewertung des erforderlichen Mindestdurchflusses in den Flüssen zu entwickeln. Das Ziel wird erreicht durch (1) Analyse des Phänomens mit geringem Durchfluss und des Mindestdurchflussbedarfs; (2) Quantifizierung des potenziellen Wasserbedarfs aus den verschiedenen Aktivitäten; (3) Bewertung der Leistung des bestehenden Bewässerungssystems hinsichtlich der Verfügbarkeit der Wasserversorgung und des Wasserbedarfs; (4) Bestimmen des erforderlichen Mindestdurchflusses in Flüssen, um das Eindringen von Salz zu verhindern und den Wasserbedarf aus verschiedenen Aktivitäten während einer Periode mit geringem Durchfluss zu decken; und dann (5) Ableiten einer allgemein anwendbaren Methodik zur Bewertung der Mindestdurchflussanforderungen in multisektoralen Wassermanagementszenarien.

Zunächst wurde eine statistische Analyse durchgeführt, um Trends bei Niederschlag und Abfluss während des Untersuchungszeitraums zu analysieren. Danach wurden eine Abflussdauer-Kurve und ein SPEI-Index berechnet, um die Abflussmuster und Dürreereignisse in der Region zu verstehen. Der potenzielle Wasserbedarf wurde quantifiziert, um das Wassernutzungsmuster abzubilden. Die Berechnung des Mindestdurchflussbedarfs wurde unter Anwendung des hydrodynamischen Modells MIKE 11 durchgeführt. Das Modell wurde für verschiedene Abflussdatensätze ausgeführt, um die Reaktion bezüglich der Salzkonzentration zu testen und dann zu definieren, wo die Salzkonzentration an ausgewählten Messpunkten unter den Schwellenwerten bleibt. Es wurden sechs verschiedene Szenarien entwickelt, um den Mindestdurchflussbedarf für die Änderung des potenziellen Wasserverbrauchs, des Anstiegs des Meeresspiegels und der Wassernutzungseffizienz vorherzusagen. Die Ergebnisse der sechs Szenarien wurden kartiert und zeigten das räumliche und zeitliche Ausmaß der Mindestströmungsanforderungen im Einzugsgebiet des Flusses Vu Gia - Thu Bon.

Im Allgemeinen ergab die Analyse der Niederschläge und des Abflusses stark ansteigende Tendenzen, die jedoch hauptsächlich in der Regenzeit zu beobachten waren. Andererseits zeigte der SPEI-Index einen Rückgang der Dürreereignisse in den Jahren nach 2000. Der jährliche potenzielle Bedarf des Vu Gia-Thu Bon-Deltas wurde mit 309 Mio. m^3 berechnet, wovon 203 Mio. m^3 auf die Landwirtschaft, 89 Mio. m^3 auf den häuslichen Gebrauch und nur 17 Mio. m^3 auf die Industrie entfallen. Die Analyse der relativen Wasserversorgung und der relativen Bewässerungsversorgung hat außerdem gezeigt, dass das Bewässerungssystem vor allem in den Monaten Februar bis Juni nicht in der Lage ist, ausreichend Wasser für die Kulturen zu liefern. Die Ergebnisse der sechs Szenarien wurden kartiert und zeigten das räumliche und zeitliche Ausmaß der Mindestströmungsanforderungen im Einzugsgebiet des Flusses Vu Gia - Thu Bon.

Die beschriebene Methodik umfasst Techniken, die es zu einem anwendbaren Ansatz machen, den Mindestdurchflussbedarf in einem anthropogen beeinflussten Flusseinzugsgebiet zu bestimmen. Diese Methode wurde im Einzugsgebiet des Flusses Vu Gia - Thu Bon erfolgreich getestet und kann auf ähnliche Einzugsgebiete hochgerechnet werden.

Tóm tắc

Hiện tượng dòng chảy kiệt là vấn đề đang được quan tâm vì nó ảnh hưởng nghiêm trọng đến các hoạt động kinh tế xã hội. Trong thời kỳ dòng chảy kiệt, nguồn nước của sông bị suy giảm nên không thể cung cấp đủ nước cho sản xuất cây trồng, sản xuất thủy điện và cấp nước đô thị, cũng như duy trì chất lượng nước do xâm nhập mặn. Do đó, xác định dòng chảy tối thiểu cần thiết trên các sông trong thời kỳ dòng chảy kiệt là nhu cầu quan trọng để giảm tác động của xâm nhập mặn và duy trì nguồn cung cấp nước bền vững cho các đối tượng sử dụng nước khác nhau như nông nghiệp, sinh hoạt và công nghiệp.

Lưu vực sông Vu Gia - Thu Bồn được chọn là khu vực nghiên cứu nằm ở ven biển miền Trung Việt Nam bị hạn hán trong mùa khô cùng với xâm nhập mặn do dòng chảy kiệt. Khu vực đã được phân tích về hiện tượng dòng chảy kiệt và tình hình hạn hán trong giai đoạn 1976 - 2014. Nghiên cứu này nhằm mục đích phát triển một phương pháp luận áp dụng chung để đánh giá dòng chảy tối thiểu cần thiết trên các con sông. Mục tiêu đạt được thông qua việc (1) phân tích hiện tượng dòng chảy kiệt và yêu cầu dòng chảy tối thiểu; (2) tính toán nhu cầu nước tiềm năng từ các hoạt động khác nhau; (3) đánh giá hoạt động của hệ thống thủy lợi hiện có liên quan đến khả năng cung cấp nước và nhu cầu nước; (4) xác định lưu lượng tối thiểu cần thiết trên các sông để ngăn mặn và đáp ứng nhu cầu nước từ các hoạt động khác nhau trong thời kỳ dòng chảy kiệt; và sau đó (5) đưa ra phương pháp luận có thể áp dụng chung để đánh giá các yêu cầu về dòng chảy tối thiểu trong các kịch bản quản lý nước đa ngành.

Đầu tiên, các phân tích thống kê được thực hiện để điều tra các xu hướng của lượng mưa và dòng chảy trong thời gian nghiên cứu. Sau đó, đường quá trình dòng chảy và chỉ số SPEI được tính toán để xem xét mô hình dòng chảy cũng như các hiện tượng hạn hán trong khu vực. Nhu cầu nước tiềm năng đã được tính toán cho lĩnh vực nông nghiệp cũng như mục đích sinh hoạt và công nghiệp để lập bản đồ mô hình sử dụng nước. Phương trình Penman - Monteith được áp dụng để tính toán khả năng bốc thoát nước sử dụng dữ liệu từ năm kiệt 2005. Sau đó, hiệu quả của hệ thống thủy lợi được đánh giá bằng cách phân tích hai chỉ số RWS và RIS. Cuối cùng, việc tính toán

yêu cầu dòng chảy tối thiểu được thực hiện bằng cách áp dụng mô hình thủy lực MIKE 11. Mô hình được chạy cho các bộ dữ liệu khác nhau để kiểm tra phản ứng của nồng độ muối, và sau đó xác định vị trí nồng độ muối còn dưới các giá trị ngưỡng tại các điểm khống chế. Sáu kịch bản khác nhau được phát triển để dự đoán yêu cầu dòng chảy tối thiểu đối với sự thay đổi trong việc sử dụng nước tiềm năng, mực nước biển dâng và hiệu quả sử dụng nước.

Nhìn chung, phân tích lượng mưa và dòng chảy cho thấy xu hướng gia tăng mạnh, tuy nhiên chủ yếu vào mùa mưa. Mặt khác, chỉ số SPEI cho thấy xu hướng giảm của các đợt hạn hán những năm sau 2000 trong suốt giai đoạn điều tra. Nhu cầu sử dụng nước tiềm năng hàng năm của VG-TB được tính là 309 triệu m^3, trong đó 203 triệu m^3 cho nông nghiệp, 89 triệu m^3 cho sinh hoạt và chỉ 17 triệu m^3 cho công nghiệp. Hơn nữa, việc phân tích hai chỉ số RWS và RIS cho thấy sự hạn chế của hệ thống thủy lợi trong việc cung cấp đủ nước cho cây trồng, đặc biệt là từ tháng Hai đến tháng Sáu. Cuối cùng, kết quả của sáu kịch bản được thiết lập thể hiện dòng chảy tối thiểu yêu cầu trên lưu vực sông Vu Gia - Thu Bồn.

Phương pháp được mô tả bao gồm các kỹ thuật hiện đại, trở thành một cách tiếp cận có thể áp dụng để xác định dòng chảy tối thiểu trong một lưu vực sông chịu tác động bởi con người. Phương pháp luận này đã được thử nghiệm thành công ở lưu vực sông Vu Gia - Thu Bồn và có thể áp dụng cho các lưu vực sông tương tự.

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Acronyms and abbreviations

%	Percent
°C	Degree Celsius
AMSL	Above mean sea-level
cm	Centimetre
DARD	Department of Agricultural and Rural Development
DPI	Department of Planning and Investment
ET	Evapotranspiration
FAO	Food and Agriculture Organization
FDC	Flow Duration Curve
GHG	Greenhouse gas
GWh	Gigawatt hours
ha	Hectare
IPCC	Inter-government Panel on Climate Change
IMHEN	The Institute of Meteorology, Hydrology and Climate Change
IMC	Irrigation Management Company
IMS	Irrigation Management Schemes
ITT	The Institute of Technology and Resources Management in the Tropics and Subtropics, TH Köln
LUCCi	Land Use and Climate Change Interactions in Central Vietnam Project
LFFC	Low Flow Frequency Curve
m	Meter
m^2	Square meter

m^3	Cubic meter
MARD	Ministry of Agricultural and Rural Development, Viet Nam
MONRE	Ministry of Natural Resources and Environment, Viet Nam
MOC	Ministry of Construction, Viet Nam
MOIT	Ministry of Industry and Trade, Viet Nam
MW	Megawatt
NSE	Nash Sutcliffe model Efficiency coefficient
RCHM	Regional Centre for Hydro-Meteorological
RIS	Relative Irrigation Supply
RMSE	Root Means Squared Error
RWS	Relative Water Supply
RCPs	Representative Concentration Pathways
UNEP	United Nations Environment Programme
VAWR	Vietnam Academy of Water Resources
VG-TB	Vu Gia –Thu Bon
WDC	Water Delivery Capacity
WMO	World Meteorological Organization
WTP	Water Treatment Plant

1 Introduction

1.1 Background

Global supplies of freshwater are strongly under pressure with at least one third of the world's population living in areas with acute water shortages and 1.1 billion people lacking access to safe drinking water (Hess *et al*., 2015). Increasing population results in an increasing demand for freshwater supply, which in turn affects freshwater drawn from surface water bodies, which also has long-term consequences for ecosystem functions (Montagna *et al*., 2002). Additionally, urbanization and the increasing population density results in overexploitation of water resources and places pressure on water availability causing water scarcity. This situation is further being compounded by low flows, which affect both surface water and ground water resources (Belal *et al*., 2012). Climate change induced hydro-climatic extremes and sea level rise are also expected to aggravate the low flow phenomenon in many coastal regions worldwide. This particularly is the case in the Vietnamese coastal regions (IMHEN, 2012; IPCC, 2013). Here, due to the variety of direct or indirect anthropogenic impacts on stream-flow in river catchments, the flow regimes of many rivers have been significantly modified and the availability of water in a stream during low-flow periods has been changed (Smakhtin, 2001a). Low-flow periods severely impact socio-economic activities, as diminished freshwater resources of rivers are unable to provide adequate water for crop production, hydropower generation and urban water supply, as well as to maintain water quality of freshwater bodies due to saltwater intrusion. To compound matters, water quality has also been declining rapidly because of the increasing discharge of untreated domestic and industrial wastewater, irrigation return flow, and non-point-source pollution (Pringle and Scatena, 1999; Scatena, 2004). This is more apparent in low-flow periods when the assimilative capacity of the river decreases (Liu *et al*., 2005) and leads to a reduction of freshwater availability in the rivers.

Minimum flow in rivers and streams aims to provide a certain level of protection for the ecosystem functions (Liu *et al*., 2005). It refers to the water considered sufficient for protecting the structure and function of an ecosystem and its dependent species (Elhatip *et al*., 2014). Moreover, minimum flow in rivers during low flow periods becomes an important requirement for ecosystem restoration, and multi-sectorial water resource management (Arthington *et al*., 2006; Acreman *et al*., 2014). Accordingly, releasing minimum inflow can reduce the impact of saltwater intrusion and maintain a sustainable water supply for different water users such as agriculture, domestic and industries downstream during low flow seasons.

1.2 Problem statement

The delta of a river basin represents a transitional environment where land combines with rivers and the sea (Costanza *et al*., 1993). These systems present a continuum along the fresh-brackish-salt water gradient, serving as one of the most productive natural habitats (Costanza *et al*., 1993). The dominant features of ecosystems in a delta of a river basin are their salinity variance, which is governed by physical processes such as tides and inland freshwater inflow. Therefore, these ecosystems are very sensitive to changes induced by both human activities and natural dynamics such as urbanization, physical alterations of the estuarine systems, and nutrient enrichment (Alber, 2002; Rozas and Hackney, 1984; Wan *et al*., 2014). Climate change has induced global mean sea level rise at a rate of 1–2 mm per year since 1900 with an apparent change in rate to 3 mm year during the past 30 years (IPCC, 2013). Increases in sea levels is consequently induces an increase in salinity by bringing more saltwater into the delta, as well as have an influence on water quality (Ross *et al*., 2015). Upstream changes in rivers can also have pronounced effects on the downstream into which they discharge. Construction of dams, diversion of fresh water, and groundwater withdrawals lower the amount of fresh water, an important factor in estuarine productivity (Day *et al*., 1989). The scientific community has tried to answer the question of how much freshwater a river needs since the mid-1970s, resulting in the development of several methodologies and approaches in different parts of the world (Mattson, 2002; Alber, 2002; Annear *et al*., 2004; Peñas *et al*., 2013). However, the ability to reproduce most of these approaches is difficult due to the scarcity of required data, and also to the large differences between the studied regions.

1.3 Research demand

Due to the topographic features and hydrological regime, the Vu Gia – Thu Bon (VG-TB) river basin which is located in Central Viet Nam frequently experiences floods during the rainy season and droughts in the dry season. With the dense human-intervention structures, wide-scale paddy rice cultivation downstream and the strong development of hydropower in upstream, the VG-TB river basin represents a characteristic region in South East Asia for studies on multi-sectorial water resources management and climate change impacts. Sea level is expected to rise up to 54 cm until 2100 (MONRE, 2016). Scenarios need to be developed considering such future changes in the region. Recently, most research has been focussing on flood risks assessment and management. After the development of hydropower in the past few years, studies on reservoir operation, impacts and institutional analysis have been initiated. Besides, defining minimum flow requirements to maintain the ecosystem and different activities downstream has become a critical issue in global water resource management (Alber, 2002). The recent study on "Estimating the impact of climate change induced saltwater intrusion on agriculture in estuaries - the case of Vu Gia - Thu Bon" proposes the required minimal river flow as a measure for mitigation of saltwater intrusion and it states that further research is required to investigate the overall influences of the proposed measure to natural and human environment of the region (Viet, 2014). In addition, worldwide delta zones like the VG-TB river basin are facing a potential threat from saltwater intrusion combined with low river discharge.

Even though a number of methodologies have been developed to assess minimum flow requirement in rivers, Tharme and Smakhtin (2003) observed that regardless of type of method used, all of them have been designed and/or applied in a developed country context. Therefore, there are clear gaps in minimum flow knowledge and practice in most of the developing countries, which lack both technical and institutional capacity (Gopal, 2013). In addition, Adams (2014) believed that the minimum flow requirements have typically been ignored, owing primarily to the lack of long-term monitoring data or incomplete understanding of responses to changes in freshwater inflow. To sum up, little attention has been given to minimum flow requirement in the context of developing countries where are seriously impacted by rapid socio-economic transformation.

The delta of a river basin is more complex than other environments. In the delta zone, freshwater from rivers and saltwater from the sea interact. So far, no systematic model has been developed in order to fully analyze and assess minimum flow requirements in the delta zone under multi-sectorial water management conditions, especially in developing countries, which are seriously impacted by rapid development and anthropogenic factors. Hence, the proposed research is needed to fill this gap.

1.4 Research questions

In this context, the following research questions are raised:

- Can the VG-TB river basin and its current irrigation system meet the agricultural water demand during low flow conditions?
- How much water is needed during low flow season to meet the demands of the different water users within the VG-TB river basin?
- What is an appropriate approach to determine the minimum flow requirement during the low flow season for an anthropogenically impacted river basin such as the VG-TB river basin?

In order to address these questions, the following objectives are defined in the subsequent section.

1.5 Research objectives

The main objective of this research is to develop an applicable methodology to assess the minimum flow requirements in the VG-TB river basin. The following specific objectives are to be achieved in fulfilment of the main objective:

- To describe and understand the low flow phenomenon and minimum flow requirements in the VG-TB river basin.
- To quantify the potential water demand from the different activities in the delta of the VG-TB river basin.
- To assess the performance of the irrigation system in the delta of the VG-TB river basin regarding irrigation water supply availability and water demand.
- To determine the required minimum flow in the Vu Gia and Thu Bon Rivers needed to mitigate and push back the salt intrusion and satisfy the water demands from different activities and sectors during low flow period.
- To derive a generally applicable methodology to assess the minimum flow requirements in multi-sectorial water management scenarios.

1.6 Overall methodology

Figure 1.1 presents the flow chart of the applied methodology. The details of individual applied methods will be discussed in the following Chapters.

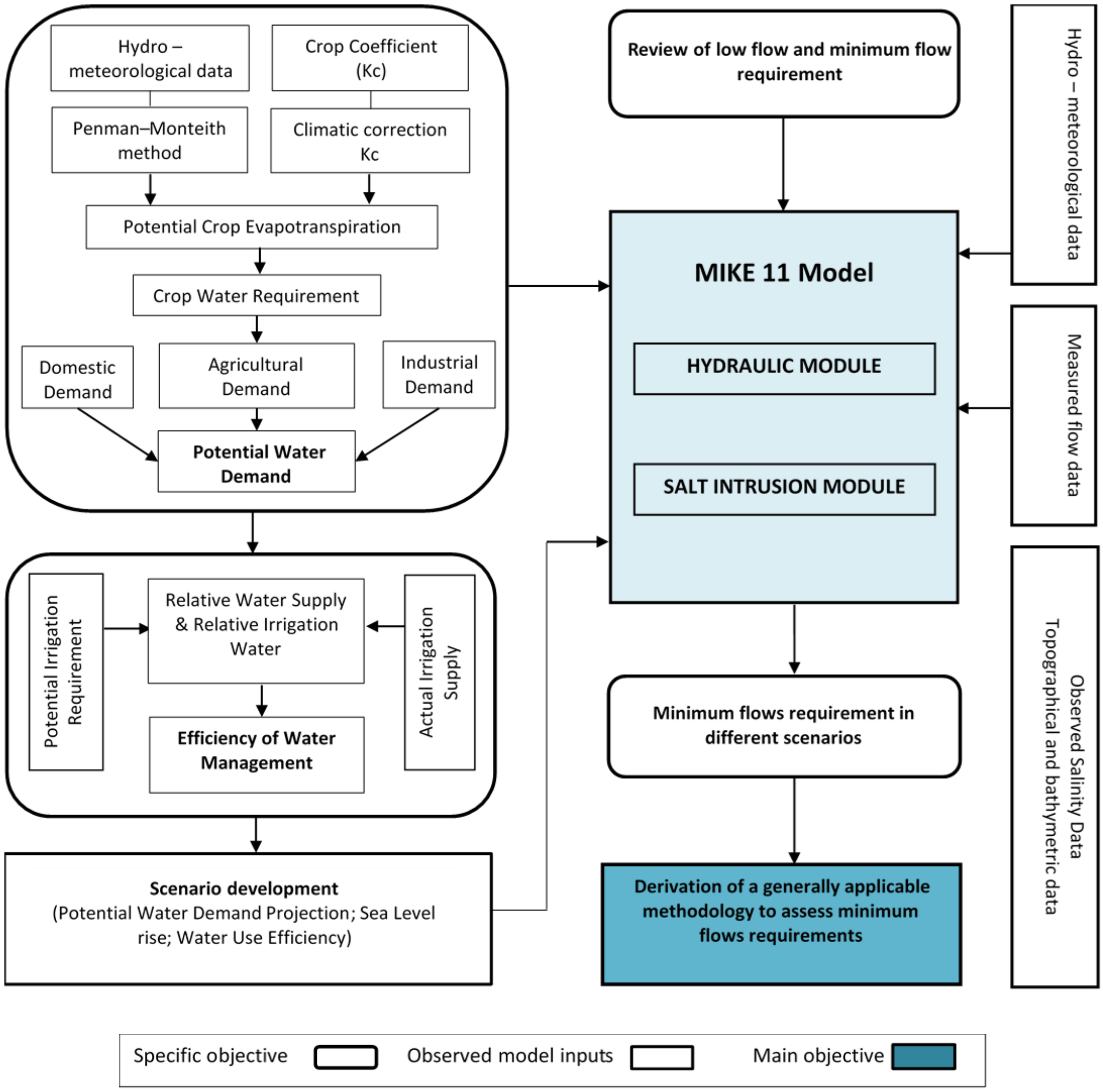


Figure 1. 1 Flow chart of the applied research methodology

A set of methods and techniques are applied to achieve the research objectives. A general description of applied methods is presented as follows:

- *To understand the low flow phenomenon and minimum flow requirement in the VG-TB river basin*

The background knowledge of low flow phenomenon and minimum flow requirement in the VG-TB river basin was revealed by undertaking an in-depth literature review on low flow phenomenon and minimum flow definition.

- *To quantify the potential water demand from the different activities in the delta of the VG-TB River Basin*

The potential water demand from different activities in the lowland of the VG-TB river basin is quantified for paddy rice and annual crops for the two annual growing seasons winter – spring and summer – autumn. The Penman – Monteith equation is applied to calculate the potential evapotranspiration using data from the dry year 2005. Crop coefficients (K_c) which are suggested by FAO 24 with climatic correction for the region are applied in this study (Doorenbos, J. & Pruitt, W. O., 1977). Due to the limits of data in this region, the domestic and service water requirements as well as industrial water requirement are calculated with per capita demand. In this study, the capita demand (m^3/person/day) for domestic, and (m^3/ha/day) for industrial uses refer to the Vietnamese standards on code of basic requirements for water supply, drainage and sanitation which was issued by the Ministry of Construction.

- *To assess the performance of irrigation system regarding water supply availability and demand*

The study considers two indicators, namely (i) Relative Water Supply and (ii) Relative Irrigation Supply to assess the performance of irrigation system regarding water supply availability and water demand.

- *To determine the minimum flow in the Vu Gia and the Thu Bon Rivers required to mitigate salt intrusion and satisfy the water demand from different activities*

The minimum flow requirements in this study are assessed under different scenarios using the hydrodynamic model MIKE 11. The MIKE 11 model includes two main modules. While the hydraulic module is applied to simulate the flows in the rivers, the advection - dispersion module is applied to simulate the salt concentration in the rivers. The minimum flow is determined firstly to control the salt concentration under the threshold at different control points and then satisfy the water demand of different activities in the delta of the basin.

- *Derive a generally applicable methodology to assess minimum flow requirements in multi-sectorial water management scenarios*

The applied techniques to fullfill the above specific objectives are framed to derive a generally applicable methodology to assess minimum flow requirements in multi-sectorial water management scenarios in the VG – TB river basin.

1.7 Structure of this dissertation

This dissertation is framed around the need to provide comprehensive and meaningful policy-relevant information on minimum flow requirements. Furthermore, the dissertation is an effort to better describe the methodology and decision support systems applicable for the given watersheds and data availability to determine of required minimum flow. The dissertation is structured into eight chapters. Each chapter discusses a specific objective as outlined above. Together these chapters form a coherent dissertation.

Chapter 1 introduces the scope of the research and the topic. The problem statement and research demand are presented to explain the gap of determining the required minimum flow in the region. The objectives and applied overall methodology to achieve the research objectives are also addressed. At the end of the chapter is the structure of the dissertation section which briefly describes the aims of each chapter.

The VG-TB river basin is selected to demonstrate the robustness of the methodology for defining the minimum flow requirements. **Chapter 2** presents the description of the study area and its hydrological and meteorological characteristics. As a background for the research activities, the suitable features of the research site are investigated and analyzed. The chapter provides the necessary information for the following investigations. In addition, the available data for the study analysis is also addressed.

Chapter 3 places emphasis on the observed low flow phenomenon in the VG-TB river basin. The first section reviews the general knowledge of low flow phenomenon regarding the overview and definition and the minimum flow requirement. The second part provide the background to understand the low flow phenomenon in the study region by analyzing the flow and precipitation data for the period 1976 – 2014. The flow duration curve and SPEI index are calculated to examine exceedance probability of flow magnitudes and the drought situation in the region.

Chapter 4 focuses on the quantification of potential water demand in the delta of the VG-TB river basin. Details of approaches to quantify potential water demand are also addressed in this chapter. The quantification considers the water demands for the agricultural sector, domestic, and industrial supply. The dry year of 2005 is selected to calculate the potential water demand to better understand the water demand when water demand increases, while there is a high probability of supply reductions. The results are analyzed to map the water utilization pattern and support wider water planning in the region. The quantification of potential water demand also sets the foundation for future analysis of the irrigation system performance and the determination of minimum flow requirements in the lowland of the VG-TB river basin.

Chapter 5 focuses on assessing the performance of the traditional irrigation practice in the low land of the VG-TB river basin. In this chapter, a review of assessing the performance of the irrigation system is provided. This was done in order to select an appropriate set of indicators. These indicator values are analyzed to understand the relation between the water demand and the water supply, currently under the stress of scarcity and conflict in the VG-TB river basin. Recommendations for improved water resource management are also given.

Chapter 6 concentrates on modelling the minimum flow requirements in the VG-TB river basin. The chapter begins with an overview of general methodology to assess the minimum flow requirement. The method to determine the minimum flow requirement in this research is also presented in detail. The chapter applies the results from chapter 4 as an input for the model simulation.

Chapter 7 describes the scenario development to assess minimum flow requirements under different boundary conditions. The chapter begins with an overview as well as general guidelines for scenario development. Then the key driving factors are identified and discussed to determine the spatial and temporal scales of the scenarios. Finally, a set of scenarios are constructed, and the results are presented. The goal of this chapter is to predict potential changes of minimum flow requirement under current and future conditions based on climate and development scenarios until 2050 and 2100.

Summary and conclusions of the current research are provided in **Chapter 8**. The advances and remaining shortcomings of the research are also addressed. The chapter frames the research with combined conclusions as well as suggestions for further research directions in the future.

2 Study area

This chapter introduces the study area of the VG-TB river basin. Detailed descriptions of the area in regard to its hydrological and meteorological characteristics, as well as important features such as hydropower development, agricultural practices and industrial services are presented. Furthermore, the collected data used for the analysis in this study are also addressed in this chapter.

2.1 Overview of the study area

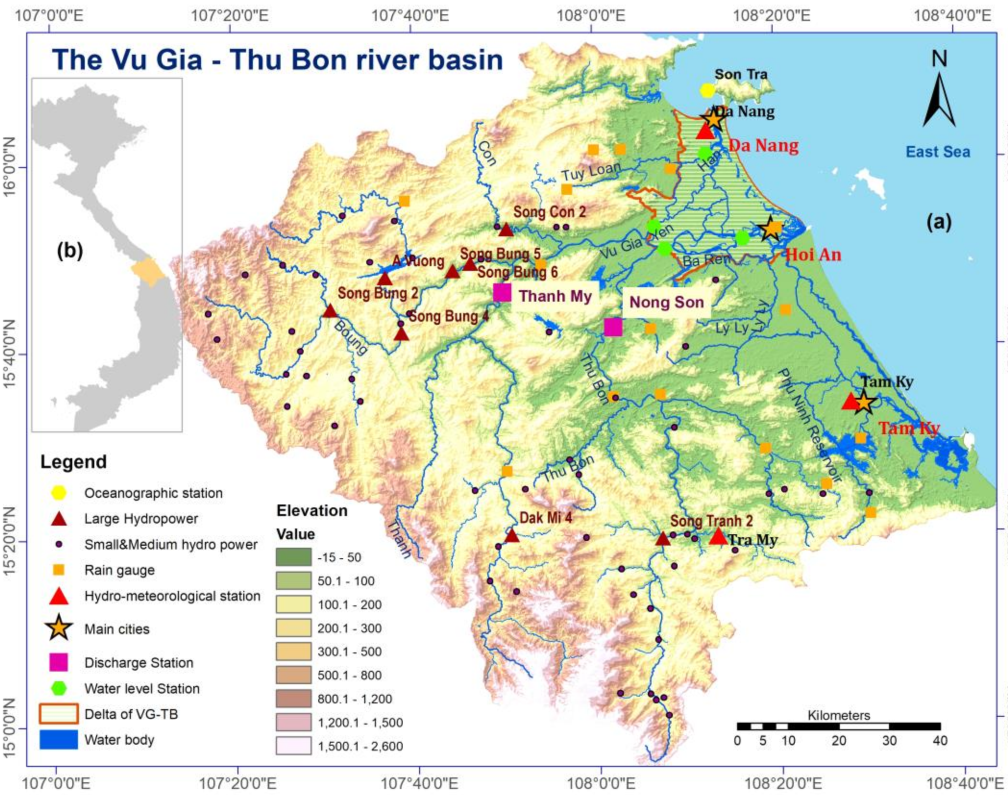


Figure 2. 1 (a) The VG-TB River Basin; (b) Location of the VG-TB River Basin in Viet Nam. Source data: MONRE; IMHEN

The VG-TB river basin is a coastal area in Central Viet Nam **(Figure 2.1)**. It is influenced by many natural and social factors, creating a diverse socio-economic region including agriculture, forestry, small industry and tourist services. It is the fifth largest river basin in Viet Nam (MARD, 2010). The river basin consists of two main rivers, the Vu Gia and the Thu Bon Rivers. Both rivers originate in the high mountains on the east side of the Truong Son Mountain Range and end at East Sea through the Han (Vu Gia River) and Dai (Thu Bon River) river mouths.

The total catchment area of the river basin is about 10,350 km^2, extending from the Truong Son Mountain Ranges to the coast, precisely at 14°54’ to 16°13’ latitude North and 107°12’ to 108°44’ longitude East. The VG-TB river basin mainly covers Quang Nam Province, Da Nang City, and a very small piece of Quang Ngai and Kon Tum Provinces. The natural topography can be classified into three landscapes namely highland, midland and lowland. The highland area characteristically shows steep sloping topography with an elevation reaching up to 2600 m, while the midland displays lower hills with elevation ranging from 150 m to 1000 m. The lowland is the coastal area with the elevation mostly under 25 m above mean sea-level (AMSL).

The highland part of the river system covers part of Quang Nam Province including Tay Giang, Nam Giang, Phuoc Son and Nam Tra My District (see location of the districts in map C – 8 **Appendix C**). In this part of the catchment, with steep topography and narrow riverbeds, streams and rivers exhibit short flow and retention times. The highest vegetation coverage is found in this area; however, agricultural cultivation is rare due to the characteristics of topography (DONRE, 2012).

The midland extends over major parts of Quang Nam Province including the Dong Giang, Nam Giang, a part of Dai Loc, Nong Son, Hiep Duc and Bac Tra My District (see location of the districts in map C – 8 **Appendix C**). This area is characterized by a large amount of hydropower plants, reservoirs and dams since the riverbed is steep and the topography is quite accommodating for the operation of these activities. Rice along with production forests, mainly Acacia mangium and Acacia auriculiformis, are representative of for the agricultural cultivation undertaken of this area (DONRE, 2012).

The lowland area of the basin stretches down to the coast of Da Nang City, as well as, some districts of Quang Nam Province including Dien Ban, Hoi An, Duy Xuyen, Dai Loc, Thang Binh, Phu Ninh, and Tam Ky (see location of the districts in map C – 8 **Appendix C**). The riverbeds are shallow in this area causing a relatively slower flow time and a higher retention time in comparison to the highland section. In this area, paddy rice is the dominant crop grown, utilizing traditional irrigation practices and a complex canal network. Maize and peanut are also widely cultivated. The lowland segment displays the highest population densities of the basin, with most people concentrated in the urban centres of Da Nang City, Hoi An and Tam Ky. The coastline consists of sandy beaches that are used for tourist services (DONRE, 2012).

In general, the VG-TB river basin displays a tropical monsoon climate. Despite the high total annual rainfall in the region, it is not evenly distributed temporally and spatially. While the northern part of the river basin has an average annual rainfall of less than 2000 mm, the southwest parts, where the upper reach of the Thu Bon River is located, receives relatively high rainfall amounts of up to 4000 mm annually. The overall features of the basin are summarized in **Table 2.1** below:

Table 2. 1 Overview of the main features of the VG-TB River Basin. Source data: Quang Nam Statistical yearbook; IMHEN

Location	Central Viet Nam (Quang Nam, Da Nang, and part of Quang Ngai and Kon Tum)
Catchment	10,350 km^2
Coordination	14°54’N -16°13’N 107°12’E -108°44’E
Main river	Thu Bon (205 km) and Vu Gia (145 km)
Source	Ngoc Linh mount (for Thu Bon); Mang mount (for Vu Gia)
Outlet	East Sea (through the river mouths of Han for Vu Gia River and Dai for Thu Bon River)
Highest point	Mount Ngoc Linh (2598 m)
Lowest point	Dai River mouth (-0.7 m)
Geology	Granite, Conglomerate, Limestone, Sandstone
Soil types	Ferrosol, Fluvisol, Acrenosol
Population	Approximately 3 million inhabitants (2019)
Urban centers	Da Nang, Hoi An, Tam Ky
Cultivated area	Total 82,000 ha (2006)
Land uses	47% forest land, 20% grassland, 26% cropland, 4.5% settlement lands (2010), 2.5% water.

2.2 The Vu Gia – Thu Bon Delta

The VG-TB Delta spans the lowland section of the basin from Ai Nghia and Giao Thuy to the Han and Dai river mouths **(Figure 2.2).** This delta area of the basin covers an area of about 1000 km^2. Here also an exchange of flows between the two rivers occurs. Right beyond Ai Nghia and Giao Thuy reaches, the Quang Hue River diverts part of the flow from the Vu Gia into the Thu Bon via the Quang Hue cross-connection. Further downstream, the Vinh Dien River returns part of the water from the Thu Bon back to the Vu Gia (Viet, 2014). Even though the delta accounts for less than 10% of the total area of the basin, 75% of the total overall basin population resides in this area (Firoz *et al*., 2018).

Industries and services have developed rapidly in recent years. However, agriculture still plays an important role in socio-economic welfare of the region (Pedroso *et al*., 2017). Half of the delta continues to be used for cultivation with traditional irrigation practices (Viet, 2014). There are about 120 pumping stations installed along the rivers to extract water to meet irrigation needs. The cultivated area can be categorized into 13 Irrigation Management Schemes (IMS) according to administrative management such as pumping station and irrigation canal sections, but not limited to their physical properties. Each IMS includes pumping stations, irrigation canal networks, drainage canals, and regulatory structures.

Paddy rice is the regions dominant crop accounting for 70% of the total cultivated area with two harvests per year, followed by maize and peanut. The first cultivation season winter – spring starts from the middle of December to the middle of April. The second season summer – autumn extends from the middle of May to the middle of September. In fact, the planting date can differ by a few days from scheme to scheme. During the period October-November, the peak of the rainy season, no or very limited cultivation takes place. For annual crops, the growing season sometimes starts one or two weeks earlier than paddy rice in the first crop season winter - spring. Arenosol and Fluvisol are the main soil types found in the delta.

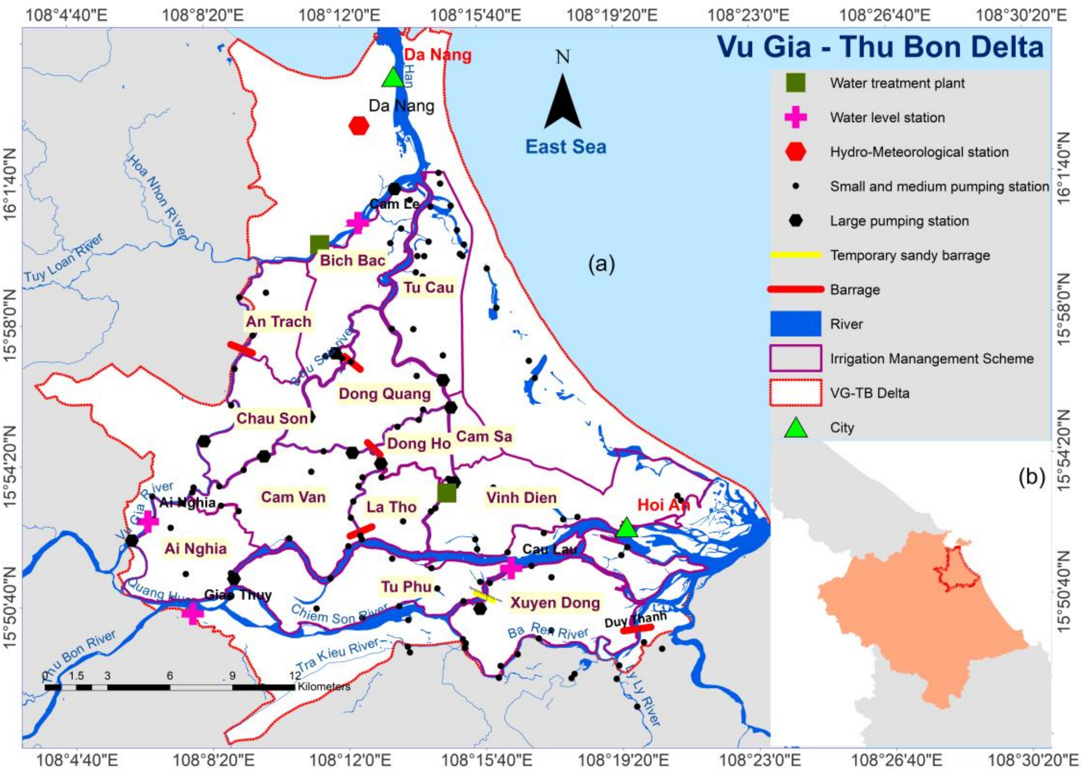


Figure 2. 2 (a) The VG-TB Delta; (b) Wider location of the VG-TB Delta. Source data: MONRE; IMHEN; IMC

2.3 Analysis of the Vu Gia – Thu Bon river basin

2.3.1 Hydro-meteorological characteristics

a. Meteorological features

The VG-TB river basin is a coastal area in Central Viet Nam formed by two main rivers the Vu Gia River and the Thu Bon River. The mean annual discharge of the Thu Bon River is 320 m^3/s (at Nong Son station in upstream of the Thu Bon River, see location at **Figure 2.1**), however it has strong seasonal variability **(Figure 2.3)**. The average discharge is about 615 m^3/s during the rainy seasons (September – December) but decreases significantly to an average of 99 m^3/s during the dry seasons (January – August). Furthermore, the Vu Gia River has a lower annual discharge than the Thu Bon River with 149 m^3/s (recorded at Thanh My station in upstream of the Vu Gia River, see location at **Figure 2.1**). Its average discharges during the rainy season and dry season of Vu Gia River are also lower than the Thu

Bon River with 270 m^3/s and 55 m^3/s respectively. The peak flow occurs in November with 1013 m^3/s at Nong Son and 385 m^3/s at Thanh My gauging station. The Vu Gia has the specific discharge 0.069 $m^3/s/km^2$ versus the 0.089 $m^3/s/km^2$ observed at the Thu Bon. More detailed of hydro-meteorological analysis can be found in the following chapter.

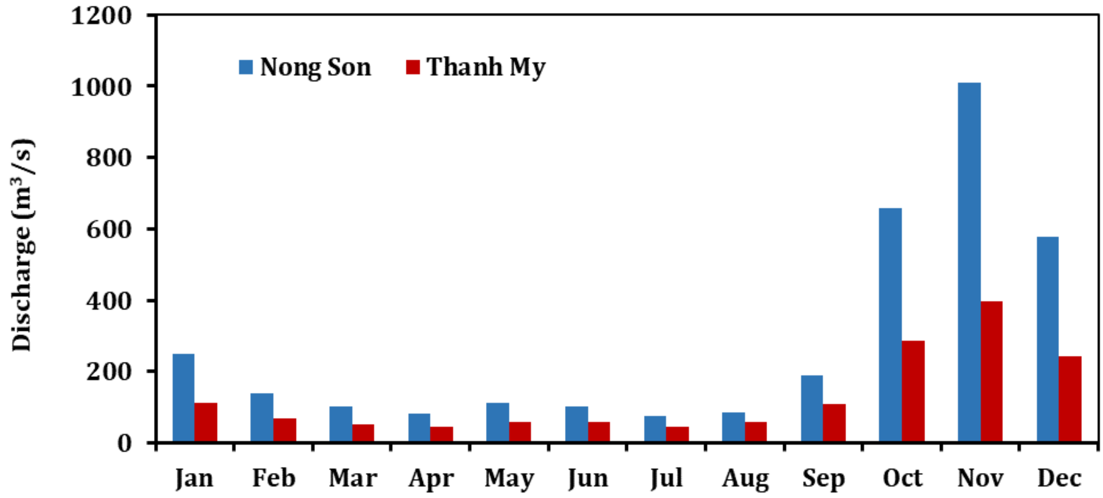


Figure 2. 3 The monthly mean flow and at the gauging stations Thanh My (Vu Gia River) and Nong Son (Thu Bon River) for the period of 1976-2014. Source data: observed data provided by IMHEN

Due to orographic effects, precipitation varies significantly with topography. It is characterized by high total annual precipitation with an average of 2400 mm. The coastal plains receive less than 2000 mm whereas the mountainous areas get up to 4000 mm per year. The precipitation is not evenly distributed temporally. The rainy season only lasts 3-4 months (September – December) providing 70 – 80% of the total annual precipitation, while the dry season lasts 8-9 months (January – August) but receives only 20 – 30% of the total annual average precipitation. The extended dry season of 8 months per year is usually accompanied by severe drought, whereas flooding is always experienced during the rainy season (Nauditt & Ribbe., 2017).

Additionally, the low flow occurring during the dry season frequently causes saltwater intrusion, increasing water demand and tidal penetration. A secondary rainfall peak occurs in May or June during the dry season due to the Inter-Tropical Convergence Zone. This is characterized by heavy rain or so-called Tieu Man flood. It usually occurs in the north western part of the region (see **Figure 2.4** – at Tra My station). The annual precipitation data of different stations in the delta region is presented in **Figure 2.5**.

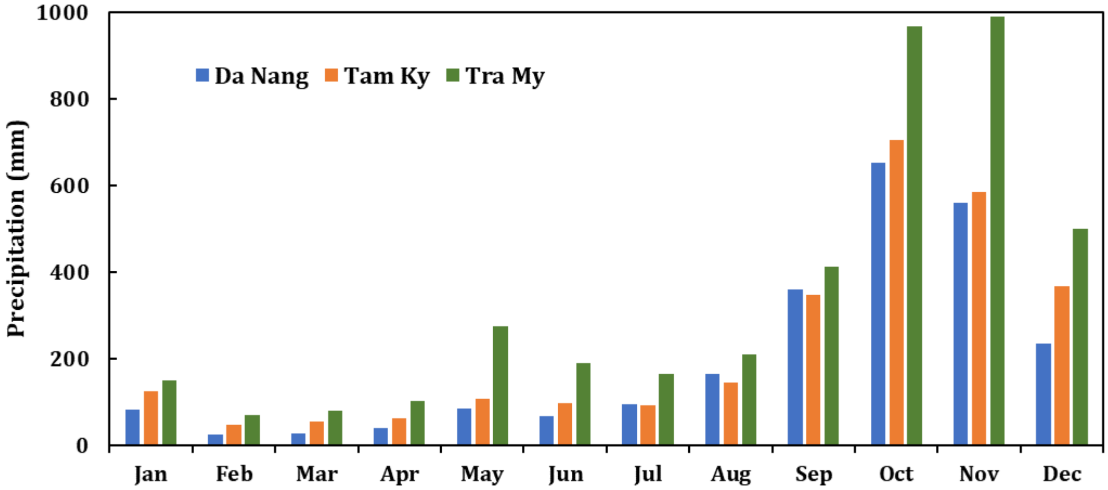


Figure 2. 4 Monthly mean precipitation period 1979 – 2014 at three hydro-meteorological stations Tam Ky (South), Da Nang (North) are located at the coast and Tra My (South) in the highlands. Locations of these hydro-meteorological stations can be found in Figure 2.1. Source data: observed data provided by IMHEN

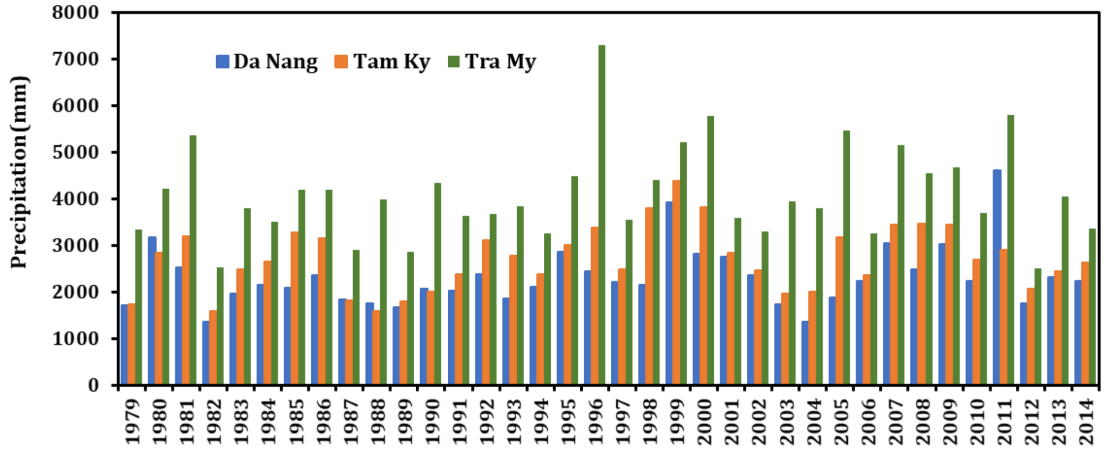


Figure 2. 5 Annual precipitation for the period 1979 – 2014 at three hydro-meteorological stations Tam Ky (South), Da Nang (North) are located at the coast and Tra My (South) in the highlands. Locations of these hydro-meteorological stations can be found in Figure 2.1 Source data: observed data provided by IMHEN

Analyzing data from the 3 hydro-meteorological stations Da Nang, Tam Ky, and Tra My revealed that annual precipitation is higher than annual potential pan evaporation (Class A) rates generating a wet and humid climate in the region **(Figure 2.6, Figure 2.7 and Figure 2.8)**. However, the potential evaporation rate is usually higher than precipitation during the dry season which was found at Da Nang, Tam Ky and Tra My, resulting in deficits in the water supply and decreased inflow.

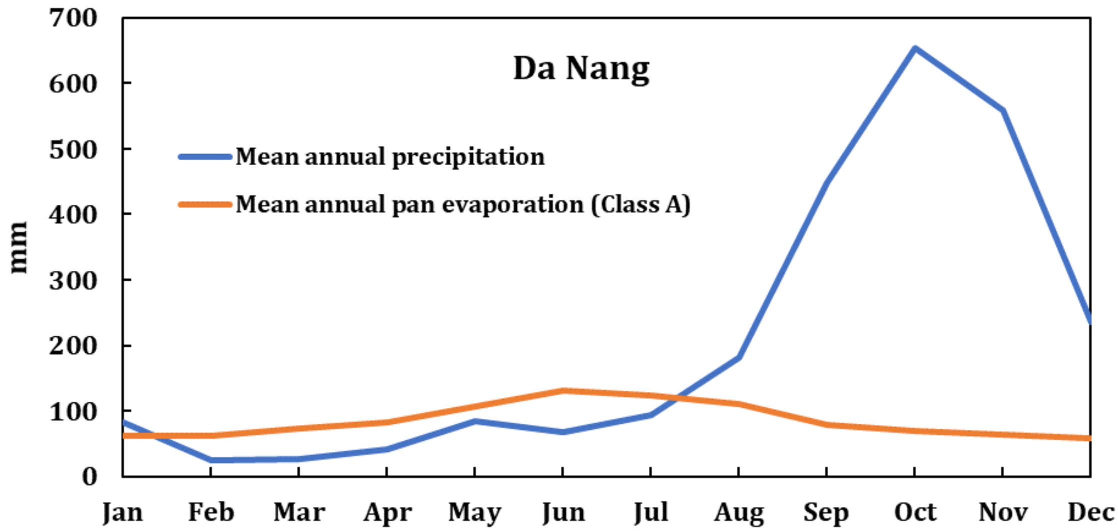


Figure 2. 6 Mean monthly precipitation and evaporation (1979-2010) in the VG-TB River Basin. Notice that the mean evaporation rate is higher than the mean precipitation during the period between January and August in Da Nang hydro-meteorological stations. Source data: observed data provided by IMHEN

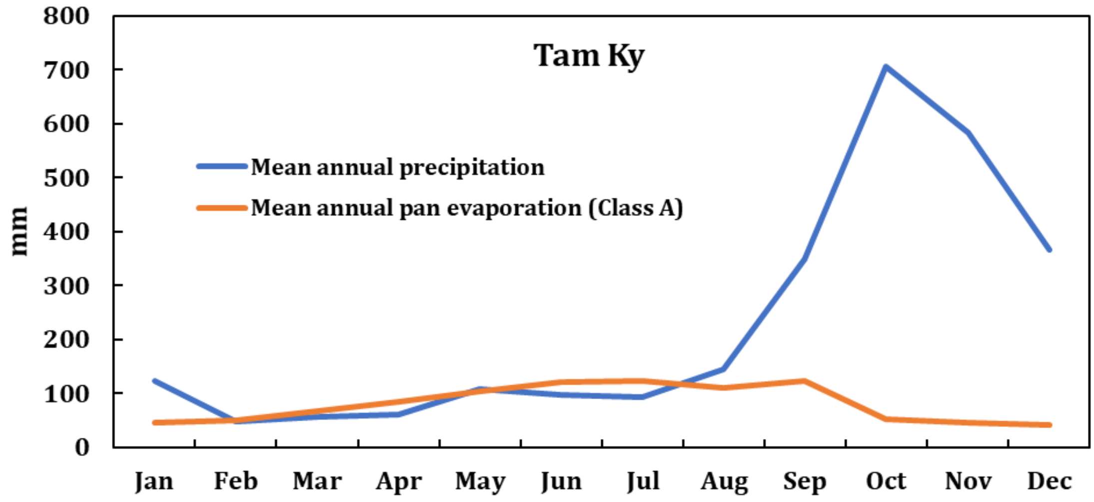


Figure 2. 7 Mean monthly precipitation and evaporation (1979-2010) in the VG-TB River Basin. Notice that the mean evaporation rate is higher than the mean precipitation during the period between January and August in Tam Ky hydro-meteorological stations. Source data: observed data provided by IMHEN

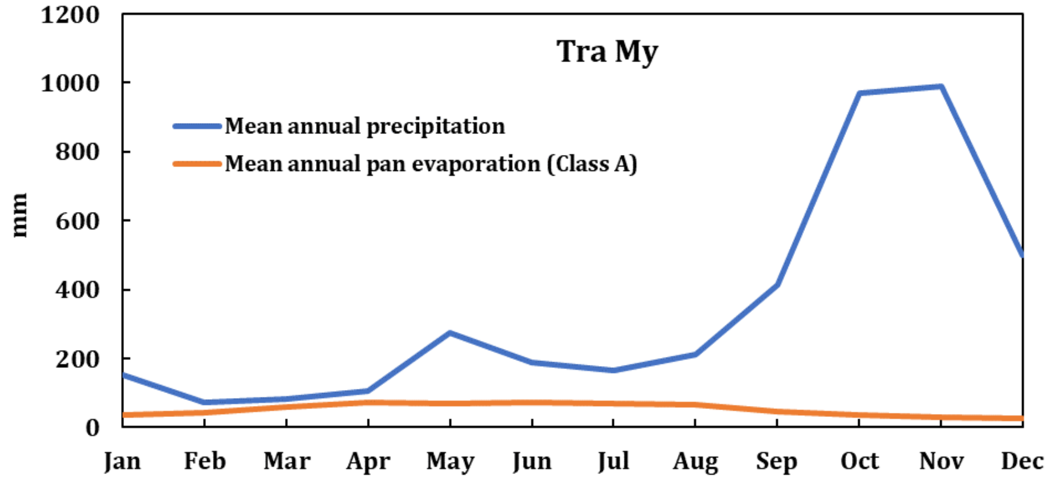


Figure 2. 8 Mean monthly precipitation and evaporation (1979-2010) in the VG-TB River Basin, at Tra My hydro-meteorological stations. Source data: observed data provided by IMHEN

Other meteorological features of the region including temperature, humidity, sunshine, wind speed and evaporation rate are presented in **Figure 2.9** to **Figure 2.13.**

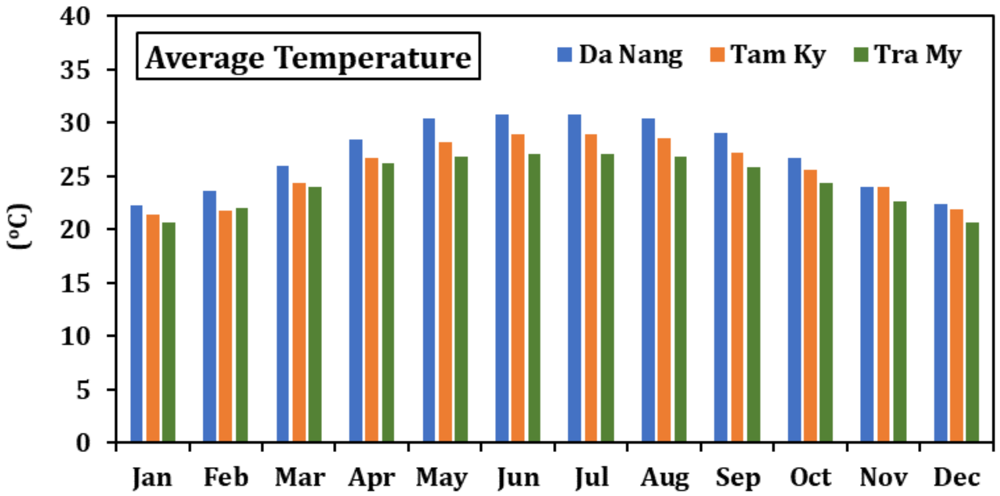


Figure 2. 9 Mean monthly temperature in the VG-TB River Basin from 1979 – 2010 at Da Nang, Tam Ky and Tra My. The Da Nang and Tam Ky Meteorological stations are presented for coastal plain at North and South respectively, while Tra My Meteorological station is presented for mountainous area. Locations of these hydro-meteorological stations can be found in Figure 2.1. Source data: observed data provided by IMHEN

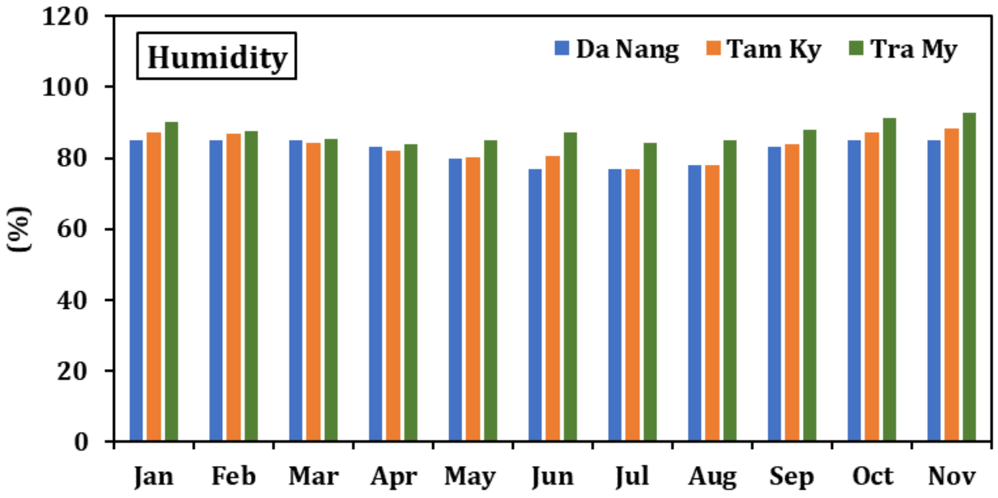


Figure 2. 10 Mean monthly humidity in the VG-TB River Basin from 1979 – 2010 at Da Nang, Tam Ky and Tra My. The Da Nang and Tam Ky Meteorological stations are presented for coastal plain at North and South respectively, while Tra My Meteorological station is presented for mountainous area. Locations of these hydro-meteorological stations can be found in Figure 2.1. Source data: observed data provided by IMHEN

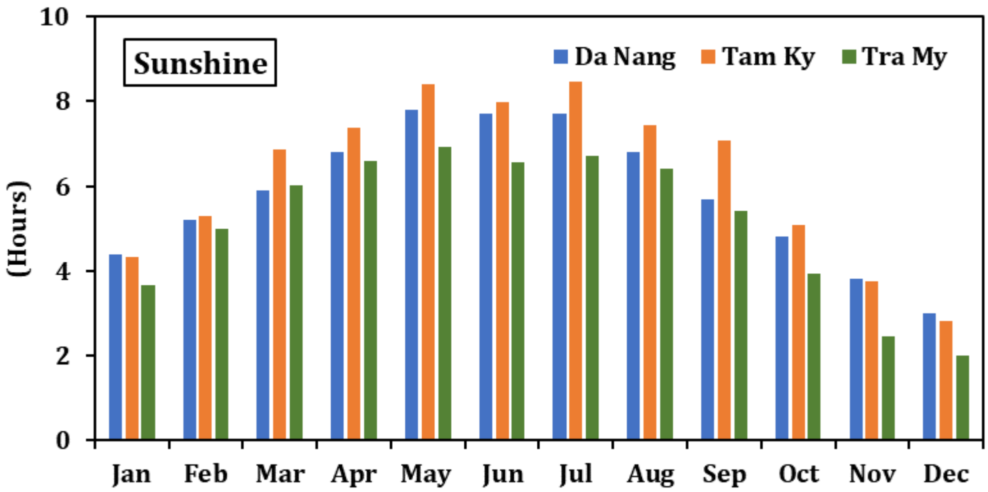


Figure 2. 11 Mean monthly sunshine in the VG-TB River Basin from 1979 – 2010 at Da Nang, Tam Ky and Tra My. The Da Nang and Tam Ky Meteorological stations are presented for coastal plain at North and South respectively, while Tra My Meteorological station is presented for mountainous area. Locations of these hydro-meteorological stations can be found in Figure 2.1. Source data: observed data provided by IMHEN

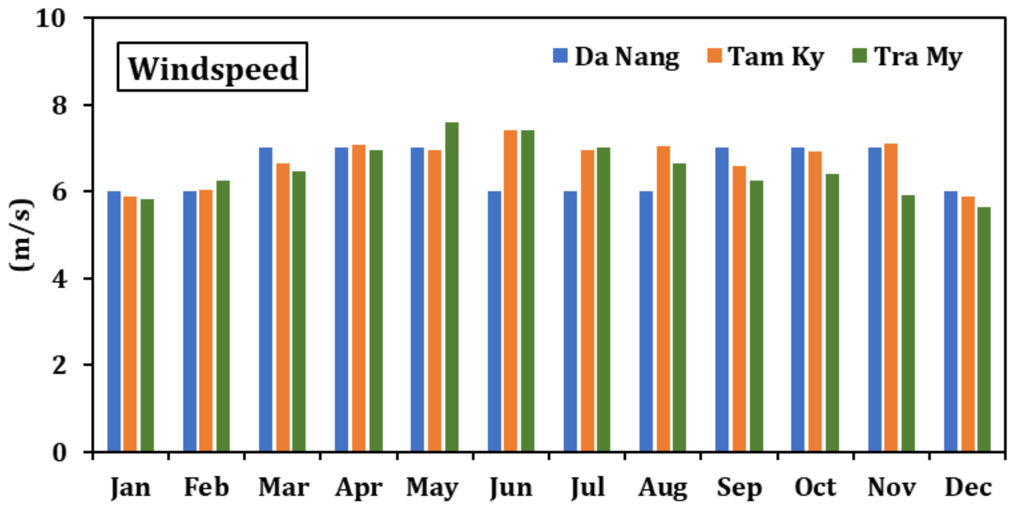


Figure 2. 12 Mean monthly windspeed in the VG-TB River Basin from 1979 – 2010 at Da Nang, Tam Ky and Tra My. The Da Nang and Tam Ky Meteorological stations are presented for coastal plain at North and South respectively, while Tra My Meteorological station is presented for mountainous area. Locations of these hydro-meteorological stations can be found in Figure 2.1. Source data: observed data provided by IMHEN

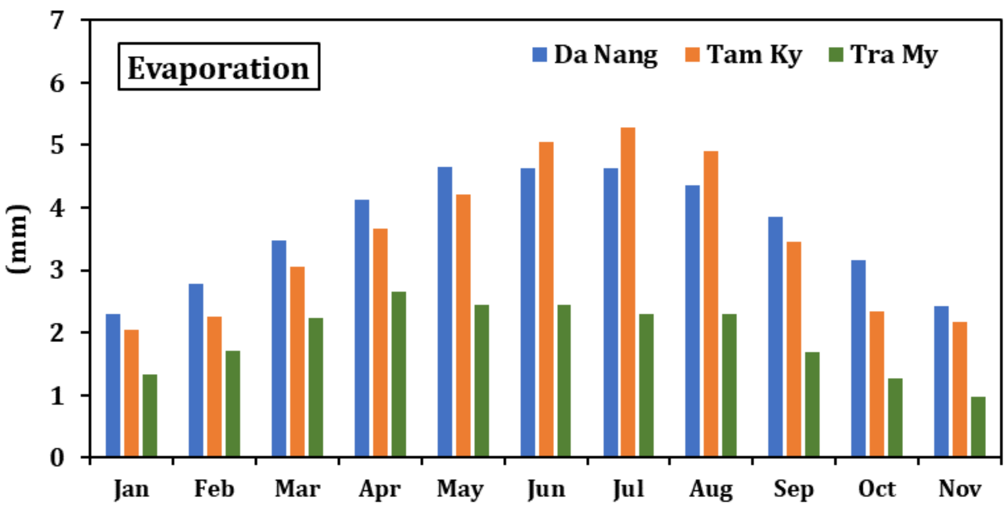


Figure 2. 13 Mean monthly evaporation in the VG-TB River Basin from 1979 – 2010 at Da Nang, Tam Ky and Tra My. The Da Nang and Tam Ky Meteorological stations are presented for coastal plain at North and South respectively, while Tra My Meteorological station is presented for mountainous area. Locations of these hydro-meteorological stations can be found in Figure 2.1. Source data: observed data provided by IMHEN

b. River network and flow distribution

As mentioned earlier, the two primary rivers in the basin are the Vu Gia River and the Thu Bon River which originate from Mang and Ngoc Linh and flow to the East Sea through the Han River mouth and Dai River mouth respectively. While the length of Vu Gia River is 145 km, the Thu Bon River is longer and reaches around 205 km. The two rivers are connected when entering the delta at Ai Nghia and Giao Thuy via Quang Hue River. At this point, Vu Gia River diverts about 34% amount of water to Thu Bon River and the rest continues downstream. The diversion rate is approximately 40% of the total Vu Gia flow during the dry period. The lower the upstream flow in the Vu Gia, the higher the diversion rate of the Quang Hue flow. Further downstream, Thu Bon River diverts part of water back to the Vu Gia via the Vinh Dien River.

c. Tide

Tide impacts on the delta of the VG-TB river basin which spans the lowland area of the basin from the Ai Nghia and Giao Thuy reaches **(Figure 2.2)** to the Han and Dai river mouths. The river mouths are connected at the western side of the East Sea (South China Sea) where the hydrological regime is significantly impacted by the mixed semi-diurnal tide **(Figure 2.14)**. In the VG-TB Delta, the tidal range increases up to Cam Le station (see location in **Figure 2.2**) on the Vu Gia River and up to Cau Lau station on the Thu Bon River (see location in **Figure 2.2**). Analyzing the tidal chart reveals that it takes on average 16 hours and 10 minutes for the water to rise from the wave trough to the wave crest, while it requires only 8 hours and 21 minutes for the water to drop from the wave crest to the wave trough. Thus, the tidal cycle in this region is about 24 hours 31 minutes. Understanding the time for water rise from wave trough to wave crest and water drop from wave crest to wave trough is essential for managing the irrigation system, as well as proper operating of the barrage system in the region.

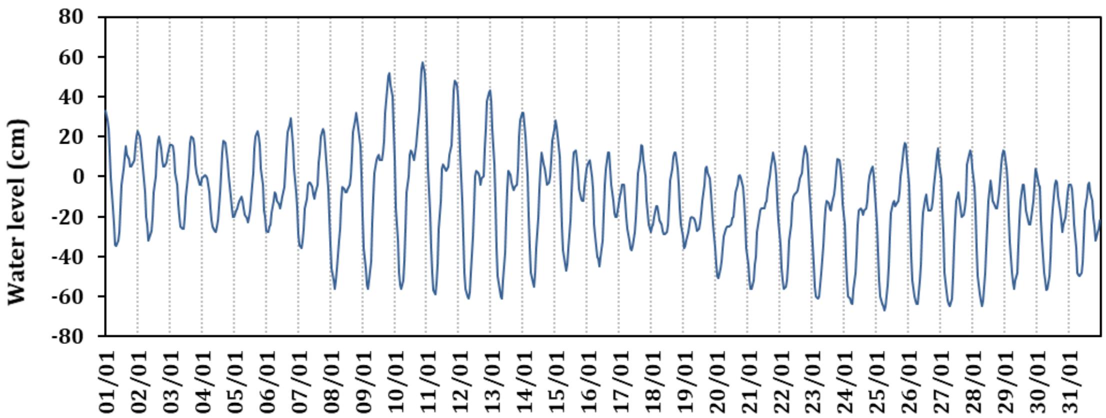


Figure 2. 14 The tidal chart at Son Tra oceanographic station during January 2005 (See location of the station in **Figure 2.1**). Source data: observed data provided by IMHEN

2.3.2 Hydraulic works

a. Hydropower dams

Hydropower plants have been rapidly developed in upstream areas of the VG-TB river basin in recent years. The river basin ranks fourth in Viet Nam as potential generation capacity of hydro-power plant with 8 large hydropower plants currently under operation and 36 small and medium hydropower plants either under operation or under construction (see location in **Figure 2.1**). The generation capacity of these hydro-power plants ranges from 0.6 MW to 210 MW. The total installed capacity in 2013 was 1026 MW and was expected to expand up to 5724 in the next few years (MOIT, 2014). These hydropower plants obviously contribute many benefits in socio-economic terms as they provide a significant amount of electric energy demanded by a growing economy not only in the basin but also exported to other areas of Viet Nam.

Although hydroelectric production does not consume water, the operation of these hydro-power plants in upstream of the basin has strong impacts on the hydrological regime downstream. Despite these issues, the reservoirs of these hydro-power plants are able to contribute to maintaining the minimum flow in rivers during low flow periods (Viet, 2014). **Table 2.2** presents the details of eight large hydro-power plants in the region. Large hydro-power plants are defined as ones installed with a capacity ≥ 30 MW.

Table 2. 2 Large hydro-power plants in upstream of the VG-TB River Basin. Source data: MOIT

Location	Hydropower plant	Installed capacity (MW)	Reservoir storage (million m^3)	Annual potential energy (GWh)	Year in operation
Vu Gia River	Song Bung 2	100	230	426	2016
	Song Bung 4	156	510	618	2015
	Song Bung 5	57	20.3	220	2014
	Song Bung 6	30	3.3	151	2014
	A Vuong	210	343.6	825	2008
	Song Con 2	46	1.2	168	2009
Thu Bon River	Dakmi 4	141	310	582	2011
	Song Tranh 2	162	733.4	621	2011

While seven of large hydro-power plants have been constructed to return water to the original rivers, Dakmi 4 (**Figure 2.1**) draws water from the Vu Gia River to operate and releases water to Thu Bon River, which helps to increase its efficiency. Since 2012 when the Dakmi 4 officially began in operation, the Vu Gia sub-catchment area was significantly decreased from 5,453 km^2 to 4,197 km^2 as the result of water diversion **(Figure 2.15)**. This diversion has led to the change of downstream flows giving the Thu Bon downstream more water, while reducing the downstream water in the Vu Gia. The result is that the Vu Gia River has a greater potential of water shortage and salt intrusion than in previous dry seasons. One of the consequences is that the Cau Do water treatment plant has been seriously affected by increasing salt levels. The impacts of these hydro-power plants on the hydrological drought and flows in the region were fully assessed in the study of Firoz *et al*. (2018). Alternatively, a coordinated operation procedure of hydro-power plants in the VG-TB river basin for both dry season and rainy season issued by the Viet Nam Ministry of Natural Resources and Environment has been applied since 2015 in order to minimize the impacts on the hydrological regime in the region.

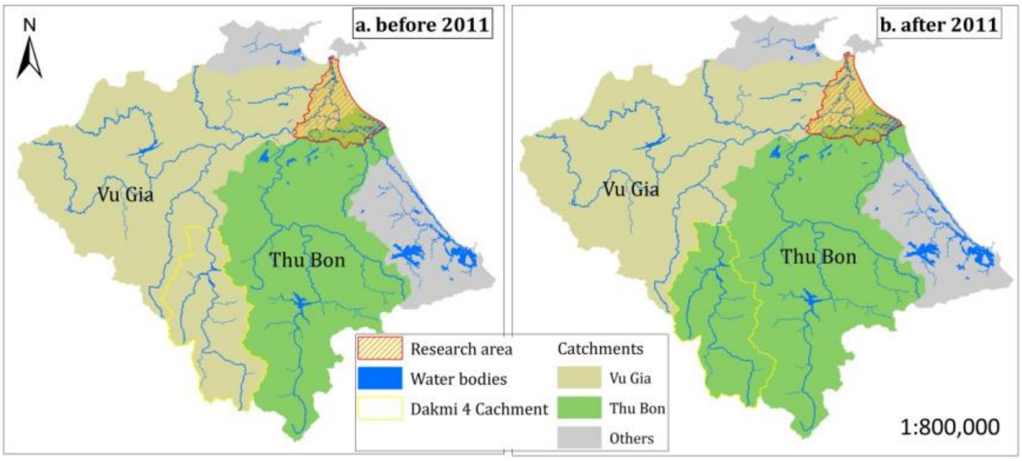


Figure 2. 15 Changes in Vu Gia and Thu Bon catchments after the construction of Dakmi 4 hydro–power plant (Viet, 2014). It can be seen that the whole Dakmi 4 catchment released to the Thu Bon catchment.

b. Barrages

A river barrage is a structure that is built to control the amount of water that flows through it. By properly operating, barrages help to regulate water for different purposes such as irrigation, domestic uses or salinity control. In the VG-TB river basin, five barrage systems have been constructed in the delta **(Figure 2.2)**. Three barrages An Trach, Bau Nit, and Thanh Quyt are in the Vu Gia and its tributaries, and two other barrages Duy Thanh and Binh Long are in the Thu Bon and its tributaries. While the main purposes of these barrages in Vu Gia River are to elevate the water level and divert water for irrigation and domestic supply, the Duy Thanh barrage is used to control the saltwater intrusion for the pumping stations in Thu Bon River.

2.3.3 Irrigation features

a. Irrigation management schemes

While the VG-TB river basin has about a total of 82,000 hectares under cultivation, only about 16,000 hectares are under irrigation (2005). This irrigated area is concentrated in the delta of the basin where a large scale of paddy rice cultivation takes place. The irrigated area was divided into 13 Irrigation Management Scheme (IMS) namely Xuyen Dong, La Tho, Tu Phu, Vinh Dien, Tu Cau, Dong Ho, Bich Bac, An Trach, Dong Quan, Chau Son, Ai Nghia, Cam Van, Cam Sa **(Figure 2.2)**. Each IMS includes pumping stations, irrigation canal networks, drainage canals, and regulatory structures. The area of IMS, paddy rice and annual crops are presented in **Figure 2.16**. Although the area of the schemes varies, paddy rice is still the dominant crop in most of the schemes except Tu Phu. The cultivation area of paddy rice of each scheme is similar in every year, whereas the cultivation area of annual crops fluctuates depending on weather conditions and market demands (Viet, 2014). Eight of the IMS receive water from Vu Gia Rivers to supply for its fields including An Trach, Chau Son, Bich Bac, Dong Quan, Cam Van, Ai Nghia, Dong Ho, La Tho. On the other hand, Tu Cau, Cam Sa, Vinh Dien receive water from Vinh Dien River, while Tu Phu and Xuyen Dong get water from Thu Bon River.

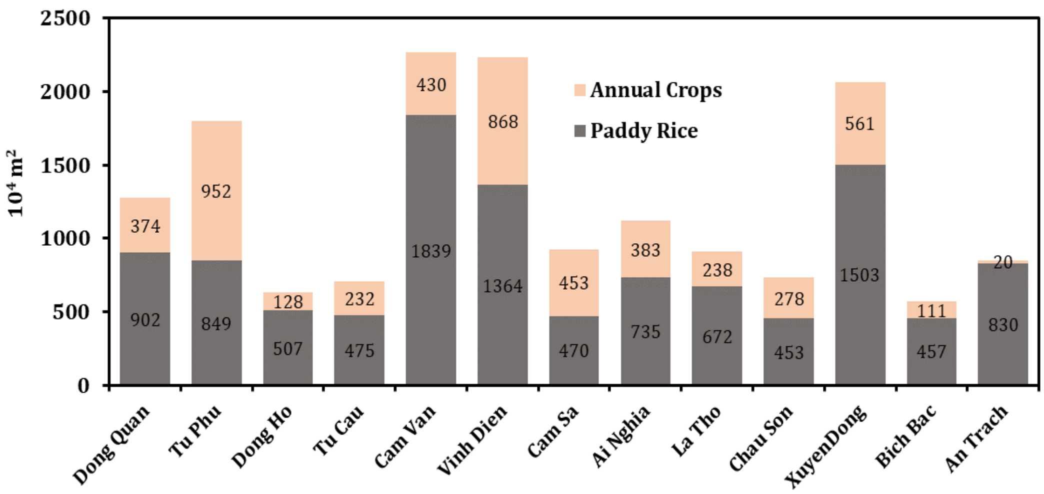


Figure 2. 16 Total Irrigation Management Scheme areas, annual crop area and paddy rice area for each Irrigation Management Scheme in 2005. Source data: IMC; DARD

b. Pumping stations

Pumping stations are an important part of an irrigation system and necessary element for agricultural production in the region. About 120 pumping stations were installed along the rivers to extract water to irrigate the cultivated area in the delta **(Figure 2.2)**. However, most of them have small operational capacities with about 95 stations are below 0.5 m^3/s. In total 13 large pumping stations with a capacity up to 1000 m^3/h are operating as primary pumps. Each large pumping station is responsible for one IMS. These pumping stations which are managed by the Irrigation Management Company take water directly from the rivers and conveys it to the main and first – order canals of the irrigation schemes. The rest of the pumping stations are medium and small which are managed by the Water User

Association. These medium and small pumping stations are responsible for receiving water at the main and first – order canals and then delivering it to the fields.

2.3.4 Agricultural practices

The VG-TB river basin is one of the most important food-producing regions in central Viet Nam (Pedroso *et al*., 2017). In 2013, half of the population in the region relied on agricultural production. Although there is a diversified crop pattern, paddy rice is still the dominant crop as it accounts for approximately 70% of the area of irrigated agriculture in the delta (Viet, 2014), followed by maize and peanut **(Figure 2.17)**. Other crops are sweet potato, cassava, bean, tobacco, and vegetables. However, these annual crops do not require as much water as paddy rice. For that reason, all IMS in the region were mainly designed to irrigate paddy fields rather than annual crops (Viet, 2014).

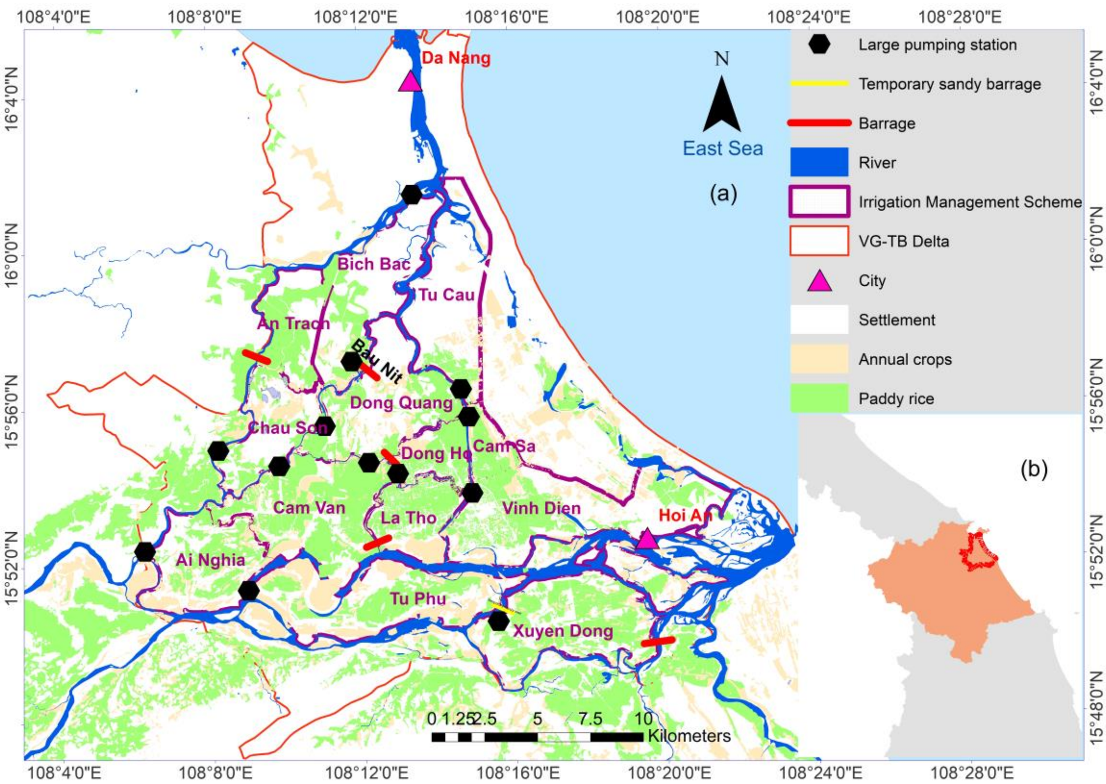


Figure 2. 17 (a) The paddy rice and annual crops (maize and peanut) in the VG-TB Delta in 2005. (b) Location of the VG-TB Delta. Source data: DARD; IMC

Two crops are planted per year. The first crop winter – spring is from the middle of December to the middle of April whereas the second crop summer – autumn is from the middle of May to the end of August **(Figure 2.18)**. During September-November, the peak of the rainy season, no or very limited cultivation takes place. The winter – spring crops start at the end of the high rain period and are harvested in the middle of April before Tieu Man flood which may occur in May. The summer – autumn crops will be harvested before the rainy season starts which is normally followed by typhoons and extreme weather events. By harvesting two crops per year, crop damage from floods and typhoons during the rainy season can be better avoided. However, the crops still suffer from droughts and saltwater intrusion during the dry season.

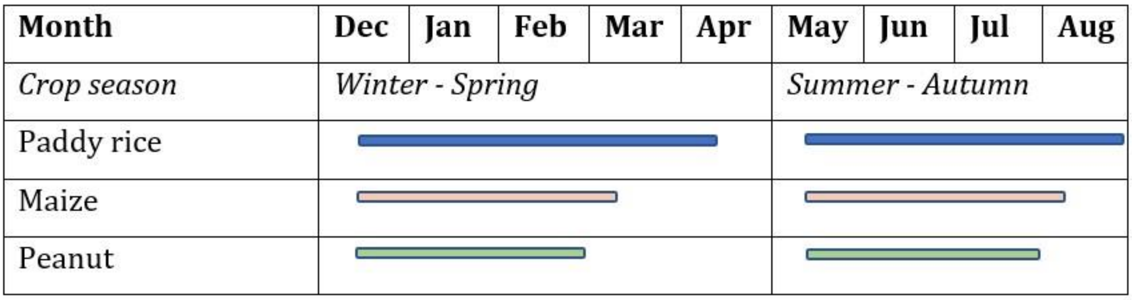


Figure 2. 18 Crop calendar in the VG-TB Delta. Source data: DARD

In general, the agricultural area in the VG-TB river basin has been significantly decreased since 1995 due to on-going urbanization, particularly the cultivated area in Da Nang. The data from the statistical office shows that the total cultivated area in the region reduced from more than 106,000 hectares in 1995 to 80,000 hectares in 2013. This is expected to be the continued trend in the region.

Beside the cultivated activities, livestock and aquaculture also play an important role in the food supply of the region. The main livestock are buffaloes, cattle, pigs, poultry and goats. However, these livestock activities in the region are taken as small scales home farming.

2.3.5 Industrial services

Table 2.3 presents the information of industrial zones in the region up to 2016.

Table 2. 3 Industrial zones in the VG-TB river basin (2016). Source data: Vietnam General Statistic Office 2016

Industrial zone	Location	Established	Area (ha)	Major industry
Lien Chieu	Da Nang	1998	289.4	Mechanical assembly, construction material
Hoa Khanh	Da Nang	1996	394.0	electronic, food processing, plastics, construction materials
Extended Hoa Khanh	Da Nang	2004	132.6	electronic, food processing, plastics, construction materials
Thuan Phuoc	Da Nang	2001	50.6	Food processing
An Don	Da Nang	1993	50.1	Textile, garment, food processing
Hoa Cam	Da Nang	2003	149.8	Construction materials, food processing
Dien Nam Dien Ngoc	Quang Nam	1996	418.0	Footwear, garment, electrics
Dong Que Son	Quang Nam	2009	237.6	Garment
Thuan Yen	Quang Nam	2009	141.0	Garments, footwear
Truong Xuan	Quang Nam	2015	478.0	Garments, footwear
Tam Thang	Quang Nam	2014	85.0	Garments, textiles
Phu Xuan	Quang Nam	2013	550.0	Food processing, textile
Viet Han	Quang Nam	2015	2000	Automobile assembly & production
Bac Chu Lai	Quang Nam	2003	357.0	Automobile assembly & production
Tam Hiep	Quang Nam	2003	718.0	Chemical products
Chu Lai Truong Hai	Quang Nam	2003	451.0	Automobile assembly & production

Even though agriculture still plays an important role in socio-economic welfare of the region, industries and services have developed rapidly in recent years. Da Nang was the biggest industrial center in the region before 2000. However, the industries of Quang Nam province have expanded significantly since 2000, with many new industrial zones with a growth rate on average of 18.7% per year in the last 10 years. The total area currently used for industrial purposes is about 6500 hectares concentrated in Da Nang City and the south of the region. The main industrial products are footwear, textile and garments, processed food and automobile assembly. The industrial sector in the region is believed to grow at a high rate in the future thanks to high investments from local and foreign investors.

2.3.6 Domestic water supply service

Water treatment plants in the basin are responsible for the domestic water supply in Da Nang City and Quang Nam Province. However, these water treatment plants only serve the urban area. There is no access to water supply services for people in the rural areas, where groundwater exploitation, as well as surface water from streams are the main water sources supplying their demands.

In Da Nang, Cau Do WTP serves the area of Da Nang City where about 93% of people have a connection to the public water supply system, while the Hoi An WTP mainly serves the city of Hoi An. Moreover, the Phu Ninh water treatment plant is available for the center of Tam Ky City. **Table 2.4** presents the information on capacity, serving area and water source of the main water treatment plants in the VG-TB river basin.

Table 2. 4 Main water treatment plants in the VG-TB river basin. Source data: Da Nang Water Supply Company; Quang Nam Water Drainage and Supply Joint Stock Company.

Province	Water treatment plant	Capacity (10^3 m^3/day)	Serving area	Water source
Da Nang	Cau Do	50	Da Nang City	Vu Gia River
	Extended Cau Do	120	Da Nang City	Vu Gia River
Quang Nam	Hoi An	21	Hoi An City	Vinh Dien River
	Phu Ninh	100	Tam Ky City	Phu Ninh Reservoir

2.4 Data collection

A wide range of data has been employed and processed in this study. This section provides an overview of these data, including meteorological and hydrological, topographical and bathymetric, land use, soil types, agricultural production, socio-economic, satellite, field measurement, and inputs from local experts. Further details of utilized data will be presented in each relevant chapter.

2.4.1 Meteorological and hydrological data

The meteorological and hydrological data were collected from the monitoring network within the VG-TB river basin. Due to historical events, the recorded data only became available after the country reunification in 1976. Within the analysis and process of this study, most of the data was acquired until 2014. However, there are gaps in certain years at some stations. In general, the monitoring stations are not evenly distributed in the river basin, with most located in the downstream and eastern part.

There are only 3 stations which monitor daily meteorological data including temperature, sunshine hours, evaporation, humidity, and wind speed in the entire basin namely Da Nang, Tam Ky and Tra My. Both the Da Nang and Tam Ky stations are situated in the lowland, Tra My station on the other hand is in the mountainous area. While Da Nang station represents the northern coastal plains, the Tam Ky represents the southern coastal plains, and the Tra My represents the mountainous area. The coordination and elevation of these stations are shown in **Table 2. 5**.

Table 2. 5 Hydro-meteorological stations in the VG-TB River Basin. Source data: National Centre for Hydro - Meteorological Forecasting

Station	Location		Elevation (m)	Coordination Reference
	Latitude	Longitude		
Da Nang	16.03	108.18	4.75	WGS 84
Tam Ky	15.57	108.44	20.89	WGS 84
Tra My	15.34	108.22	123.11	WGS 84

There are a total of 24 rain gauges (including hydro-meteorological stations, water level stations and discharge stations which record rainfall data) that were installed in the basin providing recorded rainfall data since 1976. The pre-processing by screening and plotting data revealed that the measured data at some rain gauges are not consistent. This could affect the usability of the data. To ensure the data consistency in time, only 20 rain gauges were considered after further analysis. The location of these rain gauges is shown in **Figure 2.1.**

There are only 2 discharge stations located upstream of the rivers monitoring the discharge in the basin regularly. They are Thanh My and Nong Son, which measure the Vu Gia and Thu Bon Rivers respectively **(Figure 2.1)**. Daily discharge has been recorded since 1976, however 6 hours discharge is available only from 1998 – 2008 at both stations. Moreover, discharge was monitored unevenly during dry periods at the Ai Nghia, Giao Thuy, Huong An, Tuy Loan, and Hoi Khach for some certain years.

There are 8 water level stations situated along the rivers to measure the water level. They are Ai Nghia, Giao Thuy, Cam Le, Cau Lau, Son Tra, Hoi An, Vinh Dien and Hoi Khach. While Son Tra and Hoi An stations monitor hourly tidal levels, other stations observe only daily water levels.

Salinity also has been monitored at the Cau Do WTP. Additionally, salinity is measured at the pumping stations during crop seasons for operation.

2.4.2 Topographical and bathymetric data

The study utilizes the topographical and bathymetric data to set up the hydrodynamic model MIKE 11. The river and canal networks were derived from ASTER updated high resolution satellite imagery with a resolution of 10 × 10 m (2010), within the framework of the Project Land Use and Climate Change Interactions in Central Vietnam (LUCCi). The bathymetry data of the Vu Gia, the Thu Bon and their tributaries were provided by Viet Nam Institute of Meteorology, Hydrology and Climate Change (IMHEN). The surveys for bathymetry data of the Vu Gia, Thu Bon and their tributaries were carried out in dry season 2010 and later updated in 2012.

2.4.3 Land use, soil types and agricultural production

The data on agricultural production was collected from the Departments of Agriculture and Rural Development (DARD) of Quang Nam and Da Nang. This included crop calendars, cultivation techniques, and irrigation practices.

About 120 primary and secondary pumping stations were visited during field trips to understand the operations as well as investigate the existing situations. The pumping data of the primary stations, as well as the operation of irrigation structures such as barrages and temporal closure was provided by the Irrigation Management Company (IMC) whereas the operation pumping data of secondary stations were collected from the local Water User Association.

Land use maps in 2010 for both Da Nang and Quang Nam Province and the FAO-classification soil map (scale 1:200,000) were obtained from the Ministry of Natural Resources and Environment (MONRE).

2.4.4 Social economic data

The study utilized statistical data for the quantification of water demand and further analysis in the VG-TB river basin. The statistical data for Quang Nam Province and Da Nang City were collected separately from provincial scale to commune scale. Information such as population, industries, etc. was extracted for the calculation. In addition, various types of master plans were also obtained for the scenario development and analyzing of future changes.

2.4.5 Additional measurement

Some field measurements were implemented within the framework of the LUUCi Project carried out by the Cologne University of Applied Science to validate the river and canal network which was derived from ASTER high resolution satellite imagery.

2.4.6 Input from stakeholders and experts

The study also acquired data from consultations with local stakeholders, as well as experts in Da Nang City and Quang Nam Province. These information from stakeholders and experts were obtained through meetings as well as the workshops within the scope of LUCCi Project. The details can be found in minute of meetings and workshop reports in the database of LUCCi Project (http://www.lucci-vietnam.info/). These consultations helped to gain an understanding about the challenges, as well as the impacts that the river basin is facing. The list of stakeholders and experts involved in the study is outlined in **Appendix B**.

2.5 Current challenges in the Vu Gia - Thu Bon river basin

The Vu Gia - Thu Bon is the fifth largest river basin in Viet Nam and one of the most important food-producing regions, (Pedroso *et al.,* 2017), the agriculture accounts for 70% of the total water consumption of the basin, relies mainly on irrigation (Viet, 2014). The water demand has increased in recent years due to socio economic development, and a rapid increase in population (Nauditt & Ribbe., 2017). The population is projected to increase up to 4.1 million by 2030 (DPI, 2012). According to the MARD (2010), the water demand in 2010 was 1,450 million m^3 and is expected to soar to 3,915 million m^3 by 2020. The region is now facing many challenges. In recent years hydropower plants have been rapidly developed in upstream sections of the river basin with 8 large hydropower plants currently under operation and 30 small and medium hydropower plants planned in the next few years. These hydropower plants obviously contribute many benefits in socio-economic terms as they provide a significant amount of electric energy demanded by a growing economy in Vietnam (as elsewhere in developing regions). However, due to the operation of these hydropower plants, there is also a significant impact on the hydrological and flow regime downstream. The difference in water levels at Giao Thuy and Ai Nghia gauging stations for two periods: before (1995-1999) and after (2009-2013) construction of upstream reservoirs has increased about 30 cm. This is a result of water transfer from the Vu Gia River to the Thu Bon River via Dakmi 4 hydropower plant and has seriously affected water utilization in Vu Gia River, especially in the dry season. The diversion of water by hydro-power plant Dakmi 4 giving the Thu Bon downstream more water while reducing the downstream water in the Vu Gia. The result is that the Vu Gia River has a greater potential of water shortage and salt intrusion than previously during dry seasons.

Another challenge in the region is uneven distribution of rainfall temporally. (Nauditt. & Ribbe., 2017). The rainy season only lasts 3-4 months (September – December) while the dry season lasts 8-9 months (January – August) and receives only 20 – 30% of total rainfall. For the dry weather flow, the minimum occurs in April and accounts for only 1% - 3% of total water capacity of the year (MARD, 2010). Thus, saltwater intrusion occurs due to low flow, increased water demand and tide penetration. Salt-water intrusion may occur as early as February (Viet, 2014), and have serious impacts on the agricultural production in the estuary (Zeidler, 1998; Hoang *et al*., 2009; Bhuiyan *et al*., 2011). Furthermore, it significantly reduces the availability of freshwater and deteriorates the water quality, generating an insufficiency of irrigation water and domestic supply (Chowdhury *et al*., 1990; Jiang *et al*., 2009). Water scarcity has recently become critical. Accordingly, the competition between different water users in the region has rapidly accelerated and increased the inequality in water distribution. This in turn, has caused serious water shortages for various purposes during the dry season.

2.6 Foundation works

Previous work provides the background and foundation for this research. The VG-TB River Basin has been studied intensively over the past years by a joint research project LUCCi of Institute for Technology and Resources Management in the Tropics and Subtropics (ITT) together with the Vietnam Academy of Water Resources (VAWR) and other partners. Thus, a source of data is available on the study region regarding hydrology, water use, land use and agriculture either collected from local authorities or self-observation. As a constituent of the LUCCi project, the author has been given access to these data for this study. Moreover, the region was thoroughly investigated and analyzed during the project implementation phase providing the background of challenges as well as research gaps for this study. More details can be found in the publication of Nauditt. & Ribbe., (2017).

2.7 Conclusion

An overview of the VG-TB river basin was presented. The details on hydrological and meteorological characters as well as, different features such as hydropower development, agricultural practices and industrial services were also described.

As can be seen, the strong seasonal distribution of rainfall in the region causes frequent low flow and drought in the dry season. The hydrological regime of the estuary is determined by the upstream inflow, tide, and human interventions. Furthermore, anthropogenic impacts from dams, barrage construction, and hydropower plants have already altered the river flows. This can accelerate the saltwater intrusion induced water shortages during drought periods which are the main constraints hindering agricultural production.

Paddy rice is the dominant crop and required water extraction from the rivers for irrigation, therefore the demand for irrigation supply is large. When the water resources become more vulnerable, the agricultural production becomes more vulnerable due to interrupted irrigation. Since agriculture plays an important role in the economic sector, the damage in agricultural production will cause the main damage in economy of the region,

The analysis of the study area provides essential information and sets the foundation for further steps of studying on low flow and minimum flow requirement in the VG-TB River Basin.

3 Low flow phenomenon and minimum flow requirements in the Vu Gia – Thu Bon River Basin

This chapter firstly presents the background knowledge of the low flow phenomenon. It additionally provides a theoretical basis for better understanding the investigated flow regime of the river system in the VG-TB river basin, where a long period of low flow occurs annually and competition between water users is critical. Furthermore, the low flow season in the VG-TB river basin is addressed in detail. The term "minimum flow requirement" is reviewed to form its definition in this research context. Finally, the previous studies and relevant findings in the region are discussed.

3.1 Low flow phenomenon

3.1.1 Definition of low flow

'Low flow' refers to low river discharge (Smakhtin, 2001b). The World Meteorological Organization (WMO) defines low flow as the flow of water in a stream during prolonged dry weather (WMO, 2008). Based on the above definition, the concept of low flow in the rivers is often associated with the concept of hydrological drought (Mijuskovic-Svetinovic & Maricic, 2008). Tallaksen and Van Lanen (2004) defines drought as a sustained period of below-normal water availability, which spatial and temporal characteristics that vary significantly from one region to another. Typically, drought is a natural event in which less than normal rainfall and a prolonged period of dry weather conditions causes significantly lower flow volumes in rivers. Drought can be categorized into four different types, namely meteorological drought, agriculture (soil moisture) drought, hydrological drought and socioeconomic drought (Van Loon, 2015). Hydrological drought refers to the phenomenon that groundwater or surface water levels are below normal level, and it also implies a decrease in river discharge. In short, a low flow is a seasonal phenomenon (typically during the dry season) and is considered as a critical component of the flow regime in any river or stream while a drought is an event that results from an extended period of below-average precipitation and is often associated with a decrease in river discharge. A drought includes low flows, but a seasonal low flow is not necessarily a drought (Zelenhasic and Salvai 1987; Clausen and Pearson 1995).

Generally, the lowest annual flow occurs in the same season each year. However, the magnitude and duration of low flows can differ significantly from year to year (Smakhtin, 2001b). One of the main issues of a low flow is that only a little quantity of water is available in the rivers during the low flow period (Mijuskovic-Svetinovic & Maricic, 2008). Regarding water management aspects, it is the worst situation when a drought happens during a low flow season since it exacerbates water scarcity (Van Loon, 2015). Thus, the understanding of low flow characteristics and regimes is crucial for the optimal integrated management which usually involves water-supply planning, water system and structure operating water quantity and maintaining good quality for different activities regarding irrigation, recreation, and wildlife conservation.

3.1.2 Low flow and minimum flow requirement in the VG-TB river basin

Improving the ability to predict the occurrence of low flow and drought is necessary for integrated water resource management, especially where the operation of reservoirs and conflicts between different water users exist (Ceylan and Lall, 2017). Due to the fact that the region experiences summer low flow during the dry season typically from January to August, there is the need to analyze hydrological and meteorological features in the VG-TB river basin in order to understand the low flow and drought characteristics.

During the low flow period, small amounts of water are available in the rivers (Mijuskovic-Svetinovic & Maricic, 2008). It creates a serious challenge for securing enough water supply for different sectors. To harmonize the multi-sectorial water management in a region such as the VG-TB river basin that is characterized by multiple and usually competing needs for water, the question raised is "How much water is needed to satisfy the different demand targets and functions of the rivers?". It leads to the requirement of determining the sustainable minimum flow in the rivers to manage the risk associated with alterations to the flow regime and satisfy the water demand for those depending on it. Therefore, defining the minimum flow requirement during the low flow period has received an increasing attention in the region.

Based on the above definition and the characteristics of the VG-TB river basin, the minimum flow needed to be available in the rivers during the low flow season is calculated for:

- Controlling salt below the threshold of 1 g/L (equal with 1 practical salinity unit) which is required for irrigation water and therefore it is a key threshold for the operation of the pumping stations and controlling salt below the threshold of 0.25 g/L which is needed for the operation of water treatment plants in the delta of the basin.
- Supplying sufficient water for irrigated cultivation areas in the delta of the basin.
- Supplying sufficient water to satisfy the domestic water demand for the number of inhabitants in the delta of the basin.
- Supplying sufficient water for industrial water demand for the industrial zones in the delta of the basin.
- Maintaining essential functions of the estuarine ecosystem which is defined by 10% of annual mean discharge according to the recommendation by the Viet Nam MONRE.

The threshold of 1 g/L refers to the irrigation supply requirements for the development of paddy rice. The threshold of 0.25 g/L complies with the standard for the drinking water supply in Viet Nam National Technical Regulation on Domestic Water Quality QCVN 01-1:2018/BYT.

3.1.3 Low flow and minimum flow requirement in the Vu Gia - Thu Bon river basin: previous studies

Even though the development of low flow assessment began in the late 1940s in the western part of the United States of America (Tharme, 2003), it is a relatively new subject in many developing countries (Karimi *et al*., 2012). In Viet Nam, this issue has been a topic of concern since 2003 with some studies and simple applied methods. Despite the seriousness of this phenomena in the VG-TB river basin, little attention has been paid to it in this basin. However, the subject has recently received some concern regarding low flow and minimum requirement only with very few studies dealing with the challenge.

The study of Viet (2014), which has assessed the situation of saltwater intrusion during low flow season in the VG-TB river basin, implied a further concern for the required minimum flow in the region. The minimum flow requirement has been estimated at certain points in the lowland of the VG-TB river basin. This study defined the salinity thresholds under different scenarios of sea level rise considering implementing adaptation measures or without measures. However, this study considered water quantity at certain points only, and temporal and spatial flow are not taken into account. Another study, entitled “Determining the required minimum flow in main streams of Vu Gia – Thu Bon rivers, ensuring the sustainable development of ecology system” was carried out by MONRE (2014). The minimum flow for the two main streams of Vu Gia River and Thu Bon River were assessed using the Tennant method. The study utilized hydrological data for its calculation. Actual data of water use in the region was considered. The minimum flow was calculated for the upstream parts that extend from Thanh My hydrological station to Ai Nghia hydrological station in the Vu Gia River, and from Nong Son hydrological station to Giao Thuy hydrological station in the Thu Bon River. In this study, the impacts of hydropower plants and the minimum flow in the delta were not assessed. The Vietnam Academy for Water Resource (2015) implemented a study to investigate loading capacity and minimum flow in Vu Gia – Thu Bon” using the Tennant method and mathematical models. It investigated the required minimum flows from Thanh My hydrological station to Ai Nghia hydrological station in the Vu Gia River, and from Nong Son hydrological station to Giao Thuy hydrological station in the Thu Bon River. This study included the impacts of hydropower plants. However, the minimum flow in the delta was not the focus of assessment in this study.

Since 2015, there has been insignificant studies in the VG-TB river basin which focused on drought and low flow. Nevertheless, an extensive assessment of minimum flow for the basin, especially minimum flow requirements in the delta, is still left unaddressed.

3.2 Analysis approach of the Vu Gia - Thu Bon river flow

3.2.1 River flow analysis

In order to study the low flow phenomena, it is crucial to conduct a comprehensive analysis of the river flow. To carry out the river flow analysis, different approaches and tools were employed in the present study. **Figure 3.1** presents the general methodology adopted in this analysis. The dataset used in this assessment consists of discharge data of the Vu Gia and Thu Bon rivers from two gauging stations Thanh My and Nong Son, respectively. For the precipitation, the data from the meteorological station Da Nang which is the most representative station for the study area is utilized. Besides, the temperature data from the meteorological station Da Nang was also used. Firstly, the discharge and precipitation were analyzed using descriptive statistics. Moreover, this analysis involved understanding the trends of hydrological features in the region. After that, the flow of the Vu Gia and Thu Bon rivers were examined to detect any statistically significant changes in the flow regimes and estimate the exceedance probability of various flow magnitudes. Drought frequency, duration, and intensity were also investigated using the Standardized Precipitation Evapotranspiration Index (SPEI). The period time of this analysis is 39 years from 1976-2014 for discharge at Nong Son gauging station and precipitation at Da Nang meteorological station, while the time series for discharge data from Thanh My gauging station is 38 years from 1976-2013.

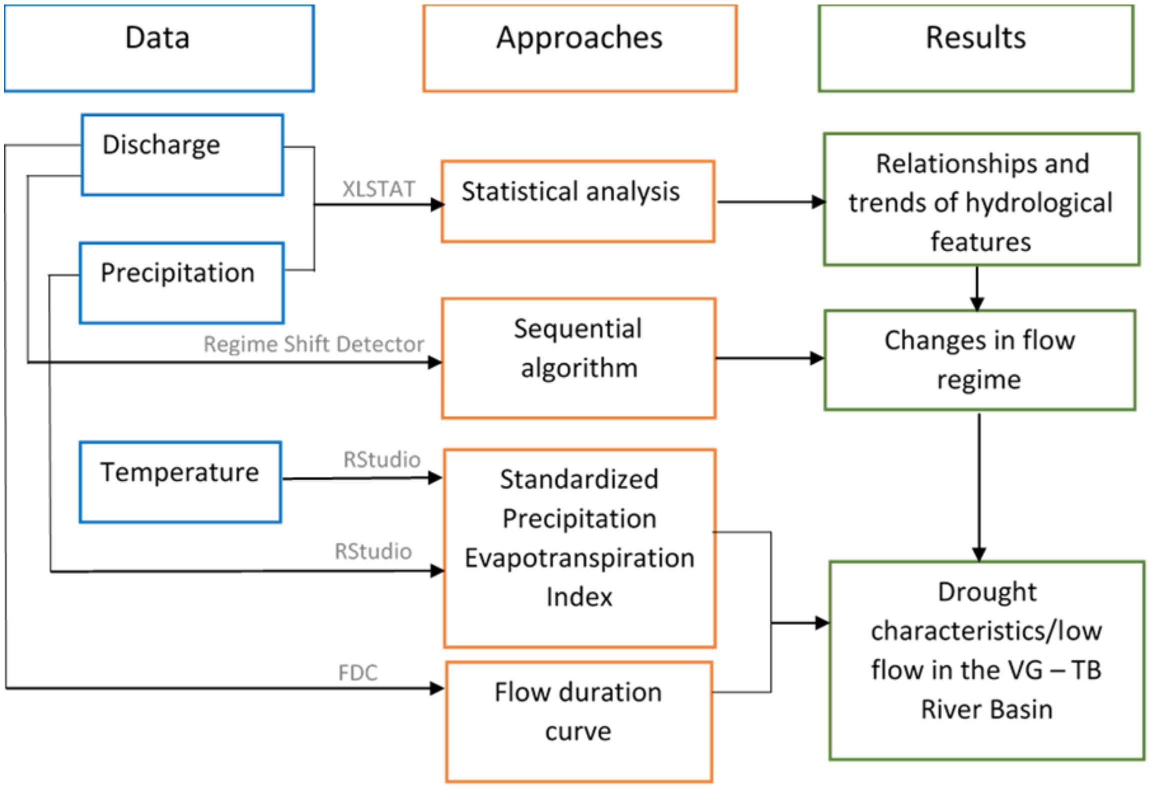


Figure 3. 1 Flowchart of the general methodology

3.2.2 Trend analysis

The non-parametric test Mann Kendall (Mann, 1945; Kendall, 1975; Kanji, 1993) was employed to test and observe any possible trend in precipitation and flows in the Vu Gia and the Thu Bon rivers. As hydrological data records are not normally distributed and usually containing outliers and non-linear trends, thus the Mann Kendall test is chosen over other tests to analyze trends in this analysis because it makes no assumption about the distribution of data (Helsel and Hirsch 1992; Birsan *et al*. 2005). The null hypothesis (H_0) indicates that there is no significant trend. Alternatively, there is a monotonic trend either upward or downward in the time series data. Two-tailed confidence levels (p = 5%) are used for the Mann-Kendall trend test. Then Sen's slope was applied to quantify the trend magnitude. This test is applied with the trend is assumed to be linear. The result presents the change per unit time (Sen 1968). A positive value of Sen's slope implies an increasing trend, whereas a negative value indicates a decreasing trend. The free Trial software XLSTAT (Addinsoft, 2020) was used to run this test.

3.2.3 Regime shift assessment

The month-per-month regime shift assessment was implemented for the flow records of Thanh My and Nong Son gauging stations to detect any changes in river flow regimes in the Vu Gia and Thu Bon rivers respectively. The sequential algorithm which tests the shifts in the mean was applied in this assessment since this approach allows to detect multiple changepoints and estimate the probability of a regime shift with a minimum delay. Moreover, this algorithm overcomes the weakness of other approaches which usually consist a priori hypotheses of the shift timing and the cause of the threshold event (Rodionov, 2004). In the sequential analysis, the number of observed values is not fixed. It detects the regime shift by statistically testing the means of the previous subsets and subsequent datasets. The Regime Shift Index (RSI) is calculated to compare whether the following values are significantly different from the mean of the previous regime. A positive RSI indicates the value is significantly different, the regime shift point is identified, and this point is considered to be the starting point of the new regime. A negative RSI indicates that the regime shift at the given year failed and is assigned zero, then recalculate the mean value for the next data range. In this study, the flow was tested with the significance level = 0.1 and the cut-off length = 2 years. The Regime Shift Detector (RSD) software (Rodionov, 2004) was utilized to perform this assessment.

3.2.4 Low flow analysis

To understand the pattern of flows in Vu Gia and Thanh My rivers, the flow duration curve was generated to examine the exceedance probability of various flow magnitudes. The flow duration curve utilizes the time series of discharge measurement taken for the same period at Thanh My and Nong Son gauging stations. To investigate the characteristics of drought, a multi-scalar drought index Standardized Precipitation Evapotranspiration Index (SPEI) proposed by Vicente-Serrano *et al*., (2010) was utilized in this study. Since SPEI uses both precipitation and evapotranspiration to quantify drought frequency, duration, and intensity, it can describe water deficit effectively with multiple time scales as well as reflect the lag relation between different water resources, precipitation, and evapotranspiration. The calculation of this index is based on a normalization of the water balance developed by Thornthwaite (1948) which integrates precipitation and temperature data following these steps:

Climatic water balance:

The difference between the precipitation (P) and PET for the month i is calculated:

$$D_i = P_i - PET_i \qquad [1]$$

where P_i is precipitation and PET_i is evapotranspiration of month i. PET_i is calculated as

$$PET = 16\left(\frac{10T}{I}\right)^m \qquad [2]$$

In which T is the mean monthly temperature (^{0}C); I is the annual heat index which is calculated as $I = \sum_{i=1}^{12}\left(\frac{T_i}{5}\right)^{1.514}$; m is a coefficient depending on I, $m = 6.75 \times 10^{-7}(I)^3 - 7.71 \times 10^{-5}(I)^2 + 1.79 \times 10^{-2} + 4.92$

Standardization of the variable:

The probability distribution function of D according to the Log-logistic distribution is then given by:

$$F(D) = \left[1 + \left(\frac{\alpha}{x - \gamma}\right)^{\beta}\right]^{-1} \qquad [3]$$

where α, β and γ are scale, shape and origin parameters, respectively, for D values in the range (γ > D < ∞). With F(D) the SPEI can be obtained as the standardized values of F(D) following the classical approximation of Abramowitz and Stegun, (1965):

$$SPEI = W - \frac{C_0 + C_1W + C_2W^2}{1 + d_1W + d_2W^2 + d_3W^3} \qquad [4]$$

where $W = \sqrt{-2\ln(P)}$ for P ≤ 0.5 and P is the probability of exceeding a determined D value, P = 1 - F(D). If P > 0.5 then P is replaced by 1 - P and the sign of the resultant SPEI is reversed. The constants are C_0=2.515517, C_1=0.802853, C_2=0.010328, d_1=1.432788, d_2=0.189269, and d_3=0.001308.

SPEI can be obtained at various time scales (one month, two months, three months, etc.). To obtain the n-month SPEI, a time series is constructed by the sum of D values from (n-1) months before to the current month. In this study, the cumulative drought of 3 months (SPEI03) is used to identify seasonal drought events and the 6-month SPEI (SPEI06) indicates medium-term drought events. The SPEI was computed using precipitation and temperature time series from 1976 to 2014 at Da Nang meteorological station applying RStudio tool (RStudio Team, 2020). The results were then analyzed following the classifications in **Table 3.1.**

Table 3. 1 Classification of Standardized Precipitation Evapotranspiration Index (SPEI)

Class	Range
Extremely wet	≥2.00
Severely wet	1.5 to 1.99
Moderately wet	1.00 to 1.49
Normal	0.99 to -0.99
Moderately drought	-1.00 to -1.49
Severely drought	-1.50 to -1.99
Extremely drought	≤-2.00

3.3 Statistical characteristics of river flow in the Vu Gia - Thu Bon river basin

The mean annual discharges at Thanh My (1976-2013) and Nong Son (1976-2014) are presented in Box-whisker plot, offering a pictorial summary of important dataset characteristics (**Figure 3.2**). Moreover, the monthly data of discharges from these stations are also plotted in **Figure 3.3**.

In general, the discharges at Nong Son are higher with the mean values at 283.2 m^3/s compared to 126.0 m^3/s at Thanh My. The data exhibits small dispersion with interquartile range at 101.3 m^3/s and 50.2 m^3/s for Nong Son and Thanh My, respectively. It can be seen that the distributions of these discharges are asymmetric when the mean values are higher than the median at both stations, displaying a positive skewness. On annual time step, the statistical data reveals that the year 1982 experienced the lowest mean annual discharges at Nong Son which was 119.1 m^3/s. At Thanh My station, the lowest mean annual discharge was noticed in two different years 1982 and 2012, which was about 59.0 m^3/s. On the other hand, the highest mean annual discharge was found at 237.5 m^3/s for Thanh My, whereas this value was 494.7 m^3/s for Nong Son in the year 1996. A similar pattern of higher discharge at Nong Son compared to Thanh My is also noticeable on a monthly time scale (**Figure 3.3**), with the period between October and December exhibit the highest discharge levels.

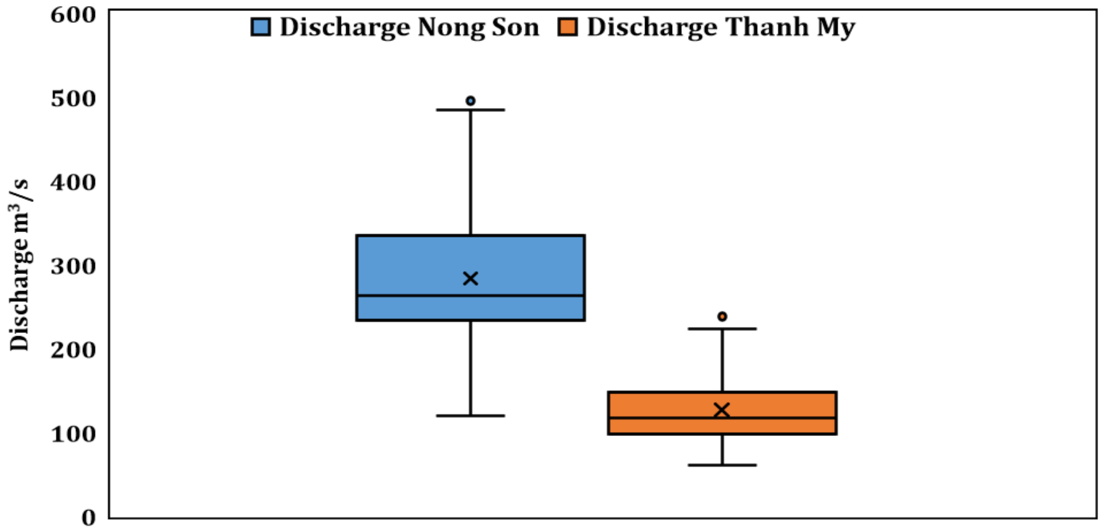


Figure 3. 2 Mean annual discharge at Nong Son (1976-2014) and Thanh My (1976-2013) gauging stations. The inner line (of the box) denotes the median value (50th percentile), while the box contains the 25th to 75th percentiles of dataset. The whiskers mark the 5th and 95th percentiles, and value beyond these upper bound is considered outlier, marked with dot. The x presents the mean value of the dataset. Source data: IMHEN

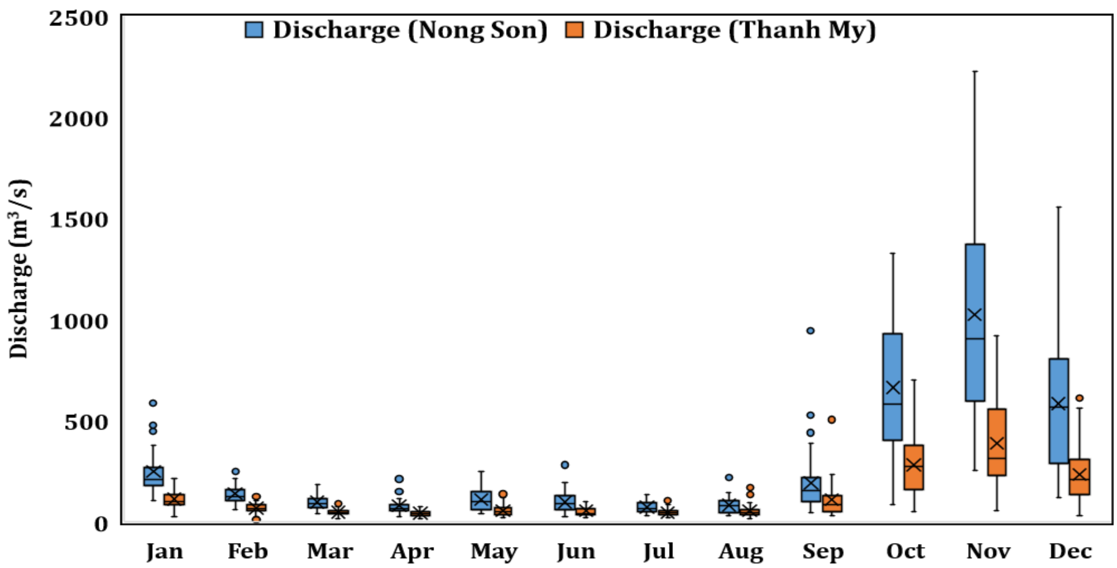


Figure 3. 3 Mean monthly discharge at Thanh My and Nong Son gauging stations (1976-2013). Source data: IMHEN

3.4 Trend analysis

The trend analysis was carried out on an annual time step as well as on monthly time scale for all the investigation years during the period 1976-2014. The result revealed a statistically increasing trend of annual precipitation and discharge which was observed at both gauging stations Thanh My and Nong Son (**Figure 3.4** and **Figure 3.5**).

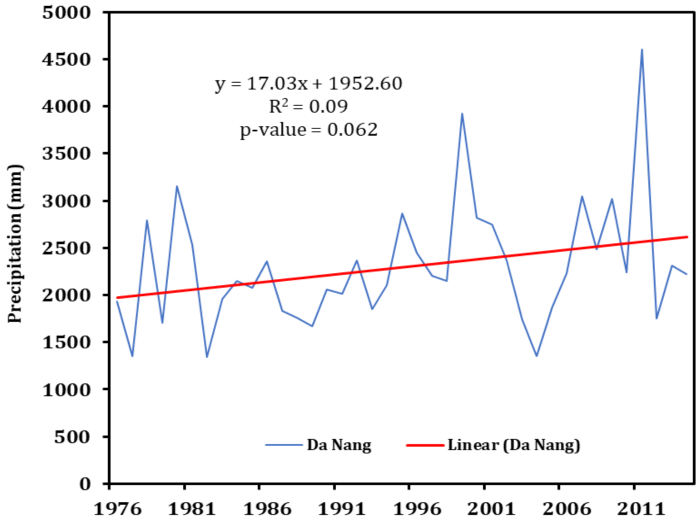


Figure 3. 4 Time series and linear trend analyses of precipitation at Da Nang station for the period 1976-2014. Source data: IMHEN

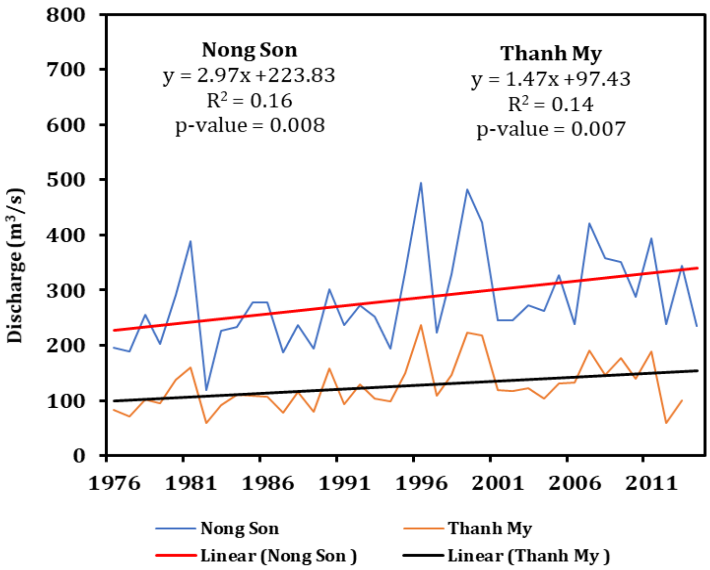


Figure 3. 5 Time series and linear trend analyses of mean annual discharge data for the period 1976-2014 at Nong Son gauging station and for the period 1976-2013 at Thanh My gauging station. Source data: IMHEN

Apparently, there is a strong increasing linear trend by 17.03 mm/year in annual precipitation for the period 1976 to 2014 (**Figure 3.4**). However, the month per month analysis found a significant increasing trend of precipitation mostly in the rainy season (**Table 3.2**). December exhibits a strong increasing and significant trend by 5.167 mm/year. On the other hand, a remarkable decreasing trend in precipitation can be seen in June with a magnitude of -2.457mm/year. Moreover, the Kendall's Tau is -0.212 indicates a moderate relationship with a negative correlation and significant probability (*p*-value=0.059). Nonetheless, an increasing trend is noticeable at the end of the dry season, especially a strong increase in August by 3.540 mm/year with a moderate relationship and a positive correlation (Kendall's Tau=0.287, *p*-value=0.010). This might be due to an earlier onset of the rainy season. The high values of coefficient of variation in dry season display the disparity in the precipitation distribution. It is likely that the precipitation increases due to a few heavy rainfall events.

Table 3. 2 Mann-Kendall trend test and Sen’s slope of precipitation at Da Nang meteorological station

Month	Kendall's Tau	*p*-value (two tailed test)	Sen slope	Mean	Std	CV	Conclusion
January	0.107	0.345	0.529	74.372	58.855	0.791	No trend
February	0.166	0.140	0.492	34.000	42.896	1.262	No trend
March	0.242	0.031	0.653	37.036	47.225	1.275	Increasing trend
April	0.147	0.191	1.348	94.382	78.556	0.832	No trend
May	-0.015	0.904	-0.162	217.944	100.250	0.460	No trend
June	-0.212	0.059	-2.457	192.282	93.454	0.486	No trend
July	0.120	0.287	1.156	161.854	90.558	0.560	No trend
August	0.287	0.010	3.540	200.482	115.048	0.574	Increasing trend
September	0.120	0.287	2.814	356.026	200.679	0.564	No trend
October	0.001	1.000	0.010	691.197	361.189	0.523	No trend
November	-0.036	0.753	-1.413	582.395	314.849	0.541	No trend
December	0.239	0.033	5.167	273.492	186.932	0.684	Increasing trend

Std = Standard Deviation, CV = Coefficient of Variation

Table 3.3 and **Table 3.4** summarizes statistics obtained from the Mann-Kendall test, including *p*-values and Sen’s slope as well as standard deviation and coefficient of variation derived for each month at Thanh My (Vu Gia River) and Nong Son (Thu Bon River) gauging stations.

Table 3. 3 Mann-Kendall trend test and Sen's slope of discharge at Thanh My gauging station

Month	Kendall's Tau	*p*-value (two tailed test)	Sen slope	Mean	Std	CV	Conclusion
January	0.378	0.001	1.630	113.011	42.905	0.380	Increasing trend
February	0.308	0.009	0.945	70.366	23.634	0.336	Increasing trend
March	0.390	0.001	0.858	51.605	17.050	0.330	Increasing trend
April	0.429	0.000	0.860	44.995	19.170	0.426	Increasing trend
May	0.298	0.011	0.923	57.833	27.969	0.484	Increasing trend
June	0.114	0.334	0.299	59.219	33.662	0.568	No trend
July	0.232	0.048	0.524	46.935	16.721	0.356	Increasing trend
August	0.327	0.005	0.793	57.317	29.693	0.518	Increasing trend
September	0.337	0.004	1.799	109.693	85.719	0.781	Increasing trend
October	0.203	0.084	4.332	287.279	157.326	0.548	No trend
November	0.187	0.111	5.126	395.463	223.871	0.566	No trend
December	0.311	0.008	4.388	247.171	129.424	0.524	Increasing trend

Std = Standard Deviation, CV = Coefficient of Variation

Table 3. 4 Mann-Kendall trend test and Sen's slope of discharge at Nong Son gauging station

Month	Kendall's Tau	*p*-value (two tailed test)	Sen's slope	Mean	Std	CV	Conclusion
January	0.199	0.077	1.800	248.497	105.451	0.424	No trend
February	0.244	0.029	1.124	140.740	46.893	0.333	Increasing trend
March	0.333	0.003	1.368	100.971	41.111	0.407	Increasing trend
April	0.331	0.003	1.214	81.069	42.644	0.526	Increasing trend
May	0.185	0.100	1.194	111.271	58.415	0.525	No trend
June	0.077	0.498	0.595	102.636	53.848	0.525	No trend
July	0.142	0.208	0.591	74.162	28.475	0.384	No trend
August	0.209	0.062	1.167	84.084	45.945	0.546	No trend
September	0.244	0.029	2.963	189.956	163.868	0.863	Increasing trend
October	0.112	0.321	4.798	657.050	333.389	0.507	No trend
November	0.093	0.411	6.839	1011.307	530.775	0.525	No trend
December	0.134	0.236	6.003	589.516	321.245	0.545	No trend

Std = Standard Deviation, CV = Coefficient of Variation

As it can be observed, the discharges at Vu Gia and Thu Bon rivers exhibit similar increasing trends with the most important ones are found at seasonal than to annual scale. For the annual statistical analysis, the discharge at Vu Gia increases approximately 1.617 m^3/s per year while discharge at Thu Bon River has a higher rate at 2.725 m^3/s per year. Although both stations reveal increasing trends in all months, the rainy season experiences stronger magnitudes than the dry season. At both stations, the most remarkable magnitudes are identified within the months of October, November and December, ranging from 4.332 - 5.126 m^3/s per year at Thanh My and 4.798 - 6.839 m^3/s per year at Nong Son, whereas the insignificant ones are found in June and July.

3.5 Regime shift analysis

The flow statistics with the regime shift of Thanh My gauging station obtained during 1976–2013 as well as the flow statistics with the regime shift of Nong Son gauging station obtained during 1976–2014 are given in **Figure 3.6** and **Figure 3.7**, respectively.

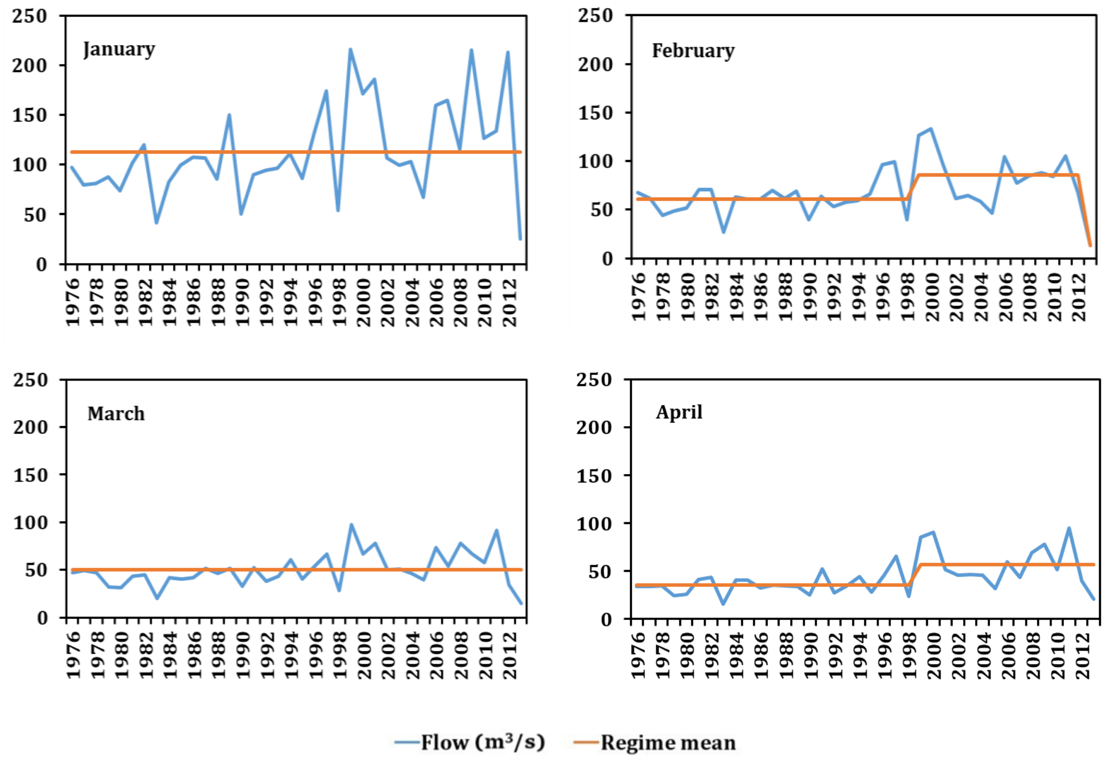


Figure 3. 6 Regime shift of monthly discharge at Thanh My gauging station for the period 1976-2013 with significance level = 0.1 and cut-off length = 2. The blue line presents the mean monthly discharge whereas orange line presents mean regime and its changing points.

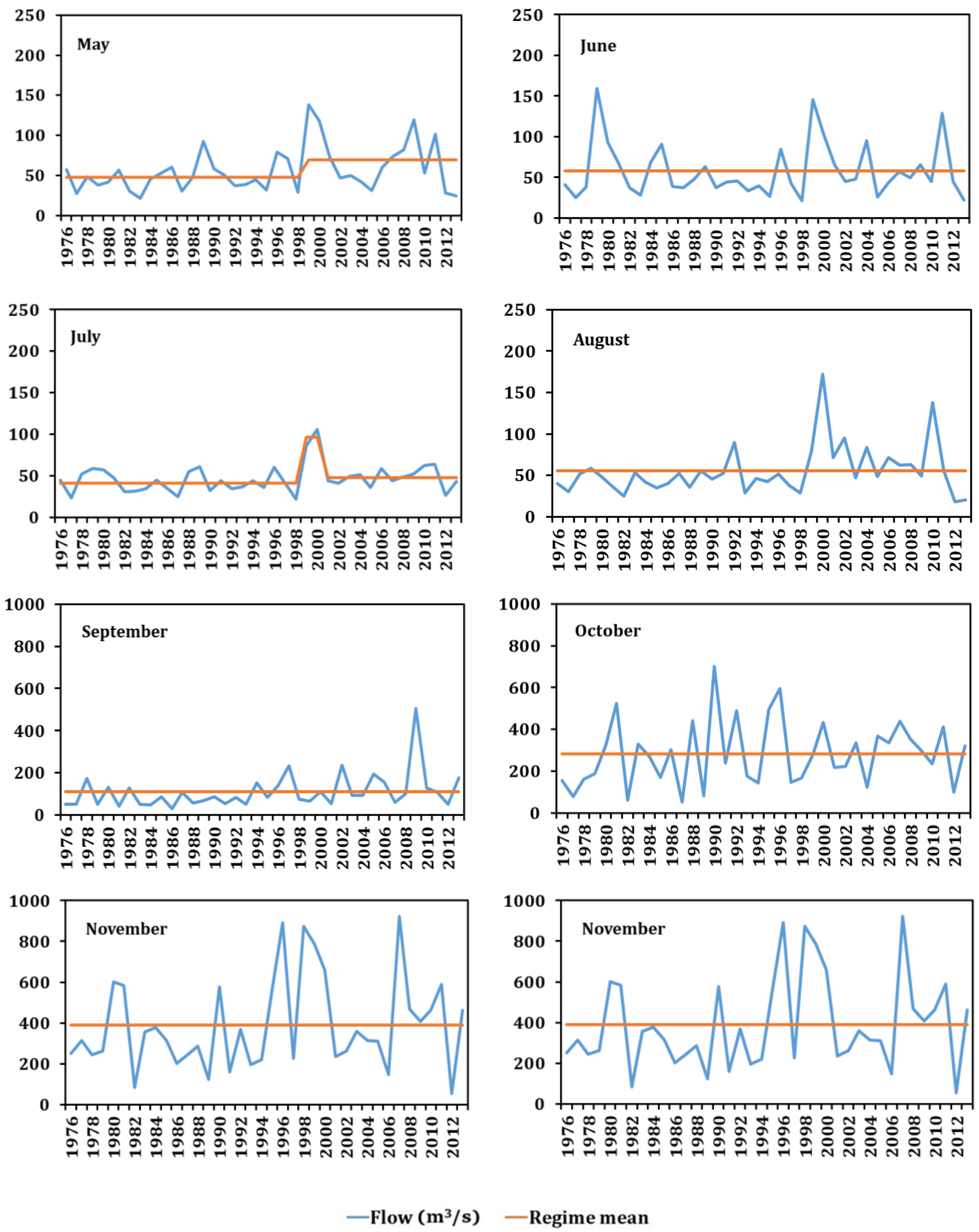


Figure 3. 6 Regime shift of monthly discharge at Thanh My gauging station for the period 1976-2013 with significance level = 0.1 and cut-off length = 2. The blue line presents the mean monthly discharge whereas orange line presents mean regime and its changing points (continued).

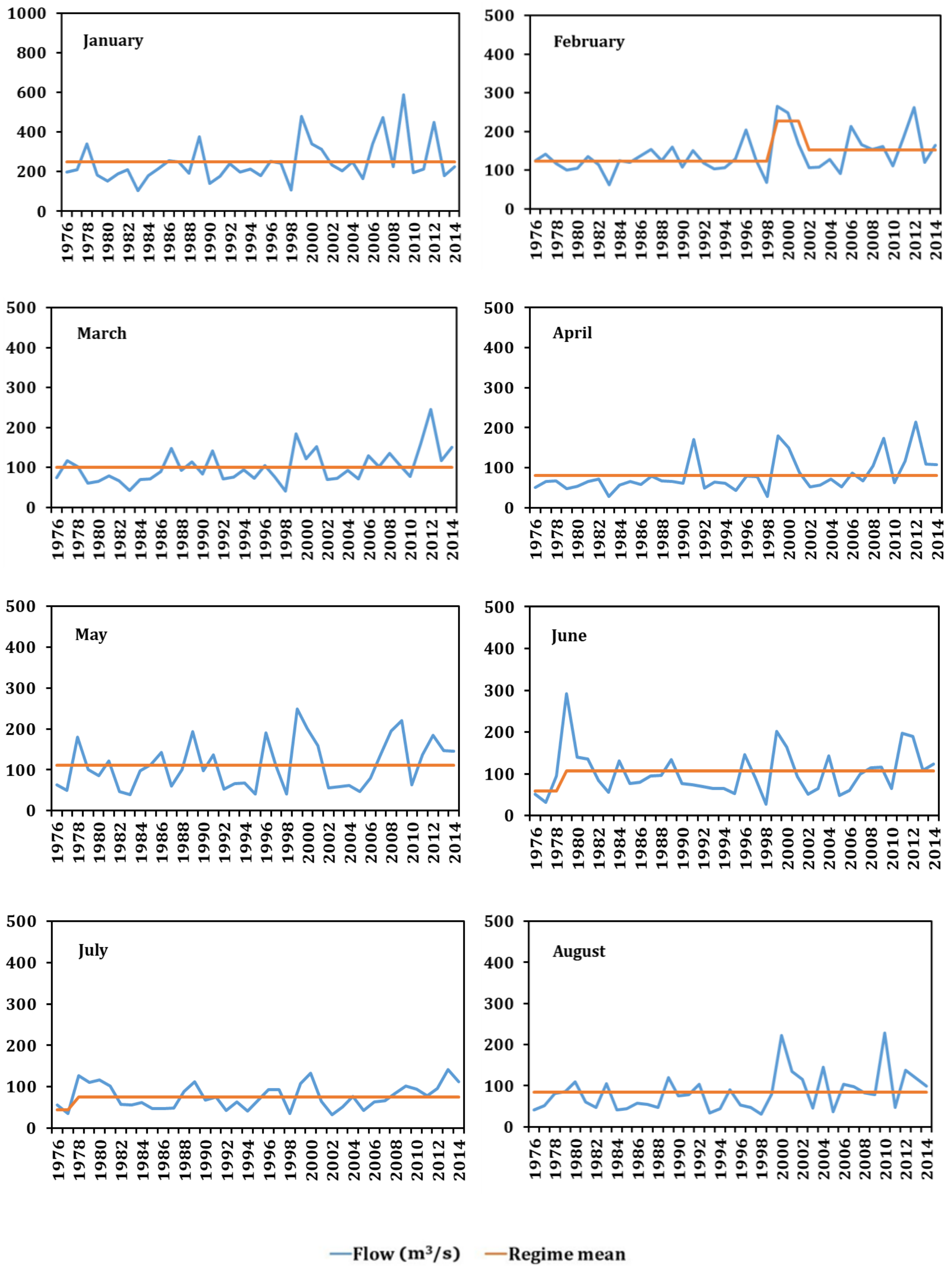


Figure 3. 7 Regime shift of monthly discharge at Nong Son gauging station for the period 1976-2014 with significance level = 0.1 and cut-off length = 2. The blue line presents the mean monthly discharge whereas orange line presents mean regime and its changing points.

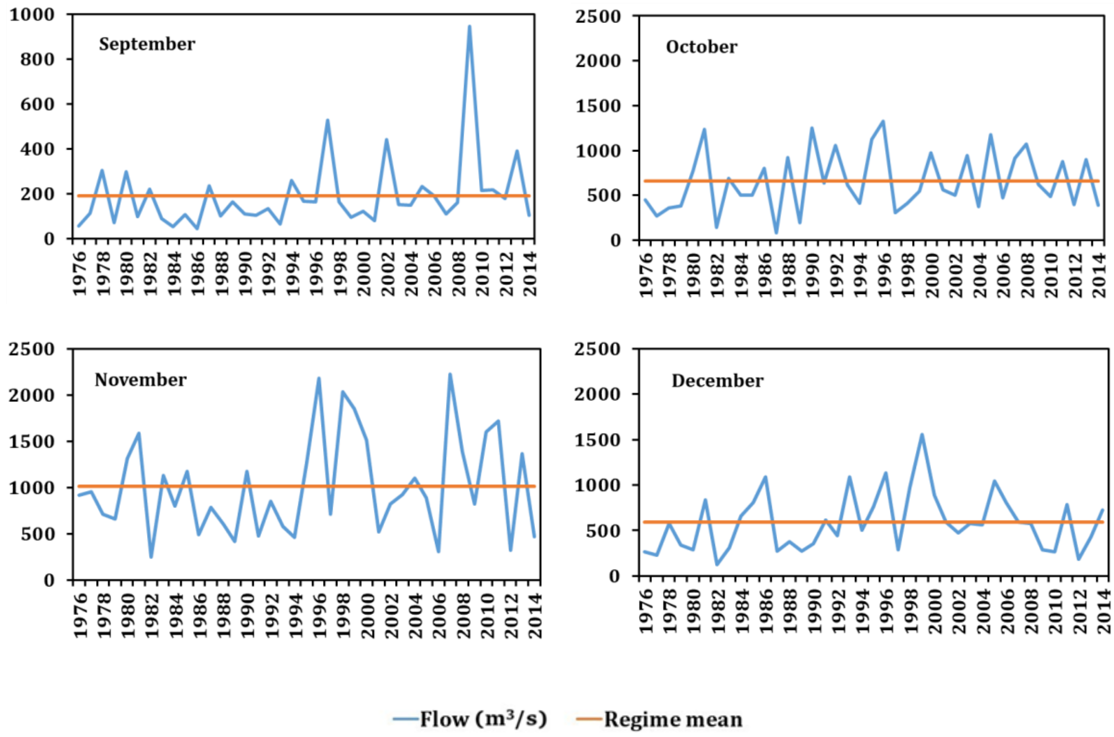


Figure 3. 7 Regime shift of monthly discharge at Nong Son gauging station for the period 1976-2014 with significance level = 0.1 and cut-off length = 2. The blue line presents the mean monthly discharge whereas orange line presents mean regime and its changing points (Continuted).

It is apparent that no statistically significant change can be detected on the flow regime in the rainy season at both stations during the investigated period. However, the prominent changes are detected in the year 1999 for some months in the dry season. The Vu Gia River experienced changes in February, April, May and July at Thanh My station while the Thu Bon River identified only one change in February at Nong Son station. Generally, a shift in the flow regime of a river can happen by natural factors or human activity (Wrzesinski & Sobkowiak, 2020). An investigation on construction of hydraulic structures in the VG – TB river basin revealed that there have been no structures constructed upstream of Thanh My and Nong Son gauging stations, until the first hydro power plant AVuong came into operation in 2008. In fact, the year 1999 which showed a significant shift in the average flow has received the highest rainfall during the period 1976-2014. (data shown in **Appendix C**). This may cause high flow discharges in the rivers, leading to the significant changes in flow regimes.

The period 2008-2013 was noticed the development of large hydropower plants in the region. Another remarkable anthropogenic impact on flow regime occurred when the hydropower plant Dakmi 4 went into operation in the beginning of 2012. The hydropower plant takes water from the Vu Gia River to operate but releases water to the Thu Bon River. Accordingly, this diversion dramatically reduced the flow in Vu Gia River which is recorded at Thanh My station. Despite the fact that mean daily discharge shows a noticeable drop in 2012 and 2013 at Thanh My station during the months in dry season, the regime shift detector was unable to recognize it. This can be regarded mainly due to the unavailability of long time series for the years after 2012 (data available until 2013 for this station). The regime shift test requires a minimum length for which the magnitude of the shifts remains intact of 2 years (cut-off length = 2). Future research with longer river discharge record might be able to detect this anthropogenic change in the river discharge.

3.6 Low flow in the Vu Gia - Thu Bon River Basin

The flow duration curve of discharge at Thanh My and Nong Son gauging stations has been drawn using mean daily discharge to provide the flow characteristics of Vu Gia and Thu Bon rivers (**Figure 3.8**). The various magnitudes of flow corresponding to exceedance probability are shown in **Table 3.5**.

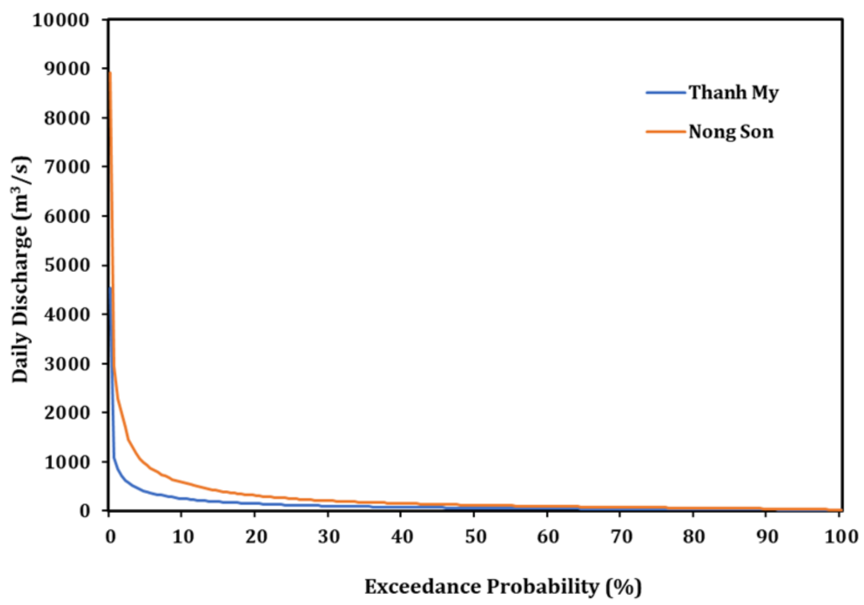


Figure 3. 8 Flow duration curve of flows at Thanh My and Nong Son gauging stations.

Table 3. 5 Discharge values at Thanh My and Nong gauging stations which correspond to the exceedance probability and recurrence intervals.

No	Exceedance probability (%)	Q Thanh My (m^3/s)	Q Nong Son (m^3/s)	Recurrence intervals (years)
1	1	846	2290	100
2	2	623	1710	50
3	5	387	936	20
4	10	251	573	10
5	20	147	311	5
6	30	101	207	3.33
7	40	76.1	152	2.50
8	50	60.2	118	2
9	60	50	93.9	1.67
10	70	42.5	75	1.43
11	80	36.2	60.2	1.25
12	90	28.3	45.5	1.11
13	95	22.9	35.8	1.05
14	100	10.9	15.8	1

The shape of flow duration curves at Thanh My and Nong Son present a similar curve with a high variation of river flows. A steep slope at the first part of the curves indicates a strong increase of discharge with decreasing recurrence rate. The graph indicates that daily discharge amounts over 387 m^3/s for Thanh My and 936 m^3/s for Nong Son occur in 5% or less cases. The shape of the curve reveals the ability of the basin to sustain low flows during dry seasons. In academic works and public studies in different regions of the world, Q95 and Q90 flows are usually considered as low flow indicators (Karakoyun *et al*., 2018). Accordingly, for annual percentile, the flow rates at 28.3 m^3/s and 22.9 m^3/s are found at Q90 and Q95, respectively for Vu Gia River (Thanh My station), whereas the flow rate 45.5 m^3/s and 35.8 m^3/s are considered at Q90 and Q95, respectively for Thu Bon River (Nong Son station).

3-month and 6-month SPEIs were calculated as the drought index from 1976 to 2014, and the results are shown in **Figure 3.9**, while the duration of drought events are summarized in **Figure 3.10**. Obviously, the region experienced more frequent drought during the years pre-2000 compared to that post-2000. There was total 25 seasonal and 13 medium-term drought events occurred during the years pre-2000 whereas only 6 seasonal and 4 medium-term events in the post-2000. Analyzing the drought events identified by SPEI03 and SPEI06 showed that the duration of seasonal drought events is longer than medium-term drought events with total 78 and 70 months, respectively. This could be seen in the years 1985, 1995, 1996, 2006, 2012, 2013 and 2014, while seasonal drought events were recognized in SPEI03, the values of SPEI06 indicate that there were no medium-term drought events. Regarding the duration of seasonal drought events, the year 1979 stand out with 8 months suffering by drought. On the other hand, total 10 months duration of medium - term drought events are found in 1983 and the maximum duration extended for 13 continuous months from October 1982 to October 1983. Concerning the intensity, 4 months of extreme medium-term drought are noticed in 1979, 1982, 1983 and 1998, while 7 months of seasonal are identified in 1977, 1979, 1982, 1988 and 1991. As mentioned in Section 3.1, there will be an additional suffering from water scarcity if drought happens during a low flow season. Obviously, they were such cases in the region during the years pre-2000. However, during the years post 2000, drought during low flow season occurred only in 2005. Analyzing the results of the SPEIs in this study reflects major drought events from 1976 to 2014. It also reveals in general that the region exhibits a decrease of droughts temporally during this investigated period in term of frequency, duration and intensity.

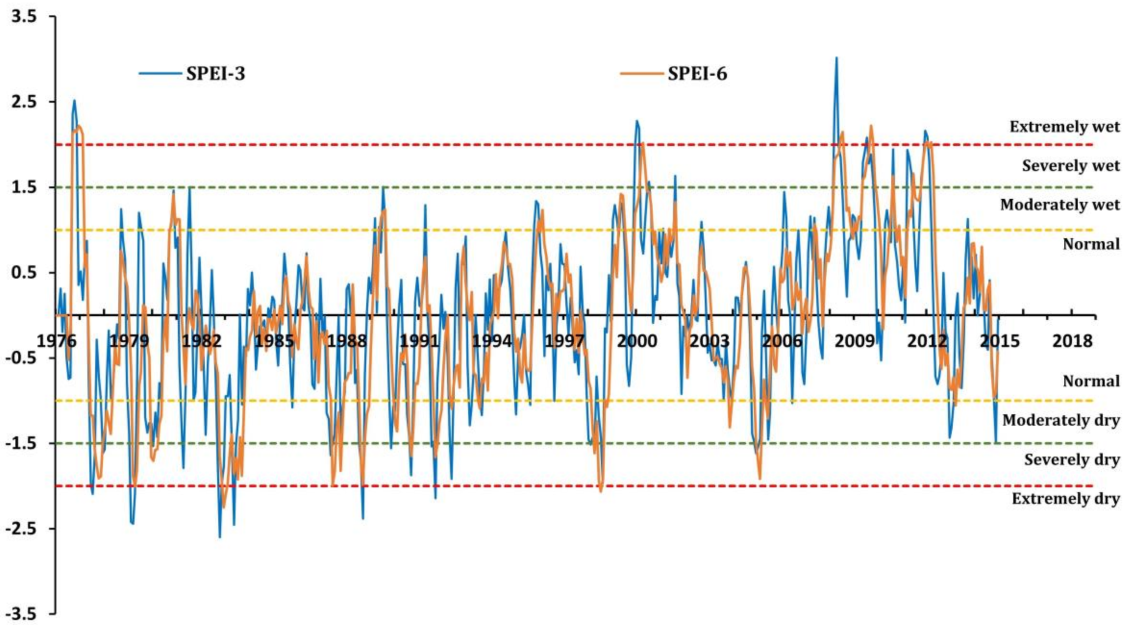


Figure 3. 9 The standardized precipitation evapotranspiration index (SPEI) 3-month and 6-month timescales during the period 1976–2014. The data used in this calculation is from Da Nang station.

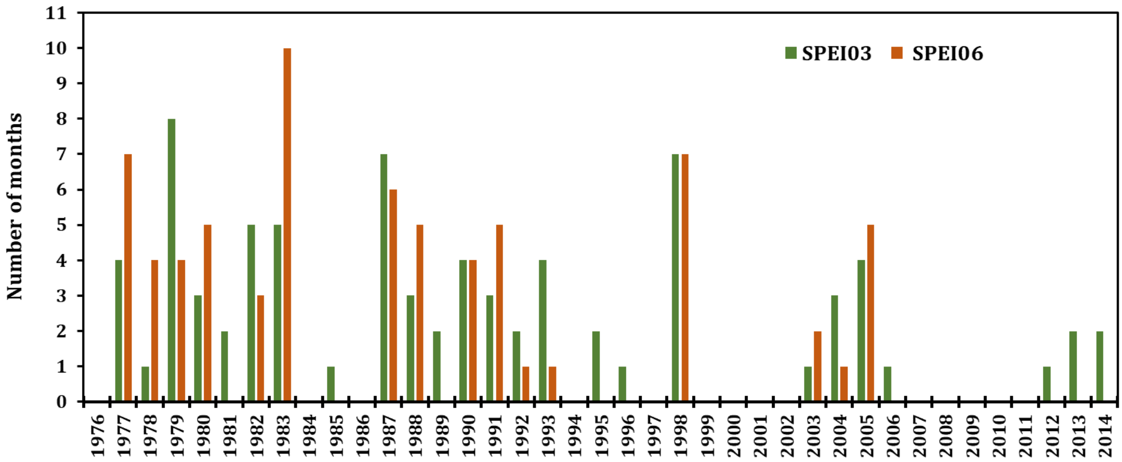


Figure 3. 10 Duration of drought events (number of months per year) including moderate, severe and extreme droughts which occurring at 3-month and 6-month timescales for the period 1976-2014. The data used in this calculation is from Da Nang station.

3.7 Conclusion

In this chapter, the low flow phenomenon in the Vu Gia – Thu Bon river basin was assessed through the analysis of discharge data at two gauging stations Nong Son and Thanh My as well as precipitation data at Da Nang station for the period 1976 – 2014. As recognized by statistical analysis, increasing trends of the runoff and precipitation has been identified in the region during the investigated period. This increase is particularly significant in the rainy season. The flow duration curve has been drawn presenting the flow pattern of the Vu Gia and the Thu Bon rivers. Moreover, the analysis of droughts showed a decrease in frequency, duration and intensity drought events for the period post 2000.

In conclusion, the use of hypothetical tests combined with sequential algorithm and Standardized Precipitation Evapotranspiration Index is an effective way to gain the understanding of the low flow and drought trends in the region. The noticeable increasing trend in rainfall and its disparity distribution at the end of dry season are helpful information for the management of agricultural cultivation. Based on that information, an adjustment in crop and irrigation should be considered to effectively use the rainfall.

This analysis provided the background of the flow regime and hydrological features that help to understand the low flow phenomenon in the region, which is crucial for further calculation of minimum flow requirement.

4 Quantification of the potential water demand for the Vu Gia - Thu Bon Delta

In this chapter, the potential water demand in the VG-TB Delta is quantified. The quantification considers the water demands for the agricultural sector, domestic supply, and the industrial supply. For these activities, the main source of water supply is fresh water extracted from rivers. Quantifying the potential water demand helps to map the water utilization pattern and to support wider water planning in the region. The quantification of potential water demand also sets the foundation for future analysis of the irrigation system performance and the determination of minimum flow requirements in the VG-TB Delta.

4.1 Overview

4.1.1 Paddy rice cultivation in the VG-TB Delta

The most important crop used as a staple food in the VG-TB is rice. It is also the dominant crop among others such as maize and peanut. The cultivation system of rice here is paddy rice. The VG-TB Delta is characterized by a warm and humid monsoon climate during cultivation periods. The type of soil in this region is mainly Fluvisol soil (**Figure 4.1**) with soil textures ranging from coarse sand to loamy soil. The planting practice of the rice in this region is by direct seeding. The cultivation period of the paddy rice from sowing to harvesting is about 110 days (16 weeks). The average time for land preparation is approximately two weeks. During this preparation period, a standing water layer of 100mm is kept in the field.

In order to quantify how much water is needed to supply the paddy rice, it is first important to know how the paddy rice is cultivated. For rice cultivation in wetland systems, the soil of paddy fields requires to be saturated which is achieved through land preparation or so-called puddling. Soil saturation is done for 2 to 4 weeks prior to seed planting (Chapagain & Hoekstra, 2010). After that, rice will be planted. From the beginning of the crop establishment until about 2 weeks before harvesting, a standing water layer is kept on the rice field. The standing water results in a constant percolation and seepage loss throughout the period (Chapagain & Hoekstra, 2010). Four different stages of crop growth are considered for the growing season of paddy rice in the VG-TB Delta. i) Initial stage: from planting through germination and plant emergence until about 10% ground is covered (about 2 weeks). In this stage, water loss is mostly evaporation. ii) Development stage: from 10% of ground cover to about 70% of ground cover (about 3 weeks). iii) Mid-season stage: from 70% ground cover to the start of maturity (about 8 weeks). iv) Late season stage: from the beginning of senescence until the crop is ready to harvest (about 3 weeks). The general scheme of water requirement for different stages of paddy rice is presented in **Figures 4.2**.

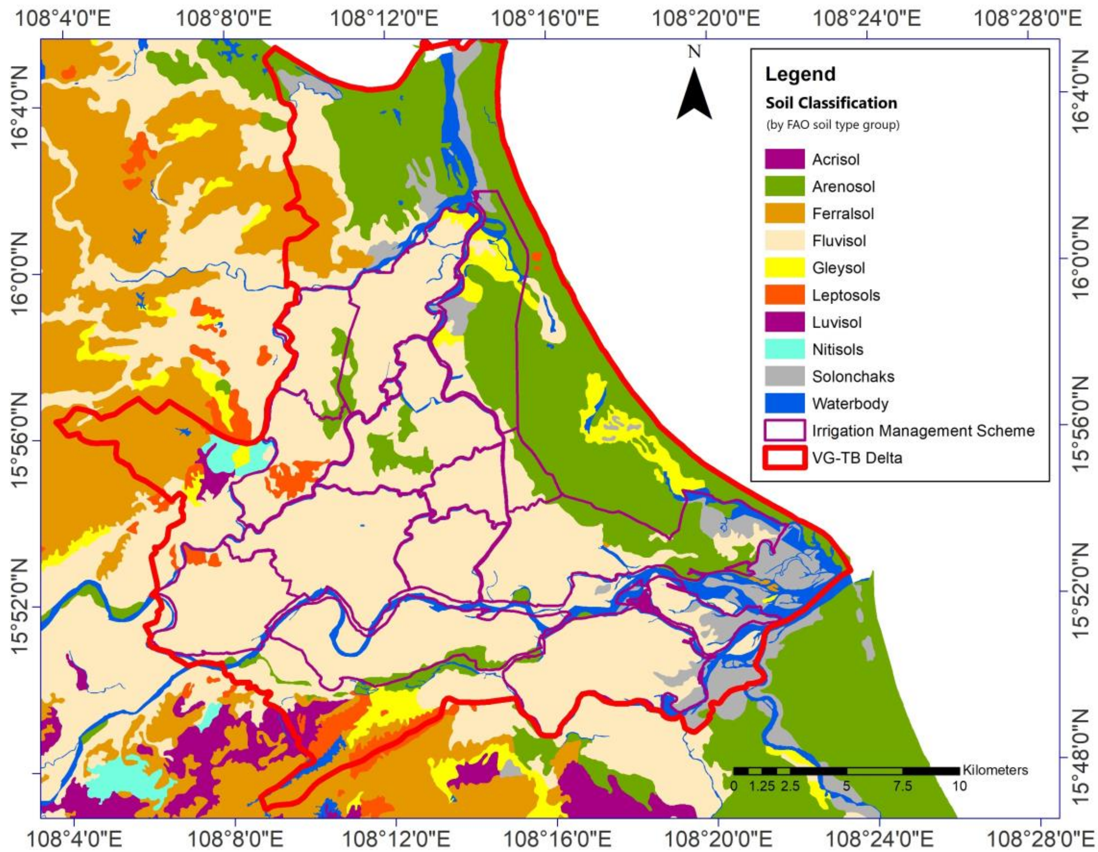


Figure 4. 1 The soil classification of the VG-TB Delta. This classification is based on the soil type group of FAO (Chesworth W. et al., 2008). Source data: MONRE

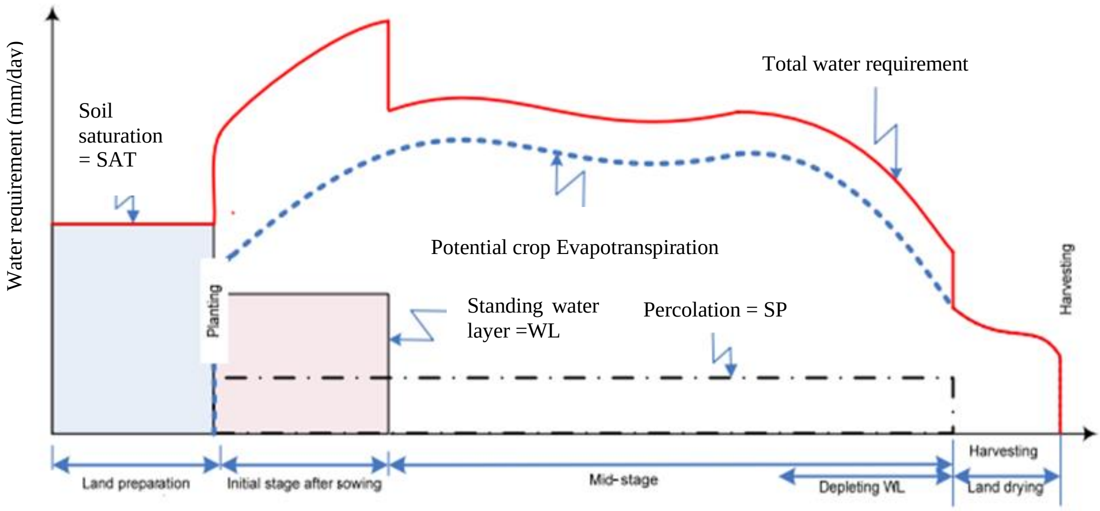


Figure 4. 2 The general scheme presenting the water requirement for different stages of paddy rice (Chapagain and Hoekstra, 2010)

4.1.2 Potential water demand in the VG-TB Delta

The potential water demand in the VG-TB Delta is the total water demand for agricultural sector, domestic supply and industrial supply. The statistical data from Da Nang and Quang Nam Statistical yearbooks as well as field research reveal that there was no aquacultural activities in the study region. Furthermore, the statistical data also shows that water demand for livestock is negligible as the livestock is raised in the small scale to partly serve individual household demands. Therefore, it is assumed that agricultural water demand only comes from crop demands. The potential water demand for agricultural sector is the sum of the water requirements for paddy rice and the water requirements for other annual crops from both crop seasons winter - spring and summer - autumn.

4.2 Quantification of potential water demand in the VG – TB Delta

4.2.1 Ground- observed data utilized in this calculation

The Da Nang station is the most representative for the study area as it is the only station situated in a lowland of the basin, with the same elevation and approximate distances (<15km) to the IMSs. Tam Ky station is situated to the south of the basin and very close to the sea, while the Tra My station is located in the mountain part of the basin. Therefore, the meteorological data of Da Nang station was used in this calculation. Daily meteorological parameters to compute Reference Evapotranspiration (ET_o) applying the Penman–Monteith method are maximum and minimum temperature (°C), relative humidity (%), wind speed (m/s) and sunshine hours.

Socio-economic statistical data were collected from the official statistical yearbook of the provinces, municipalities and prefectures in the study regions. A soil type map, land-use data, crop yield data and cultivated areas with crop calendars were obtained from the DARD in both Quang Nam Province and Da Nang City.

4.2.2 Quantification of potential water requirement for paddy rice

The water requirement for paddy rice includes the water applied during the pre-saturation period and the required water supply during the crop growing periods to compensate for the water loss through evapotranspiration, percolation or infiltration.

a. Potential water requirement for pre-saturation period

The pre-saturation duration for paddy rice in the VG-TB Delta is 2 weeks. The water requirement during pre-saturation period is calculated from equation [2] (Zawawi et al., 2010).

$$\mathrm{WR}_P = \mathrm{E} + \mathrm{SAT} + \mathrm{SP} + \mathrm{WD_i} - \mathrm{P}_{eff} \qquad [2]$$

Where:

WR_p is potential water requirement during pre-saturation period (mm), SAT is saturation water (mm), WD_i is initial depth of water layer (mm), E is evaporation rate (mm), SP is percolation loss (mm) and P_{eff} is effective rainfall (mm).

- ***Saturation of water***

The amount of water at saturation of paddy soil which depends on the porosity of the soil and depth of the top soil can be calculated as below (Zawawi et al., 2010) :

$$SAT = n\times D \quad [3]$$

Where:

SAT is saturation of water (mm), n is porosity of the plow layer soil (%) and D is depth of the plow layer (mm).

The puddling process develops a plow layer with very low hydraulic conductivity and large resistance to water movement which is essential to control the infiltration rate (Chen & Liu, 2002). In the central Viet Nam, the depth of the plow layer is about 80mm according to the Department of Agriculture and Rural Development (DARD, 2020), and the soil porosity at plow layer is 51.5 % which has been determined by The Soils and Fertilizers Research Institute of Viet Nam for Fluvial soil in the delta regions in central Viet Nam (Thuan, 2017). Therefore, the saturation of water is 41 mm. This is the total water that is required for the saturation process. It should be noted that the soil is assumed to be fully dry in this estimation.

- ***Seepage and percolation (S and P)***

Seepage and percolation rates depend on the different factors such as soil-hydraulic properties, ground water table depth, ponded water depth, field location, and condition of the bunds (Bouman *et al.*, 1994). Due to the lack of in situ experiment at the study site, the seepage and percolation value is adopted from Tuong *et al.* (1994) as 2,1mm/day. This recommended value is based on the experiment at a well puddled field during dry season for the ponding water depths of 100 mm and similar soil characteristic in this region (Tuong *et al.,* 1994). It is assumed to be constant during the growing periods.

- ***Initial depth of water layer***

For the cultivation practice in the VG-TB Delta, an average of 100mm is applied as the initial depth of water layer.

- ***Effective rainfall***

Effective rainfall is the portion of rainfall which is stored in the root zone and usable for plants. The effective rainfall is affected by different factors such as rainfall intensity, climatic parameters, crop characteristics and soil infiltration characteristics.

The crop seasons in the VG-TB Delta are cultivated during dry season under low rainfall pattern with mean monthly rainfall ranges from 34 – 217 mm. The USDA Soil Conservation Service method was employed the water balance calculations for monthly timescales and based on data representing a wide range of climatic and soil conditions. It has proven to be suitable for the areas with low intensity of rainfall (Dastane, 1974). Therefore, the USDA Soil Conservation Service method is selected over other methods to calculate effective rainfall in this study (Smith, 1992).

$$\mathrm{P_{eff}} = \mathrm{P_{tot}} \times \frac{125-0.2\mathrm{P_{tot}}}{125} \qquad \text{for } \mathrm{P_{tot}} < 250\text{mm} \qquad [4]$$

$$\mathrm{P_{eff}} = 125 + 0.1 \times \mathrm{P_{tot}} \qquad \text{for } \mathrm{P_{tot}} > 250\text{mm} \qquad [5]$$

Where:

P_{eff} is the effective rainfall; P_{tot} is the measured total monthly rainfall.

b. Potential water requirement during the crop growing period

A study by Lee *et al*. (2005) (as cited in Zawawi, Mustapha and Puasa, 2010) suggested that the water required during the crop growing period is calculated as [6].

$$\mathrm{WR}_c = \mathrm{ET_c} + \mathrm{RP} + \mathrm{SP} - \mathrm{WD}_c - \mathrm{P}_{eff} \qquad [6]$$

Where:

WR_c is the potential water requirement during the crop growing period (mm), ET_c is the potential crop evapotranspiration (mm), RP is the required ponding depth (mm), SP is the seepage and percolation (mm), WD is the water depth in the field (mm), P_{eff} is the effective rainfall (mm).

The RP and WD_c values are equal for this calculation. Therefore, the water required during the crop growing period can be written as below:

$$WR_c = ET_c + SP - P_{eff} \quad [7]$$

- ***Potential crop evapotranspiration of paddy rice***

$$ET_c = K_c \times ET_o \quad [8]$$

Where:

ET_c is the potential crop evapotranspiration of paddy rice, K_c is the crop coefficient of paddy rice, ET_o is the reference evapotranspiration.

The Penman–Monteith method recommended by FAO 56 is applied in this study for estimating reference ET (Allen et al., 1998)

$$ETo = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad [9]$$

Where:

ET_o is reference evapotranspiration [mm day^{-1}], R_n is net radiation at the crop surface [MJ m^{-2} day^{-1}], G is soil heat flux density [MJ m^{-2} day^{-1}], T is mean daily air temperature at 2 m height [°C], u_2 is wind speed at 2 m height [m s^{-1}], e_s is saturation vapour pressure [kPa], e_a is actual vapour pressure [kPa], $e_s - e_a$ is saturation vapour pressure deficit [kPa], Δ is slope vapour pressure curve [kPa °C^{-1}], γ is psychrometric constant [kPa °C^{-1}].

Due to the limited number of field experiments and in situ data, the crop coefficient in this study is adopted from FAO 24 studies for the humid and tropic Asian region (**Figure 4.3**). The mid-season crop coefficient K_c value was then adjusted for the local region using the climatic correction method (Doorenbos & Pruitt, 1977). The climatic correction equation for mid -season Kc values is as follows:

$$K_{c-mid} = K_{c-ref} + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)]\left(\frac{h_{max}}{3}\right)^{0.3} \qquad [10]$$

Where:

K_{c-mid} is midseason climate-corrected K_c value, K_{c-ref} is reference K_c value for mid-season stage defined by FAO, u_2 is wind speed measured at 2m height [m/s], RH_{min} is minimum relative humidity [%], h_{max} is maximum plant height [m].

Maximum height of the paddy rice is 1.4m within the VG-TB Delta according to DARD of Quang Nam.

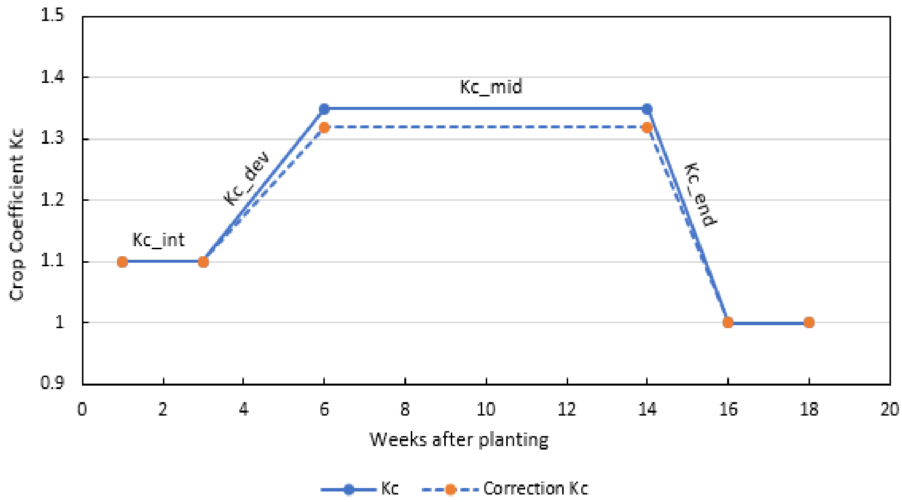


Figure 4. 3 The Crop Coefficient (K_c) of Paddy Rice during crop growing stages in VG – TB Delta

The software CROPWAT was applied to calculate the reference evapotranspiration in this study using the data of the year 2005.

4.2.3 Quantification of potential water requirement for annual crops

The main annual crops in the VG-TB Delta are maize and peanut. These crops do not require land preparation like paddy rice. The length of the growing season is about 70 days for peanuts and 80 days for maize. In this region, annual crops are often cultivated 2 weeks earlier than paddy rice in both winter – spring and summer – autumn crops, at the same time of land preparation for paddy rice.

For the annual crops, the potential water requirement is defined as the water supply necessary during the crop growing periods to compensate for water loss of disease free crop, growing in large fields under non-restricted soil conditions and given growing environment to achieve full potential production through the loss through the evapotranspiration and percolation or infiltration process (Pereira and Alves, 2013). The potential water requirement is calculated according to equation [11]:

$$\mathrm{WR}_{ca} = \mathrm{ET}_{\mathrm{ca}} - \mathrm{P}_{eff} \quad [11]$$

Where:

WR_{ca} is the potential water requirement during the annual crop growing period, ET_{ca} is the potential evapotranspiration of annual crop (mm)P_{eff} is the effective rainfall (mm).

The potential evapotranspiration of annual crop is calculated using the equation [8]. The crop coefficient K_c of annual crop was adopted from FAO 24 with climatic correction for the region.

4.2.4 Potential irrigation water requirement for agricultural sector

a. Net potential irrigation water requirement (NIWR)

The potential net irrigation water requirement in the VG-TB Delta is calculated as follow:

$$NIWR = WR_c \times S \quad [12]$$

Where:

NIWR is the potential net irrigation water requirement (m^3), WRc is the potential crop water requirements (mm 10^{-3}), and S is the cultivated area of the crop (m^2). The cultivated area of the crop is given in subsection 2.3.3, chapter 2.

b. Gross potential irrigation water requirement (GIWR)

The potential gross irrigation water requirement for agriculture is calculated considering the irrigation efficiency of the system at about 60%, defined by the IMC. This value is also verified within the research of Pedroso *et al*. (2017).

The potential gross irrigation water requirement in the VG-TB Delta is then defined:

$$GIWR = \frac{NIWR}{E} \quad [13]$$

Where: GIWR is the gross irrigation water requirement, E is the irrigation efficiency of the system.

4.2.5 Water demand for domestic supply

The basic demand for human needs such as drinking and household usage is estimated about average 50 litres of water per day (Gleick, 1996). However, this value varies significantly by country and region. In the VG-TB Delta, the water demand for domestic supply was quantified considering population number and the per capita demand (l/person/day).

The total demand per person is calculated following the Vietnamese standards on the code of basic requirements for water supply, drainage and sanitation which was issued by Ministry of Construction TCXDVN 33:2006 Water Supply – Distribution System and Facilities – Design Standards (MOC, 2006). The category of rural and urban area follows the Decree No 72/2001/ND-CP of Viet Nam Government (**Table 4.1**). The suggested per capita demand either for domestic use or industrial use in this document was based on the studies for national scale.

Table 4. 1 The capita demand of and total demand of domestic uses in Viet Nam. Source data: MOC, 2006

No	Category	Domestic water demand	
		Capita demand (a) (l/person/day)	Total demand per person (l/person/day)
1	Rural Area	60	60 + b + d
2	City (class IV, V)	60	60 + b + d
3	City (class II, III)	120	120 + b + c + d
4	City (class I)	165	165 + b + c+ d

Where: (a) The capita demand: l/person/day; (b) Water use for public services: 10% of the per capita demand. This rate is based on the average estimation for class I cities in Viet Nam by MOC; (c) Water use for industrial services in urban area: 10% of the capital demand; (d) Water loss.

For the VG-TB Delta, the water loss rate is defined as 20% of the capital demand (a) which is mainly due to conveyance and treatment processes. This rate is based on the data of the water treatment plants in the region.

Finally, the total water demand for domestic supply in the VG-TB Delta is quantified as total demand per person multiply with the population (see the cities and districts as well as population in the VG-TB Delta in **Appendix A**).

4.2.6 Water demand for industrial supply

In the VG-TB Delta, the water demand for industrial supply was quantified considering the area of industrial zones and the types of industries with per capita demand. The capita demand (m^3/person/day) for domestic and (m^3/ha/day) for industrial refers to the Vietnamese standards on code of basic requirements for water supply, drainage and sanitation “TCXDVN 33:2006 Water Supply – Distribution System and Facilities – Design Standards” (MOC, 2006). The official statistical data from Da Nang City and Quang Nam Province was utilized in this calculation.

Table 4.2 presents the capita demand of industrial water use in Viet Nam as suggested by the MOC.

Table 4. 2 The capita demand of water uses for different types of industry in Viet Nam. Source data: MOC, 2006

Category	Per capita demand (m^3/hectare/day)
Dairy products	45
Food processing	45
Beverage	45
Paper	45
Textile, garment	45
Footwears	45
Others	22

There is a total of 7 industrial zones in the VG-TB Delta with several different types of industries. Until 2005, light industry focussing on food processing, plastics, textile, footwear and garment was the main class of industry in the region. It is assumed that the industrial structure in the region remain unchanged. **Table 4.3** presents industrial zone information for the VG-TB Delta regarding area and types of industrial zones in the region.

Table 4. 3 Area and types of industrial zones in the Vu Gia – Thu Bon Delta (until 2005). Source data: Statistical Yearbook of Da Nang, 2005; Statistical Yearbook of Quang Nam, 2005

Industrial zone	Area (hectare)	Major industry
Lien Chieu	289.4	Mechanical assembly, construction material
Hoa Khanh	394.0	Electronic, food processing, plastics, construction materials
Extended Hoa Khanh	132.6	Electronic, plastics, construction materials
Thuan Phuoc	50.6	Food processing
An Don	50.1	Textile, garment, food processing
Hoa Cam	149.8	Construction materials, food processing
Dien Nam Dien Ngoc	418.0	Footwears, garment

4.3 Results and discussion

4.3.1 Potential water requirement for agricuture

Table 4.4 summarizes the results of effective rainfall, potential water requirement, net potential irrigation water requirement (NIWR) and potential gross irrigation water requirement (GIWR) for paddy rice and annual crops in the VG-TB Delta during the cultivated period 2005. Their variations with respect to the change in crop coefficient by ±10% are also presented in this table.

Table 4. 4 Summary of effective rainfall, potential water requirement, net potential irrigation water requirement (NIWR) and potential gross irrigation water requirement (GIWR) for paddy rice and annual crops in the VG-TB Delta during the cultivated period 2005 as well as their variations with respect to the change in crop coefficient by ±10%.

Month	Effective rainfall (mm/day)	Potential water requirement (mm/day)		NIWR (million m³)		Total NIWR (million m³)	Total GIWR (million m³)
		Rice	Annual crops	Rice	Annual crops		
December	2.19	3.87 ± 0.00	0.00	13.25 ± 0.00	0.00	13.25 ± 0.00	22.08 ± 0.00
January	1.09	4.30 ± 0.34	1.87 ± 0.30	14.74 ± 1.17	2.91 ± 0.47	17.65 ± 1.63	29.42 ± 2.72
February	0.21	6.48 ± 0.46	3.76 ± 0.40	20.06 ± 1.42	5.29 ± 0.56	25.35 ± 1.99	42.25 ± 3.31
March	1.11	5.65 ± 0.48	1.00 ± 0.11	19.36 ± 1.65	1.56 ± 0.17	20.92 ± 1.82	34.87 ± 3.03
April	0.39	6.00 ± 0.45	0.00	19.91 ± 1.49	0.00	19.91 ± 1.49	33.18 ± 2.49
May	0.63	9.72 ± 0.20	1.55 ± 0.21	33.33 ± 0.69	2.41 ± 0.33	35.74 ± 1.01	59.57 ± 1.69
June	0.71	9.02 ± 0.77	5.88 ± 0.66	29.91 ± 2.55	8.85 ± 1.00	38.76 ± 3.55	64.60 ± 5.92
July	3.44	4.64 ± 0.68	1.578 ± 0.58	15.92 ± 2.33	2.46 ± 0.90	18.38 ± 3.23	30.63 ± 5.39
August	4.50	3.36 ± 0.66	1.19 ± 0.17	11.50 ± 2.26	1.86 ± 0.26	13.36 ± 2.53	22.27 ± 4.21
Total				**177.98 ± 13.56**	**25.34 ± 3.69**	**203.32 ± 17.25**	**338.87 ± 28.76**

For paddy rice, the lowest water requirements fall in December and August with 3.87 mm/day and in 3.36 mm/day, respectively. Typically, the pre-saturation process in paddy rice fields for the winter – spring season started at the middle of December and finished by the end of the month. Therefore, the water requirement in December for paddy rice comes from pre-saturation process only. Furthermore, the low water requirement in August could be explained by compensation of rainfall. The month of August was recorded with the highest rainfall in the region with calculated rainfall as 4.50 mm/day. The highest water requirements for paddy rice are in May and June with 9.72mm/day and 9.02 mm/day, respectively. During May, the pre-saturation for the fields was carrying out and then following by the planting of paddy rice. Besides, the highest reference ET was found in these months with 5.95 mm/day in May and 6.48 mm/day in June (See **Appendix A**), while it was less of rainfall in the region for this period with only 0.65 mm/day and 0.73 mm/day in May and June, respectively. For annual crops, there is no water requirement in December and April. This implies that the effective rainfall in December was able to compensate for the loss of water due to evapotranspiration processes. During the April, there is no water requirement since no annual crops was cultivated in this period of time.

There are about 110.560.000 m^2 of paddy rice and 50.280.000 m^2 of annual crop in the VG-TB delta. The total NIWR is 203.32 million m^3 and GIWR is 338.87 million m^3 for two crop seasons winter – spring and summer – autumn. In which 88% are applied for paddy rice and 22% for annual crops with 177.98 million m^3 and 25.34 million m^3, respectively. The lowest NIWR fall in December with 13.25 million m^3 and in August with 13.36 million m^3 while the highest are in May with 35.74 million m^3 and in June with 38.76 million m^3. It could be seen that the second crop summer – autumn (from May to August) requires more irrigation supply with 106.24 million m^3 compared to the first crop winter – spring (from December to April) with 97.08 million m^3.

Furthermore, an error assessment was carried out to examine the change of potential water requirement as well as potential irrigation water requirement for crops corresponding to change in crop coefficient by ±10%. The month of June displays the most sensitive with the change in crop coefficient with changing magnitudes in potential water requirement are ±0.77 mm/day and ±0.66 mm/day for paddy rice and annual crops, respectively. The change in potential water requirement in June leads to the most change in total net irrigation with magnitude ±3.55 million m^3. In general, the change in crop coefficient of rice and annual crops by ±10% will lead to change in total NIWR about ±8.3%, which is approximately ±17.25 million m^3. The NIWR for rice and annual crops will vary ±13.56 million m^3 and ±3.69 million m^3 respectively. Since the water requirement for paddy rice in

December comes from pre-saturation process, there is no change in water requirement when crop coefficient is changed.

4.3.2 Total potential water demand of the Vu Gia – Thu Bon Delta

The yearly potential demand of the VG-TB Delta was calculated as 309 million m^3, of which 203 million m^3 is for agriculture, 89 million m^3 is for domestic use, and only 17 million m^3 is for industry.

Figure 4.4 presents the temporal distribution of water demand in a monthly basis. The highest demands were found in May and June with 45 million m^3 and 47 million m^3 respectively, while the lowest demand was found in September, October and November at about 9 million m^3 per month when there were no active cultivation activities.

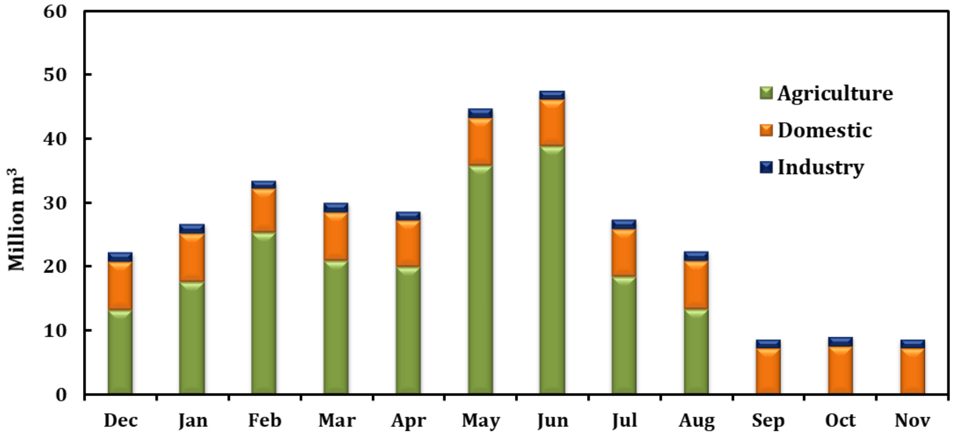


Figure 4. 4 The monthly water demand for agricultural sector, domestic supply and industrial supply (2005)

In the VG-TB Delta, part of water withdraw for domestic and industrial sectors is treated and released to rivers. In this study, the recycling rate for these categories is defined using the recorded data from wastewater treatment plants in the region. The calculation shows that 36.27% of extracted water for domestic and industrial sector will be released to the rivers. **Figure 4.5** presents the surface water withdrawal in the VG-TB Delta. It considers gross irrigation water requirement for crops, domestic and industrial uses with recycling rate is taken into account. Finally, the water extraction for irrigation, domestic and industry account for 83%, 14% and 3%, respectively.

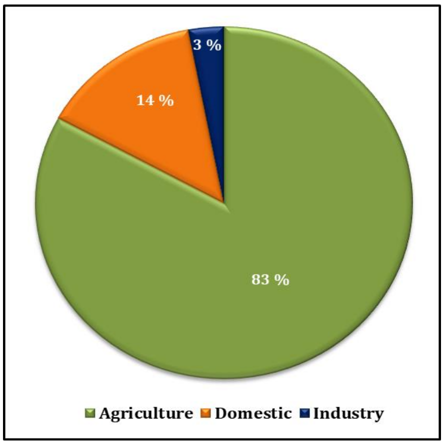


Figure 4. 5 Water extraction in the VG-TB Delta (2005)

An error assessment was implemented to examine changes in domestic and industrial water use corresponding to changes in per capita demand by ±10%. The changes in per capita demand by ±10% will lead to ±9.62 million m^3 difference in the domestic water demand and ±1.75 million m^3 in the industrial water demand. Therefore, total yearly potential demand of domestic and industrial sectors will vary ±11.37 million m^3.

4.4 Conclusion

The annual potential water demand for the VG-TB Delta was quantified considering the agricultural sector, domestic and industrial demand. This total water demand covers all activities in the downstream of the basin which required freshwater extraction from the rivers. Water demand for agriculture accounts for 83% of water extraction in the region, follows by domestic and industry. The highest potential water demand is found in May and June due to high water requirement for irrigation supply, the lowest potential water demand is in September, October and November as there is no cultivation activities in the region during this time.

It can be seen that agricultural activities consume the largest water amount in the region through irrigation supply which directly extract water from the rivers. Therefore, this activity is sensitive to hydrological change, particularly when drought happens during low flow period. An assessment of irrigation system performance is necessary to investigate wether the water availability is able to meet the irrigation supply in the region.

Finally, the water demand pattern was set for the further analysis and study of minimum flow requirements as well as water management in the region.

5 Assessing the irrigation system within the Vu Gia – Thu Bon Delta

In the context of water scarcity and conflict, the question raised is “Can the VG-TB river basin and its current irrigation system meet the agricultural water demand during low flow conditions?”. To answer that question, this chapter focuses on assessing the current irrigation practices of the VG-TB Delta in order to better understand the relationship between water availability and water supply. Review and assessment of the current irrigation system performance is undertaken to select an appropriate set of indicators. Indicator values are analyzed to understand the relation between the water demand and the water supply. The assessment has the potential benefit of improving irrigation efficiency and strategic water resource planning for the region.

5.1 Overview

Irrigation has played an important role in growing agricultural production and enhancing food security over the past decades (FAO, 2018). Globally, irrigated agriculture is the major user of fresh water, accounting for 70% of total freshwater consumption (Fischer *et al.*, 2006). The increase of population has made it crucial to use the limited available water resources efficiently. This is particularly true in developing countries, where economies mainly rely and are dependent upon agriculture (Beshir & Bekele, 2008). To meet the food demands of increasing population, safeguarding of water supply for agriculture has been set as a priority (Geleto et al., 2019). However, irrigated agriculture efficiency needs to be improved due to limited freshwater resources and increasing competition between different water users, (Molden *et al.*, 1998). Therefore, assessment of irrigation performance plays a major role in improving irrigation water management, reducing competition for scarce water resources and enhancing food security (Abuzar et al., 2017).

As the existing traditional irrigation practice is the largest water consumer in the VG-TB river basin, it is critical to assess the relation between water supply and water demand in the irrigation system (Nauditt & Ribbe, 2017). The operation of the irrigation system in the region has mainly depended on local experience in accordance with the existing conditions, hereby including water level in the rivers and saltwater intrusion situation at the time of pumping. This has often led to a mismatch between water supply and crop water needs in regard to both timing and discharge. Additionally, assessing the irrigation system helps to improve equity in water distribution and reduce the gap between potential crop water requirements and actual water use. It acts as a precondition to the effectiveness of water use, as we can use less amount of water or lower input investment but gain higher production and save more water in the freshwater sources thus helping maintain the ecological cycle and environment of the river basin (Bareng et al., 2015).

5.2 Factors impacting the performance of the current irrigation system

In the VG – TB river basin, the actual area irrigated by pumping stations in the region is only about 70% of the designed irrigated area. The performance of the current irrigation system is impacted by various factors. However, according to DONRE, (2012) main factors that cause significant impacts on the overall irrigation system performance are: i) the shortage of irrigation water due to freshwater availability, ii) a high rate of conveyance water loss.

The low flow period in the region occurs at the same time the crops are growing, typically from February to August each year. During the low flow period, water availability in the rivers is significantly reduced, resulting in an upstream movement of saltwater intrusion further. When the salt concentration at the pumping intakes exceeds the practical salinity threshold, the pumping station's operations are stopped. Therefore, excess salt concentration will interrupt the operation of pumping stations and cause a distinct shortage of irrigation water supply during the growing season. The operation of pumping stations in the region is usually affected in the following cases:

- The salt concentration which appears at the inlets of the pumping station is over the threshold 1.0 g/L.
- The duration of salt concentration under-threshold is too short for the operation of pumping stations. When the duration of salt concentration under-threshold is less than three hours, it is not possible for the operation of pumping works to respond sufficiently (Viet, 2014).
- The duration of excessive salt is retained between two consecutive of pumping events. The time between two consecutive pumping events in the region is typically from 4 – 10 days.

In addition, a dense canal system is used to convey water from rivers to supply the fields. Water loss in the canal system used for conveyance occurs due to evaporation, seepage, percolation, cracking, and damaging of the earth canal (Ali, 2011). Here, the seepage in an irrigation water conveyance system is about 40% and it is considered as a major part of the water loss in the irrigation system (Sen, Fahmida and Akter, 2018). The loss in conveyance through the seepage process is unpreventable unless the canal is concreted (Ali, 2011). In the VG-TB Delta, only 23% of the main canals in the system are concreted, the remaining parts, as well as distributing canals are earthen. As a consequence, the poor structure of the canal system causes significant loss of irrigation water, lowering the overall efficiency of water use. Suggested measures to improve this loss are concreting, proper inlet structures and regular periodical cleaning of the canal system.

In recent years, pumping stations have faced many challenges to reach their designed operating capacity. Accelerated sedimentation and erosion of the riverbeds cause reduced water levels at the pumping heads. This also causes a significant increase of sediment and sand at the suction tanks and pumps, thus reducing equipment life and increasing maintenance costs.

5.3 Relevant indicators

Given the greater concern for water scarcity and water shortage issues in the case study region, factors which focus on the efficiency of water use by the irrigation system regarding the availability of water supply and water demand are considered for the assessment. Relative Water Supply (RWS) and Relative Irrigation Supply (RIS) are used to assess an irrigation system as they illustrate the relationship between supply and demand (Al Zayed *et al.*, 2015). RWS is defined as the ratio of the total water supply to the total water demand and RIS is defined as the ratio of irrigation supply to irrigation demand (Levine, 1982). Furthermore, the performance of an irrigation system can be analyzed and interpreted at different time intervals such as annual, seasonal, monthly or special periods, as well as to compare the performance of different systems within a region (Sakthivadivel *et al.,* 1993). While RWS represents the condition of water abundance or scarcity, RIS represents how irrigation water demand is met (Levine, 1982). Therefore, RWS and RIS were chosen to assess the irrigation system in this study.

5.4 Method

As mentioned above, RWS is defined as the ratio of the total water supply to the total water demand as originally defined by Levine (1982). Values of RWS exceeding 1 indicate that there is excess water for supplying.

$$\text{Relative water supply} = \frac{\text{Total water supply}}{\text{Total crop water requirement}} \qquad [1]$$

The total water supply is the actual amount of irrigation water supply by pumping system via irrigation canals plus the total rainfall.

RIS is defined as the ratio of irrigation supply to irrigation requirement (total demand less effective rainfall) and it is the inverse of irrigation efficiency.

$$\text{Relative irrigation supply} = \frac{\text{Irrigation supply}}{\text{Irrigation requirement}} \qquad [2]$$

Irrigation supply is actual irrigation water abstracted and supplied by pumping systems via irrigation canals. The actual irrigation water supply is calculated using the daily operational data obtained for these pumping stations.

By definition, effective rainfall in some periods can be equal to or exceed the crop water requirement. In cases where effective rainfall equals or exceeds crop water requirement, there is no need for irrigation and the RIS value is zero and the higher RIS, the lower irrigation efficiency of system.

When the irrigation water supply equals the crop water demand, both RWS and RIS have a value of 1.00. This implies 100% irrigation efficiency, which is not possible under field conditions (Salvador *et al.*, 2011). However, in the real condition at the VG-TB Delta, the irrigation efficiency is at about 60% which is translated to RIS ≅1.67. This value was defined by the IMC and verified within the research of Pedroso *et al.* (2017). Therefore, an RWS or RIS value below 1.67 implies under-irrigation, whereas a value above 1.67 implies over-irrigation for the surface irrigation systems.

5.5 Results and discussion

5.5.1 Potential irrigation requirement vs actual water supply

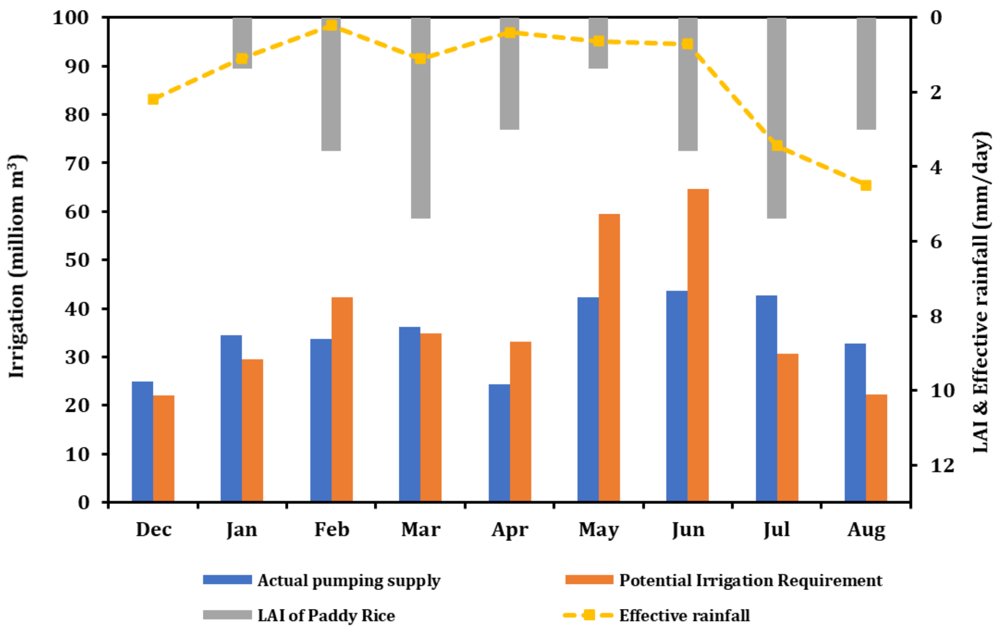


Figure 5. 1 Monthly actual pumping supply and potential irrigation requirement as well as Leaf Area Index (LAI) of paddy rice (for two crop seasons Winter – Spring and Summer – Autumn) and effective rainfall in the VG-TB Delta in 2005. The pumping data and potential Irrigation Requirement data can be found in Appendix A.

Figure 5.1 presents the comparison between monthly potential irrigation requirement and actual pumping supply of water in the VG-TB Delta. LAI values were employed from the Huyen and Minh, (2014) which were calculated for the paddy rice in Soc Trang Province, Viet Nam where the dry season and type of paddy rice are similar to the study region. In general, the situation of shortage in irrigation supply occurred in both winter – spring and summer – autumn growing seasons. During the months of February, April, May and June, the potential irrigation requirements were not met by actual pumping supply. The months from April to June were seen to be the most serious period affected by a distinct shortage of irrigation supply when the actual pumping supply was lower than the potential irrigation requirement. While the potential irrigation requirement was satisfied by the irrigation supply in December, January and March, the region was over irrigated in July and August. Recorded data reveals that the high rainfall in July and August was contributed mainly by a few big events at the end of the months (**Figure 5.2**), while the consecutive pumping events in the region was scheduled typically from 4 – 10 days. It could be the reason why in these months, the field still get irrigation supply when rainfall is sufficient.

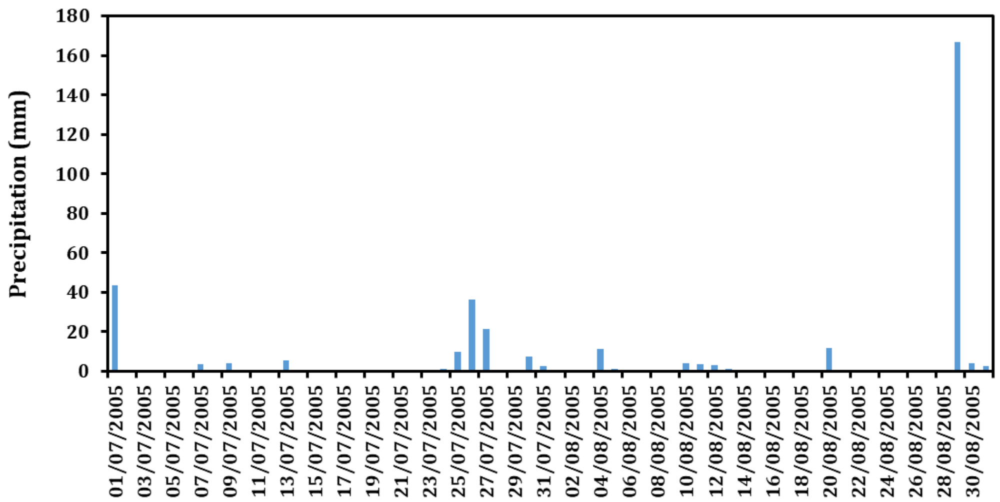


Figure 5. 2 Rainfall events in the VG-TB Delta during July and August in 2005 at Da Nang station. Data source: IMHEN

5.5.2 RWS and RIS of irrigation management schemes

Figure 5.3 presents the monthly RWS and RIS for the 13 IMSs sorted by its location from downstream to upstream. The results can be seen to differ from scheme to scheme. To understand the performance of each irrigation system, the results were analyzed individually.

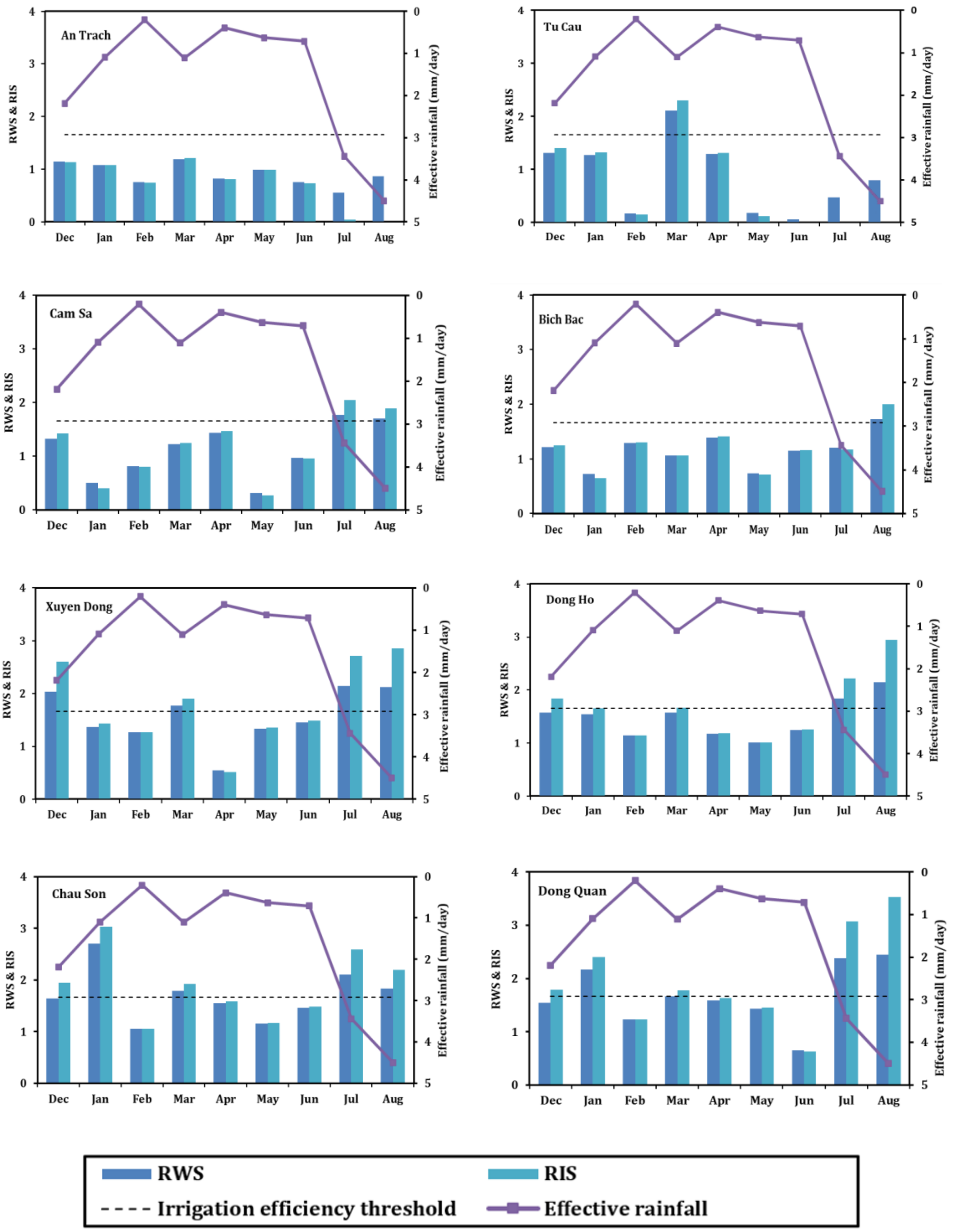


Figure 5. 3 Relative water supply and relative irrigation supply at the 13 different irrigation management schemes in the VG-TB Delta in 2005. The graphs are sorted by its location from downstream to upstream. The input data to calculate these indicators is presented in Appendix A.

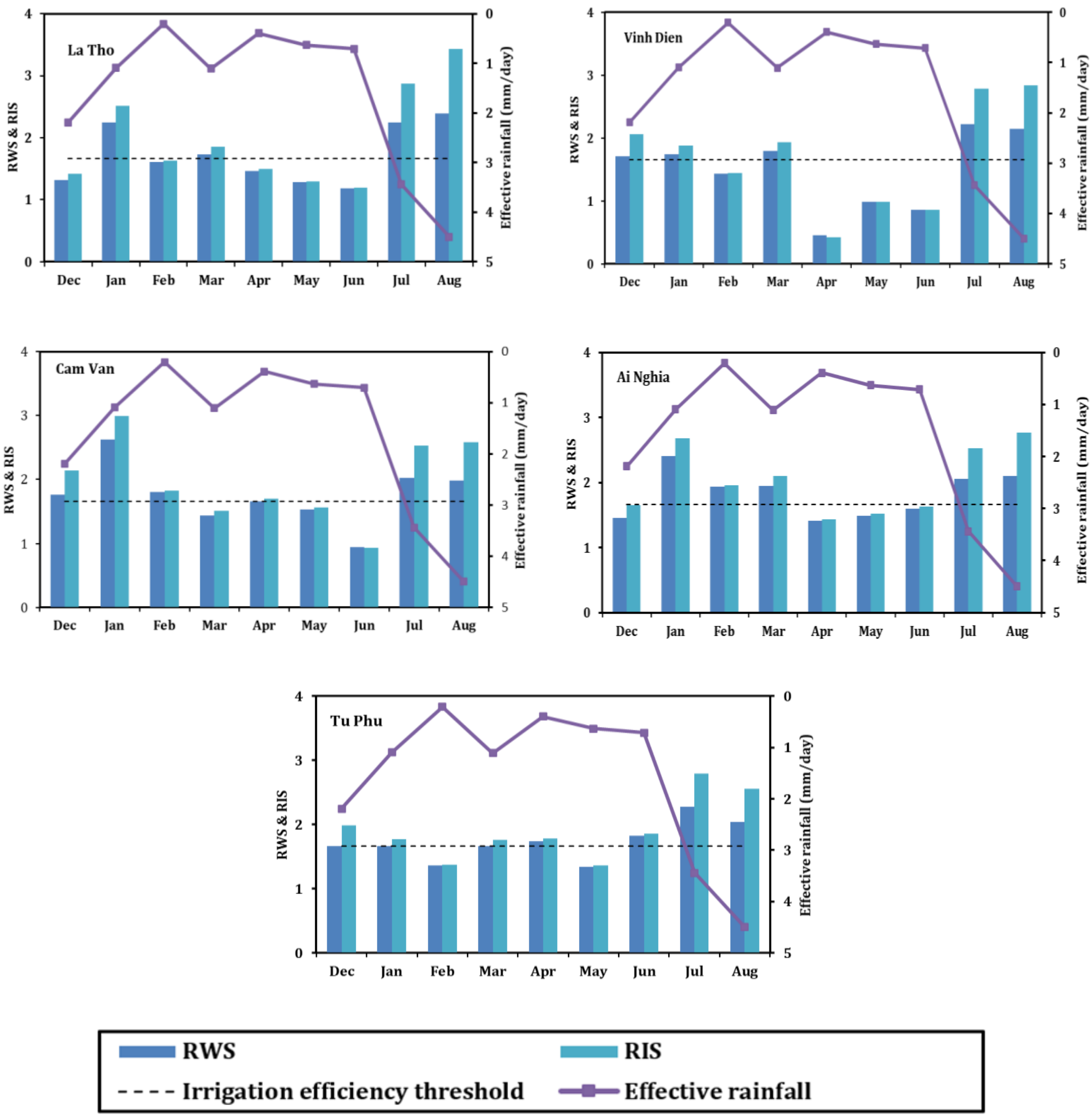


Figure 5. 4 Relative water supply and relative irrigation supply at the 13 different irrigation management schemes in the VG-TB Delta in 2005. The graphs are sorted by its location from downstream to upstream. The input data to calculate these indicators is presented in Appendix A (Continued).

The values of RWS and RIS plotted in **Figure 5.3** indicates a wide variation in the RWS and RIS values among the studied systems. Values for RWS vary between 0.06 and 2.63, whereas values for RIS ranges from 0 to 3.03. The values 0 fall in June, July, August at Tu Cau IMS and in July, August at An Trach IMS when these pumping stations were not operated due to high salinity concentration at the pump heads. Where the indicator values show a lower magnitude, it indicates a more constrained water supply and irrigation supply situation.

Basically, most of IMSs suffered from a deficient water supply in the months of February, April, May and June. While in the winter – spring season, the irrigation management schemes suffered from under-irrigation and water supply during the land preparation period in December and at end of the season in beginning of April, the summer – autumn season incurred a longer suffering period starts from end of April, May and June. The low rainfall during low flow which accelerated salt intrusion was the main problem for irrigation supply in this period.

The An Trach, Bich Bac pumping stations are located in very downstream of Vu Gia River, while Tu Cau, Cam Sa are at downstream of Vinh Dien River and Xuyen Dong at downstream of Thu Bon River (see location in **Figure 2.1**). Analyzing the RWS and RIS values at An Trach, Bich Bac, Tu Cau and Cam Sa IMSs revealed that these IMSs suffered from under-irrigation most of the time during growing seasons. It is likely that the topographical dependence is one of factor that contribute to the shortage of irrigation supply. The IMSs which are located in downstream get less water than the ones at upstream. Besides, the lower IMSs have longer duration of over salinity threshold that interrupt the operation of the pumping stations. The salinity data recorded at the Tu Cau pumping station displays that salt-water intrusion occurred early in February and heavily in April, May, and June. Therefore, the Tu Cau pumping station could not operate during this time. Similarly, the recorded data at An Trach also presents the interrupted operation in July and August. This could explain for the RIS values at Tu Cau at 0 in May, June, July and August. As the scheme did not receive irrigation supply from May when the summer – autumn season starts, the crops were abandoned in this scheme. Investigation on Xuyen Dong pumping record data revealed that it was also under salt intrusion during the months February to June. However, during this time, the IMS could receive supplement water for irrigation supply from Vinh Trinh reservoir which is stored water from Vinh Trinh tributary. A suggested mitigation measure was using the water from Dong Xanh – Dong Nghe reservoir which is located 15 km from the An Trach pumping station instead of water from river. This would require new investment in pipelines and increase the electric consumption, but it would address the problems of under water supply at An Trach and Bich Bac IMSs. Nevertheless, Cam Sa IMS would still suffer from an inadequate irrigation supply.

5.6 Conclusion

The two indicators namely RWS and RIS were calculated for two crops for the year 2004 – 2005 in the VG-TB Delta. Due to the constraint and intermittent gaps of data collected from pumping stations, the assessment in this study was carried out in light of a critical year which is under dry condition. The results were analyzed for a better understanding of the irrigation system performance. An intermittent shortage of water and an inefficient irrigation system were revealed after analyzing the two indicators RWS and RIS. This helps to answer the question whether the irrigation system could provide sufficiently water for agriculture during low flow situation. It also provides necessary information to develop scenario to assess the minimum flow requirement in the context of irrigation efficiency.

In conclusion, the irrigation system faces the constraint to meet the water supply demand due to under water availability and salt intrusion, especially during the period of February to June. Besides, the topographical dependence clearly affects the performance of irrigation system in the region. Thus, a better strategy to manage the operation such as optimizing the irrigation efficiency, irrigation schedule adjusting and efficiently using rainfall could be considered to enhance the irrigation system performance.

Despite large improvements could be made through these management measures, a significant improvement is always hard to achieve without major investment. When the management capacity has been reinforced and stabilized, it is worthwhile to increase the infrastructure investments.

The indicators and results can also be applied by the local stakeholders to improve the irrigation water management over schemes, as well as enabling water planners and policy makers to better rely on in their integrated water resource planning.

6 Modelling the minimum flow requirement in the Vu Gia – Thu Bon river basin

This chapter presents the calculation of the required minimum flow in the VG-TB river basin. To answer the question how much water is needed during low flow season to meet the demands of the different water users within the VG-TB river basin, an 1D Hydrodynamic model Mike 11 was set up to simulate the flow and the distribution of salinity in the rivers. The calibration and validation process were undertaken through Maning's roughness coefficient to obtain the best comparison between observed and simulated parameters for the hydrodynamic model and through the dispersion coefficient for the advection dispersion module. Finally, the flow at the upstream section of the Vu Gia and Thu Bon rivers was gradually increased in 3 m^3/s increments until the salt concentration satisfied the threshold at different control points in the downstream section.

6.1 Overview

The use of models to investigate complex hydrodynamic problems has been widely increased in the recent decades. With advances in computer technology, applied models in water resource have become more detailed for the processes they represent or approach (Loucks and Beek, 2017). Besides, the expansion in computer science has made these models to become easily accessible. Different studies were found applying hydrodynamic models to simulate the flow and salinity concentration in the estuaries and river systems such as the Mekong (Nguyen *et al.*, 2008), the Kapuas (Deynoot, 2011), and the Brahmaputra (Bhuiyan & Dutta, 2012). They are proven to be an efficient, comprehensive tool to examine the tidal influenced water dynamics as they are able to be applied for the simulation of currents, water levels, sediment transport and salinity. Therefore, hydrodynamic modeling is an advanced approach for estimating the required minimum flow within a changing system caused by different influential factors.

After analysing the system, reviewing the literature as well as justifying the objectives of this research, a full one-dimensional hydrodynamic model (MIKE 11) with two modules (hydraulic (HD) and advection-dispersion (AD)) was chosen to simulate the minimum flow requirement in the VG-TB River Basin. MIKE 11 is known as top quality river modelling and currently the most widely used (DHI, 2104). This model provided necessary information to understand the dynamic changes of water in the rivers along with saltwater intrusion in order to calculate the required minimum flow in the study area. Due to the constraint of data for the model input, the simulation of this model is carried out using data for one year 2005. However, a simulation of typical dry year 2005 serves the purpose to assess the minimum flow requirement during low flow period in the study region.

6.2 Model description and setup

6.2.1 Model schematization

Based on a field investigation, the available data, and the objectives of the research, the computational network to simulate the required minimum flows in the VG-TB river basin was defined from Nong Son and Thanh My stations to the estuary mouths, covering all of the rivers, streams, and canals in the estuary. To establish the Mike 11 model, it is critical to analyze the river system in order to generate its scheme. The estuary of the VG-TB River Basin is featured by connected rivers, pumping stations, water treatment plants and hydraulic structures. The schematic presents the connections between the water works, water sharing, water extraction and hydraulic links.

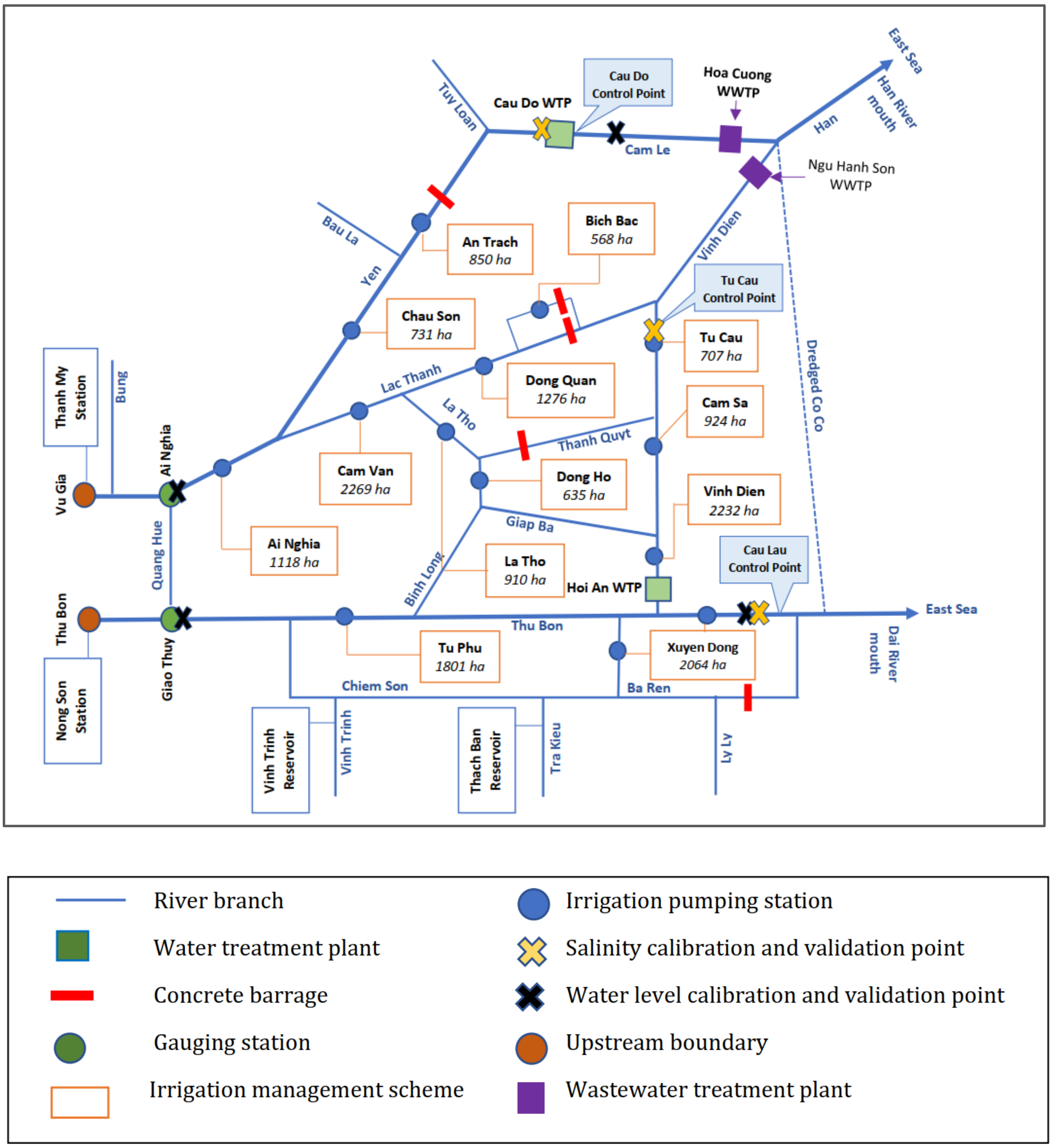


Figure 6. 1 Hydraulic scheme of the VG-TB River Basin (2005)

The main source of fresh water for the estuary comes from the two main rivers, the Vu Gia and the Thu Bon. In order to engage most of the upstream flows from the Vu Gia and the Thu Bon into the model, the upstream boundaries are selected upstream of the confluences of Quang Hue River. With this selection, the catchment area taken into account up to the Quang Hue River is 5,453 km^2 for the Vu Gia and 3,532 km^2 for the Thu Bon. Overall, the catchment area from selected upstream boundaries of the hydraulic model to the Quang Hue River accounts for 86% area of the whole basin. The selected boundaries allow modeling of the role of Quang Hue confluence on the water diversion from the Vu Gia River to the Thu Bon River as this affects the saltwater intrusion and thus, affects the minimum flow requirements in downstream.

Beyond the Quang Hue confluence, the Thu Bon River receives water from three different tributaries: the Vinh Trinh, Tra Kieu and Ly Ly. Even though the Ly Ly catchment is about 298 km^2, the river is not able to provide water for irrigation or any other purposes, as the flow is dismissed during dry period due to high water demand in the upstream section of the river. Water from two other tributaries, namely Vinh Trinh and Tra Kieu is stored in the Vinh Trinh and Thach Ban reservoir and then used for irrigation purposes, thus they supply insignificant lateral flows for the estuary. On the other hand, the Vu Gia River receives water from two different tributaries: the Bau La and Tuy Loan. The flow from Bau La is negligible due to its insignificant catchment area of only 60 km^2. The field measurement during the dry season in 2013 which has been done in the framework of LUCCi in Central Viet Nam project specified that the flow from Tuy Loan River contributed only 6% of the low flow in the Vu Gia River at Ai Nghia. This analysis implies that the hydrological regimes of the delta are defined by the upstream flows of the Vu Gia and Thu Bon Rivers combined with the tide regimes at the river mouths.

Figure 6.1 presents the computational network, covering from upstream at Nong Son – Thanh My to the estuary at river mouths. The model network presents the actual river network of the VG-TB river basin, hydrological and hydraulic regimes in the estuary and natural boundaries. The scheme begins at Thanh My and Nong Son hydrological stations which define the upstream boundaries in the hydraulic scheme while the downstream boundaries are at the Han River mouth and the Dai River mouth for Vu Gia River and Thu Bon River respectively. After Thanh My, the Vu Gia receives the amount of water contribution from Bung River. The network includes all of the rivers, streams, canals and hydraulic structures. There are 13 large pumping stations included in the computational network to simulate the freshwater extraction for irrigation. Additionally, two water treatment plants Cau Do WTP at Cam Le River and Hoi An WTP at Vinh Dien River are also considered as they represent the water withdrawal for domestic and industrial purposes. Two wastewater treatment plants Hoa Cuong WWTP and Ngu Hanh Son WWTP are taken into account as they release part of treated grey water to rivers. Hydraulic structures in the network include five concrete barrages. While An Trach, Bau Nit, Thanh Quyt are in the Vu Gia and its tributaries, two other barrages Duy Thanh and Binh Long are in the Thu Bon and its tributaries.

6.2.2 Model Equations

After analyzing the system, the model scheme was drawn to set up a full one – dimensional hydrodynamic model MIKE 11. The model includes two modules: hydrodynamic module (HD) and advection – dispersion module (AD).

a. Hydrodynamic module HD

The hydrodynamic module applies the Saint-Venant equations to solve the issues of conservation of continuity and momentum with the assumptions:

- Flow is mainly one-dimensional and subcritical (dominated by gravitational forces and behaves in a stable way)
- The water is incompressible and homogeneous
- The bottom-slope is small
- The wavelengths are large compared to the water depth to assure that the flow is parallel to the bottom.

Physical laws applied are expressed as follows:

Conservation of mass: $$\frac{\partial Q}{\partial x} + \frac{\partial z}{\partial t} = q$$

Conservation of momentum: $$\frac{\partial Q}{\partial t} + \frac{\partial(\alpha\frac{Q^2}{A})}{\partial x} + gA\frac{\partial h}{\partial x} + \frac{g|Q|Q}{C^2AR} = 0$$

Where:

Q is discharge at location x and at time t [m^3/s]; A is cross-sectional flow area [m^2]; q is lateral inflow per unit length into the segment [m^2/s]; h is stage above datum [m]; C is Chezy resistance coefficient [$m^{1/2}/s$]; R is hydraulic or resistance radius [m]; A is momentum distribution coefficient; g is acceleration due to gravity.

b. Advection – dispersion module AD

The advection – dispersion module (AD) is used to simulate the advection and dispersion of dissolved and fine suspended matter. In this research, the advection –

dispersion module is setup to simulate the salinity distribution in the river. The module is based upon the one-dimensional equation of the conservation of mass. Therefore, it requires the results file from the hydrodynamic module for the flows, water levels and channel geometry. The advection – dispersion module employs the Fick's diffusion law applies with the assumptions:

- The substance is mixed over the cross-sections
- The substance is conservative or subject to a first order reaction (linear decay)
- The dispersive transport is proportional to the concentration gradient

The physical law applied is expressed as follows

$$\frac{\partial AC}{\partial t} + \frac{\partial QC}{\partial x} - \frac{\partial}{\partial x}\left(AD\frac{\partial C}{\partial x}\right) = -AKC + C_2 q$$

Where:

C is concentration [g/m^3]; C_2 is the source/sink concentration [g/m^3]; q is lateral flow [m^3/s]; A is cross-sectional area [m^2]; D is dispersion coefficient [m^2/s]; K is the linear decay coefficient; x is space coordinate [m]; t is time coordinate [s].

6.2.3 Input data

The quality of the model simulation is related to the quality and quantity of data used. The hydrological input data for the MIKE 11 model includes river discharges at the inlet and water levels at the outlet, precipitation, water demand for agriculture, industry and domestic sectors. The measured precipitation from the stations which covers the computation area of the VG-TB river basin are used.

Geometric data of the river and hydraulic structures are required to build the river network within the model. The rivers and canal network of the model were derived from high-resolution (10×10m) ASTER satellite imagery. The imagery was projected to WGS-UTM-1984-48N applying ArcGIS before utilizing. Bathymetric data was provided by the Vietnam Institute of Meteorology, Hydrology and Climate Change (IMHEN). This bathymetric data of the Vu Gia, Thu Bon and their tributaries was surveyed in dry season 2010 under the scope of LUCCi Project.

Finally, to setup the model, the required data is summarized as follows:

(1) Model setup

- The topographical and bathymetric data including channel cross-sections and hydraulic structures (data surveyed by IMHEN in 2010, updated in 2012)
- The daily rainfall data from rain gauges within the computational network.

(2) Boundary conditions

- Observed daily discharge upstream boundaries at Thanh My station (Vu Gia River), Nong Son station (Thu Bon River), and Tuy Loan station (Tuy Loan River).
- Observed hourly water level downstream boundaries at Son Tra station for Han mouth (Vu Gia River) and Hoi An station for Dai mouth (Thu Bon River).
- Daily inflow flows of small streams entering the estuary.
- Water withdrawal for irrigation (pumping records from 13 large pumping stations) and the water withdrawal for domestic and industrial use from Da Nang and Hoi An water supply plants.
- Salt concentration data at downstream boundaries at Son Tra station for Han mouth (Vu Gia River) and Hoi An station for Dai mouth (Thu Bon River).

(3) Calibration data

- Observed water level from the same period December 2004 to August 2005 was used to calibrate the hydrodynamic module.
- Observed salt concentration from February– July 2005 was used to calibrate the advection-dispersion module.

(4) Validation data

- Observed data of water level from December 2009 to August 2010 was used to validate the hydrodynamic module due to the availability
- Observed salt concentration data from March - July 2010 was used to validate the advection-dispersion module.

6.2.4 Model setup

The computational network expands from Nong Son and Thanh My stations to the estuary mouths, covering all of the rivers, streams, and canals in the estuary. The hydrodynamic model was constructed ensuring the following requirements:

- The network includes all the diverted water structures and hydraulic works in the computational area to make sure that any changes in the system will induce the corresponding changes in the others.

- The computational network represents the actual river network and the controlled natural boundaries of the hydrological and hydraulic regimes in the Vu Gia – Thu Bon river basin.

The model is expanded with the Advection – dispersion parameters editor to simulate the distribution of salinity in the river network. Finally, the computational area of hydraulic area for simulating saltwater intrusion in the estuary consists of:

- 15 river branches and tributaries
- 301 channel cross-sections
- 2 downstream water level boundaries
- 2 upstream discharge boundaries
- 5 concreted barrages
- 13 large pump stations
- 2 water supply plants
- 2 wastewater treatment plants

The simulation results can be extracted for certain points within the computational network. The water level was simulated at 259 points while the discharge was simulated at 221 points along the rivers. The salinity distribution can be extracted at 480 points within the network.

6.2.5 Model performance

The performance of the model was evaluated using three goodness-of-fit criteria recommended by the ASCE Task Committee (ASCE, 1993). These were the root means squared error (RMSE), the Nash Sutcliffe model Efficiency coefficient (NSE) and the correlation coefficient (R^2).

While NSE is used to assess the predictive power of models and RMSE is a measure of how well the model predicts the response, R^2 is a statistical measure of how well the regression line approximates the real data points. The value NSE or R^2 of 1.0 indicates a perfect fit whereas a value RMSE of 0 indicates a perfect fit to the data. For the calculation of R^2, it is required to calculate Pearson correlation (R) and then square it. The equations to calculate these indicators are as following: [2]

$$R = \frac{\sum_{i=1}^{n}(H_{obs,i} - \overline{H}_{obs})(H_{sim,i} - \overline{H}_{sim})}{\sqrt{\sum_{i=1}^{n}(H_{obs,i} - \overline{H}_{obs})^2 \sum_{i=1}^{n}(H_{sim,i} - \overline{H}_{sim})^2}} \quad [1]$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(H_{obs,i} - H_{sim,i})^2}{n}}$$

$$NSE = 1 - \frac{\sum_{i=1}^{n}(H_{obs,i} - H_{sim,i})^2}{\sum_{i=1}^{n}(H_{obs,i} - \overline{H}_{obs})^2} \quad [3]$$

where:

$H_{obs,i}$ *and* $H_{sim,i}$ are observed and simulated values at the time step i

$\overline{H}_{obs}$ and $\overline{H}_{sim}$ are average of observed and simulated water level values.

Table 6.1 presents the reference of performance criteria for the hydrodynamic model evaluation.

Table 6. 1 Performance criteria for model evaluation (Moriasi *et al.*, 2007)

Performance indicator	Very good	Good	Satisfactory	Unsatisfactory
R^2	>0.90	0.72-0.90	0.56-0.72	<0.56
NSE	> 0.75	0.65-0.75	0.5-0.65	< 0.5

6.3 Simulation

The model was set up to simulate the minimum flow requirement for the dry season of 2005 using the timeseries from December 2004 to August 2005. The simulation includes the processes of calibration and validation of the model. There are several elements that impact on the model accuracy. However, bed roughness is a primary calibration variable for all coastal and estuarine models, presenting in Manning's coefficient (Williams & Esteves, 2017). Thus, the calibration and validation processes were undertaken through Manning's roughness coefficient n to obtain the best comparison between observed and simulated parameters for the hydrodynamic module. Based on the relevant literature and previous research within the VG-TB river basin, the values of roughness are available. Therefore, trial and error is a suitable and simplest method in this case. The model firstly was calibrated to ensure that the simulated values and the observed data (in 2005) match well. After that, the calibrated hydrodynamic model was then run using an independent dataset (in 2010) for the validation process, and the simulated and observed values were compared. It was necessary to use two independent datasets for the calibration and validation processes. For the advection-dispersion module, the dispersion coefficient was utilized for the calibration process. In both processes, the higher the agreement values are, the better the model is.

6.4 Calculation of the required minimum flow

After the model was set up, the minimum flows were calculated by simulating increased discharge at the upstream boundary until the salt concentration was under the threshold at the defined control points. The control points are the end - water supply points at the downstream to ensure the water supply function of irrigation pumping stations and water treatment plants are satisfied.

The control points were defined at the end points of water users in Vu Gia, Thu Bon and Vinh Dien Rivers. They were Cau Do (where is Cau Do WTP), Cau Lau hydrological station (where is Xuyen Dong pumping station) and Tu Cau (where is Tu Cau pumping station), respectively **(Figure 6.1)**. At Cau Do where there is a water treatment plant, the salt concentration is controlled under the threshold of 0.25 PSU (Practical Salinity Unit equal with 0.25 g/L) according to the standard of drinking water supply Viet Nam. At Cau Lau and Tu Cau where there are pumping stations, the salt concentration is controlled under the threshold of 1 PSU (Practical Salinity Unit equal with 1 g/L) as this is the standard for paddy rice irrigation.

To test the response of salt intrusion in the downstream and define the required minimum flows, the flow at the upstream sections of Vu Gia and Thu Bon were gradually increased in $3m^3/s$ increments until the salt concentration satisfied the threshold.

6.5 Results

6.5.1 Calibration

a. The Hydrodynamic module

In the VG-TB River Basin, the Manning's roughness values were found to be higher upstream than downstream which is ranged from 0.040 – 0.060 at upstream and 0.020 – 0.035 at the estuary (**Table 6.2**).

Table 6. 2 Range of roughness in the VG – TB river basin

River	Reach kilometer (km)	Range of roughness
Vu Gia	0 - 41	0.040 – 0.052
	41 – 64	0.035 – 0.042
	64 – 79	0.020 – 0.035
Thu Bon	0 - 28	0.042 – 0.060
	28 – 47	0.030 – 0.042
	47 - 62	0.020 – 0.030
Vinh Dien	0 - 23	0.030 – 0.045
Quang Hue	0 - 6	0.025 – 0.030

Figure 6.2 presents the comparison of daily observed and simulated water levels at the 4 different gauging stations Ai Nghia, Giao Thuy, Cam Le and Cau Lau in the calibration process.

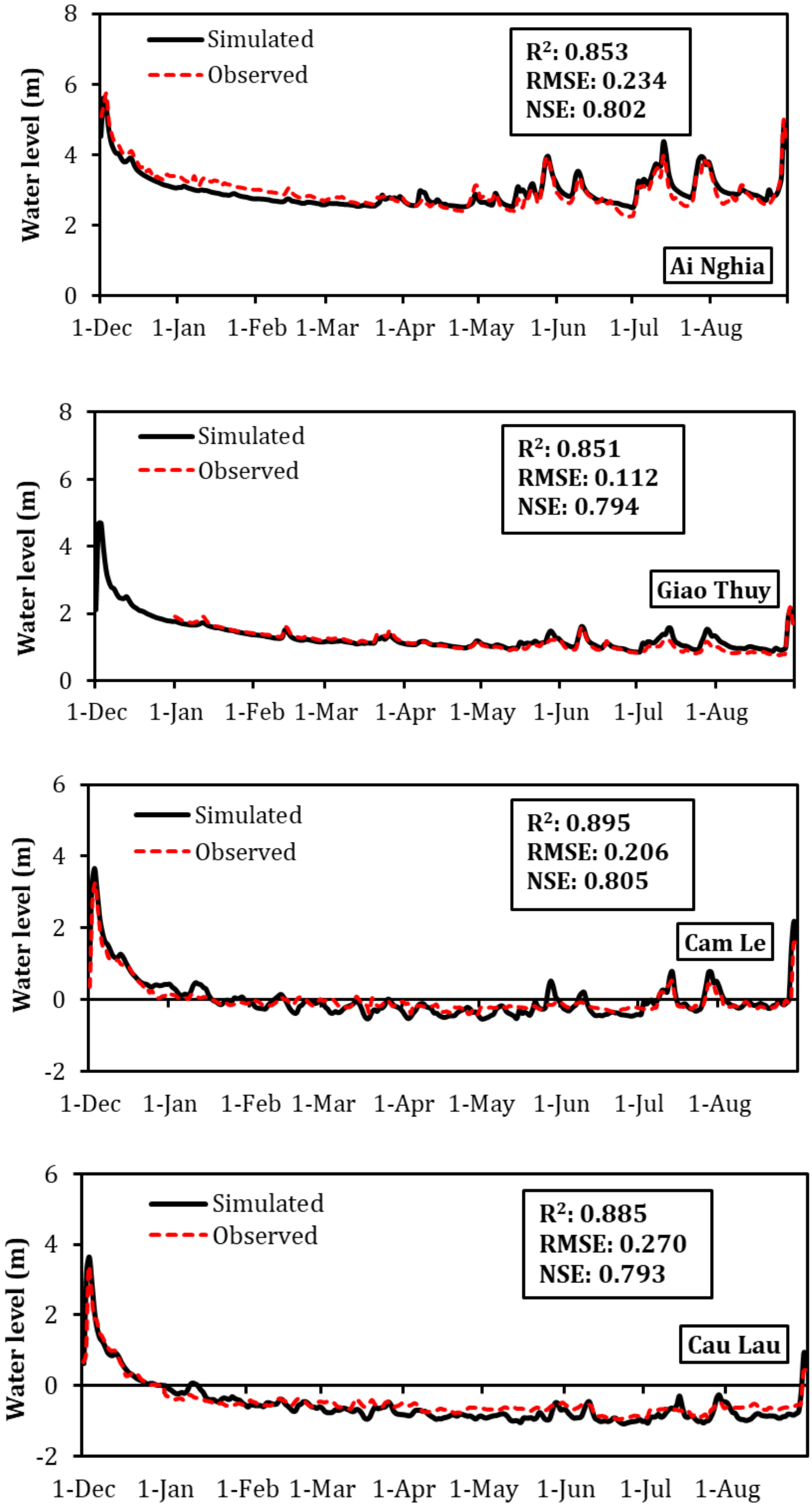


Figure 6. 2 Comparison of temporal variation between daily observed and simulated water level in 2005 as well as performance criteria at 4 calibrated points Ai Nghia, Giao Thuy, Cam Le and Cau Lau gauging stations in the calibration process. It should be noted that the water level is negative due to the low absolute altitude at the measured point.

It can be seen that the daily simulated water level is well captured with the observed water level at all examined gauging stations. The performance criteria R2 are 0.853, 0.851, 0.895 and 0.885 at Ai Nghia, Giao Thuy, Cam Le and Cau Lau respectively. Similarly, NSE values range from 0.793 at Cau Lau station to 0.805 at Cam Le station. Moreover, RMSE values vary from 0.112 to 0.270. These values prove that the calibration of the model shows the good fit between the simulated and observed data.

b. The Advection – dispersion module

Figure 6.3 presents the comparison between observed and simulated salinity values as well as performance criteria at Cau Do and Cau Lau stations in the calibration process.

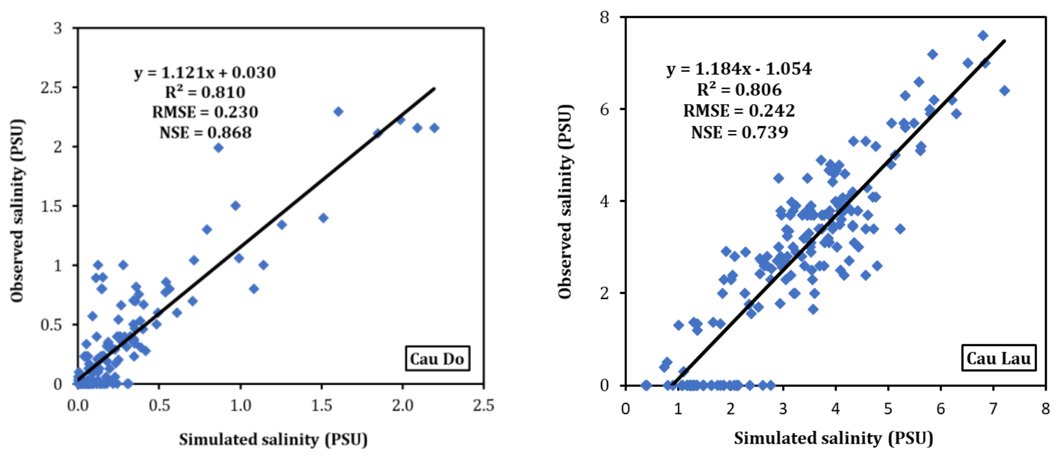


Figure 6. 3 Comparison between observed and simulated salinity as well as performance criteria at Cau Do and Cau Lau station in the calibration process in February– July 2005. The observed salinity data was taken at Cau Do WTP (provided by Cau Do WTP) and at Cau Lau gauging station (provided by IMC). Please noted that the samples of salinity were collected at different depths and the results are on mixing samples.

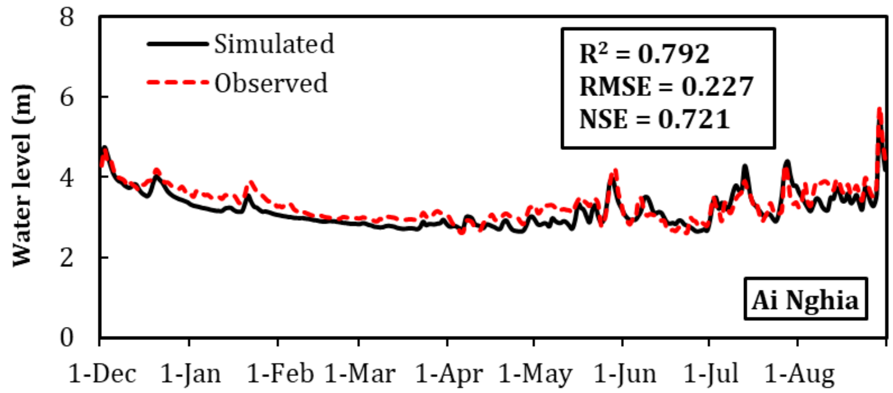
The performance criteria R^2 are 0.810 and 0.806 at Cau Do and Cau Lau respectively. Similarly, NSE values range from 0.739 at Cau Lau station to 0.868 at Cau Do station. Moreover, RMSE values vary from 0.230 to 0.242.

The values of R^2, RMSE and NSE present the good agreement between the simulated and observed data in the calibration process.

6.5.2 Validation

a. The Hydrodynamic module

Figure 6.4 presents the comparison of daily observed and simulated water levels as well as performance criteria R^2, RMSE and NSE at the 4 different gauging stations of Ai Nghia, Giao Thuy, Cam Le and Cau Lau in the validation process.



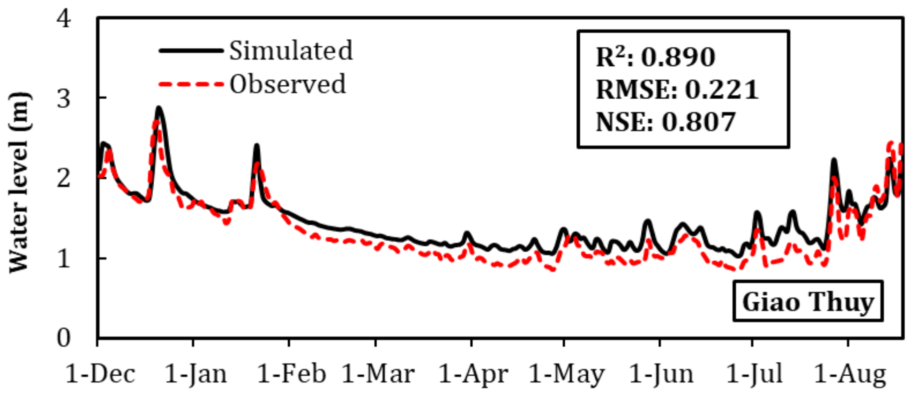


Figure 6. 4 Comparison of temporal variation between daily observed and simulated water level in 2009 as well as performance criteria at 4 validated points Ai Nghia, Giao Thuy, Cam Le and Cau Lau gauging stations in the validation process. It should be noted that the water level is negative due to the low absolute altitude at the measured point.

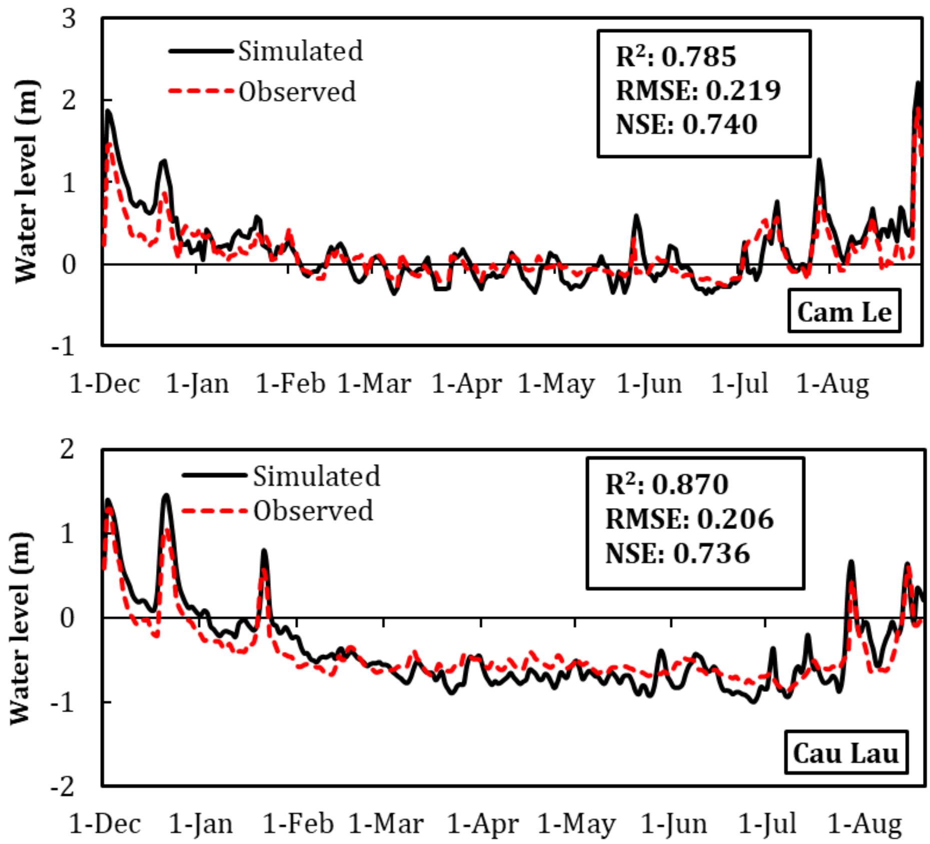


Figure 6. 4 Comparison of temporal variation between daily observed and simulated water level in 2009 as well as performance criteria at 4 validated points Ai Nghia, Giao Thuy, Cam Le and Cau Lau gauging stations in the validation process. It should be noted that the water level is negative due to the low absolute altitude at the measured point (continued).

The performance criteria R^2 are 0.792, 0.890, 0.785 and 0.870 and NSE values were 0.721, 0.807, 0.740 and 0.736 at Ai Nghia, Giao Thuy, Cam Le and Cau Lau respectively. Moreover, RMSE values vary from 0.206 to 0.227. These values show that the validation of the model demonstrated a good fit between the simulated and observed data. However, the values of performance criteria of the calibration process display the better fit between simulated and observed data than the validation process.

b. The Advection – dispersion module

Figure 6.5 presents the comparison between observed and simulated salinity values at Cau Do and Cau Lau stations in the validation process.

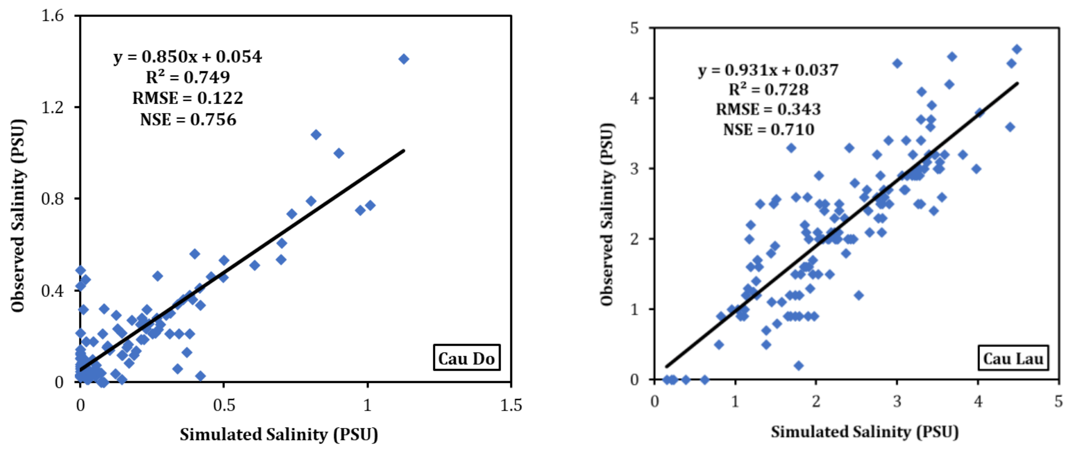


Figure 6. 5 Comparison between observed and simulated salinity at Cau Do and Cau Lau station in the validation process in March – July 2010. The observed salinity data was taken at Cau Do WTP (provided by Cau Do WTP) and at Cau Lau gauging station (provided by IMC). Please noted that the samples of salinity were collected at different depths and the results are on mixing samples.

The values of R^2, RMSE and NSE present good agreement between the simulated and observed data in the validation process.

Both calibration and validation processes showed good agreement between the simulated and observed data. The model setup was assessed to have performed well based on the values of R^2, RMSE and NSE. It can be concluded that the hydrodynamic module is accepted to simulate and compute the hydraulic processes and interest hydraulic features for the river network in the VG-TB river basin, and the Advection – dispersion module is suitable to simulate the salinity distribution is in the rivers. Therefore, the setup model is satisfactory to calculate the required minimum flow in the VG-TB river basin.

The setup model was then applied to calculate the minimum flow requirements with increasing upstream discharge in 3 m^3/s increments. For the coherence of the presentation, the results of the minimum flow requirements are introduced in the subsequent chapter.

6.6 Conclusion

The hydrodynamic model Mike 11 has been set up to determine the minimum flow requirement for the VG-TB river system. After comparing the simulated and observed data, the simulated water levels and salinity at the chosen points agree with the observed data in terms of their values, fluctuation amplitudes, and phase changes. The calibration and validation processes present the good performance of the model.

Based on the good agreement between the observed and simulated results, the applied model has proven that it is suitable for simulating the flow dynamic and salinity distribution in the VG-TB river basin. The model was then applied to simulate the minimum flow requirements under different scenarios.

7 Scenario development

In the previous chapter, the model MIKE 11 was set up to simulate the minimum flow requirement. Subsequently, this chapter focuses on the development of scenarios used to assess changes in required minimum flow in the VG-TB river basin under different conditions. Besides, an overview of scenario development provides the definition of scenarios, describes the purpose of scenario development and the basic principles of scenario approaches. The driving factors that significantly impact minimum flow changes are also identified and discussed in order to define their spatial and temporal scales of changes. Finally, the results of developed scenario are introduced.

7.1 Overview

Scenarios have been widely applied and proven to be a helpful tool to aid the understanding of the development possibilities for an area where uncertainties or future trends need to be addressed (Kosow & Gaßner, 2008). The Inter-government Panel on Climate Change (IPCC) defines scenarios as "A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces and relationships" (Nakicenovic *et al.*, 2000). Scenarios provide a rough illustration of future change by examining the driving factors (Viet, 2014). In general, scenarios focus on what might happen, and the responses toward the development of both complexity and uncertainty for an area in a future context.

There are many different scenario approaches currently used, ranging from the highly exploratory to the decision-oriented, and intuitive to analytical. For different contexts, different scenario approaches are required which reflects the level of complexity (Döll *et al.*, 2008). However, Kosow and Gaßner, (2008) suggested a general guideline to develop scenarios **(Figure 7.1)** that is widely applied such as Grecksch, (2019), Marthaler *et al.,* (2020), Terrapon-Pfaff *et al.*, (2021), This process includes five consecutive steps. The first step of the scenario process is identification of the scenario field. In this step, the precise questions will be established to address the scenario field within the scope of the study. It leads to the selection and framing of the addressed issue. The second step is to identify the key driving factors that might have significant influence on how changes occur in the future. The third step is determination of spatial and temporal scales for these driving factors. This step examines how the key driving factors will change and what range of these changes could be. This is then followed by a fourth step termed scenario logics. This step focuses on the central factors or various key factor values together that produce a short list of meaningfully distinguishable scenarios. The fifth step is the selection of a scenario type such as qualitative or quantitative, or a combination of the two. The final step is a practical process of applying tools and instruments to finalize the scenarios. In the subsequent section, the key driving factors which possibly induce the changes in minimum flow requirements in the VG-TB river basin are identified as well as their spatial and time scales are determined.

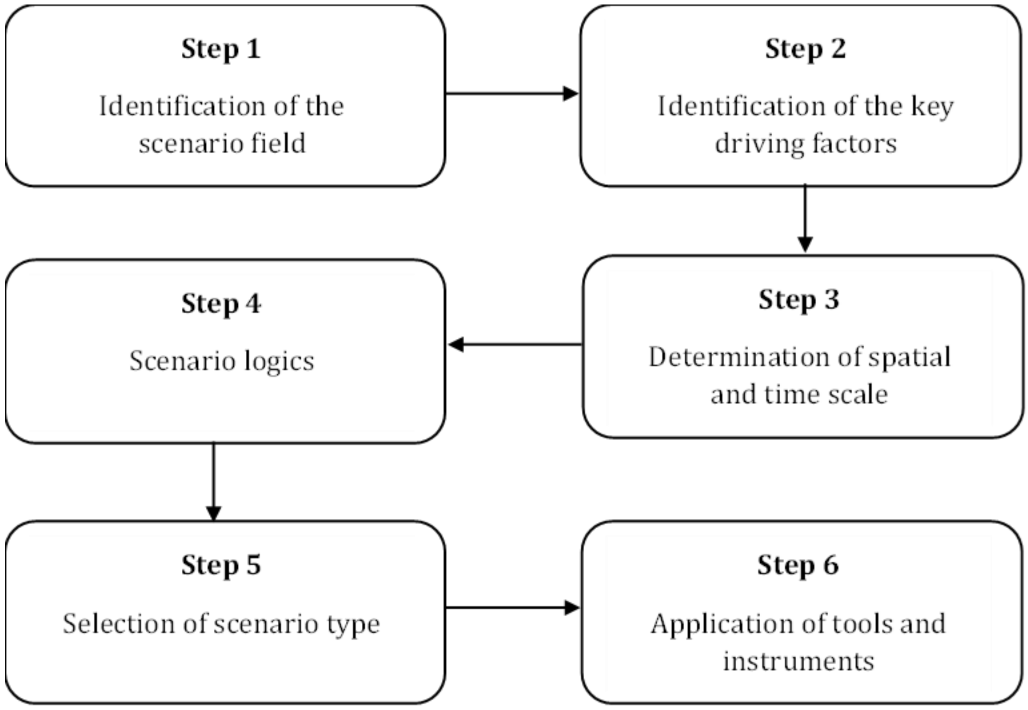


Figure 7. 1 The general guideline of scenario development suggested by (Kosow & Gaßner, 2008)

7.2 The key driving factors

The low flow occurs during the dry period in the VG-TB river basin from January to August, resulting in tidal inundation and serious saltwater intrusion that affects water supply for different water users. Since the required minimum flow in the VG-TB river system is determined to push back the saltwater intrusion and to satisfy and meet the demand of different human activities in the downstream, the research focuses on developing a set of future scenarios to examine the changes in salt intrusion situation and water supply which cause changes in minimum flow requirements. There are different factors that possibly induce the changes in minimum flow requirements in the rivers. These factors can either affect the upstream, lateral or downstream boundaries of the river system. In the context of this research, the scenarios will be constructed around three different key driving factors that are influenced by both anthropogenic and natural variables and with regard to future changes under multi-sectorial water management. These are changes in water use for domestic and industrial sectors, changes in water use for irrigation, and change in the sea level rise.

- Changes in water use for domestic and industrial sector

The VG-TB Delta has experienced high population growth and urbanization in recent years. Furthermore, the industries in the region have expanded significantly with many new industrial zones constructed in the last 10 years. The population growth and industrial expansion are two main reasons of increased water supply for domestic and industry in the VG-TB Delta. This increasing demand will lead to increasing water extraction from rivers. Consequently, it induces changes in the minimum flow requirements to meet the growing demands.

According to the data of the Vietnamese General Statistical Office, the population of the Da Nang City increased from 0.85 million inhabitants in 2005 to 1.1 million inhabitants in 2020. It is expected that the population of Da Nang City will reach 2.5 million inhabitants by the year 2050 (MOC, 2015). For the industrial sector, Da Nang City has planned to expand the industrial area by up to 5000 hectares by 2050 compared to only 1000 hectares in 2005 (MOC, 2015). Likewise, the same expansion is projected in Quang Nam Province where a change only 500 hectares to 2600 hectares during the same period is planned (MOC, 2015). It is assumed that the categories of industry will not change. To cope with this change in domestic supply, the required water supply demand will increase from 2.7 m^3/s in 2005 to 8.1 m^3/s in 2050. Similarly, the required water supply demand for industry will increase from 0.6 m^3/s to 3 m^3/s.

- Changes in water use for irrigation

There are two main factors that cause changes in water use for irrigation in the VG-TB Delta. In recent years, the cultivated area has been reduced due to urbanization in the region. The decrease of agricultural land has resulted in the reduction of water use for irrigation. On the other hand, the improvement of irrigation system will improve the efficiency of water use for irrigation. Since the improvement of irrigation system helps to reduce the water loss of conveyance, the gross water use for irrigation will be reduced. Any change in water extraction will cause change in minimum flow requirements in the rivers. In the analysis of the local irrigation system based on soil types as well as canal length and the optimal irrigation efficiency of FAO (Brouwer *et al.*, 1989), the value 75% was selected as a realistic improved irrigation efficiency for this scenario.

- Change in sea level

The main contributors to the sea level rise in Viet Nam are the thermal expansion of the oceans, ice sheet dynamic and ice melting (MONRE, 2016). Sea level rise will increase the saltwater intrusion further upstream (Viet, 2014). Therefore, it increases the required minimum flow to control salt concentration under current thresholds for the operation of irrigation pumping stations and water supply plants in the delta. Analyzing recorded data in the period 1984 – 2005 at Son Tra oceanographic station (see location in **Figure 2.1**) indicated the increasing trend in sea level at a rate 0.36 cm/year (**Figure 7.2**). This rate is fairly high compared to the global rate of 0.17 cm/year over the last century (Bindoff *et al.*, 2007). The projections of sea level rise for the study region by MONRE is presented in **Table 7.1** (MONRE, 2016). It was assumed that the tidal ranges would not be affected by sea level rise and that those values remain unchanged.

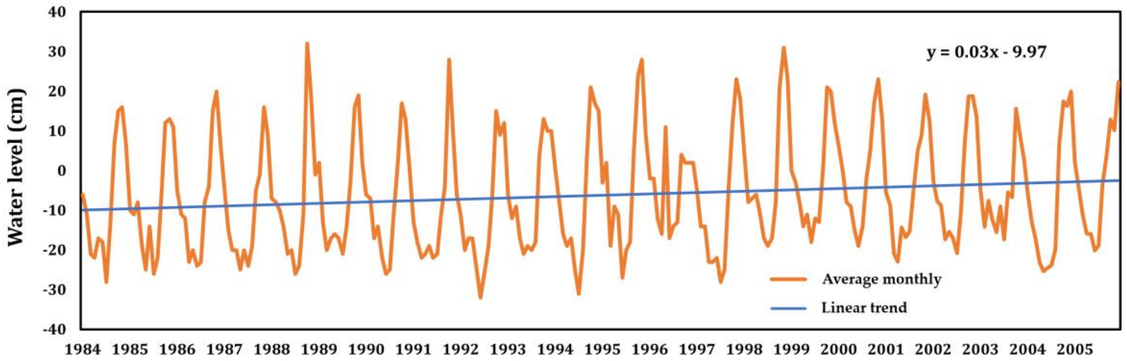


Figure 7. 2 Average monthly water level at Son Tra oceanographic station during period 1984 - 2005

Table 7. 1 The mean sea level (cm) rise projections for the study region compare to the period 1986 - 2005. Source: MONRE, 2016

Year	2030	2040	2050	2060	2070	2080	2090	2100
Sea level rise (cm)	+13	+17	+23	+28	34	+40	+47	+57

To sum up, **Figure 7.3** presents the visualization of the elements in the system of the VG – TB river basin under the existing condition and under the changes of key driving factors.

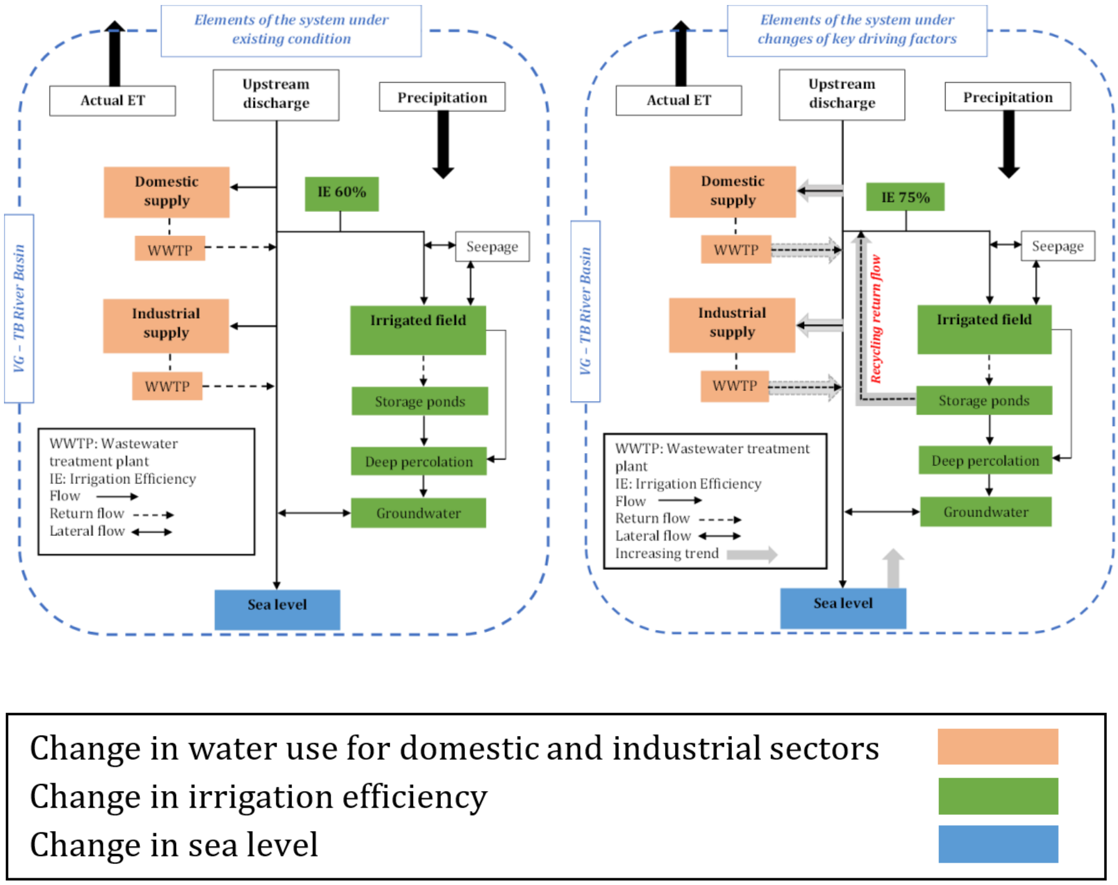


Figure 7. 3 Visualizing the elements in the system of the VG – TB River Basin under existing condition and under changes of key driving factors

7.3 Scenario development

Scenario development assists the assessment of potential future change by considering different driving factors that influence the changes. This research concerns the required minimum flow to meet the potential water demand in the region; the required minimum flow when changes in water uses; the required minimum flow in the context of sea level rise in the future; and the required minimum flow when the water use efficiency for agricultural sector is improved. Six different scenarios were developed to evaluate these changes in the region.

- The baseline scenario (S0) presents the “business-as-usual” state. Observed data in 2005 were used to develop this scenario.
- The scenario (S1) assesses the required minimum flow to satisfy the calculated potential water demand for all human activities. The potential water demand for each sector including agriculture, domestic and industry were calculated (Chapter 4). The results were used to simulate in this scenario.
- The scenario (S2) assesses the required minimum flow to satisfy the calculated potential water demand for all human activities with the change in water use due to the population growth and industrial expansion in 2050. As a result of urbanization in the region, the domestic and industrial water use increase to meet the growing demand. The projected number of populations by the General Statistical Office is used to construct this scenario. The expanded areas of industry are extracted from the master plans of Da Nang City and Quang Nam Province.
- The scenario (S3) assesses the required minimum flow to satisfy the calculated potential water demand for all human activities under the improvement of water efficiency management context. In this scenario, the water resource management in the region will be improved focus on the upgrading of the irrigation system. It helps to optimize the irrigation efficiency by reducing the loss of water during the conveyance and recycling return flow.
- The scenario (S4) assesses the required minimum flow to satisfy the calculated potential water demand for all human activities in the sea level rise context. The sea level projection in 2050 was used to develop this scenario.
- The scenario (S5) assesses the required minimum flow to satisfy the calculated potential water demand for all human activities in the sea level rise context. The sea level projection in 2100 was used to develop this scenario.

Table 7.2 presents the summary of developed scenarios with the changes in boundary conditions.

Table 7. 2 The overview of the developed scenarios

Scenario	Upstream boundaries	Downstream boundaries	Water use in the low land		
			Irrigation	Domestic	Industry
S0	$Q_{Thu\ Bon\ 2005}$ $Q_{Vu\ Gia\ 2005}$	H_{2005}	$Q_{Irrigation\ 2005}$	$Q_{Domestic\ 2005}$	$Q_{Industry\ 2005}$
S1	$Q_{Thu\ Bon\ 2005}$ $Q_{Vu\ Gia\ 2005}$	H_{2005}	Potential $Q_{Irrigation}$ *(Irrigation efficiency 60%)*	$Q_{Domestic\ 2005}$	$Q_{Industry\ 2005}$
S2	$Q_{Thu\ Bon\ 2005}$ $Q_{Vu\ Gia\ 2005}$	H_{2005}	Potential $Q_{Irrigation}$ *(Irrigation efficiency 60%)*	$Q_{Domestic\ 2005}$ + 5.4 m^3/s	$Q_{Industry\ 2005}$ + 2.4 m^3/s
S3	$Q_{Thu\ Bon\ 2005}$ $Q_{Vu\ Gia\ 2005}$	H_{2005}	Potential $Q_{Irrigation}$ *(Improved Irrigation efficiency 75%)*	$Q_{Domestic\ 2005}$	$Q_{Industry\ 2005}$
S4	$Q_{Thu\ Bon\ 2005}$ $Q_{Vu\ Gia\ 2005}$	H_{2005} + 23cm	Potential $Q_{Irrigation}$ *(Irrigation efficiency 60%)*	$Q_{Domestic\ 2005}$	$Q_{Industry\ 2005}$
S5	$Q_{Thu\ Bon\ 2005}$ $Q_{Vu\ Gia\ 2005}$	H_{2005} + 57cm	Potential $Q_{Irrigation}$ *(Irrigation efficiency 60%)*	$Q_{Domestic\ 2005}$	$Q_{Industry\ 2005}$

7.4 Results and discussion of developed scenarios

The obtained minimum flow requirement of the VG-TB river system by the simulation of Mike 11 model is presented for different scenarios below. The required minimum flow for the VG-TB river system is defined at the flow rate where salinity values at the three control points are under their thresholds. The simulation processes revealed that the Cau Do control point (see location in **Figure 6.1**) is the first to reach the flow rate that control salinity under the threshold (See the summary in **Table 7.3**). Thereafter, the flow rate is only increased at the upstream section of Thu Bon until the salinity at Tu Cau and Cau Lau (see location in **Figure 6.1**) are under thresholds. The result shows that Tu Cau is the next control point to reach the required flow rate, and Cau Lau is the last. It implies that the Cau Lau control point is required highest flow rate at upstream of the Thu Bon River to reach the required minimum flow compared to Tu Cau control point. The required minimum flow in the VG-TB river system also includes the environmental flow to maintain the estuarine ecosystem functions. The Tennant or Montana method (Tennant, 1976) defines the value of environmental flow as percentage of the average daily discharge or mean annual flow with 10% mean annual flow (Zeiringer et al., 2018). This value is also in line with the recommendation of the Viet Nam MONRE for the required environmental flow of the river system in Viet Nam. For this purpose, the observed discharge of Thanh My station (Vu Gia River) and Nong Son station (Thu Bon River) in 31 years from 1994 – 2014 were used. Finally, the environmental flows which are required to be available in the rivers were defined as 15 m^3/s and 32 m^3/s for the Vu Gia and the Thu Bon River respectively.

7.4.1 Operation of water utilizers in the Vu Gia - Thu Bon Delta

Figures 7.4 to **Figure 7.8** present the number of days that salt concentration exceeds the threshold (days/year) at control points with respect to the change in upstream discharge of the Vu Gia and Thu Bon Rivers in scenarios S1 to S5. **Table 7.3** summaries the duration of interrupted operation at control points and corresponding required additional discharge in order to satisfy the thresholds.

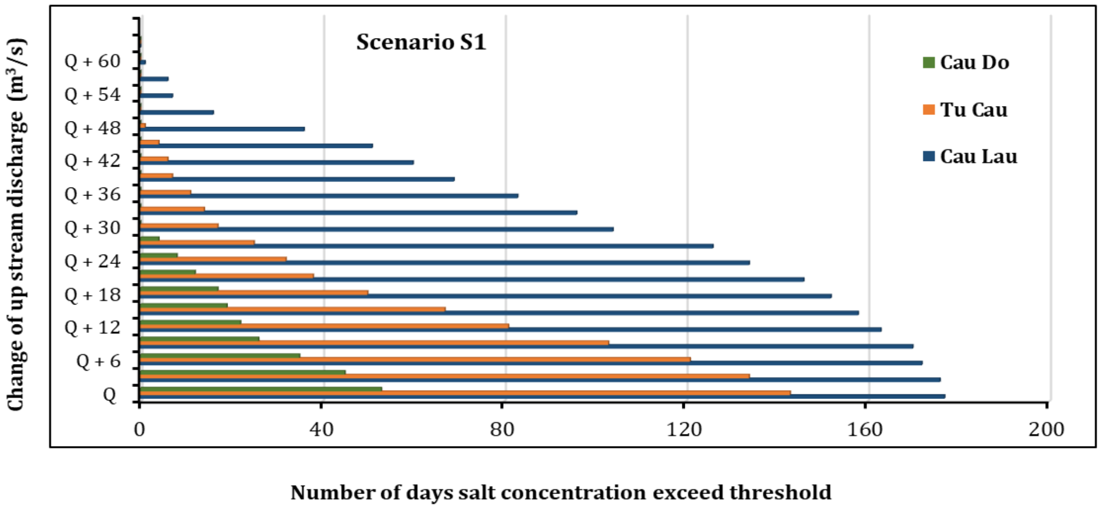


Figure 7. 4 The number of days that control points exceeds salinity threshold corresponding to changes of flow in upstream of the Vu Gia and the Thu Bon under the potential water demand scenario S1. The upstream discharge is increased at 3 m^3/s increments to see the response of salt concentration at 3 control points Cau Do, Tu Cau, Cau Lau.

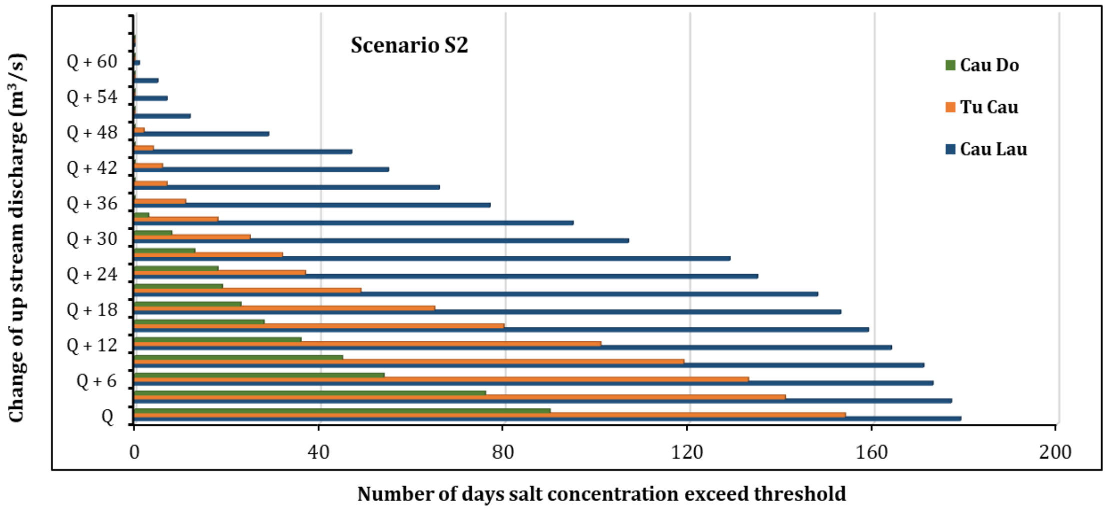


Figure 7. 5 The number of days that control points exceeds salinity threshold corresponding to changes of flow in upstream of the Vu Gia and the Thu Bon under the population growth and industrial expansion in 2050 scenario S2. The upstream discharge is increased at 3 m^3/s increments to see the response of salt concentration at 3 control points Cau Do, Tu Cau, Cau Lau.

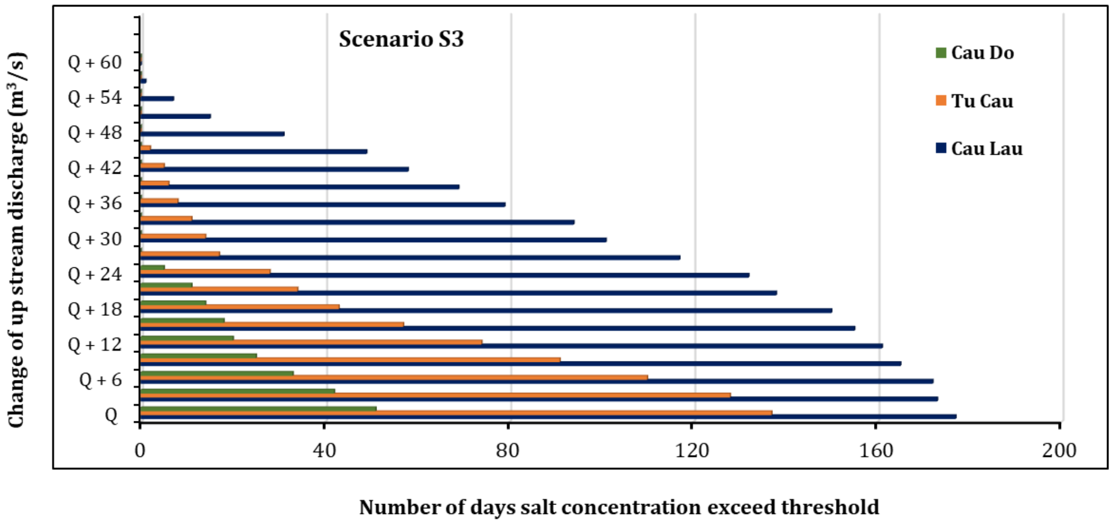


Figure 7. 6 The number of days that control points exceeds salinity threshold corresponding to changes of flow in upstream of the Vu Gia and the Thu Bon under the improvement of water efficiency management context scenario S3. The upstream discharge is increased at 3 m^3/s increments to see the response of salt concentration at 3 control points Cau Do, Tu Cau, Cau Lau.

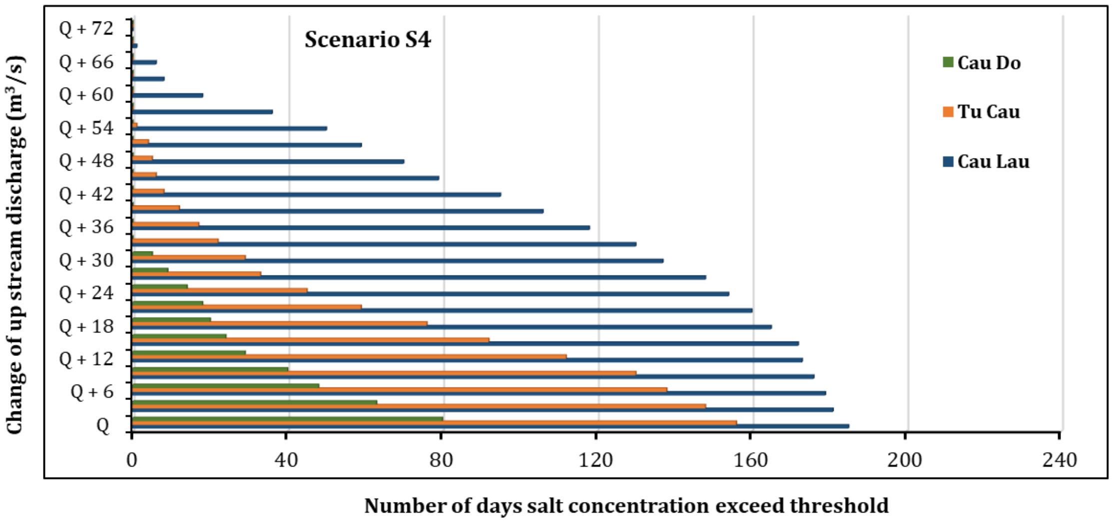


Figure 7. 7 The number of days that control points exceeds salinity threshold corresponding to changes of flow in upstream of the Vu Gia and the Thu Bon under the sea level rise projection in 2050 scenario S4. The upstream discharge is increased at 3 m^3/s increments to see the response of salt concentration at 3 control points Cau Do, Tu Cau, Cau Lau.

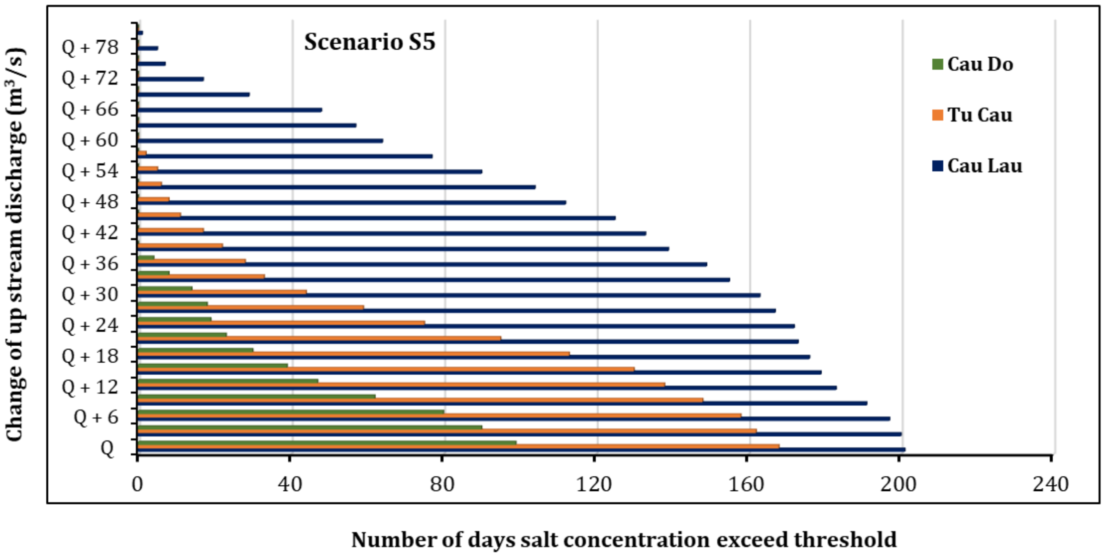


Figure 7. 8 The number of days that control points exceeds salinity threshold corresponding to changes of flow in upstream of the Vu Gia and the Thu Bon under the sea level rise projection in 2100 scenario S5. The upstream discharge is increased at 3 m^3/s increments to see the response of salt concentration at 3 control points Cau Do, Tu Cau, Cau Lau.

Table 7. 3 Summary of the duration of interrupted operation at control points and required additional discharge.

Scenario	Duration of interrupted operation (day/year)			Required additional discharge at upstream for fully operation (m^3/s)		
	Cau Do	Tu Cau	Cau Lau	Cau Do	Tu Cau	Cau Lau
S1	53	143	177	30	45	60
S2	90	154	177	33	45	60
S3	50	137	175	27	42	57
S4	80	156	185	33	51	69
S5	99	168	201	39	57	81

During the salt concentrations at Cau Do, Tu Cau and Cau Lau control points are over threshold, all water treatment plants and pumping stations are interrupted in their operation. Increasing of flow at upstream sections of the rivers is able to push back salinity and satisfy the threshold of these control points, so that these structures can be in fully operation. Under the impacts of sea level rise in 2100, scenario S5 experiences the longest duration of salt concentrations over the threshold at Cau Do, Tu Cau and Cau Lau with 99, 168, 201 days per year, respectively. To control the salt concentrations under the threshold in this scenario, an additional flow of 39 m^3/s is required at upstream sections of Vu Gia to satisfy the salinity threshold at Cau Do. Similarly, the increasing of flow at upstream sections of Thu Bon River by 57 m^3/s will satisfy the threshold at Tu Cau, while an increase of 81 m^3/s will satisfy both Tu Cau and Cau Lau. On the other hand, with the improvement in irrigation efficiency, the scenario S3 undergoes the shortest duration of salt concentrations over the threshold at Cau Do, Tu Cau and Cau Lau with 50, 137, 175 days per year, respectively. The lowest additional flow at upstream to satisfy the salinity threshold was found in this scenario with 27 m^3/s to control salinity at Cau Do, 42 m^3/s will satisfy the threshold at Tu Cau, and 57 m^3/s will satisfy both Tu Cau and Cau Lau.

7.4.2 Minimum flow requirement at control points

a. Cau Do control point

Figure 7.9 presents the simulated discharge and water level of baseline scenario S0 and the minimum flow requirements with the corresponding water levels of scenarios S1 to S5 to satisfy the salinity threshold at Cau Do control point. Moreover,

Figure 7.10 and **7.11** present their interrelated discharge at the locations before and after the Quang Hue confluence.

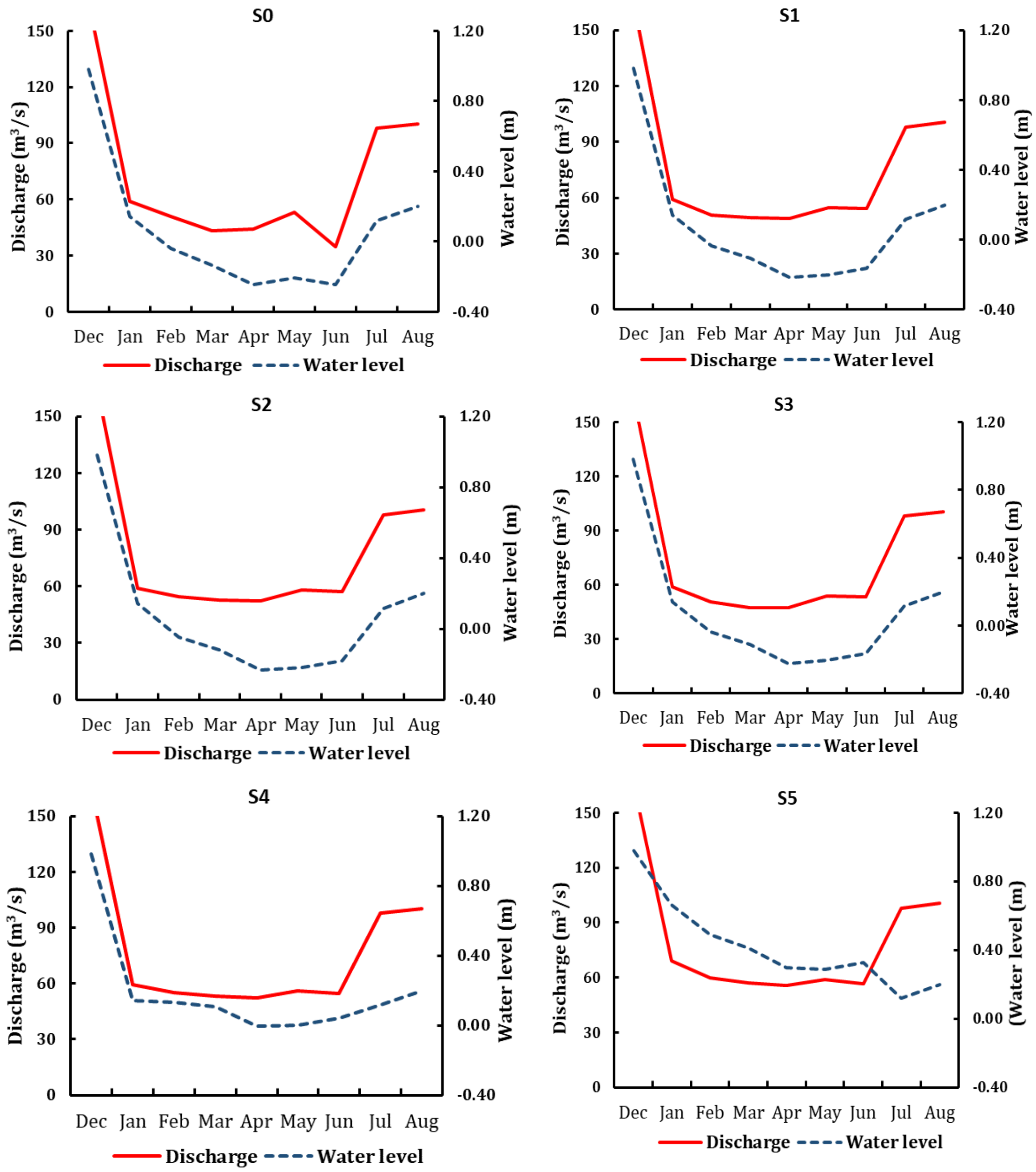


Figure 7. 9 Simulated discharge and water level of baseline scenario S0 and the minimum flow requirements with corresponding water levels of scenarios S1 to S5 to satisfy the salinity threshold at Cau Do control point. It should be noted that the water level is negative due to the low absolute altitude at the measured point.

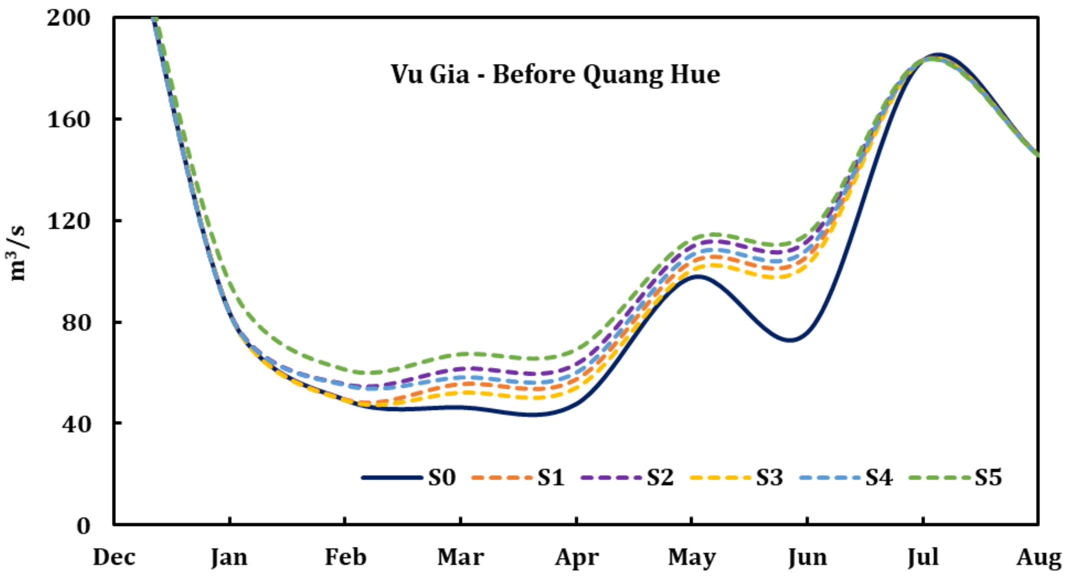


Figure 7. 10 Interrelated discharge of scenario S0 to S5 at Vu Gia river (before Quang Hue confluence) to the required minimum flow at Cau Do control point

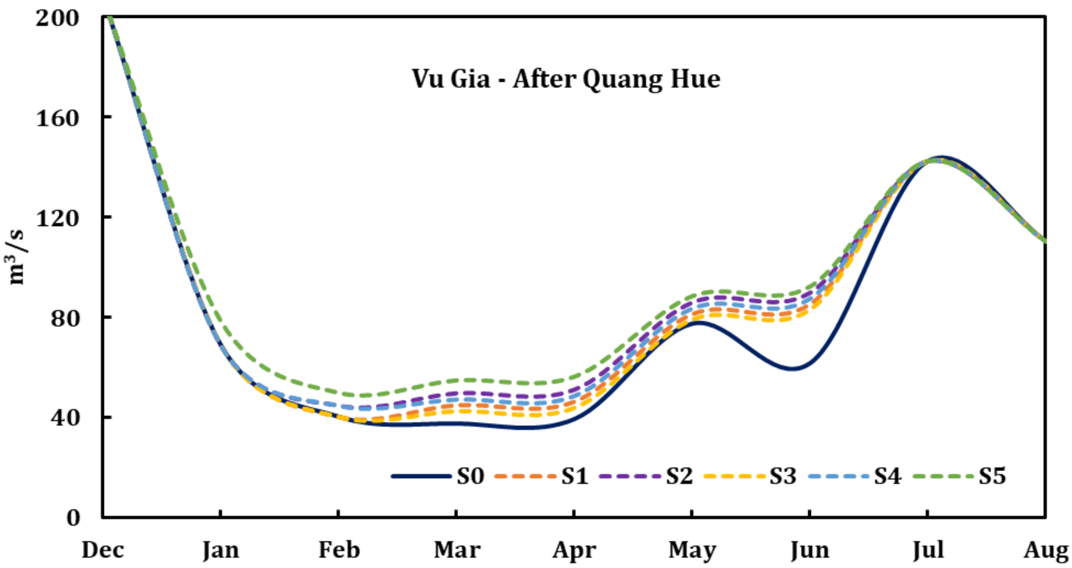


Figure 7. 11 Interrelated discharge of scenario S0 to S5 at Vu Gia river (after Quang Hue confluence) to the required minimum flow at Cau Do control point

The highest discharge and water level were found in December with 165 m^3/s and the lowest discharge, as well as the water level was found in June with 35 m^3/s. During July and August, a high monthly discharge and water level was found at Cau Do with 98 m^3/s and 100 m^3/s respectively. It can be explained by the high precipitation was recorded at Cam Le gauge station and high discharge at Thanh My station.

The Cau Do control point experiences salt concentration over the operating threshold from March to June. Therefore, the minimum flow requirement will be defined for the period of March to June in scenarios S1 to S4. In scenario S5, the sea level rise in 2100 causes the salt concentration excess the threshold from January to June.. It affects the operation of Cau Do water treatment plant during this time. Thus, the minimum flow requirement will be defined for the period of January to June in scenario S5. The highest required minimum flow is seen in May and June in all scenarios. It can be explained by the highest water demand in the region at this time. While the increasing domestic and industrial demand S2, as well as sea level rise S4, S5 caused the increase of minimum flow supplement, the improvement of water resource management by upgrading the irrigation system in order to increase the irrigation efficiency S3 lead to the reduce in minimum flow requirement in the Vu Gia River.

b. Cau Lau control point

Figure 7.12 presents the simulated discharge and water level of baseline scenario S0 and the minimum flow requirements with corresponding water levels of scenarios S1 to S5 to satisfy the salinity threshold at Cau Lau control point.

In general, the baseline S0 presents the current average flow and water the level. The highest discharge, as well as water level was found in December with 299 m^3/s whereas the lowest discharge was found in August with 37 m^3/s. The low discharge combined with the lowest water level was seen in April, May and June. It could be seen that the low flow period causing the salinity excesses beyond the threshold from February to August in S1 – S4 affected the operation pumping station at Cau Lau. Therefore, the minimum flow requirement will be defined for the period of February to August in scenarios S1 to S4.

Similar to the Cau Do control point, the sea level rise for the year 2100, not only increased the peak of salt concentration, but also increase the time of salt concentrations in excess of the threshold. The salt intrusion starts earlier in January and lasted until August in scenario S5, affects the operation of Xuyen Dong pumping station. Therefore, the minimum flow requirement will be defined for the period of January to August in scenario S5. The increasing domestic and industrial demand S2 only impact the required minimum flow of Vu Gia River as the water withdraw for domestic and industrial purpose mainly functioned by Cau Do WTP. Thus, there was not much change in the Thu Bon River flow. While the sea level rise causes the increase of minimum flow requirement in scenario S4 and S5, the improvement of water resource management by upgrading the irrigation system in order to increase the irrigation efficiency S3 led to a reduction in the minimum flow requirement in the Thu Bon River.

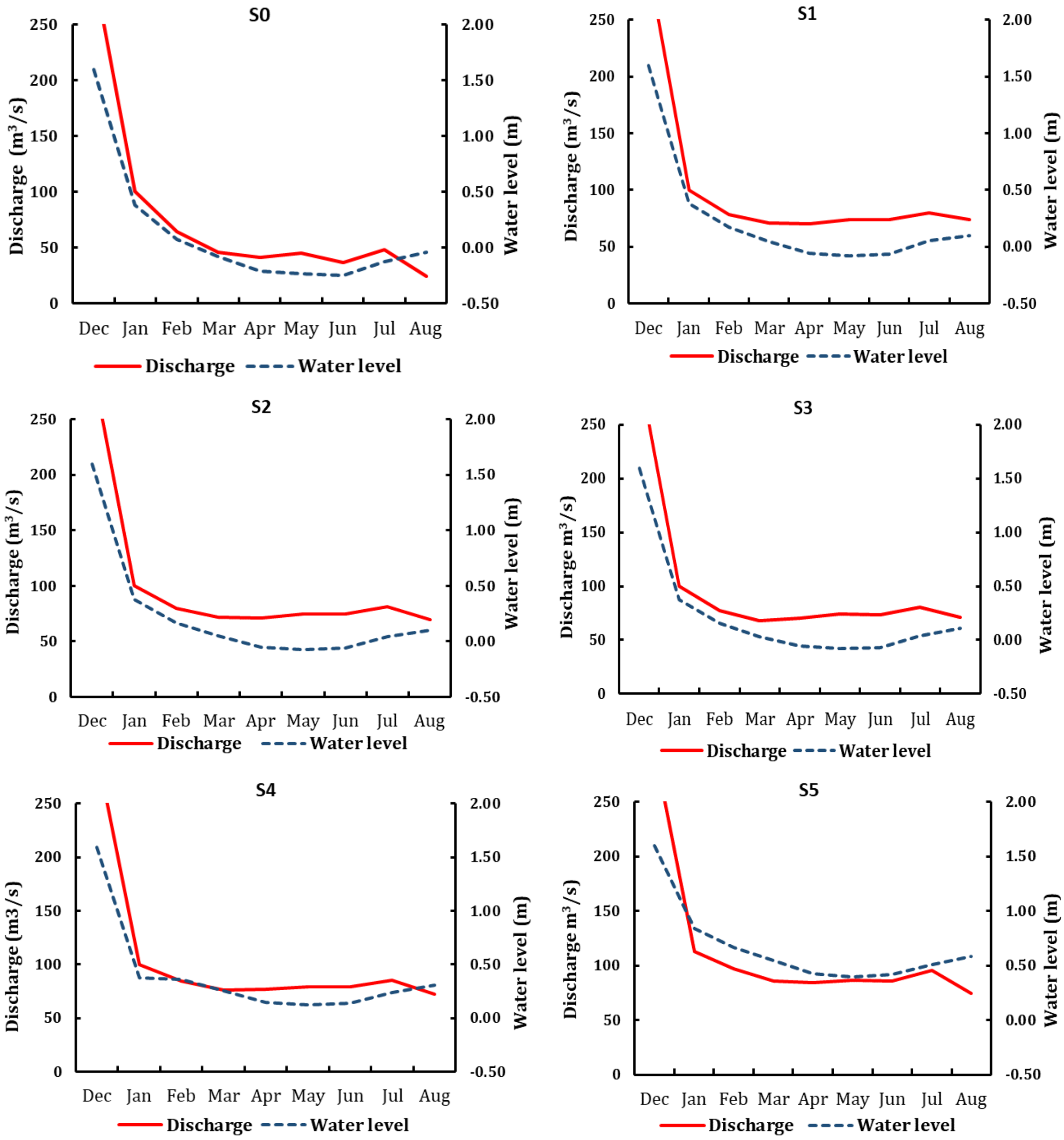


Figure 7. 12 Simulated discharge and water level of baseline scenario S0 and the minimum flow requirement with corresponding water level of scenarios S1 to S5 at Cau Lau control point. It should be noted that the water level is negative due to the low absolute altitude at the measured point.

Figure 7.13 and **7.14** present their interrelated discharge at the location before and after Quang Hue confluence.

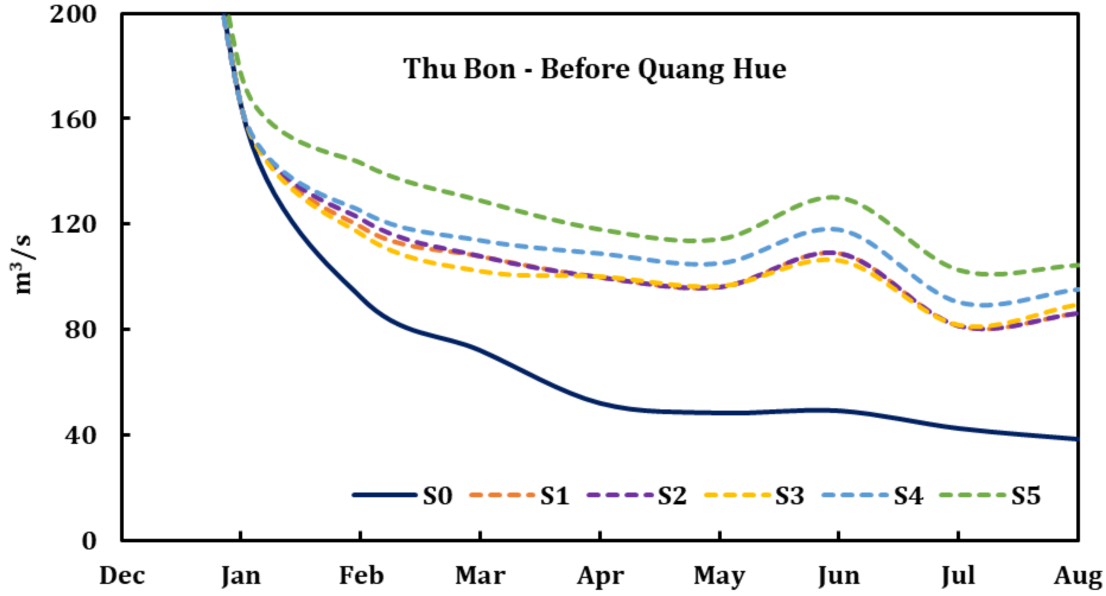


Figure 7. 13 Interrelated discharge of scenario S0 to S5 at Thu Bon River (before Quang Hue confluence) to the required minimum flow at Cau Lau control point

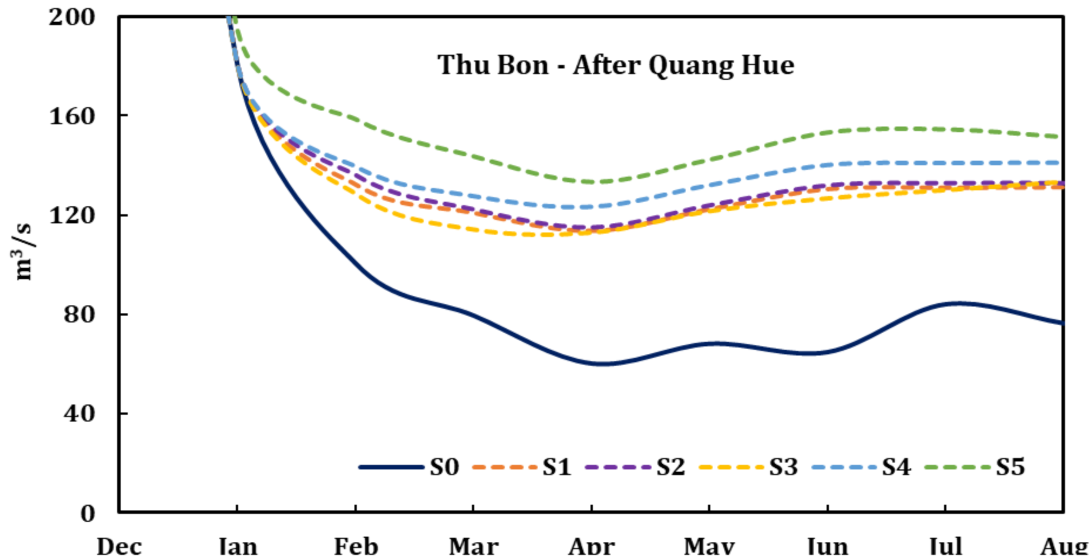


Figure 7. 14 Interrelated discharge of scenario S0 to S5 at Thu Bon River (after Quang Hue confluence) to the required minimum flow at Cau Lau control point

c. Tu Cau control point

Figure 7.15 presents the simulated discharge and water level of baseline scenario S0 and the minimum flow requirements with corresponding water levels of scenarios S1 to S5 to satisfy the salinity threshold at the Tu Cau control point.

The highest discharge, as well as water level was found in December with 134 m^3/s while the lowest discharge was found in August with -15 m^3/s in the baseline scenario. However, the water level is 0.01 m. This indicates that the Tu Cau control point is seriously affected by saltwater intrusion due to water strongly moves upward.

The low flow period causes the salinity to exceed the threshold from February to August in scenario S1 to S5 that affect the operation of Tu Cau pumping station. Therefore, the minimum flow requirement will be defined for the period of February to August in scenarios S1 to S5. Even August is the month mostly affected by saltwater intrusion, the lowest minimum flow requirement was found in this month. There are 3 pumping stations Tu Cau, Cam Sa and La Tho that extract water from Vinh Dien River and the lowest agricultural demand is in August. This could explain the lowest minimum flow requirement at Tu Cau control point during August. The increasing domestic and industrial demand S2 only impact on the required minimum flow of Vu Gia River as the water withdraw for domestic and industrial purpose is mainly supplied by Cau Do WTP. Even though Vinh Dien River receives water from Thu Bon River, it is the connection between Vu Gia and Thu Bon Rivers. Thus, the minimum flow requirement at Tu Cau control point is slightly increased when there is greater water extraction in Vu Gia River. Similar to Cau Do and Cau Lau control points, while the sea level rise causes the increase of minimum flow requirement in scenario S4 and S5, the upgrading of irrigation system in order to increase the irrigation efficiency in scenario S3 leads to the reduction in minimum flow requirement in Vinh Dien River.

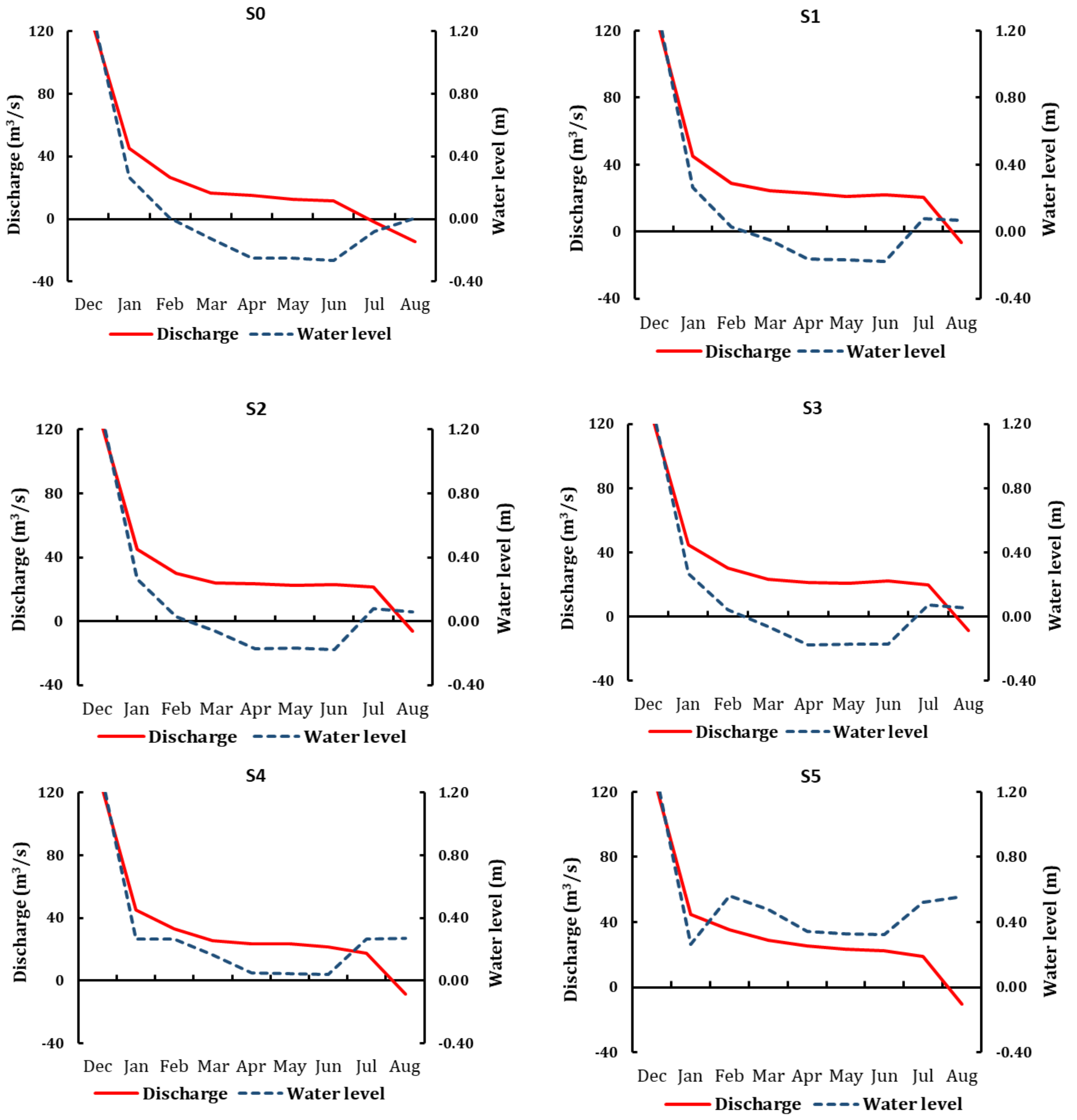


Figure 7. 15 Simulated discharge and water level of baseline scenario S0 and the minimum flow requirement with corresponding water levels of scenarios S1 to S5 at Tu Cau control point. It should be noted that the water level is negative due to the low absolute altitude at the measured point.

Figure 7.16 and **7.17** presents their interrelated discharge at the location before and after the Quang Hue confluence.

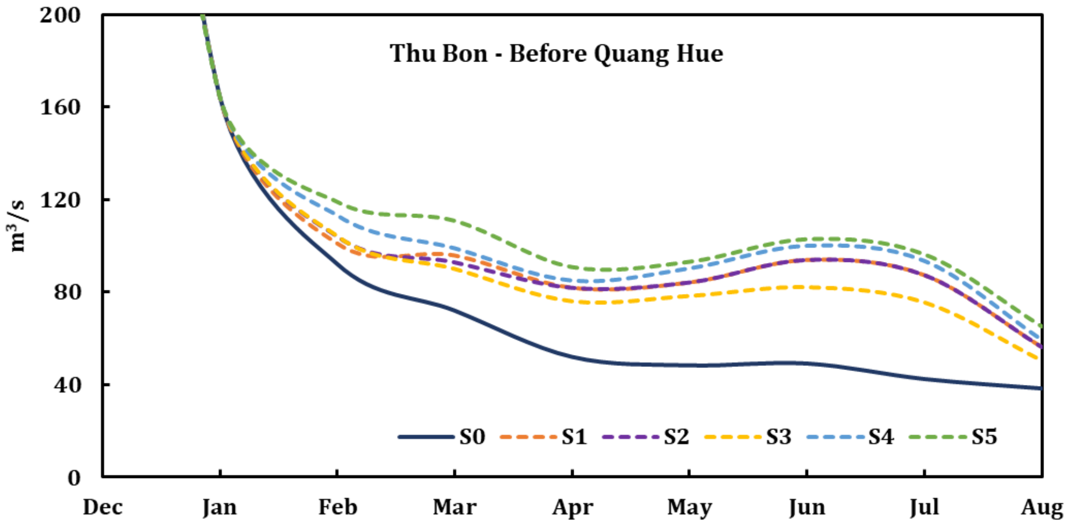


Figure 7. 16 Interrelated discharge of scenario S0 to S5 at the Thu Bon River (before the Quang Hue confluence) to the required minimum flow at the Tu Cau control point

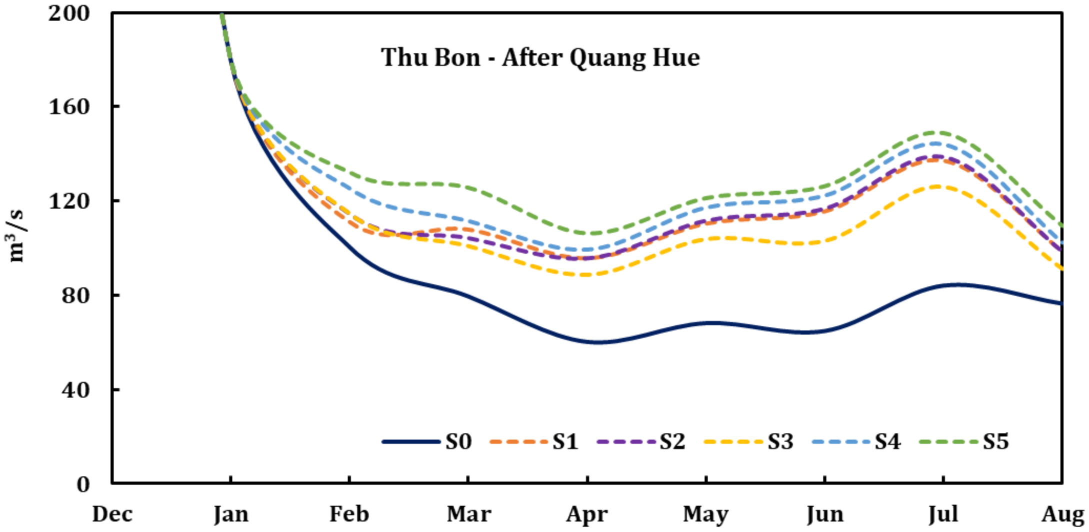


Figure 7. 17 Interrelated discharge of scenario S0 to S5 at the Thu Bon River (after the Quang Hue confluence) to the required minimum flow at the Tu Cau control point

7.4.3 Minimum flow requirement in the Vu Gia – Thu Bon River Basin

To set out the minimum flow requirement for the VG-TB river system, the flow rate that satisfies the threshold at Cau Do control point is defined for Vu Gia River and the flow rate that satisfies the threshold at Cau Lau control point is defined for Thu Bon River. During the growing season in the VG-TB Delta, June is the month with the lowest water flow rate in the rivers, but it has also the highest water demand in the region. Therefore, the minimum flow requirement in this month is the highest one compared to other months. In this section, the minimum flow requirements in June are selected as the typical to present and discuss.

a. Scenario S0

Figure 7.18 shows the simulated flow discharge in the VG-TB river system under the actual condition. In the actual condition, the flow rate at the upstream of the Vu Gia and the Thu Bon is 76 m^3/s and 50 m^3/s respectively. Before entering the estuary, the Vu Gia River diverts water at the rate 14 m^3/s to Thu Bon River through the Quang Hue confluence. After that, the Vu Gia splits 44 m^3/s into the Yen River and 18 m^3/s into the Lac Thanh River. Further downstream, Thu Bon River returns water back to the Vu Gia River via the Vinh Dien at the rate of 8 m^3/s.

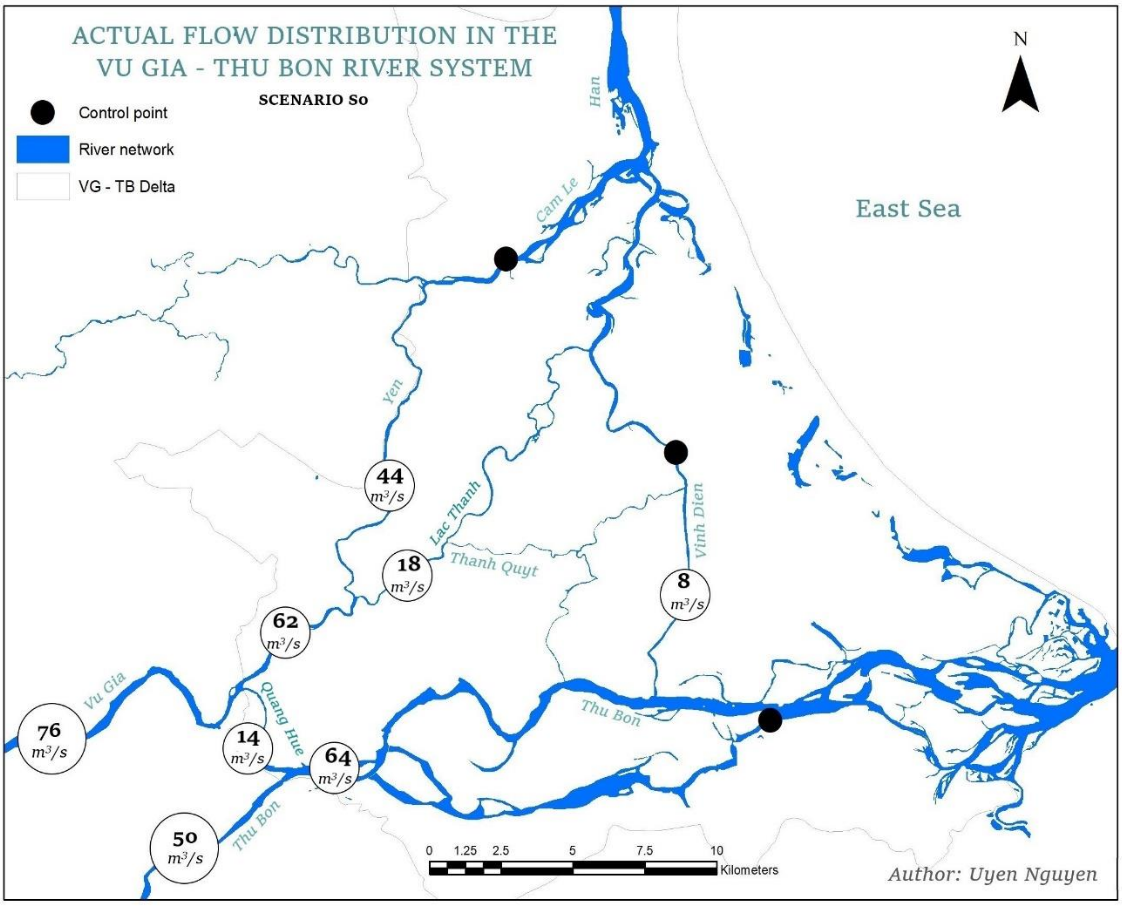


Figure 7. 18 Actual flow distribution in the VG-TB River System in June 2005

b. Scenario S1

In scenario S1, the required minimum flow is determined to satisfy the potential water demand for all human activities in the delta. To counteract salt intrusion and control salt concentration below the threshold at the 3 control points Cau Do, Cau Lau and Tu Cau, an additional discharge of 30 m^3/s in the upstream section of the Vu Gia River and 59 m^3/s in upstream section of Thu Bon River is required. The minimum flow requirement is defined as 106 m^3/s and 109 m^3/s at upstream sections of the Vu Gia and the Thu Bon respectively. In this scenario, the Vu Gia River diverts 21 m^3/s to Thu Bon River. After the Quang Hue confluence, the flow rates are 85 m^3/s and 130 m^3/s at the Vu Gia River and the Thu Bon River respectively. Downstream of the Quang Hue confluence, the Thu Bon River diverts return part of water as 19 m^3/s to the Vu Gia River through the Vinh Dien River **(Figure 7.19)**.

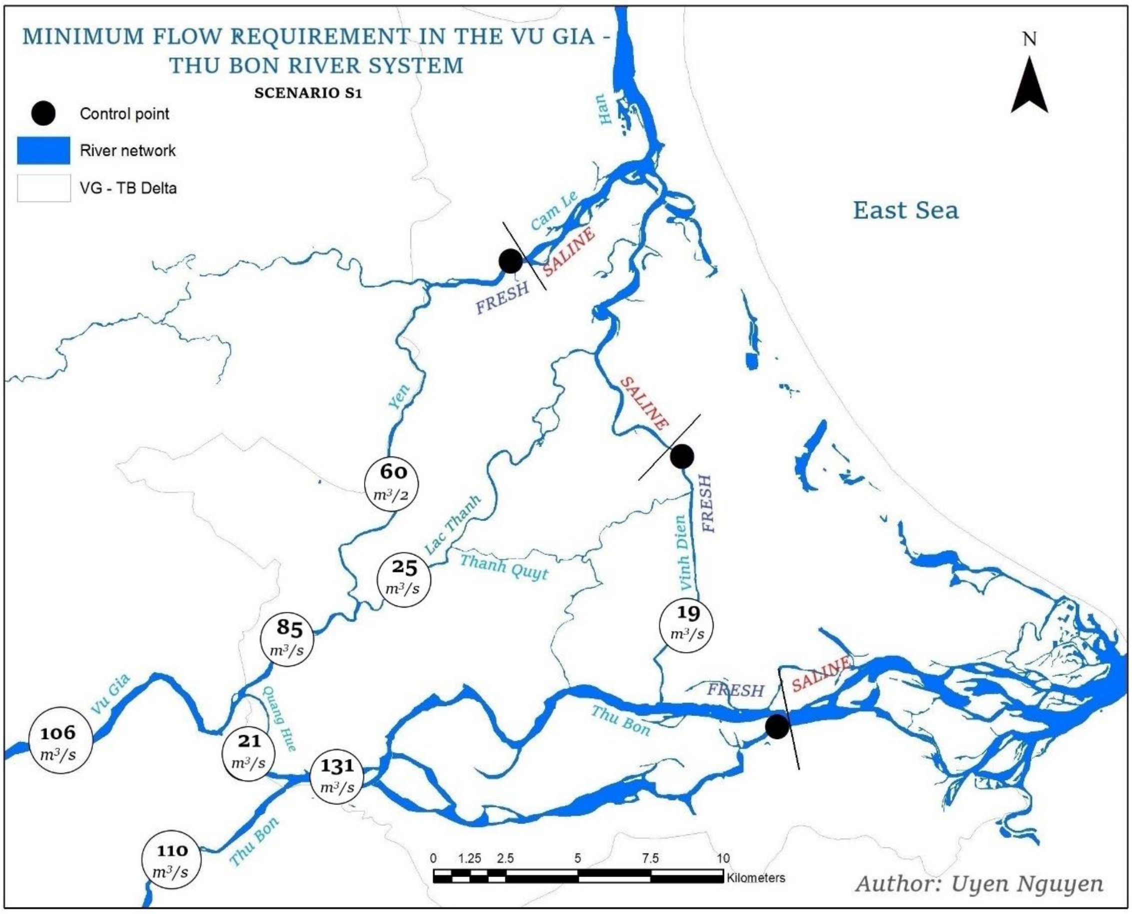


Figure 7. 19 Minimum flow requirement in the VG-TB River System under Scenario S1

c. Scenario S2

In scenario S2, the required minimum flow is determined to satisfy the potential water demand for all human activities in the delta under the change in water use due to both population growth and industrial expansion. To counteract salt intrusion and control salt concentration below the threshold at the 3 control points Cau Do, Cau Lau and Tu Cau, an additional discharge of 36 m^3/s in the upstream section of the Vu Gia River and 59 m^3/s in upstream section of Thu Bon River is required. The minimum flow requirement is defined as 112 m^3/s at upstream section of the Vu Gia River and 109 m^3/s at the Thu Bon River. The Vu Gia River diverts 22 m^3/s to Thu Bon River in this scenario. After the Quang Hue confluence, the flow rates are 90 m^3/s and 131 m^3/s at Vu Gia River and Thu Bon River respectively. Downstream of Quang Hue confluence, Thu Bon River diverts return part of water as 19 m^3/s to Vu Gia River through the Vinh Dien River **(Figure 7.20)**.

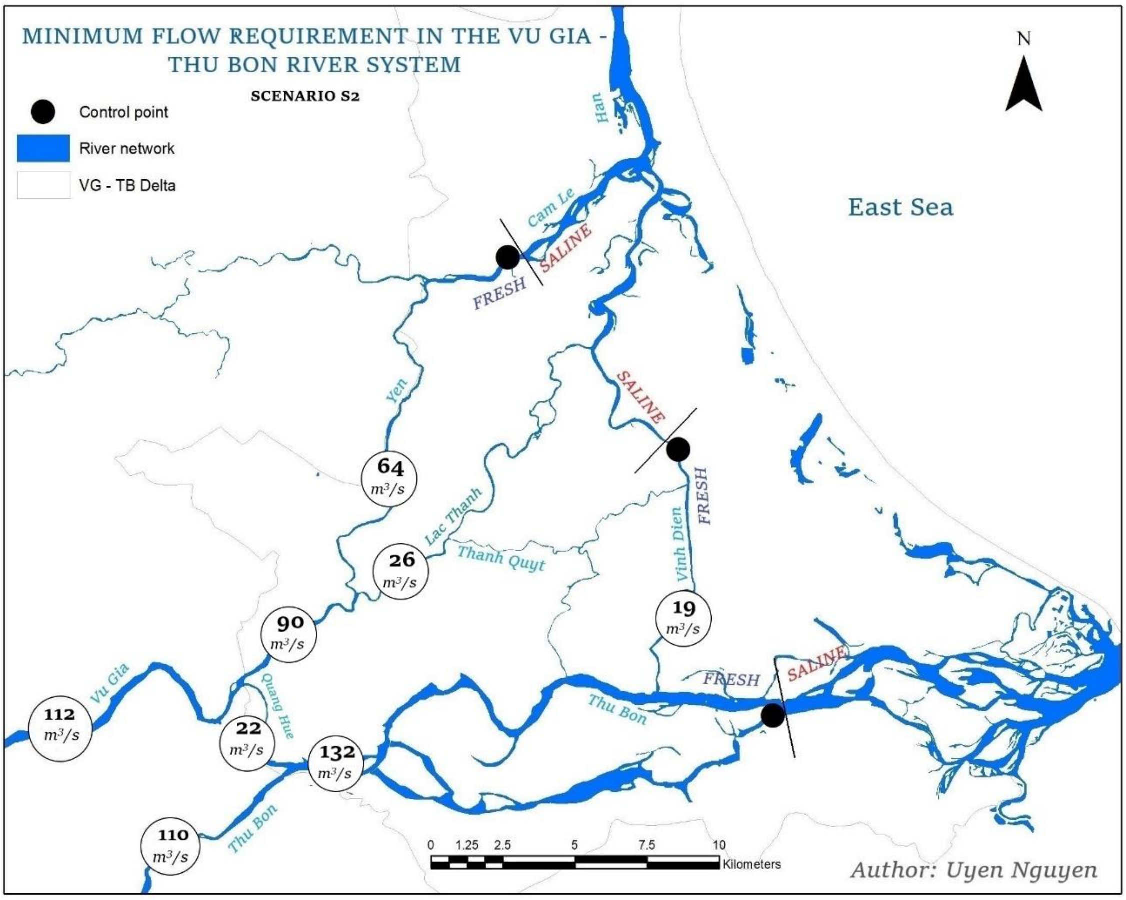


Figure 7. 20 Minimum flow requirement in the VG-TB River System under Scenario S2

The population growth and industrial expansion cause an increase of water extraction from Cau Do WTP. As the result, the Vu Gia River requires 6 m³/s more at its upstream section compared to the scenario S1. The minimum flow requirement of Thu Bon River is similar to the scenario S1 as there is no change in the water withdrawal or boundary conditions.

d. Scenario S3

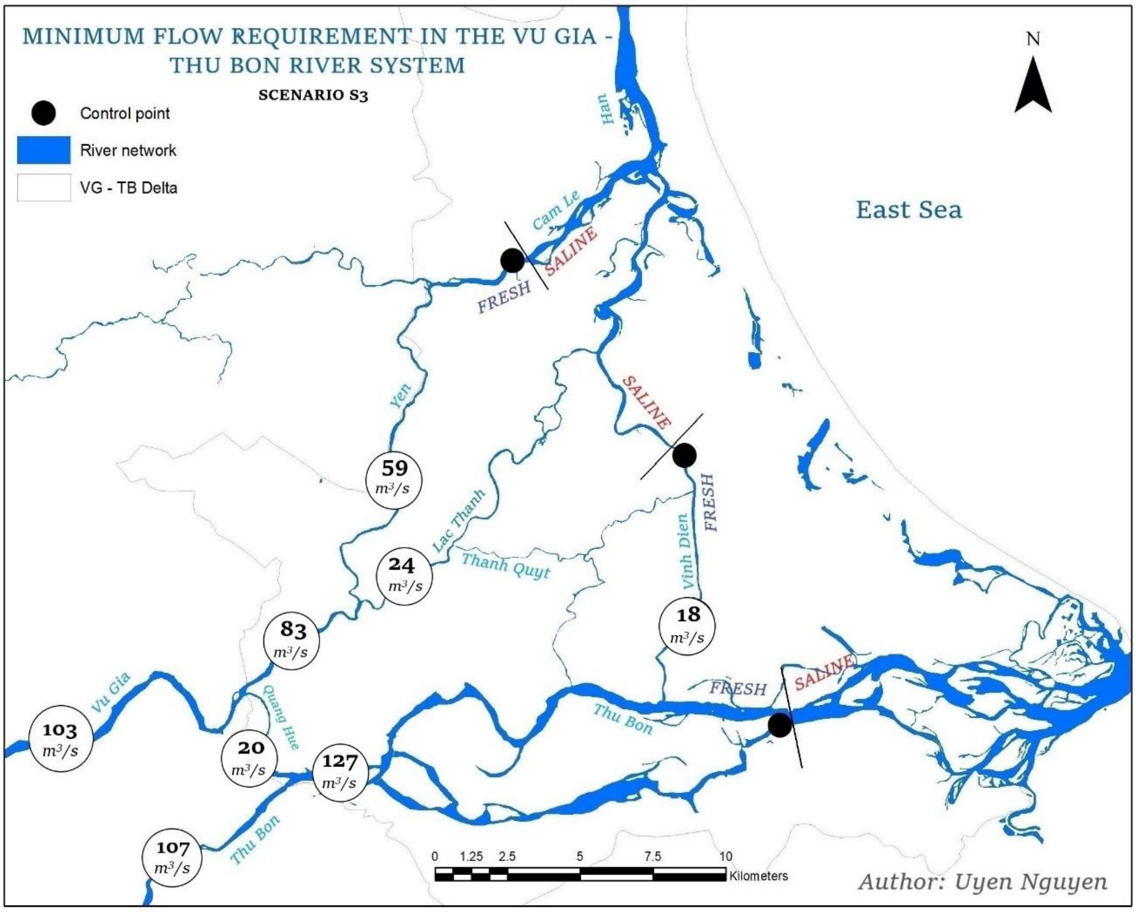


Figure 7. 21 Minimum flow requirement in the VG-TB River System under Scenario S3

In scenario S3, the required minimum flow is determined to satisfy the potential water demand for all human activities in the delta under the improvement of water efficiency management context. To counteract salt intrusion and control salt concentration below the threshold at the 3 control points Cau Do, Cau Lau and Tu Cau, an additional discharge of 27 m³/s in the upstream section of the Vu Gia River and 56 m³/s in upstream section of the Thu Bon River is required. The minimum flow requirement is defined as 103 m³/s and 106 m³/s at upstream of the Vu Gia and the Thu Bon Rivers respectively. The Vu Gia River diverts 20 m³/s to the Thu

Bon River in this scenario. After the Quang Hue confluence, the flow rates are 83 m³/s and 126 m³/s at Vu Gia River and Thu Bon River respectively. Further downstream, the Thu Bon River returns part of water as 18 m³/s to the Vu Gia River through the Vinh Dien River **(Figure 7.21)**.

The improvement of water use management by enhancing of the irrigation system efficiency from 60% to 75% leads to the reduction of water withdraw for agricultural demand. Accordingly, the minimum flow requirement in scenario S3 is lower than scenario S1 by 3 m³/s at upstream sections of both the Vu Gia and the Thu Bon Rivers.

e. Scenario S4

In scenario S4, the required minimum flow is determined to satisfy the potential water demand for all human activities in the delta under the impact of sea level rise by the year 2050 **(Figure 7.22).**

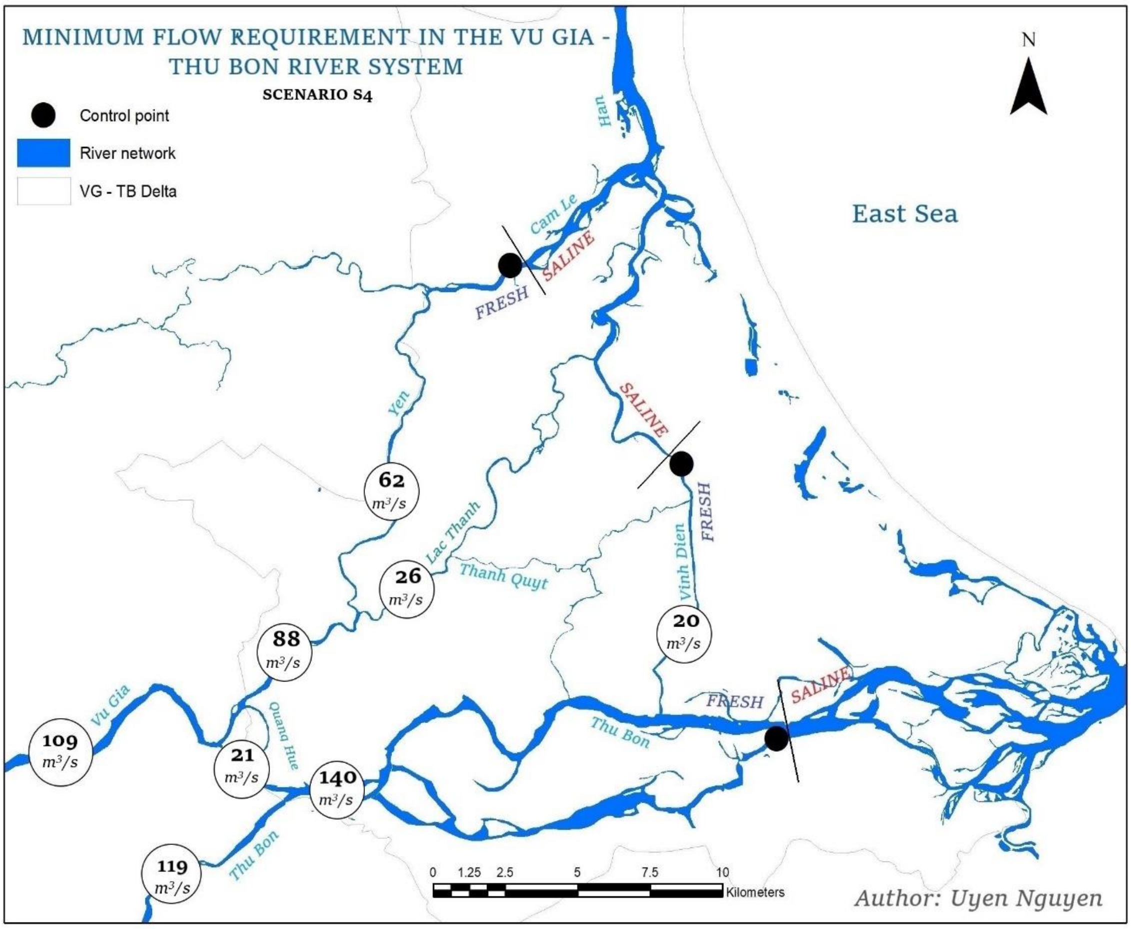


Figure 7. 22 Minimum flow requirement in the VG-TB River System under Scenario S4

To counteract salt intrusion and control salt concentration below the threshold at the 3 control points Cau Do, Cau Lau and Tu Cau, an additional discharge of 33 m^3/s in the upstream section of the Vu Gia River and 68 m^3/s in the upstream section of Thu Bon River is required. The minimum flow requirement is defined as 109 m^3/s and 118 m^3/s for the Vu Gia and the Thu Bon rivers respectively. The Vu Gia River diverts 21 m^3/s to the Thu Bon River in this scenario. After the Quang Hue confluence, the flow rates are 88 m^3/s and 139 m^3/s at the Vu Gia River and the Thu Bon River respectively. Downstream of the Quang Hue confluence, the Thu Bon River returns part of this water as 20 m^3/s to the Vu Gia River through the Vinh Dien River.

The impact of climate change on sea level rise results in more severe salt intrusion in both duration and intensity within the VG-TB Delta. Using the projected of sea level rises up to 23 cm by the year 2050, the salinity exceeds the threshold at the 3 control points in early February. While the Cau Do WTP is suffering under salt intrusion until the beginning of July, salt intrusion at Tu Cau Pumping station and Cau Lau Station impacts last until the end of August. Therefore, the increase of the minimum flow requirement compared to scenario S1 is mainly for the purpose of salinity control. Subsequently, the required minimum flow in this scenario is higher than in scenario S1 as 3 m^3/s and 9 m^3/s at the upstream sections of the Vu Gia and the Thu Bon Rivers respectively.

f. Scenario S5

In scenario S5, the required minimum flow is determined to satisfy the potential water demand for all human activities in the delta under the impact of sea level rise by the year 2100. To counteract salt intrusion and control salt concentration below the threshold at the 3 control points Cau Do, Cau Lau and Tu Cau, an additional discharge of 39 m^3/s in the upstream section of Vu Gia River and 80 m^3/s in the upstream section of Thu Bon River is required. The minimum flow requirement is defined as 115 m^3/s and 130 m^3/s at the upstream sections of the Vu Gia and the Thu Bon Rivers respectively. The Vu Gia River diverts 22 m^3/s to the Thu Bon River in this scenario. After Quang Hue confluence, the flow rates are 93 m^3/s and 153 m^3/s at Vu Gia River and Thu Bon River respectively. Downstream of Quang Hue confluence, the Thu Bon River diverts returns part of water as 22 m^3/s to the Vu Gia River through the Vinh Dien River **(Figure 7.23)**.

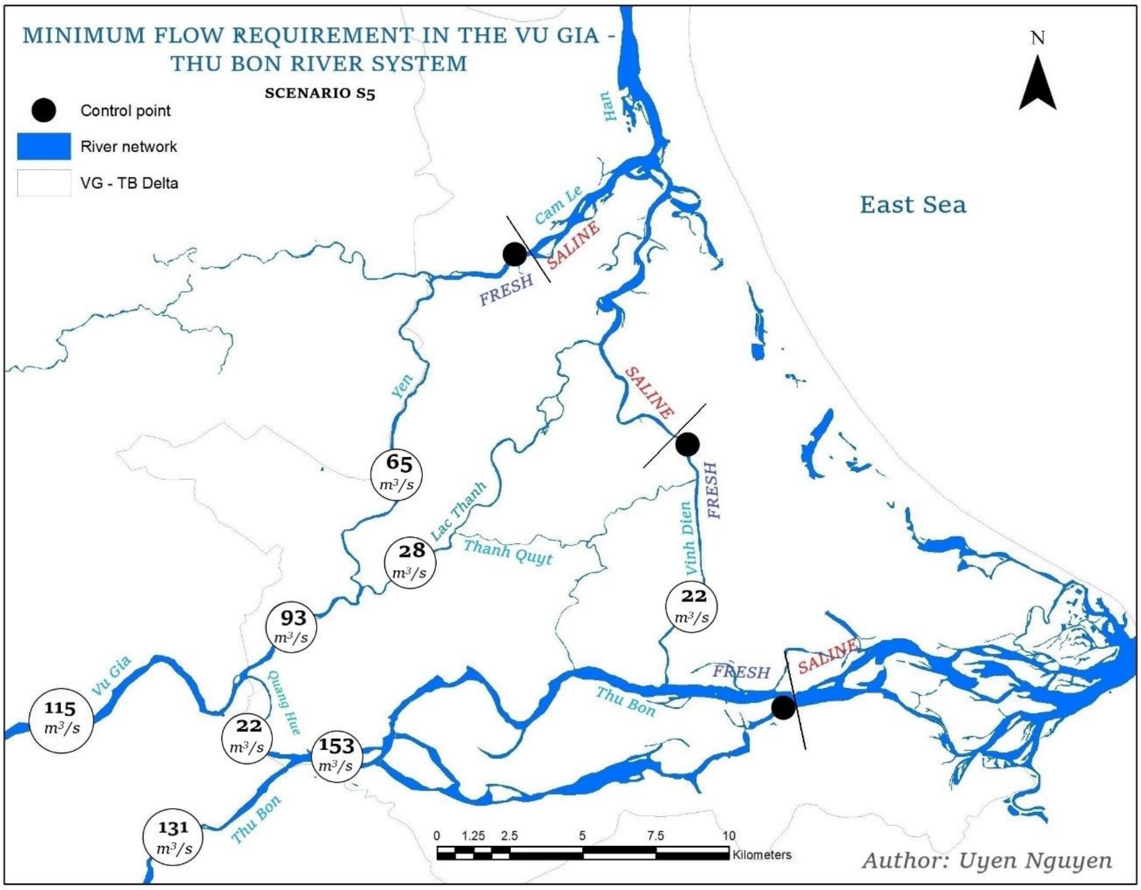


Figure 7. 23 Minimum flow requirement in the VG-TB River System under Scenario S5

Similar to the scenario S4, the projected sea level will rise up to 57 cm by the year 2100 causes an extreme salt intrusion in the delta of VG-TB. The salinity exceeds the threshold all 3 control points earlier than other scenarios by the end of January. The highest minimum flow requirement was found in this scenario with an additional 9 m^3/s and 21 m^3/s at the upstream sections of the Vu Gia and the Thu Bon Rivers respectively compared to scenario S1.

7.5 Conclusion

In total six scenarios have been developed to simulate the changes in minimum flow requirement under different development and socio-economic transformation contexts in the region. The developed scenarios assess the minimum flow requirement in the VG-TB river system with the changes in boundary conditions. Any changes in river flow, water use, management practices and sea level have led to the changes in required minimum flow in the downstream section of the basin.

The minimum flow requirement under the different scenarios is finally calculated to satisfy the purposes of controlling salt below the threshold at the 3 control points for the operation of pumping stations and water treatment plants in the delta of the basin. This allows for the uninterrupted supply of sufficient agricultural water demand for irrigated cultivation areas, sufficient domestic water demand for the number of inhabitants, sufficient industrial water demand for the industrial zones in the delta of the basin and maintaining valued features of the estuarine ecosystem. While the change in water use for domestic and industrial sectors as well as change in sea level put the negative impacts on the water extraction causing increase in minimum flow requirement, the improvement of irrigation efficiency of the irrigation system helps to reduce the water extraction and thus reduce the minimum flow requirement. The results in this chapter provide crucial information that can be used by water planners and policy makers to better undertake integrated water resource planning for the river system.

8 Summary and conclusions

This research was conducted to address a number of knowledge gaps. The main aim of this research was to develop an applicable methodology to assess the minimum flow requirements in the VG-TB river basin. To achieve this, the main objectives of this research were as follows: (1) to understand the low flow phenomenon and minimum flow requirement; (2) to quantify the potential water demand from the different activities in the VG-TB Delta; (3) to assess the performance of the irrigation system in regards to water supply availability and water demand; (4) to determine the required minimum flow in the Vu Gia River and the Thu Bon River to combat salt intrusion and satisfy the water demand from different activities during the low flow period; (5) to derive a generally applicable methodology to assess minimum flow requirements in multi-sectorial water management scenarios. These objectives have been fulfilled within previous chapters and summarized in the below section. The last section of this chapter describes the general conclusion and outlook for further studies in the future.

8.1 Summary of results

Through addressing the objectives, the research questions have been answered. The main results are summarized as follows.

a. To understand the low flow phenomenon and minimum flow requirement

The combined approach with statistical analysis and flow duration curve as well as Standardised Precipitation-Evapotranspiration Index (SPEI) was applied to provide a deeper understanding of the low flow in the region. Furthermore, the low flow season in the VG-TB river basin, where a long period of low flow occurs annually and high competition between water users, was also addressed in detail. The trends of precipitation and discharge for the period 1976 – 2014 were analyzed and exhibit an increasing trend strongly in rainy season. The low flow and drought events were also investigated displaying a decrease in drought periods for the year post 2000. It seems that the year post 2000 is a wetter period compared to the year pre-2000. Additionally, the concept of minimum flow requirements has been defined for this research. Minimum flow requirements in this study are determined for (1) Controlling salt below the threshold of 1 g/L (equal with 1 practical salinity unit) for the operation of pumping stations and below 0.25 g/L (equal with 0.25 practical salinity unit) for the operation of water treatment plants in the delta of the basin; (2) Supplying sufficient agricultural water demand for irrigated cultivation areas in the delta of the basin; (3) Supplying sufficient domestic water demand for the number of inhabitants in the delta of the basin; (4) Supplying sufficient industrial water demand for the industrial zones in the delta of the basin; and (5) Maintaining essential functions of the estuarine ecosystem. The analysis is crucial to understand the background of the low flow phenomenon in the region.

b. To quantify the seasonal water demand for different activities in the region

The research applied CROPWAT with the Penman-Monteith equation to calculate the potential crop evapotranspiration and then derived the water requirement for the agricultural sector related to irrigated cultivation VG-TB Delta. The domestic and industrial water demand were also calculated using standard values and guidelines issued by the Viet Nam Ministry of Construction. The data of the dry year 2005 was used to quantify the water demand. Over the entire basin, the yearly demand is 309 million m^3, of which 203 million m^3 is for agriculture, 89 million m^3 is for domestic use, and only 17 million m^3 is for industry. The lowest demands were found in September, October and November at about 9 million m^3 per month while the highest demands were found in May and in June at about 45 million m^3 and 47 million m^3 respectively. The calculation helps to set the water use pattern and is important for the analysis and study of minimum flow requirements as well as water management in the region.

c. To assess the performance of irrigation system regarding water supply availability and demand

The monthly Relative Water Supply (RWS) and the Relative Irrigation Supply (RIS) for each Irrigation Management Scheme (IMS) in the VG-TB Delta have been calculated. The condition of water abundance or scarcity has been revealed by analyzing the RWS. The irrigation supply and demand have been assessed through the indicator RIS. An intermittent shortage of water and an inefficient irrigation system were revealed after analyzing the two indicators relative water supply and relative irrigation supply. It was found that the agriculture suffered of underirrigation during the period of February to June. Therefore, irrigation schedule adjusting and efficient use of rainfall should be considered to enhance the irrigation system efficiency.

d. To determine the seasonal varying minimum flows in the Vu Gia and the Thu Bon rivers required to push back the salt intrusion and satisfy the water demand from different activities

The model MIKE 11 has been set up to simulate the flows and salt concentration in the river in order to calculate the required minimum flow. The comparison between simulated and observed data through calibration and validation processes showed generally good agreement. Thus, the model is deemed suitable to simulate the flows and salt concentration within the basin. The model was run for different upstream discharge datasets, to test the response of the salt concentration, and then define where salt concentration is under threshold at the 3 control points at Cau Do, Cau Lau and Tu Cau to ensure the river system is able to supply water for all activities. The minimum flow requirements in the rivers were determined for 6 scenarios. The first scenario (S0) presents the flows in existing conditions for the year 2005. The second scenario (S1) shows the minimum flow requirement under the potential water demand in the region. The third scenario (S2) shows the minimum flow requirement under the potential water demand in the region with changes in domestic water use and industrial water use. The fourth scenario (S3) shows the minimum flow requirement under the improvement of water use efficiency. The fifth scenario (S4) shows the minimum flow requirement under the impact of sea level rise for the year 2050. Finally, the sixth scenario (S5) shows the minimum flow requirement under the impact of sea level rise for the year 2100. The highest minimum flow requirement was seen to occur in the context of extreme sea level rise for the year 2100, while the lowest required minimum flow has been found when the irrigation system efficiency is improved.

The model proved to be a good tool to assess the minimum flow requirement in the VG – TB river basin. Additionally, the set of developed scenarios could address mainly the projection of future changes under the impacts from natural as well as anthropogenic factors.

e. To derive a generally applicable methodology to assess minimum flows requirements in multi-sectorial water management scenarios

The overall tested framework of this study **(Figure 1.1)** finally provides an applicable methodology to define the minimum flow requirements in the river in the context of multi-sectorial water management scenarios.

8.2 General conclusions

The precipitation exhibits a strong increasing trend in rainy season whereas a decreasing trend is found in dry season. This would escalate the shortage of water availability during low flow period and severe flooding during rainy season. The system analysis also indicates that the changes in upstream flows due to damming, water diversion, and downstream flow due to sea level rise are the primary factors causing the changes in saltwater intrusion, which lead to the changes in required minimum flow. Consequently, the analysis is helpful in establishing appropriate measures to meet the required minimum flow during low flow season. It has become clear that physical structural measures such as dams and storage reservoirs are essential to regulate the unevenly temporal rainfall in the region, so that the required minimum flow could be met. Therefore, it is necessary to have a further study on potential capacity of dams and reservoirs at the upstream of the region to regulate the rainfall as a measure in order to meet the required minimum flow in the estuaries.

The result indicates that for the purpose of meeting the minimum flow requirement, an additional discharge about 50%, 61%, 46%, 56%, 66% of current mean low flow of the upstream Vu Gia River is needed for scenario S1, S2, S3, S4, S5, whereas the upstream of the Thu Bon River demands a higher additional discharge about 58%, 58%, 55%, 67%, 78% of current mean low flow, respectively. Despite of the physical structural measures mentioned above, most of the large hydropower reservoirs and dams are constructed at the upstream of the Vu Gia River, while only the Song Tranh

2 hydropower reservoir is at the upstream of the Thu Bon River **(Figure 2.1)**. Thus, there could be a restriction for the Thu Bon River to reach the required minimum flow if only rely on the reservoir of the Song Tranh 2.

It should be noted that there exist a number of limitations to the quantification of water demand in the Vu Gia - Thu Bon delta. This includes the lack of in situ experiments, limits in data and the validity of assumptions. Due to the limitation of field experiment in the region, the calculation for amount of saturation water based on porosity and the depth of the plow layer soil with assumption that the soil is fully dry. This may lead to the error in potential agricultural water demand and thus, contributed to the error of difference in total potential water demand of the region. Another assumption made in the quantification of industrial water demand which were based on standards and guidelines by the Viet Nam Ministry of Construction. As the calculation used the per capita demand (m^3/hectare/day), the water demand will be different when the industrial structure is changed. However, the portion of water extraction for industrial sector after all accounts only 3% in total water extraction. Therefore, the error of difference due to limited data is insignificant.

The fully-one-dimensional-hydrodynamic model MIKE 11 has proven its advantages for modeling the minimum flow requirement in the basin with is affected by salt intrusion. Despite of the desirable outputs from the model, it is still a one-dimensional model with its own shortcomings, for example the full mixing salinity in each river segment is assumed while in reality salinity levels are stratified. With regard to future research, it would be beneficial to apply a two-dimensional model for an intensive assessment of required minimum flow in the region.

The described methodology includes state-of-the-art techniques, making it an applicable approach to determine the minimum flow requirement in an anthropogenically impacted river basin. This methodology has been successfully tested in the Vu Gia Thu Bon River Basin and can be extrapolated to similar river basins.

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Appendix A The potential water demand in the Vu Gia – Thu Bon Delta

Table A - 1 The weather data, reference evapotranspiration and effective rainfall in the Vu Gia – Thu Bon Delta (Calculated using data in 2005 at Da Nang station)

Month	Min Temp °C	Max Temp °C	Humi-dity %	Wind km/day	Sun hours	Rad MJ/m^2/day	ET_o mm/day	Effective Rainfall mm/day
Dec	19.8	23.4	88	379	0.4	7.5	1.85	2.19
Jan	19.1	25.1	84	320	5.1	13.9	2.89	1.09
Feb	21.8	27.8	85	401	6.1	16.6	3.55	0.21
Mar	20.5	26.9	84	368	4.9	16.2	3.56	1.11
Apr	23.4	30.2	83	420	6.4	19.4	4.53	0.39
May	25.6	35.1	77	400	7.9	21.7	5.95	0.63
Jun	27.1	36.3	71	414	7.1	20.2	6.48	0.71
Jul	25.2	33.2	80	342	7	20.1	5.07	3.44
Aug	25.6	33.5	78	343	5.5	17.8	4.94	4.50
Sep	24.9	32.1	82	478	6	18.1	4.6	7.38
Oct	24	29.2	86	515	3.5	13.3	3.41	15.43
Nov	22.9	28.3	86	396	4.6	13.5	3.19	9.70
Average	23.3	30.1	82	398	5.4	16.5	4.17	4.09

Table A - 2 The potential water demand and irrigation requirement at Dong Quan Irrigation Management Scheme

Month	Dong Quan Million m^3			
	Rice	Annual Crops	Total potential net irrigation requirement	Total potential gross irrigation requirement*
Dec	1.08	0.00	1.08	1.80
Jan	1.20	0.22	1.42	2.37
Feb	1.64	0.39	2.03	3.39
Mar	1.58	0.12	1.70	2.83
Apr	1.63	0.00	1.63	2.71
May	2.72	0.18	2.90	4.84
Jun	2.44	0.66	3.10	5.17
Jul	1.30	0.18	1.48	2.47
Aug	0.94	0.14	1.08	1.80

Table A - 3 The potential water demand and irrigation requirement at Tu Phu Irrigation Management Scheme

Month	Tu Phu Million m^3			
	Rice	Annual Crops	Total potential net irrigation requirement	Total potential gross irrigation requirement*
Dec	1.02	0.00	1.02	1.70
Jan	1.13	0.55	1.69	2.81
Feb	1.54	1.01	2.55	4.25
Mar	1.49	0.30	1.79	2.98
Apr	1.53	0.00	1.53	2.55
May	2.56	0.46	3.02	5.03
Jun	2.30	1.68	3.98	6.64
Jul	1.22	0.47	1.69	2.82
Aug	0.88	0.35	1.24	2.06

Table A - 4 The potential water demand and irrigation requirement at Dong Ho Irrigation Management Scheme

Month	Dong Ho Million m^3			
	Rice	Annual Crops	Total potential net irrigation requirement	Total potential gross irrigation requirement*
Dec	0.61	0.00	0.61	1.01
Jan	0.68	0.07	0.75	1.25
Feb	0.92	0.14	1.06	1.76
Mar	0.89	0.04	0.93	1.55
Apr	0.91	0.00	0.91	1.52
May	1.53	0.06	1.59	2.65
Jun	1.37	0.23	1.60	2.66
Jul	0.73	0.06	0.79	1.32
Aug	0.53	0.05	0.57	0.96

Table A- 5 The potential water demand and irrigation requirement at Tu Cau Irrigation Management Scheme

Month	Tu Cau Million m^3			
	Rice	Annual Crops	Total potential net irrigation requirement	Total potential gross irrigation requirement*
Dec	0.57	0.00	0.57	0.95
Jan	0.63	0.13	0.77	1.28
Feb	0.86	0.24	1.11	1.85
Mar	0.83	0.07	0.90	1.51
Apr	0.86	0.00	0.86	1.43
May	1.43	0.11	1.54	2.57
Jun	1.29	0.41	1.70	2.83
Jul	0.68	0.11	0.80	1.33
Aug	0.49	0.09	0.58	0.97

Table A - 6 The potential water demand and irrigation requirement at Cam Van Irrigation Management Scheme

Month	Cam Van Million m^3			
	Rice	Annual Crops	Total potential net irrigation requirement	Total potential gross irrigation requirement*
Dec	2.21	0.00	2.21	3.68
Jan	2.45	0.25	2.70	4.50
Feb	3.34	0.45	3.79	6.32
Mar	3.22	0.13	3.36	5.60
Apr	3.31	0.00	3.31	5.52
May	5.55	0.21	5.76	9.59
Jun	4.98	0.76	5.74	9.56
Jul	2.65	0.21	2.86	4.77
Aug	1.91	0.16	2.07	3.46

Table A - 7 The potential water demand and irrigation requirement at Vinh Dien Irrigation Management Scheme

Month	Vinh Dien Million m³			
	Rice	Annual Crops	Total potential net irrigation requirement	Total potential gross irrigation requirement*
Dec	1.64	0.00	1.64	2.73
Jan	1.82	0.50	2.32	3.87
Feb	2.48	0.92	3.39	5.66
Mar	2.39	0.27	2.66	4.44
Apr	2.46	0.00	2.46	4.10
May	4.12	0.42	4.53	7.56
Jun	3.69	1.53	5.23	8.71
Jul	1.97	0.43	2.39	3.99
Aug	1.42	0.32	1.74	2.90

Table A - 8 The potential water demand and irrigation requirement at Cam Sa Irrigation Management Scheme

Month	Cam Sa Million m³			
	Rice	Annual Crops	Total potential net irrigation requirement	Total potential gross irrigation requirement*
Dec	0.56	0.00	0.56	0.94
Jan	0.63	0.26	0.89	1.48
Feb	0.85	0.48	1.33	2.22
Mar	0.82	0.14	0.97	1.61
Apr	0.85	0.00	0.85	1.41
May	1.42	0.22	1.64	2.73
Jun	1.27	0.80	2.07	3.46
Jul	0.68	0.22	0.90	1.50
Aug	0.49	0.17	0.66	1.10

Table A - 9 The potential water demand and irrigation requirement at Ai Nghia Irrigation Management Scheme

Month	Ai Nghia Million m^3			
	Rice	Annual Crops	Total potential net irrigation requirement	Total potential gross irrigation requirement*
Dec	0.88	0.00	0.88	1.47
Jan	0.98	0.22	1.20	2.01
Feb	1.34	0.40	1.74	2.90
Mar	1.29	0.12	1.41	2.35
Apr	1.33	0.00	1.33	2.21
May	2.22	0.18	2.40	4.00
Jun	1.99	0.68	2.67	4.45
Jul	1.06	0.19	1.25	2.08
Aug	0.77	0.14	0.91	1.51

Table A - 10 The potential water demand and irrigation requirement at La Tho Irrigation Management Scheme

Month	La Tho Million m^3			
	Rice	Annual Crops	Total potential net irrigation requirement	Total potential gross irrigation requirement*
Dec	0.81	0.00	0.81	1.34
Jan	0.90	0.14	1.03	1.72
Feb	1.22	0.25	1.47	2.45
Mar	1.18	0.07	1.25	2.09
Apr	1.21	0.00	1.21	2.02
May	2.03	0.11	2.14	3.57
Jun	1.82	0.42	2.24	3.73
Jul	0.97	0.12	1.09	1.81
Aug	0.70	0.09	0.79	1.31

Table A - 11 The potential water demand and irrigation requirement at Chau Son Irrigation Management Scheme

Month	Chau Son Million m^3			
	Rice	Annual Crops	Total potential net irrigation requirement	Total potential gross irrigation requirement*
Dec	0.54	0.00	0.54	0.91
Jan	0.60	0.16	0.77	1.28
Feb	0.82	0.29	1.12	1.86
Mar	0.79	0.09	0.88	1.47
Apr	0.82	0.00	0.82	1.36
May	1.37	0.13	1.50	2.50
Jun	1.23	0.49	1.72	2.86
Jul	0.65	0.14	0.79	1.32
Aug	0.47	0.10	0.57	0.96

Table A - 12 The potential water demand and irrigation requirement at Xuyen Dong Irrigation Management Scheme

Month	Xuyen Dong Million m^3			
	Rice	Annual Crops	Total potential net irrigation requirement	Total potential gross irrigation requirement*
Dec	1.80	0.00	1.80	3.01
Jan	2.01	0.33	2.33	3.88
Feb	2.73	0.59	3.32	5.54
Mar	2.63	0.18	2.81	4.68
Apr	2.71	0.00	2.71	4.52
May	4.54	0.27	4.81	8.01
Jun	4.07	0.99	5.06	8.43
Jul	2.17	0.28	2.44	4.07
Aug	1.57	0.21	1.77	2.96

Table A - 13 The potential water demand and irrigation requirement at Bich Bac Irrigation Management Scheme

Month	Bich Bac Million m^3			
	Rice	Annual Crops	Total potential net irrigation requirement	Total potential gross irrigation requirement*
Dec	0.55	0.00	0.55	0.91
Jan	0.61	0.06	0.67	1.12
Feb	0.83	0.12	0.95	1.58
Mar	0.80	0.03	0.84	1.39
Apr	0.82	0.00	0.82	1.37
May	1.38	0.05	1.43	2.39
Jun	1.24	0.20	1.43	2.39
Jul	0.66	0.05	0.71	1.19
Aug	0.48	0.04	0.52	0.86

Table A - 14 The potential water demand and irrigation requirement at An Trach Irrigation Management Scheme

Month	An Trach Million m^3			
	Rice	Annual Crops	Total potential net irrigation requirement	Total potential gross irrigation requirement*
Dec	0.98	0.00	0.98	1.64
Jan	1.09	0.00	1.09	1.82
Feb	1.49	0.00	1.49	2.48
Mar	1.44	0.00	1.44	2.39
Apr	1.48	0.00	1.48	2.46
May	2.47	0.00	2.47	4.12
Jun	2.22	0.00	2.22	3.70
Jul	1.18	0.00	1.18	1.97
Aug	0.85	0.00	0.85	1.42

*Total potential gross irrigation requirement was calculated with the irrigation efficiency as 60%

Table A - 15 The cities and districts, population, industrial zone areas, domestic demand and industrial demand in the Vu Gia – Thu Bon Delta (calculated using data in 2005)

No	Administrative (City, District, Ward, Commune)	Population (Person)	Domestic Demand (m^3/day)	Industrial area (hectare)	Industrial Demand (m^3/day)
	Vu Gia - Thu Bon Delta	**1,462,793.00**	**243,165.00**	**1,485.00**	**48,035.00**
A	**Quang Nam Province**	**575,273.00**	**38,147.91**	**418.00**	**18,810.00**
I	**Hoi An City**	**90,150.00**	**13,279.95**	**0.00**	**0.00**
1	Minh An Ward	6,676.00	1,121.57	0.00	0.00
2	Tan An Ward	9,273.00	1,557.86	0.00	0.00
3	Cam Pho Ward	10,117.00	1,699.66	0.00	0.00
4	Thanh Ha Ward	11,246.00	1,889.33	0.00	0.00
5	Son Phong Ward	4,605.00	773.64	0.00	0.00
6	Cam Chau Ward	10,472.00	1,759.30	0.00	0.00
7	Cua Dai Ward	5,446.00	914.93	0.00	0.00
8	Cam An Ward	5,420.00	910.56	0.00	0.00
9	Cam Nam Ward	6,170.00	1,036.56	0.00	0.00
10	Cam Ha Commune	6,844.00	533.83	0.00	0.00
11	Cam Kim Commune	4,038.00	314.96	0.00	0.00
12	Cam Thanh Commune	7,458.00	581.72	0.00	0.00
13	Tan Hiep Commune	2,385.00	186.03	0.00	0.00
II	**Dai Loc District**	**145,935.00**	**3,259.78**	**0.00**	**0.00**
1	Dai Hiep Commune	8,275.00	645.45	0.00	0.00
2	Dai Hoa Commune	6,969.00	543.58	0.00	0.00
3	Dai An Commune	7,742.00	603.88	0.00	0.00
4	Ai Nghia Town	18,806.00	1,466.87	0.00	0.00
III	**Dien Ban District**	**205,394.00**	**16,020.73**	**418.00**	**18,810.00**
1	Vinh Dien Town	9,146.00	713.39	0.00	0.00
2	Dien Minh Commune	11,393.00	888.65	0.00	0.00
3	Dien An Commune	14,660.00	1,143.48	0.00	0.00
4	Dien Phuoc Commune	12,737.00	993.49	0.00	0.00
5	Dien Tho Commune	13,756.00	1,072.97	0.00	0.00
6	Dien Hong Commune	14,477.00	1,129.21	0.00	0.00
7	Dien Tien Commune	7,551.00	588.98	0.00	0.00
8	Dien Hoa Commune	11,940.00	931.32	0.00	0.00
9	Dien Thang Bac Commune	6,318.00	492.80	0.00	0.00
10	Dien Thang Trung Commune	7,501.00	585.08	0.00	0.00
11	Dien Thang Nam Commune	6,556.00	511.37	0.00	0.00
12	Dien Ngoc Commune	15,507.00	1,209.55	418.00	18,810.00
13	Dien Nam Bac Commune	5,322.00	415.12	0.00	0.00
14	Dien Nam Trung Commune	7,351.00	573.38	0.00	0.00

15	Dien Nam Dong Commune	6,565.00	512.07	0.00	0.00
16	Dien Duong Commune	12,799.00	998.32	0.00	0.00
17	Dien Phuong Commune	14,698.00	1,146.44	0.00	0.00
18	Dien Phong Commune	10,573.00	824.69	0.00	0.00
19	Dien Trung Commune	6,359.00	496.00	0.00	0.00
20	Dien Quang Commune	10,185.00	794.43	0.00	0.00
IV	**Duy Xuyen District**	**133,794.00**	**5,587.45**	**0.00**	**0.00**
1	Nam Phuoc Town	24,221.00	1,889.24	0.00	0.00
2	Duy Chau Commune	8,208.00	640.22	0.00	0.00
3	Duy Trinh Commune	8,212.00	640.54	0.00	0.00
4	Duy Phuoc Commune	13,340.00	1,040.52	0.00	0.00
5	Duy Thanh Commune	7,508.00	585.62	0.00	0.00
6	Duy Vinh Commune	10,145.00	791.31	0.00	0.00
B	**Da Nang City**	**887,520.00**	**205,017.12**	**1,066.50**	**29,224.50**
I	Lien Chieu District	128,350.00	29,648.85	816.00	17,952.00
1	Hoa Hiep Bac Ward	13,420.00	3,100.02	289.40	6,366.80
2	Hoa Hiep Nam Ward	15,120.00	3,492.72	0.00	0.00
3	Hoa Khanh Bac Ward	40,180.00	9,281.58	394.00	8,668.00
4	Hoa Khanh Nam Ward	24,080.00	5,562.48	132.60	2,917.20
5	Hoa Minh Ward	35,550.00	8,212.05	0.00	0.00
II	**Thanh Khe District**	**174,580.00**	**40,327.98**	**0.00**	**0.00**
1	Tam Thuan Ward	17,190.00	3,970.89	0.00	0.00
2	Thanh Khe Tay Ward	17,820.00	4,116.42	0.00	0.00
3	Thanh Khe Dong Ward	14,150.00	3,268.65	0.00	0.00
4	Xuan Ha Ward	17,850.00	4,123.35	0.00	0.00
5	Tan Chinh Ward	12,790.00	2,954.49	0.00	0.00
6	Chinh Gian Ward	20,720.00	4,786.32	0.00	0.00
7	Vinh Trung Ward	16,720.00	3,862.32	0.00	0.00
8	Thac Gian Ward	18,470.00	4,266.57	0.00	0.00
9	An Khe Ward	21,630.00	4,996.53	0.00	0.00
10	Hoa Khe Ward	17,240.00	3,982.44	0.00	0.00
III	**Hai Chau District**	**189,580.00**	**43,792.98**	**0.00**	**0.00**
1	Thanh Binh Ward	20,670.00	4,774.77	0.00	0.00
2	Thuan Phuoc Ward	17,850.00	4,123.35	0.00	0.00
3	Thach Thang Ward	14,230.00	3,287.13	0.00	0.00
4	Hai Chau 1 Ward	12,460.00	2,878.26	0.00	0.00
5	Hai Chau 2 Ward	12,090.00	2,792.79	0.00	0.00
6	Phuoc Ninh Ward	9,670.00	2,233.77	0.00	0.00
7	Hoa Thuan Tay Ward	13,530.00	3,125.43	0.00	0.00
8	Hoa Thuan Dong Ward	14,260.00	3,294.06	0.00	0.00
9	Nam Duong Ward	8,210.00	1,896.51	0.00	0.00
10	Binh Hien Ward	11,940.00	2,758.14	0.00	0.00
11	Binh Thuan Ward	12,800.00	2,956.80	0.00	0.00
12	Hoa Cuong Bac Ward	23,490.00	5,426.19	0.00	0.00

13	Hoa Cuong Nam Ward	18,380.00	4,245.78	0.00	0.00
IV	**Son Tra District**	**127,700.00**	**29,498.70**	**100.70**	**4,531.50**
1	Tho Quang Ward	26,280.00	6,070.68	50.60	2,277.00
2	Nai Hien Dong Ward	16,550.00	3,823.05	0.00	0.00
3	Man Thai Ward	14,510.00	3,351.81	0.00	0.00
4	An Hai Bac Ward	26,170.00	6,045.27	50.10	2,254.50
5	Phuoc My Ward	15,190.00	3,508.89	0.00	0.00
6	An Hai Tay Ward	11,760.00	2,716.56	0.00	0.00
7	An Hai Dong Ward	17,240.00	3,982.44	0.00	0.00
V	**Ngu Hanh Son District**	**63,060.00**	**14,566.86**	**0.00**	**0.00**
1	Bac My An Ward	22,550.00	5,209.05	0.00	0.00
2	Khue My Ward	10,140.00	2,342.34	0.00	0.00
3	Hoa Quy Ward	11,540.00	2,665.74	0.00	0.00
4	Hoa Hai Ward	18,830.00	4,349.73	0.00	0.00
VI	**Cam Le District**	**87,710.00**	**20,261.01**	**149.80**	**6,741.00**
1	Khue Trung Ward	22,720.00	5,248.32	0.00	0.00
2	Hoa Phat Ward	11,950.00	2,760.45	0.00	0.00
3	Hoa An Ward	18,360.00	4,241.16	0.00	0.00
4	Hoa Tho Tay Ward	9,460.00	2,185.26	149.80	6,741.00
5	Hoa Tho Đong Ward	12,700.00	2,933.70	0.00	0.00
6	Hoa Xuan Ward	12,520.00	2,892.12	0.00	0.00
VI	**Hoa Vang District**	**116,540.00**	**26,920.74**	**0.00**	**0.00**
1	Hoa Bac Commune	3,770.00	870.87	0.00	0.00
2	Hoa Lien Commune	12,400.00	2,864.40	0.00	0.00
3	Hoa Ninh Commune	4,670.00	1,078.77	0.00	0.00
4	Hoa Son Commune	12,530.00	2,894.43	0.00	0.00
5	Hoa Nhon Commune	13,500.00	3,118.50	0.00	0.00
6	Hoa Phu Commune	4,960.00	1,145.76	0.00	0.00
7	Hoa Phong Commune	14,340.00	3,312.54	0.00	0.00
8	Hoa Chau Commune	12,540.00	2,896.74	0.00	0.00
9	Hoa Tien Commune	15,240.00	3,520.44	0.00	0.00
10	Hoa Phuoc Commune	11,550.00	2,668.05	0.00	0.00
11	Hoa Khuong Commune	11,040.00	2,550.24	0.00	0.00

Table A – 16 Pumping data from different irrigation management scheme

Month	Dong Quan (Million m^3)	Tu Phu (Million m^3)	Dong Ho (Million m^3)	Tu Cau (Million m^3)	Cam Van (Million m^3)	Vinh Dien (Million m^3)	Cam Sa (Million m^3)
Dec	1.93	2.02	1.12	0.80	4.74	3.38	0.80
Jan	3.41	2.99	1.24	1.02	8.07	4.35	0.36
Feb	2.50	3.50	1.21	0.16	6.92	4.88	1.07
Mar	3.03	3.15	1.55	2.07	5.06	5.13	1.21
Apr	2.66	2.73	1.08	1.13	5.62	1.03	1.24
May	4.21	4.11	1.61	0.19	9.03	4.46	0.45
Jun	1.94	7.40	2.01	0.00	5.35	4.46	1.99
Jul	4.55	4.73	1.76	0.00	7.23	6.67	1.84
Aug	3.82	3.18	1.68	0.00	5.36	4.93	1.25

Table A – 17 Pumping data from different irrigation management scheme

Month	Ai Nghia (Million m^3)	La Tho (Million m^3)	Chau Son (Million m^3)	Xuyen Dong (Million m^3)	Bich Bac (Million m^3)	An Trach (Million m^3)
Dec	1.45	1.15	1.05	4.68	0.69	1.11
Jan	3.22	2.59	2.33	3.34	0.44	1.17
Feb	3.40	2.39	1.18	4.23	1.23	1.11
Mar	2.97	2.32	1.69	5.34	0.89	1.75
Apr	1.91	1.81	1.30	1.39	1.16	1.20
May	3.65	2.78	1.75	6.52	1.02	2.45
Jun	4.36	2.69	2.55	7.52	1.66	1.62
Jul	3.16	3.13	2.05	6.61	0.83	0.05
Aug	2.52	2.71	1.25	5.06	1.04	0.00

Appendix B List of involved stakeholders and experts

No.	Organization/person	Role	Relevance in study area
1	Quang Nam Centre for Hydrology and Meteorology	Stakeholder	Hydrological-meteorology forecasting, data collection, and drought warning for Quang Nam
2	Irrigation Management Company of Quang Nam	Stakeholder	Irrigation water supply for Quang Nam Province
3	Quang Nam Department of Agriculture and Rural Development	Stakeholder	Management of agriculture, irrigation, and disaster in Quang Nam
4	Da Nang Department of Agriculture and Rural Development	Stakeholder	Management of agriculture and disaster in Da Nang, irrigation
5	Prof. Dr. Nguyen The Hung – Da Nang University	Stakeholder, Expert	Local resident of Da Nang, experienced in the Vu Gia Thu Bon river basin, and hydraulic system.
6	Vo Nguyen Duc Phuoc – Da Nang University	Stakeholder, Expert	Local resident of Quang Nam, experienced in the Vu Gia Thu Bon river basin, and hydraulic system.

Appendix C The minimum flow requirement in the Vu Gia – Thu Bon River Basin

1. Cau Do control point

C - 1 Interrelated discharge (m^3/s) of scenario S0 to S5 to the required minimum flow at Cau Do control at Vu Gia River location before Quang Hue confluence

Vu Gia River - before Quang Hue confluence						
	S0	S1	S2	S3	S4	S5
Dec	270	270	270	270	270	270
Jan	84	84	84	84	84	96
Feb	49	49	55	49	55	61
Mar	46	55	61	52	58	67
Apr	48	57	63	54	60	69
May	97	103	109	100	106	112
Jun	76	106	112	103	109	115
Jul	183	183	183	183	183	183
Aug	146	146	146	146	146	146

C - 2 Interrelated discharge (m^3/s) of scenario S0 to S5 to the required minimum flow at Cau Do control at Vu Gia River location after Quang Hue confluence

Vu Gia River - after Quang Hue confluence						
	S0	S1	S2	S3	S4	S5
Dec	208	208	208	208	208	208
Jan	69	69	69	69	69	79
Feb	40	40	45	40	45	50
Mar	38	45	50	43	48	55
Apr	39	46	51	44	49	56
May	78	81	86	79	84	89
Jun	62	85	90	83	88	92
Jul	143	143	143	143	143	143
Aug	111	111	111	111	111	111

2. Cau Lau control point

C - 3 Interrelated discharge (m³/s) of scenario S0 to S5 to the required minimum flow at Cau Lau control at Thu Bon River location before Quang Hue confluence

Thu Bon River - before Quang Hue confluence						
	S0	S1	S2	S3	S4	S5
Dec	513	513	513	513	513	513
Jan	165	165	165	165	165	177
Feb	92	119	122	116	125	143
Mar	72	108	108	102	114	129
Apr	52	100	100	100	109	118
May	48	96	96	96	105	114
Jun	49	109	109	106	118	130
Jul	42	81	81	81	90	102
Aug	38	86	86	89	95	104

C - 4 Interrelated discharge (m³/s) of scenario S0 to S5 to the required minimum flow at Cau Lau control at Thu Bon River location after Quang Hue confluence

Thu Bon River - after Quang hue confluence						
	S0	S1	S2	S3	S4	S5
Dec	588	588	588	588	588	588
Jan	180	180	180	180	180	194
Feb	101	132	136	129	139	159
Mar	80	121	122	114	128	144
Apr	60	114	115	113	123	133
May	68	122	124	122	132	142
Jun	65	131	132	127	140	153
Jul	84	131	133	130	141	155
Aug	77	131	133	134	141	152

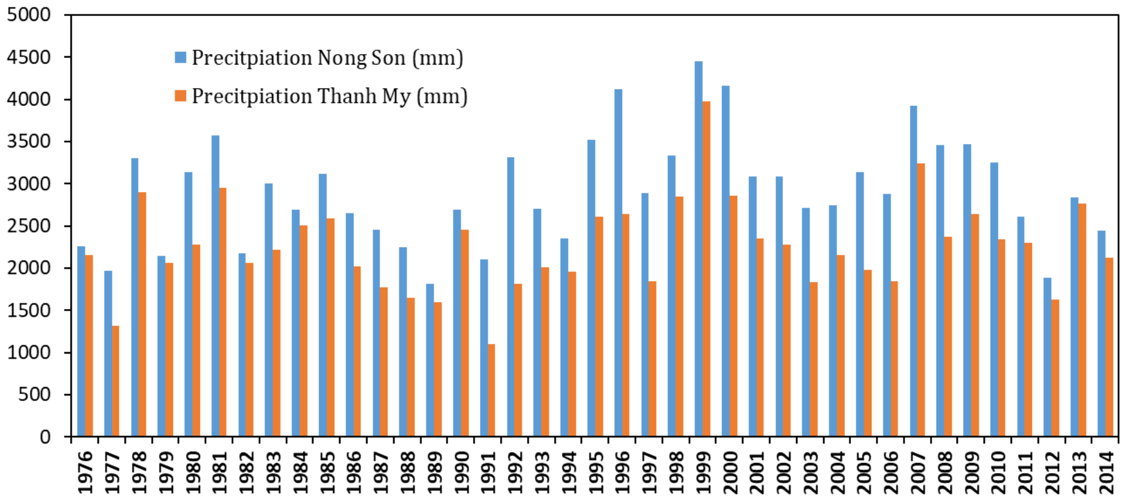
3. Tu Cau control point

C - 5 Interrelated discharge (m^3/s) of scenario S0 to S5 to the required minimum flow at Tu Cau control at Thu Bon River location before Quang Hue confluence

Thu Bon River - before Quang Hue confluence						
	S0	S1	S2	S3	S4	S5
Dec	513	513	513	513	513	513
Jan	165	165	165	165	165	165
Feb	92	101	104	104	113	119
Mar	72	96	93	90	99	111
Apr	52	82	82	76	85	91
May	48	84	84	78	90	93
Jun	49	94	94	82	100	103
Jul	42	87	87	75	93	96
Aug	38	56	56	50	59	65

C - 6 Interrelated discharge (m^3/s) of scenario S0 to S5 to the required minimum flow at Tu Cau control at Thu Bon River location after Quang Hue confluence

Thu Bon River - after Quang Hue confluence						
	S0	S1	S2	S3	S4	S5
Dec	588	588	588	588	588	588
Jan	180	180	180	180	180	180
Feb	101	111	115	115	125	132
Mar	80	108	104	101	111	126
Apr	60	96	96	89	99	106
May	68	110	112	104	117	121
Jun	65	116	117	103	122	126
Jul	84	137	139	126	144	149
Aug	77	98	98	91	102	109



C -7 Annual precipitation at Nong Son and Thanh My stations during the period 1976-2014

C – 8 (a) The districts and cities in the VG-TB River Basin; (b) Location of the VG-TB River Basin in Viet Nam. Source data: MONRE; IMHEN

Erklärung zur Dissertation

gemäß der Promotionsordnung vom 12. März 2020

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Cologne, 2021 **Nguyen Thi Ngoc Uyen**