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RESEARCH ON CHARACTERISTICS OF FRESH WATER DISTRIBUTION IN THE RIVER ESTUARIES OF THE VIENAMESE MEKONG DELTA - THE CASE OF CO CHIEN RIVER

SUMMARY OF DISSERTATION ON HYDROLOGY

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INTRODUCTION

1 Necessity of thesis topic

In the coastal estuaries of the Vietnamese Mekong Delta (VMD), lacking fresh water for essential needs is raising a big concern for scientists, residents, and the government. In the dry season, saltwater intrusion has increased, and freshwater scarcity has greatly affected people in daily life as well as in production. The main source of fresh water for domestic use is currently exploited from groundwater. However, the over-exploitation of groundwater has shown many signs of degradation. Requesting a source of fresh water to supplement is an urgent matter.

On the estuaries of the Mekong River integrated with saline water intrusion, the salinity value changes continuously with the tidal rhythm, and the lowest salinity value has many periods maintained at the fresh threshold. There is still potential opportunity in terms of space and time that freshwater can be used and exploited.

From the reality above, the Ph.D. has chosen the title "*Research on characteristics of freshwater distribution in the river estuaries of the Vietnamese Mekong Delta - The case of Co Chien River*". This study proposes a new approach to the study of adapting the livelihood of coastal communities surrounding the Mekong River mouth under saline intrusion by "Exploring freshwater". Since then, solutions and techniques would be proposed to exploit fresh water on the river to supply the essential needs of coastal people.

2 Study objectives:

- Identify the characteristics of freshwater distribution in the interaction of river and sea in the Cuu Long estuary (study case for Co Chien River);
- Assess the future occurrence of fresh water in estuaries under the impact of changes in upstream flows;
- Proposed solutions to exploit surface water to supply water users in the study area.

3 Study Subject and Scope

Study Subject: Characteristics of fresh water in the Cuu Long estuaries (surface water), forecast of fluctuations and solutions for exploiting freshwater in the estuaries.

Study Scope:

Spatial scope: include: Cua Tieu, Cua Dai, Ba Lai, Ham Luong, Co Chien, Cung Hau, Dinh An, Tran De, and details for Co Chien estuary.

Temporal scope: freshwater distribution characteristics are analyzed over the period 1996÷2021. Impact factors are considered over the period 1980÷2019.

4 Methods

Approaches: (1) Approach to inherit scientific and technological achievements; (2) A systematic, comprehensive, and integrated approach from the whole to the details; (3) Community outreach.

Methods: (1) Statistical analysis methods: descriptive statistics, linear regression analysis, correlation analysis, ...; (2) Field measurement method; (3) Mathematical modeling method; (4) Geosynthetic method.

5 New contribution of the thesis

(1) It has been initially identified the spatial and temporal distribution characteristics of freshwater in the estuaries of the Mekong River; as well as the relationship between the upstream flow and the characteristics of freshwater in the estuaries of the Mekong River.

(2) The distribution maps of freshwater in the estuaries of the Mekong River have been studied, calculated, and developed corresponding to the current scenario in 2005 and some climate change scenarios updated until 2030.

(3) Technical solutions have been proposed to serve the exploitation of freshwater in estuaries of the Mekong River for household scale. Additionally, calculations have been made to determine the scale and capacity of extracting fresh water from the Co Chien River to the Lang The reservoir to provide drinking water for Tra Vinh City.

CHAPTER 1 OVERVIEW OF STUDY ISSUES

1.1 Overview of the Study Issues

Estuaries are the geographical areas where seawater blends with fresh water that originates from inland. This has made the estuary one of the most prolific natural habitats in the world, while also being very densely populated. This raises critical issues of water security in coastal areas. Indeed, a key concern of our times is the efficient distribution and use of freshwater resources in coastal areas, to conserve and restore brackish ecosystem services while also providing for the socio-economic needs of residents and economic activity.

Freshwater inflows are fundamental to the functioning of estuarine processes. However, the spatial and temporal distribution of freshwater is undergoing a major change in many coastal estuaries, due to a combination of issues such as sea level rise and changes in hydrological flow regimes caused by the development of reservoir systems upstream, alongside local exploitation of freshwater.

Freshwater resources make an essential contribution to the livelihoods of millions of local people in the coastal estuaries of the Vietnamese Mekong Delta (VMD). The main source of fresh water for domestic use is currently exploited from groundwater. However, the over-exploitation of groundwater has shown many signs of degradation. Requesting a source of fresh water to supplement is an urgent matter.

The salinity of estuary waters is a result of an interaction between freshwater fluxes from upstream and salt water from the sea, with salinity levels varying both vertically and horizontally. Tide is the main driving force pushing seawater into rivers, causing fluctuations in estuary salinity. From the upstream side, the river flows push against tidal currents, resisting salinity intrusion while creating a brackish zone in the middle area. In the dry season, seawater usually makes its way farther inland throughout the estuaries, due to the lower river flows typically measured in this period. When the river flows increase, floodwaters flush saline water back downstream in a process that provides various benefits to aquatic habitats.

Against this backdrop, this study posed two principal research questions: (i) How is the freshwater distributed in the coastal area of the VMD? (ii) How strong is the influence of the hydrological dynamics of upstream flows on the freshwater distribution downstream? (iii) How to exploit fresh water in the coastal area of the VMD? These questions have not been fully answered in previous studies, which principally considered analyzing the highest salinity values to determine the highest saline intrusion boundaries to explore prevention or mitigation solutions. Previous studies, therefore, have not explicitly identified the boundaries of freshwater availability in months of the dry season for potential exploitation in the VMD coastal areas as well as have not investigated the influences of flow dynamics in the upstream delta on freshwater appearance downstream.

The current study sought to gain a deeper understanding of trends in the distribution of freshwater in the VMD, as a first step towards finding solutions to sustain brackish ecosystems here. It also sought to clarify how upstream flows have changed and the effects of these changes on freshwater availability in the estuaries. Understanding these changes is essential not only to maintain sufficient freshwater in estuary ecosystems but also to provide appropriate freshwater-exploitation alternatives instead of groundwater over-extraction for local communities in areas affected by salinization.

1.2 Overview of research history

There have been numerous studies related to freshwater resources and the issue of salinity intrusion in the Mekong Delta with painstaking detail. These studies have highlighted the importance of the Mekong Delta and the role of freshwater for the region, providing detailed guidelines for managing river mouths and freshwater resources. However, there are still limitations in studying the distribution of freshwater in the Mekong Delta, especially in the Cuu Long section where there have been fewer studies.

Studies on salinity intrusion have affirmed that the process of saltwater intrusion in rivers depends on various factors, including river flow, coast tidal waves, terrain characteristics, meteorological factors, and human impact. Among these factors, upper stream flow and coastal tidal waves play a major role in determining the laws of salinity intrusion. Tidal waves cause fluctuations in salinity depending on the tide cycle, while upper stream flow causes fluctuations in salinity according to the season.

Upstream, the impacts on the watershed such as hydroelectric reservoirs, increased water use, and water transfer out of the watershed have been and will continue to change the flow regime into the Mekong Delta. Concerning the dissertation topic, research on seasonal flow has shown that water flows into the lower Mekong River tend to increase during the dry months.

Studies related to the sea have also been mentioned, such as calculations of the hydrodynamic regime of the East Sea, evaluations of sea level rise due to climate change, mathematical models of hydrodynamic regimes, waves, sediment transport, etc.

Studies on exploiting the Mekong Delta continue to evolve, commencing from an early period and conducted painstakingly over the decades. Based on investigation and research results, government agencies have implemented and developed the Mekong Delta.

Overall, there has been a multitude of studies related to the dissertation topic, incorporating past experiences and research results which can be useful for the dissertation.1.2

1.3 Overview of the Mekong Delta and related water usage issues.

The process of exploiting the Mekong Delta has been a constant adaptation and environmental manipulation by humans, and during this period, water resources have always been considered core elements. All measures for exploiting the delta impact the water regime.

Currently, this trend is still affirmed. In addition to freshwater, brackish and saline water are also considered resources for economic development. As a result, freshwater resources serving daily needs and essential activities in the Mekong Delta have become increasingly difficult.

Water supply for daily needs in the Mekong Delta mainly comes from groundwater sources. Rainwater and surface water are less stable due to the effects of droughts and saltwater intrusion, so they are not extensively used. However, excessive exploitation of groundwater sources has led to many signs of ecological degradation. Therefore, water supply directives in the Mekong Delta have called for limiting groundwater exploitation and shifting to surface and rainwater sources. Solutions such as inter-regional water supply and reservoir storage have been approved to address the instability caused by droughts and saltwater intrusion.

Identifying the laws of freshwater distribution in the estuaries of the Mekong River will facilitate the calculation and determination of the scale, capacity, and operation method of reservoirs in the region. Techniques for extracting freshwater from rivers for household or cluster household scales have also been discussed. The results will contribute to solving the challenge of providing clean water to an area in the Mekong Delta that is experiencing difficulties in the water supply.

CHAPTER 2 DATA AND METHODS.

2.1 Concepts and theoretical bases on the distribution of fresh water in estuaries

Thesis using the salinity standard of 0.30 ‰ for the boundary of fresh water. The upper limit of the river mouth region is the boundary that consistently has fresh water (salinity ≤ 0.3 ‰), taking into account future conditions.

The spatial and temporal criteria (based on observation, experience, and literature review) applied in this study to identify freshwater distribution in the research area are presented in Table 1

Table 1 The criteria applied to identify freshwater distribution

No	*Sign*	*Criteria*	**Definition**
I	The spatial criteria		
I.1	FWA	Non-salinity boundary	At this boundary, the highest salinity level is always less than or equal to 0.3‰.
I.2	FWD	Daily freshwater boundary	Freshwater appears here at least once on any day.
I.3	FW4	The boundary of freshwater in April	Freshwater appears here at least once in April

No	Sign	Criteria	Definition
I.4	FW2	The boundary of freshwater in February	Freshwater appears here at least once in February
I.5	FWN	The non-freshwater boundary in the dry season	There is no freshwater here between February and April
II	The temporal criteria		
II.1	FWE	The end date of freshwater	This date specifies the first of five consecutive days without any freshwater at the beginning of the dry season.
II.2	FWS	The start date of freshwater	This is the first date on which freshwater makes its appearance at the end of the dry season with thereafter five consecutive days of freshwater observed and the situation remaining similar for the next 15 days.
II.3	NFW	The number of hours each month with freshwater	The total hours that freshwater appears within a month.
II.4	DFW	The largest number of days without freshwater	The greatest number of consecutive days of the year with no freshwater available.

2.2 Methods

2..2.2 Statistical analysis methods

Including: descriptive statistics, linear regression, correlation analysis.

Descriptive statistics method is used to process collected data, summarize characteristics and present them in the form of tables, graphs, etc.

Linear regression method is used to analyze upstream flow trends and sea level trends.

The correlation analysis method was used to establish the relationship between upstream flow and estuarine freshwater characteristics.

2..2.3 Geosynthetic methods

The geosynthesis method is used to extract freshwater distribution features over time and space, and spatial interpolation to determine the boundaries of freshwater features along the main rivers.

The geographical synthesis method is also used to synthesize the results, consider relationships, and draw out the laws of evolution of the flow regime at

Kratie, Tan Chau, as well as the relationship between them and the flow regime. VCS freshwater characteristics.

2.2.4 Field measurement methods

Field measurement survey methods were used to clarify the possibility of stratified flow occurring during the dry season in the Mekong estuary.

We designed five campaigns of field surveys to measure the vertical distribution of salinity. Each cross-section was measured at the center of the cross-section. At one point, measurement was done over the full depth at 0.3 m intervals starting from the surface to the bottom with a conductivity meter with a 30 m cable.

The schedule and hydrological characteristics of each survey are summarized in Table 2.

Tabke 2 The schedule and hydrological characteristics of survey.

No	Time	Location	Hmax (m)	W_T ($10^6 m^3$)	W_S ($10^6 m^3$)	W_T/W_S
1	24/04/2017	TV1	1.17	180	86	2.1
2	25/04/2017	TV2	1.35	283		3.3
3	26/04/2017	TV3	1.45	292		3.4
4	27/04/2017	TV4	1.40	288		3.3
5	11/04/2018	TV5	0.79	131	81	1.6

2.2.5 Mathematical modeling method

Mathematical modeling methods are used to detail the spatial distribution of fresh water and calculate flow exchange through estuaries.

In the thesis, the Mike 11 hydrodynamic modeling was implemented. We used the available MIKE 11 model, which the authors had calibrated and validated in previous studies. We set up the model using two modules: (i) the hydrodynamic (HD) module to simulate flow modes and (ii) the advection-dispersion (AD) module for salinity simulation. These modeling methods have been widely applied in studies of the Mekong Delta. The results of the hydraulic calculations were used to create freshwater distribution maps for the Mekong River estuaries.

2.3 Data

Our analyses used the following data: (i) Salinity measures from 1996 to 2017 from 21 monitoring stations throughout the VMD coastal region, obtained from the Hydro-Meteorological Data Center of Vietnam. These data were registered manually at a frequency of every 2 hours based on a specific schedule, equivalent to 12 data points at the odd hours of each day. Data were recorded during the dry season from February to June for the period before 2012. After 2012, data were recorded from January to June. At each measurement site, we collected the samples at three depths—0.2H, 0.5H, and 0.8H—with H being the depth, which varied depending on the location (The average salinity (STT) is calculated using the following formula: STT = (S0.2h + 2 × S0.5h + S0.8h)/4 (‰)). (ii) Salinity and water level data were recorded automatically at 20-minute intervals over the 2015–2018 period at Tra Vinh station, located on the Co Chien River. These data were measured using WTW-LF 196 German conductivity meters with samples in glass bottles with a cork. (iii) Water levels measured at Kratie station in the Mekong River for the period 1990–2019. This location is considered the starting point of the Mekong Delta. It is 215 km from Phnom Penh and 310 km from the Vietnam border along the river. The discharges at Kratie were calculated from the water levels using the following formula: Rising stage: $Q = (8.158H-10.155)^{2.1}$; Falling stage: $Q = (3.300H+1.256)^{2.5}$ in which, Q is discharged and H is water level. The Mekong River Commission provided these upstream data. (iv) Flow monitoring data at the Tan Chau station of the Tien River for the 2001–2019 period. (v) Water levels measured at Vung Tau marine station, Ben Trai station of Co Chien River, and Tra Vinh station of Co Chien River for 1985-2017. The hydro-Meteorological Data Center of Vietnam provided this data.

CHAPTER 3 RESULTS AND DISCUSSION

3.1 Distribution of Freshwater in the Delta Estuaries

3.1.1 Temporal Distribution of Freshwater

Salinity data from Tra Vinh shows that freshwater usually did appear during the rainy season from 2015 to 2018. During the dry seasons of 2015, 2017, and 2018, the salinity level was less than 0.3‰ on many days.

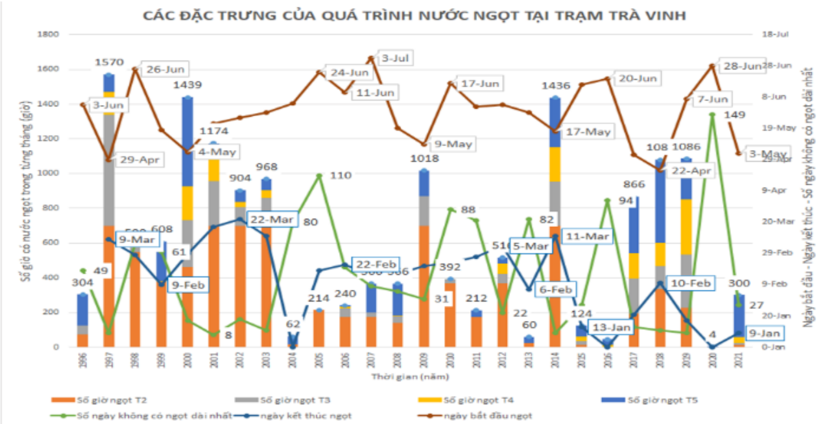


Figure 1 Statistics on freshwater at Tra Vinh, 1996–2021.

The measurement data show variation in the appearance of freshwater at Tra Vinh from 1996 to 2021 (Figure 1). The results show that: (1) FWE: from the 26 years with available data, on average on 12/2, 7 years of freshwater lasted until March; 8 years with freshwater lasted between February; 5 years with freshwater lasted in the first half of February; 6 years with freshwater lasted before January, all recent years (2016-2021). (2) FWS: Freshwater began to appear from late May to early June (average on 29/5). There were 13 years in which freshwater first appeared in May; 12 years in which freshwater first appeared in June; and one year in which freshwater first appeared in July. (3) NFW: In saline months, freshwater was found at an average of 311 h, 108 h, 57 h, and 137 h, respectively, in February, March, April, and May. (4) The longest observed period without freshwater was in 2021, with 149 consecutive days, followed by 2005 with 110 days, and 2016 with 94 days. The average DFW was 46 days.

Rules were derived for freshwater distribution, based on which appropriate freshwater exploitation regimes can be developed. Distribution details include the beginning of the freshwater season; the end of the freshwater season; the number of days without freshwater per year; and the hours of freshwater each month. The mean values of the criteria indicate favorable access to fresh water in estuaries of the MRD. However, the criteria were not stable with large Cv values. This is a point to note in freshwater exploitation.

In recent years, the FWE trend has come sooner, and the DFW is fewer, with up to 5 years DFW < 27 days.

3.1.2 Spatial Distribution of Freshwater

3.1.2.1 Spatial Distribution of Freshwater Based on Monitoring Data

The years 2005, 2009, and 2014 were selected to depict freshwater boundaries in the study area, as they were statically representative of years with the lowest, average, and greatest amounts of freshwater, respectively. Figure 2 presents freshwater boundaries in February, April, and daily, based on measurement station data.

FW2: Upstream flows tended to still be high in February, producing a rather stable freshwater boundary in the estuaries (Figure 2a). In 2005, the FW2 was about 25 km from the sea. In 2009 and 2014, that distance was about 15 km.

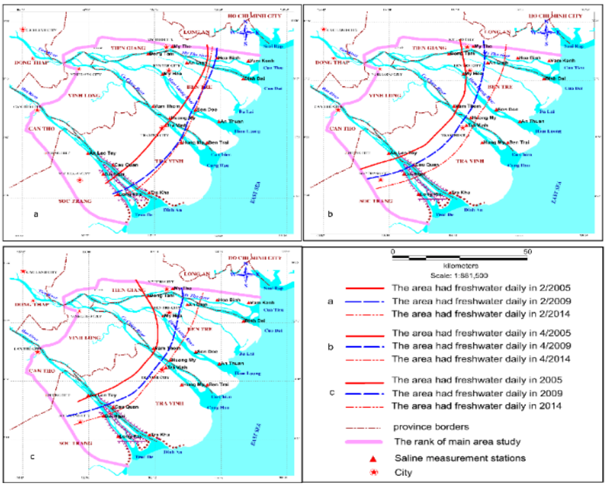


Figure 2 *Freshwater boundaries estimated for 2005, 2009 and 2014.*

FW4: The lowest upstream flows tended to be measured in April, which is why FW4 is so close to the FWD (Figure 2b). On the My Tho River, which is particularly sensitive to changes in upstream flows, the FW4 was about 60 km from the sea and similarly found salinity on the My Tho River to be sensitive to upstream flows.

FWD: In 2005, there was always fresh water on the Hau and Co Chien Rivers, the Ham Luong River, and the My Tho River, respectively, some 45 km, 55 km, and 65 km from the sea (Figure 2c). In 2009, there was always fresh water on the Hau and Co Chien Rivers at about 40 km from the sea. For the Ham Luong and My Tho rivers, these distances were, respectively, 45 km and 47 km from the sea. In 2014, the freshwater boundary was often observed 30 km from the sea during the dry season, and the trend was relatively stable. The boundaries fluctuated an average of about 20 km; that is, 15 km on the Hau and Co Chien Rivers, 25 km on the Ham Luong River, and 35 km on the My Tho River

3.1.2.2 Spatial Distribution of Freshwater Based on Hydrologic Modeling

Results from MIKE 11 models indicate five types of areas: (i) where there is always fresh water (non-saline areas), (ii) where there is freshwater daily, (iii) where there is freshwater until April, (iv) where there is freshwater until March and (v) where there is no fresh water in the dry season (Figure 3). FWA was found to be 80 km from the sea on the Tien River, 72 km on the Ham Luong River, 77 km on the Co Chien River, and 62 km on the Hau River. FWD was 49 km (Tien River), 48 km (Ham Luong River), 38 km (Co Chien River), and 38 km (Hau River) from the sea. The simulation results were verified by our 2005 observation data.

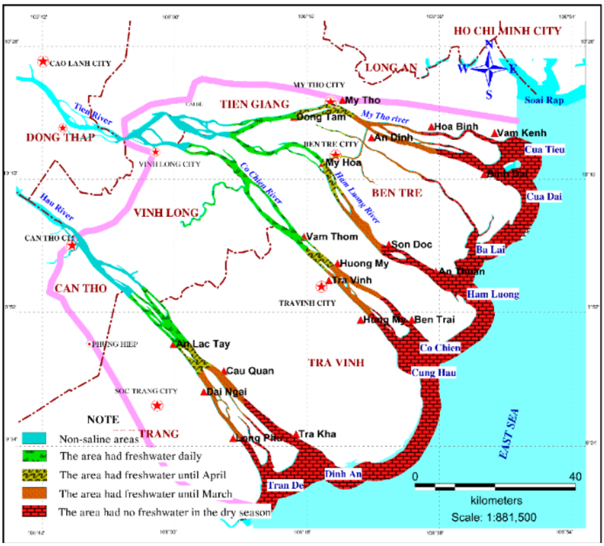
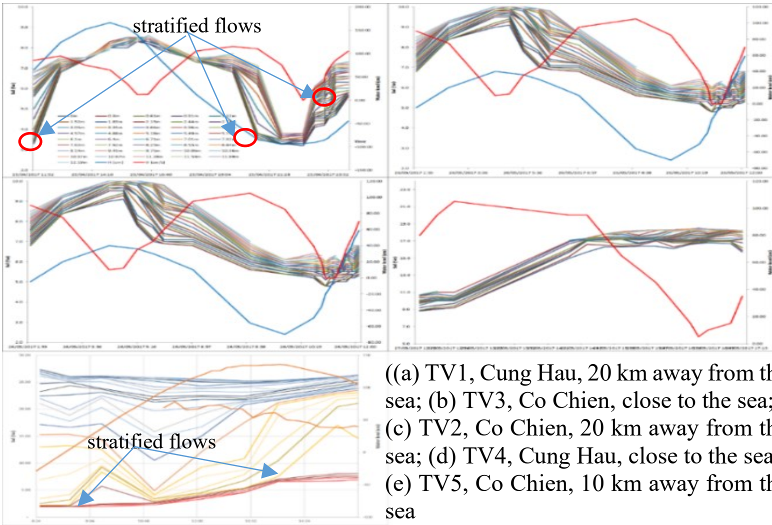


Figure 3 *Freshwater zones in the dry season (January to May), 2005.*

3.1.3 The vertical distribution of freshwater (stratified flows)

Figure 4 presents the vertical distribution of salinity at Co Chien estuaries. The results show that:



((a) TV1, Cung Hau, 20 km away from the sea; (b) TV3, Co Chien, close to the sea; (c) TV2, Co Chien, 20 km away from the sea; (d) TV4, Cung Hau, close to the sea; (e) TV5, Co Chien, 10 km away from the sea

Figure 4 *Vertical distribution of salinity.*

On the days of spring tide, the stratification parameter W_T/W_S is 3.4 (Figures 4b, c, d), the mixing between salt water and fresh water takes place strongly, and there is no obvious differentiation between salt water and fresh water.

During normal tidal days, the stratification parameter W_T/W_S is 2.1 (Figure 4a), the mixing between salt water and fresh water was weaker, and stratification was detected in the ascending or descending phases.

On the day of a neap tide, the stratification parameter W_T/W_S is 1.6 (Figure 4e), the mixing between salt water and fresh water was weak, and stratification was detected during all tidal cycles.

There are few measurement data, so it cannot be possible to summarize in to rule. However, the results allow confirming that there is flow stratification at the Co Chien estuary. This is a point to note in the exploitation of fresh water in the river. During the rainy season or the early or late months of the dry season, the flow in the river is higher, the flow stratification may be more obvious.

3.2 Upstream Discharges and Changes Thereof

3.2.1 Upstream Discharges at Kratie

Figure 5 presents trendlines of discharges at Kratie in the dry season (January to May), 2001–2019. The results show that: Discharges in the dry season have increased in all months of the dry season. April is the month with the strongest increase. The discharges of April were almost equal to January, much higher than that of February and March. The lowest discharges in the dry season have shifted from April to February.

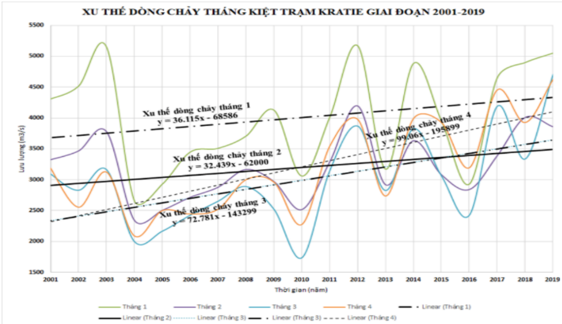


Figure 5. Trendlines of water discharges at Kratie, 2001–2019

Upstream activities, especially reservoirs, have strongly influenced the discharges in the dry season. The discharges have increased sharply in all months, after each time the big reservoir operation. This is as reported by previous studies. Our new findings also point out that the driest period has shifted from April to February.

3.2.2 Trendlines of discharges to Viet Nam

3.2.2.1 Upstream Discharges at Tan Chau

There is a difference in discharge trends at Tan Chau compared to Kratie. The average discharge in the dry season after 2013 is higher than before, but the average discharge in December is much lower, January is unchanged, and the following months are higher. The lowest discharges in the dry season have shifted from April to March.

Figure 6 presents trendlines of discharges at Tan Chau in the dry season (January to May), 2001–2019. The results show that: the trendlines of discharges decreased slightly in the first months of the dry season (in January and February). In March, the discharges start to increase. The discharges increased the strongest in April.

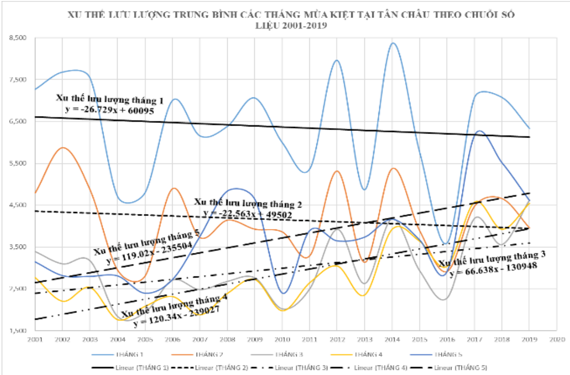


Figure 6. Trendlines of water discharges at Tan Chay, 2001–2019

The lowest discharges shifts in the dry season from April to March in Tan Chau, especially the decreased discharges in the first months of the dry season, which will have a strong impact on a saline intrusion in estuaries of the MRD.

3.2.2.2 Discharges through Estuaries

According to the survey results of the SIWRP from April 9-24, 2010, the largest proportion of flow distribution to estuaries is Dinh An (27.7%), followed by Tran De (19.7%), Ham Luong (14.5%), Co Chien (13.3%), Cung Hau (11.0%), Cua Dai (6.6%), Cua Tieu (2.4%).

The results show that the three estuaries of Ham Luong, Co Chien, and Cung Hau account for a large proportion of discharges in the dry season. These are the main rivers supplying fresh water throughout and in the middle of the delta. These estuaries play an important role in allocating water resources to the Mekong estuary.

3.2.3 Impact of Upstream Flows on Freshwater Distribution

Figure 7a presents the relationship between the average flows in January at Tan Chau and flows at the end of the freshwater season in Tra Vinh. In general, the two flows are related, but not closely (R2 = 0.47). Figure 7b presents the relationship between the average flow for three months (Qtb) in the dry season (April, May, and June) at Tan Chau and the beginning of the freshwater season.

The relationship found here is closer (R2 = 0.72). A relationship was found between average annual flows at Tan Chau from January to May and the longest period (in the number of days) without freshwater in the year (Figure 7c). Our results show that this relationship is quite tight (R2 = 0.70). Figure 7d presents the relationship between mean annual flows at Tan Chau from January to May and the highest number of days without freshwater at Tra Vinh. Our results show that this relationship is quite tight (R2 = 0.80).

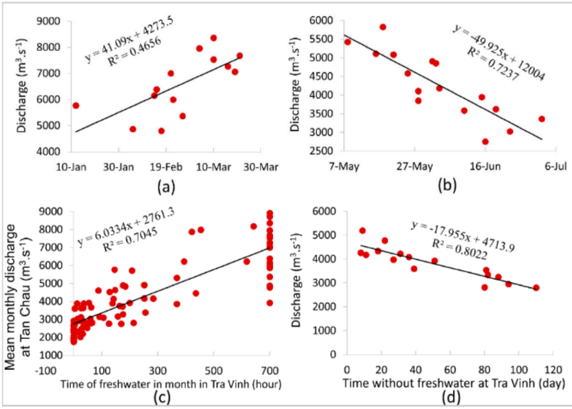


Figure 7. *(a) Relationship between flows at Tan Chau from January to April and FWE at Tra Vinh. (b) The relationship between flows at Tan Chau in the three-month dry season (from April to June) and the FWS at Tra Vinh. (c) The relationship between Qtc and the NFW at Tra Vinh (d) The relationship between mean annual flows at Tan Chau from January to May and the DFW at Tra Vinh*

Based on the identified correlations with upstream flows, we were able to make some predictions regarding freshwater flows in the estuaries (Figure 11). Our findings suggest the following trends: (i) average flows at Tan Chau in January will continue to decrease, causing the end of the freshwater season to come sooner; (ii) flows in the three months of March, April and May will continue to increase, leading to an earlier start of the freshwater season; (iii) average flows at Tan Chau in January and February will decrease, with average flows in March, April and May increasing, resulting in a similar development in freshwater availability in those months; and (iv) dry season flows will increase, reducing the greatest number of days without fresh water.

3.3 Tide, Sea Level Rise, and Salinity Intrusion.

3.3.1 Tide and tidal transmission into the estuaries of the MRD

Figure 8 presents the water level Hmax, Hmin, and the amount of seawater in Co Chien estuaries in the months dry season. The results show that:

- In the days of spring tide, the seawater volume is about 292-307 million m3/day. Compared with the amount freshwater of upstreams in the driest months (83.9 million m3/day), the ratio WT/Ws was 3.6.

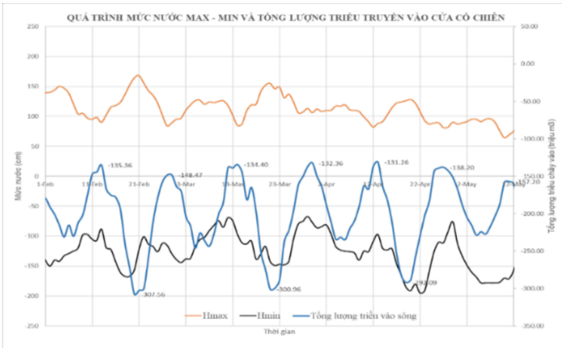


Figure 8 *Max/min water level and total tidal volume transmitted to the Co Chien river*

- On neap tide days, the seawater volume is about 131-148 million m3/day, and the WT/Ws ratio is about 1.6.

In general, at Co Chien estuaries, in the dry season, moderate mixing takes place. On the neap tide days, the flow stratification is more obvious. Especially when the upstream discharges increase, weak mixing will occur.

3.3.2 Sea level rise

In Vung Tau, the mean sea level tends to increase by an average of 3.18mm/year. At the estuary (Ben Trai), the water level increased faster, the average water level increased by 5.38mm/year. Notably, here the lowest water level rises faster than the highest water level. Compared with Vung Tau, the water level characteristics at Ben Trai increased faster, especially in Hmin.

Moving to the mainland, in Tra Vinh, the average water level tends to increase by 5.3mm/year, approximately the same as that of Ben Trai. The ebb water level increases less than that of Ben Trai, indicating that it is the result of operating the system of freshwater works from Tra Vinh to Ben Trai.

3.3.3 Salinity intrusion

In recent years, the salinity trend has changed significantly. Before 2013, the peak salinity occurred in March, April, and even May. From 2013 to 2017, the peak has shifted to February (2013, 2016, 2017), and even January (2015). The maximum salinity value also tends to increase. In the period of 9 years from 2009 to 2017, there were 6 years when the maximum salinity value was higher than the average of the analyzed data.

The fluctuation of the upstream flow, especially the decrease of flow in the first month of the dry season in Tan Chau, and the shift of the minimum month had a strong impact on the salinity in the main river.

3.4 Forecast of fresh water distribution to 2030

The flow in Kratie up to 2030 is expected to follow current trends. The coastal tidal boundary uses the RCP 4.5 scenario according to the 2016 climate change report. Water demand is based on the 2005 levels.

Figure 9 illustrates the calculated results of freshwater partitioning from the present day up to 2030. Results show that by 2030, under the influence of upper and lower exploitation scenarios, the freshwater boundary will change compared to current levels. In February, the freshwater boundary will extend 3-5km.

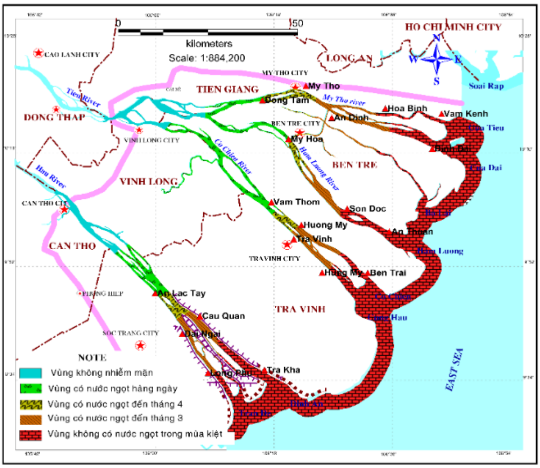


Figure 9 *Freshwater zones in the dry season (January to May), 2030.*

Along the Tien River, the freshwater boundary extends past My Tho up to 60km, Ham Luong is 52km and Co Chien is 40km. On the Hau River, the boundary extends to An Lac Tay.

CHAPTER 4 FRESHWATER EXPLOITATION SOLUTIONS IN THE CUU LONG ESTUARY - A CASE STUDY FOR THE CO CHIEN RIVER

4.1 Freshwater exploitation techniques in estuarine areas

Freshwater resources appear for a very short time and can be at very low levels, requiring specific techniques for water exploitation to meet demand. Key considerations include (i) accurate prediction of the time and date of freshwater appearance; (ii) the use of appropriate equipment and operational processes that allow for quick and efficient water collection, regardless of water level; (iii) water storage measures.

4.1.1 Equipment for freshwater collection/storage suitable for household-scale or small-scale water supply stations, and operational processes.

4.1.1.1 Equipment:

Freshwater collection/storage equipment includes Floats: the main component, always floating on the water surface; Water bags: made of flexible material that can be raised or lowered to collect water; Water quality monitoring equipment; Control system including an anchoring system for stability; Towing equipment; Safe refuge area for the system when inactive.

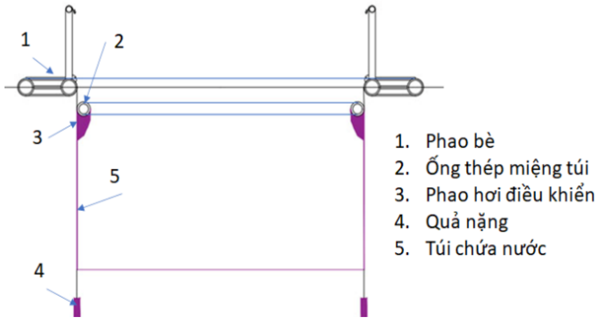


Figure 10 *Cross-sectional view of freshwater intake/storage device*

4.1.1.2 Operational processes for equipment:

Freshwater collection processes on the river are carried out in the following steps:

Step 1: readiness preparation for water collection - Figure 11 (a): installation of the water collection system, anchoring the equipment to prevent drifting, and salinity monitoring.

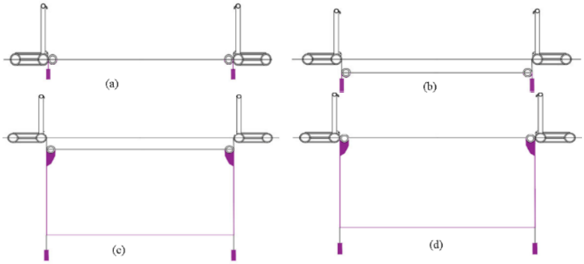


Figure 11 *Water intake control process: (a) ready to intake water; (b) sinking the bag mouth; (c) sinking the bag bottom; (d) lifting the bag to the water surface.*

Step 2: freshwater collection when water quality meets requirements:

- Sink the water bag at the level of water extraction (Figure 11 (b));
- If the water quality meets the requirements, sink the water bag to the bottom with heavy objects (Figure 11 (c));
- When the heavy objects reach the desired depth, operate the inflatable float system to raise the water bag to the water surface (Figure 11 (d)).

Step 3: Extraction of freshwater collected.

4.1.2 Forecasting the timing of freshwater Availability

Identifying the likelihood of freshwater availability according to monthly and yearly cycles by applying numerical modeling for forecasting.

Determining the likelihood of freshwater availability on the expected day of extraction using the trend of salinity from the previous day and the current day to forecast the trend for the following day.

Determining the time of freshwater availability at the extraction site based on the time of the lowest salinity level from the previous day to forecast the time of freshwater appearance.

4.2 LARGE-SCALE WATER SUPPLY SOLUTIONS AND WATER SUPPLY CAPACITY OF LÁNG THÉ RESERVOIR

4.2.1 Reservoir Solutions for large-scale water supply

The presence of freshwater in the Mekong Delta region, affected by saltwater intrusion, has been clarified. To exploit this water source, a reservoir is needed for use during times when there is a shortage of freshwater.

Reservoirs can be newly excavated or utilized from naturally occurring or artificial water-logged areas near the freshwater supply source.

Three techniques can be used to exploit additional water sources during periods of freshwater availability: direct freshwater extraction (pumping station); indirect freshwater extraction through an intermediary facility; supplementary regulation.

To further clarify these issues, the next section analyzes and assesses Láng Thé reservoir in terms of providing water supply to the city of Trà Vinh.

4.2.2 Evaluation of the project's ability during the 2016 saltwater intrusion and solutions for exploiting additional water sources.

4.2.2.1 Purposes

- Determine the minimum amount of water that needs to be extracted to meet objectives.
- Determine the reservoir's capacity according to different techniques for exploiting additional water sources (direct, indirect, supplementary regulation).

4.2.2.2 Scenarios

Determine the minimum amount of water that needs to be extracted to meet water demand: 18,000m^3/day and 36,000m^3/day.

Determine the reservoir's water supply capacity according to different scenarios of additional water extraction: 2,000m^3/h, 5,000m^3/h, 10,000m^3/h, and 20,000m^3/h.

Determine the reservoir's water supply capacity when using supplementary regulation scenarios.

4.2.2.3 Results

The assessment results are presented in Table 3. The results show that Láng Thé reservoir can still meet the objectives set under the 2016 saltwater intrusion scenario.

Table 3 Results of the assessment of additional water requirements and capacity of the reservoir.

No	Water demand (m^3/day)	Additional solutions		
		Direct (m^3/h)	Indirect (m^3/h)	Additional regulation (l/s)
Scenario 1: Determine additional demand				
1	18,000	1,051	0	0
2	36,000	0	12,495	0
Scenario 2: Evaluate the water supply capacity of the lake				
3	20,830	2,000	0	0
4	26,360	5,000	0	0
5	33,647	0	10,000	0
6	39,052	0	20,000	0
Scenario 3: Evaluate the water supply capacity of the lake with additional regulation.				
7	42,195	0	10,000	100
8	50,900	0	10,000	200l

The proposed solutions for exploiting additional water sources in each phase are (1) a small direct extraction pumping station for short-term objectives; (2) using an intermediary reservoir formed from the excavation of a dam for long-term objectives; (3) using supplementary regulation solutions for when water demand continues to increase.

CONCLUSION AND RECOMMENDATIONS

CONCLUSIONS

To achieve the initial goals set out in the dissertation, after the learning and researching process, the researcher has fully implemented the contents outlined in the research outline. The issues that the dissertation has addressed include:

(1) Identifying the distribution characteristics of freshwater in the estuaries of the Mekong River. Clarifying the features of freshwater appearance over time, including the end of the freshwater season, the start of the freshwater season, the number of hours with fresh water in each dry season month, and the longest period without fresh water. Developing the distribution maps of freshwater in the estuaries of the Mekong River in the past and forecasting up to 2030. Discovering the stratification of flow during the weak tide and transition tide of the leanest month in the Co Chien River.

(2) Clarifying the trend of seasonal flow changes to the lower Mekong River (Kratie) and Vietnam (Tan Chau). The seasonal flow in Kratie increased in all lean months, and the month with the lowest flow shifted from April to February. Unlike Kratie, the lean flow in Tan Chau in the early lean months tends to decrease and the flow only increases from March. The month with the lowest flow in Tan Chau shifted from April to March. The difference is due to the influence of the flow from the Tonle Sap Lake. The reduction of flow in the early lean months in Tan Chau has strongly affected saline intrusion in the estuaries of the Mekong River. The time of peak saline intrusion has shifted to February, instead of April as previously reported.

(3) Clarifying the relationship between the upstream flow and freshwater characteristics in the estuaries of the Mekong River, and thus forecasting the changing trend of freshwater characteristics in the future.

Among them, freshwater during the lean season in the estuaries of the Mekong River will develop in a more favorable direction. Although the earliest occurrence of freshwater, FWE, comes earlier, the start date of the freshwater season also comes earlier. The number of days without freshwater decreases, and the time of freshwater in March and April increases. Therefore, the exploitation of freshwater following the freshwater process becomes more favorable.

(4) Based on the laws of freshwater distribution, the dissertation proposed solutions for freshwater exploitation in the Mekong Delta. Calculating the scale, ability, and techniques for exploiting water sources for the Lang The reservoir. Proposing techniques to serve freshwater exploitation in the Mekong Delta for household-scale or small-scale water supply stations.

RECOMMENDATIONS

Applying the research results to calculate and determine measures for freshwater exploitation on the river. Specifically, calculating the scale, ability to exploit, and how to operate freshwater storage reservoirs. Applying water collection/storage devices and operating procedures for freshwater exploitation for household scale or small-scale water supply stations in the Mekong Delta.

The characteristics of freshwater in the estuaries of the Mekong River lack stability, especially in extreme years. Therefore, in addition to inter-regional water supply solutions, parallel water supply solutions can also be used. Surface water and rainwater are given priority for maximum exploitation. In extreme years or incidents that affect water sources, groundwater is used as a supplement. Groundwater sources will be protected and regenerated annually.

Although the dissertation has achieved the goal of identifying the laws of freshwater distribution, forecasting the process of freshwater change, and proposing solutions for freshwater exploitation in the Mekong Delta, there are still many unresolved issues within the scope of the dissertation. Some issues that need further research include: Continuing to investigate the distribution of saltwater in the cross-section of flow to confirm the basic laws and have clearer quantitative data. Continuing to analyze the laws of freshwater distribution in space and time for all river gates and other monitoring stations.

LIST OF THE PUBLICATIONS RELATED TO THE DISSERTATION

1. Pham Thi Bich Thuc, **Dang Hoa Vinh.** “Impact asessment of factor to freshwater resources Mekong downstream basin”, Scientific and Technical Hydro-Meteorological Journal, 2016.
2. **Dang, Vinh Hoa**, Dung Duc Tran, Thuc Bich Thi Pham, Dao Nguyen Khoi, Phuong Ha Tran, and Ninh Trung Nguyen. 2019. "Exploring Freshwater Regimes and Impact Factors in the Coastal Estuaries of the Vietnamese Mekong Delta" Water 11, no. 4: 782. https://doi.org/10.3390/w11040782.
3. **Dang, Vinh Hoa**, Dung Duc Tran, Dao Dinh Cham, Phan Thi Thanh Hang, Hung Thanh Nguyen, Hieu Van Truong, Phuong Ha Tran, Man Ba Duong, Ninh Trung Nguyen, Kiem Van Le, Thuc Bich Thi Pham, and Au Hai Nguyen. 2020. "Assessment of Rainfall Distributions and Characteristics in Coastal Provinces of the Vietnamese Mekong Delta under Climate Change and ENSO Processes" Water 12, no. 6: 1555. https://doi.org/10.3390/w12061555