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Research article

Assessment of water resources using comprehensive sustainability indicators for water and land resources - a pilot study for the Southern Hau River basin

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Abstract: Currently, water resources planning is paying attention in Vietnam with several master plans established in some large basins across the country. However, in the context of water resources planning, the water allocation task still has inconsistency in calculation methodology. Therefore, this study aims to provide a set of indicators to estimate water and land resources to serve as the foundation for water resources allocation task. We have been used the following methods: (i) data collection, analysis and processing; (ii) field surveying; (iii) expert consultation; and (iv) mathematical modelling. We selected the Southern Hau River basin (SHRB) as our pilot study. The results indicate that the total amount of surface water from the Hau River supplying to the entire SHRB region in the dry season months (January to April) is about 487 million m^3/month. The total amount of groundwater (saltwater and freshwater) is 35.5 million m^3/day, with 16.7 million m^3/day coming from freshwater. The SHRB has a great variation in season - 3.8 billion m^3 (19%) for the dry season and 16.19 billion m^3 (81%) for the flood season. The outcomes of this study provide basis information for implementing water resources planning's steps in allocating water resources to the SHRB's sub–basins.

Keywords: Indicator; Sustainability; Water Resources; Land Resources; Southern Hau River basin.

1. Introduction

There have been a number of studies worldwide on sustainability indicators in the field of water resources. In particular, at the level of the river basin, [1] integrated issues of hydrology, environment, life and policies on water resources into a single sustainability index - Watershed Sustainability Index (WSI). The authors of this study applied the Pressure - State - Responses model to the indicators (H-Hydrology, E-Environment, L-Life and P-Policy) and placed them in a matrix frame, from which a typical WSI index for the whole basin was calculated [1]. This WSI index has a value from 0 to 1, representing the lowest and highest watershed sustainability. The study also applied the calculation method to the SF Verdadeiro

River Basin in Brazil. The results show that this basin has a WSI index of 0.65 which is equivalent to the average sustainability level [1].

[2] applied the WSI method [1] for calculating the sustainability index of the Reventazón River Basin in the province of Cartago and Limón, Costa Rica. In this study, the river basin was divided into three regions: highland, midland and lowland according to the elevations of the regions to calculate more accurately the indicators of the basin. The average WSI for the entire basin is 0.71, which equates to a fairly sustainable level. However, the research team focused on analyzing the indicators with the lowest scores, thereby making recommendations to the Commission for Conservation and Management of the Watershed of the Reventazón River (COCUMRE) for better improvement as well as to make the future WSI calculations for the watershed more accurate. The calculation method [1] was also applied to the Elqui River basin in Chile and the Motru river basin in Romania, and gave the results of 0.61 and 0.36 respectively (WSI values for the Motru river basin were calculated for an approximate period of 5 years), respectively with moderate and poor sustainability values [2–3].

In Vietnam, a number of research and projects have also developed indicators related to the assessment and use of water resources. Some notable research projects include as follows:

The Vietnam Water Sector Review Project was funded by the Asian Development Bank on behalf of international development partners with the objective of strengthening water resource management, poverty reduction and national development [4]. The project has synthesized the river basin monitoring data, the data on water exploitation and use, the relationship between the society, the population community and the river basin to build a set of indicators including 58 indicators as an approach tool to water sector management. Among these 58 indicators, there are 13 indicators on surface water resources, 3 indicators on groundwater, 15 indicators on social aspects, 12 indicators on economic aspects and 15 indicators on environmental aspects. These indicators were used to assess the current status of 16 main river basins in our country, thereby affirming that many large river basins have been in an alarming state of exploitation and over–use of water resources, which provide advanced information to the authorized managers for better planning of allocation, sharing and economical use of water resources. However, these indicators are only individual indicators and have not been placed in an overall framework for sustainable development [4].

While employing this set of indicators [5], the Department of Water Resources Management has developed the set of indicators to 81 indicators to serve the "Planning of Management of the Red River–Thai Binh River Basin" from 2013 to 2015. This set of indicators represents the factors on surface water, groundwater, social, economic, environmental and water resource management. However, this set of indicators only provides individual parameters in water resource planning and management, but it does not provide a general index of water resource use in the basin [5].

In the study [6], through the consultation method with experts in the Central Highlands provinces and experts specialized in sustainable development in various fields, a set of sustainable development indicators were synthesized and developed which include 77 regional–level indicators, 70 provincial–level indicators, and 49 district–level indicators. In this set of indicators, water resource was a topic in the field of the environment along with other topics namely land, atmosphere, natural disasters and biodiversity. Although the study has not provided specific assessment levels for each indicator, the set of indicators has demonstrated the correlation between the indicators and the topics, thereby stimulating a 'more comprehensive measure' of an overall development towards a sustainable manner.

For groundwater resources, [7] proposed a set of indicators including 6 main indicators: (i) the renewable groundwater resources per capita; (ii) the total groundwater resources exploited /supplied; (iii) the total exploited groundwater resources/total exploitable groundwater resources; (iv) the total amount of groundwater for drinking/total drinkable water in the area; (v) the groundwater depletion indicator; and (vi) the groundwater vulnerability indicator. The groundwater resource indicators were evaluated at 3 levels: high, medium and low; then illustrated on the map with a value varying from 1–5, corresponding from less stable to very stable status. However, these indicators were still calculated separately, not integrated to provide a general index for the study area.

[8] analyzed the factors affecting the sustainability of river basins in Vietnam and included four groups of rivers based on current emerging issues in water resource planning, management and protection such as the Law on Water Resources 2012. The study proposed a set of parameters affecting the sustainability of the river basin for each specific river group. The study also proposed 35 parameters affecting the sustainability of the river basin, a basis for determining the level of sustainability, and how to calculate parameter values, thereby determining the level of sustainability of indicators (i.e., the fields) of water resources on environment, life, human activities and policies, then calculating the river basin sustainability index for Vietnam. In addition to the above studies, a number of studies have proposed statistical indicators on surface water resources, groundwater resources, water use [9], or water resource vulnerability index [10].

With a special geographical location, the hydrological regime in the southern area of the Hau River is directly affected by the upstream flow, the tidal regime of the East Sea, part of the tide in the Gulf of Thailand and the rainfall regime in the entire field. At the time of the flood, due to the upstream recedes, and the tidal regime strengthens, therefore the increase in water level and the discharge leading to a high possibility of large floods is still to occur in this flood period. The high–tide days are the time–period of temporary accumulation of water in the infield canals as well as an increase in the average water–level and vice versa. The complex hydrological–hydraulic regime in the Southern Hau River basin (SHRB) and the interweaving combination of varying degrees between flood–rain–tide and fresh–salt water are major limitations in calculating the distribution of water resources in the region.

Preliminary assessment revealed that although current indicators of sustainable use of water and land resources in the world and Vietnam are quite available, they have neither been fully complete yet nor presented the specificity in the planning of water resources distribution. Therefore, a study on a set of indicators of sustainable use of water and land resources in order to apply in the allocation of water resources would meet the urgent current needs. Within the scope of the research, this paper focuses on clarifying the general picture of the characteristics of the research area in order to propose a set of indicators for sustainable use of water and land resources and demonstrate a pilot calculation using a number of indicators to evaluate water resources in the SHRB. Specifically, in this research, the authors use Mike NAM hydrological model, Mike 11 hydraulic model, Feflow groundwater model to calculate and assess water resources (both surface water and groundwater) in the SHRB.

2. Materials and Methods

2.1. Description of the study area

The SHRB is part of the Mekong River basin with a natural area of 23,534.45 km^2 and a population of 8,737,454 people, including the area of 7 provinces and cities (An Giang, Bac Lieu, Ca Mau, Can Tho, Hau Giang, Soc Trang and Kien Giang) (Figure 1). The main terrain of the study area is the delta plain and the edged delta plain in the Southwest region with the topographical features of mainly low, flooded plains such as the Long Xuyen quadrangle region. The network of rivers and canals is quite developed due to the topography and influence of the Mekong River. The two mainstreams of the Tien and Hau Rivers strongly dominate the development of the Mekong Delta. After My Thuan River, Tien River has successive major distributaries, namely Co Chien River, Ham Luong River, Ba Lai River, Cua Dai River and Cua Tieu River. The Hau River flows in a straight line and only splits into two before discharging into the sea about 30 km through Dinh An and Tran De estuaries. Both Tien and Hau rivers have formed many islets, curved river sections and flow diversions... Thus, the process of bank erosion and river bed sedimentation is very complicated, causing instability of the riverbed. The climate in the SHRB has the common characteristics of the Mekong Delta's climate, with a sub–equatorial monsoon climate regime with high temperature all year round and heavy rainfall with seasonal variation. A year has two seasons: The rainy season starts in May and ends in November; The dry season starts in December and ends in April of the following year. In addition, it is also influenced by the tropical monsoon climate regime and is typical of the coastal plain [11].

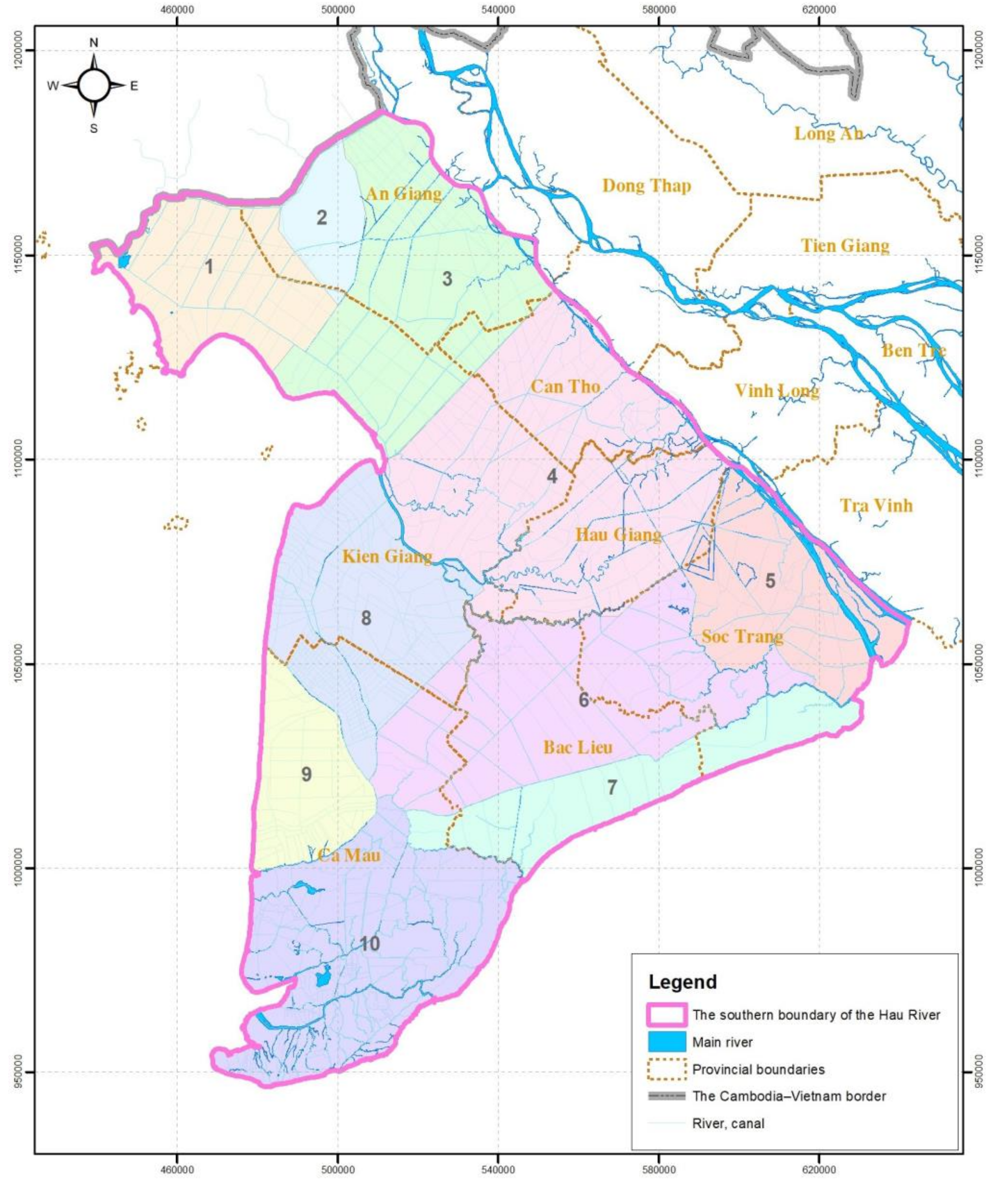

Figure 1. Map of the Southern region of Hau River.

2.2. Scientific basis for the proposed set of indicators

The basis of the proposed sustainable use indicators is:

(1) Based on the factors affecting the sustainability of water and land resources in the river basin;

(2) Based on a German study to develop an assessment framework, selecting indicators and parameters to calculate the sustainability index of water and land use in accordance with natural and social conditions in the research area.

(3) Referred to relevant domestic and foreign studies on the group of indicators and parameters affecting the sustainability of water and land resources in the river basin.

According to the approach of the research in the country and in the world, the sustainability of a system in general must ensure to be considered in three areas: environment, economy and society. However, the research proposing parameters into these three areas is still general, neither showing which specific groups of parameters affect natural resources in general and water resources - the important natural resources in the river basin in particular, nor which groups of parameters reflect human exploitation and use of natural resources... Therefore, the paper chose a set of indicators examining areas that affect river basin sustainability, including: Natural resources (mainly water resources); environment (soil environment, forests, ecosystems, etc.); life and policies of the river basin.

In addition, since the study targeted the integrated indicators on land and water resource sustainability, the research team proposed to also take land resource indicators into account. The assessment method is based on the land suitability classification, comparing the appropriateness between the requirements of the usage types in economic, social and environmental conditions related to the optimally effective use of land. The three main groups of criteria in FAO's sustainable land use assessment include environmental, social and economic performance.

In fact, many factors are affecting the sustainability of water and land resources that can be selected, however, it is not possible to choose all of these parameters as they will make the application process complicated; moreover, due to the lack of data for calculation, they cannot be also totally quantifiable. Therefore, only the dominant indicators were selected [12–16]. The indictor selection was based on the following principles:

The selected indicators need to ensure:

(1) Their representativeness and significance in the fields of water and land resources;

(2) To be based on a clear scientific basis, i.e the parameters can be qualified (quantitatively) and verified through actual data;

(3) To be widely accepted (previously consulted with experts to exclude non–representative indicators and add more relevant ones);

(4) To be understandable, reliable, highly sensitive, independent and not overlapping.

The selected set of indicators needs to ensure:

(1) The representativeness: a set of indicators will provide an overview of the current stress and status and their pressure on the fields of water and land resources.

(2) The number of parameters is reasonable, neither too much nor too little so that their accessibility to policymakers is greater at an acceptable cost.

2.3. Collect, analyze and process data

A range of documents on economic, social and environmental aspects related to water and land use issues in the study area were collected. The collection was carried out through many management and research agencies as well as through a variety of other sources such as seminars, surveys, interviews, etc. The collected data for calculation will be updated to 2020 and in accordance with the requirements of each mathematical model:

- Groundwater model FEFLOW: collected data includes: DEM map; data on the bottom elevation of aquifers and weak permeable layers (397 boreholes in the study area and vicinity); conductivity of aquifers; specific yield for the subterranean basins is taken according to the general survey of the projects implemented in the Mekong Delta and has been corrected by the German expert BGR through the software TTIM; Hydrometeorological data and data on the current status of exploitation and use of ground water resources in the region.

- With the hydrological model MIKE NAM: input data includes (precipitation and evaporation) from 20 meteorology stations in the area; Soil data, land use map of the study area to conduct analysis, evaluation and selection of suitable parameters for calculation based on TCVN 10406-2015, ground flow coefficient is referenced from the model FEFLOW.

- The MIKE11 hydraulic model includes: Topographic map of the land surface with 17,796 elevation points; Cross-sectional data: 12,316 cross-sections/3,553 rivers, about 625 flood plains including embankments and sluices; System of works: about 15,000 km of main canals and grade I canals, nearly 27,000 km of grade II canals, about 50,000 grade III and inland canals, 450 km of sea dykes, 1,290 km of river dykes and about 7,000 km of embankments, 80 wide sluices over 5 m (the largest is Lang The sluice-dam at 100 m and Ba Lai sluice with 84 m), over 800 culverts 2-4 m wide and tens of thousands of small culverts and culverts, over 1,000 large and medium-sized electric pumping stations. thousands of small pumps to actively irrigate and drain; Data of 21 water level measurement stations, 4 flow measurement stations in the area [17].

2.4. Mathematical Modelling Methods

The mathematical modelling method used to solve the problem of water resource allocation in the SHRB is diagrammed in Figure 2.

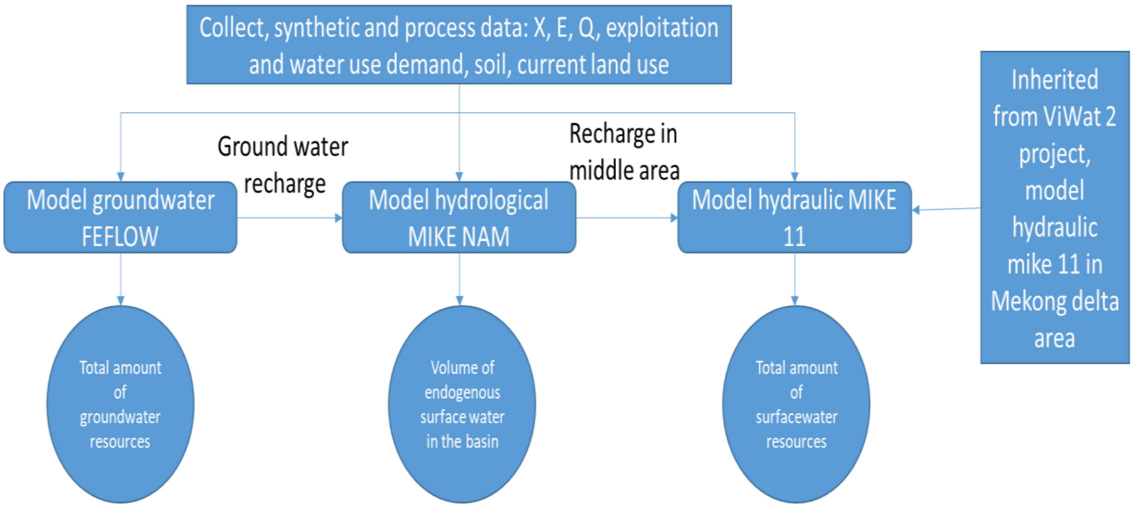

Figure 2. The calculation process of water resource assessment indicators.

The research team used the FEFLOW model to calculate the groundwater resource assessment index. Calculation results of groundwater recharge from the model combined with the current land use and soil characteristics determine a set of parameters for the Mike NAM hydrological model to calculate the amount of endogenous surface water in the basin. To calculate the total amount of surface water resources, the research team used the Mike 11 hydraulic model with the amount of middle–zone recharge determined from the hydrological model. The results are extracted at predefined allocation locations.

Accordingly, the SHRB area is divided into 7 regions, in which each region will have basic and relatively uniform characteristics of nature, environment, development form..., with relatively similar problems of water source system that need to be solved; especially the areas in the region are related to each other through the system of focal irrigation works (Table 2).

Within each region, it can be divided into a number of sub–regions if there are relative differences in natural conditions, construction measures, water source conditions and exploitation methods between regions. Thus, in each sub–region, there will be a higher homogeneity of exploitation methods, water source conditions and a closer relationship between irrigation works. Accordingly, the calculation area was divided into 66 sub–basins to serve the calculation (Figure 3).

Table 2. The statistics of regions and sub–regions for calculation in the SHRB.

No.	Region	Sub–region	Area (km^2)
1	N1 (freshwater)	11TLV	4228.4
2	M3 (saltwater)	6TLV	426.02
3	L1 (brackish water)	2TLV	1249.57
4	M1 (saltwater)	4TLV	749.21
5	M2 (saltwater)	27TLV	6730.18
6	N4 (freshwater)	9TLV	4517.75
7	L2 (brackish water)	7TLV	2462.76

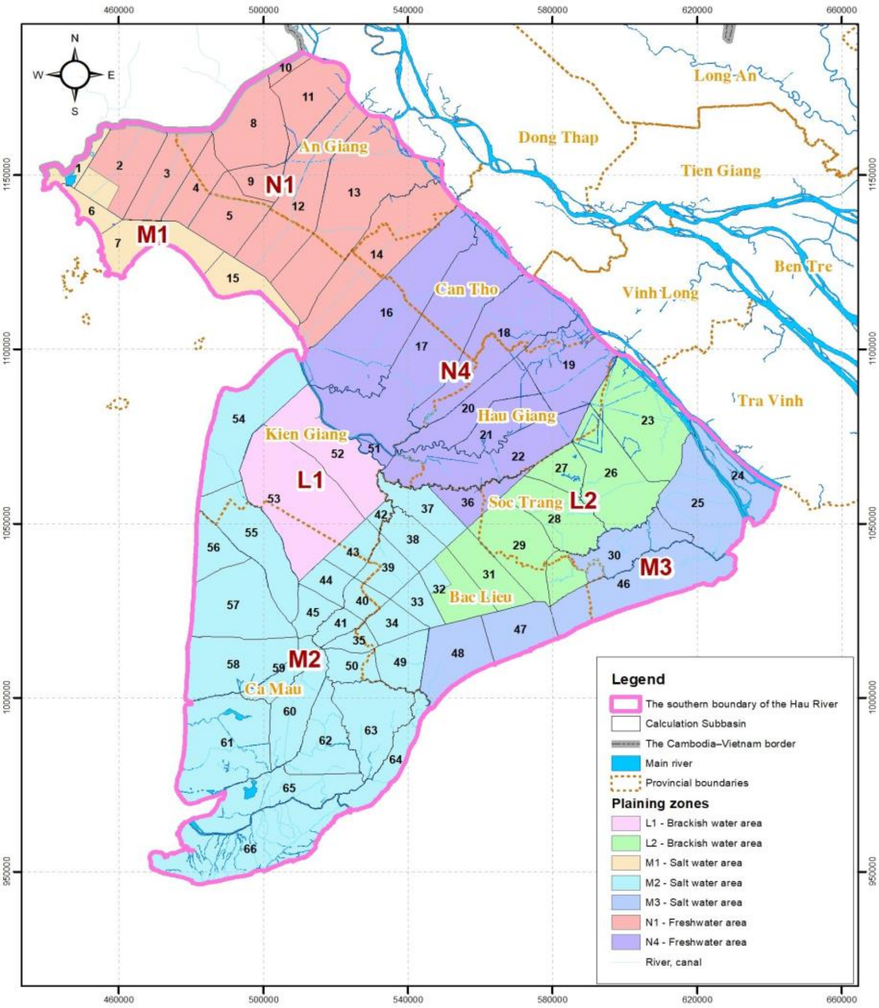

Figure 3. The demarcation of regional and sub–regional boundaries in the Southern Hau River area.

In addition, the analysis of regional flow characteristics and the assessment of locations and water sources in the SHRB, including surface water, groundwater at the representative points and locations in the sub–regions showed that the main distribution points and locations are the beginning of the main canals taking water from the Hau River, including 27 points (Table 3). Calculation results from these 27 points were used to calculate the allocation of water resources for 7 planning regions in the SHRB.

Table 3. Table of points (locations) distributed in the southern area of Hau River (names of rivers and channels for distribution of water resources from the mainstream of Hau river).

No.	Sub–region	Region	River (channel)
1	1	1	C. Vinh Te

No.	Sub–region	Region	River (channel)
2	10	10	C. Muoi Chau Phu
3	142	142	C. Dao
4	143	143	C. Can Thao
5	149	149	C. No. 1
6	25	25	C. Ba Chieu
7	33	33	C. Thom Rom
8	27	27	C. Thot Not
9	144	144	C. Chac Ca Dao
10	6	6	C. Tri Ton
11	12	12	C. Ba The
12	20	20	C. Tron
13	148	148	C. Nang Mau
14	36	36	C. O Mon
15	18	18	C. Rach Gia – Long Xuyen
16	150	150	C. Dai Ngai
17	48	48	C. Cai Con
18	75	75	C. Mac Can Dung
19	22	22	C. Cai San
20	147	147	C. KH9
21	146	146	C. Kh8
22	145	145	C. Kien Hao
23	1	46	C. Can Tho
24	41	132	Quan lo–Phung Hiep 132
25	53	159	Chac Bang
26	39	158	Quan lo–Phung Hiep 158
27	53	89	C. Lang thu 7

The lacking documents on natural and socio–economic characteristics were collected, especially the situation of exploitation, use and pollution of water and land resources in the SHRB. The research team also conducted a survey to take samples of the current state of the water and land environment and assess their pollution status in the study area.

2.5. Proposing a set of indicators for sustainable use of water and land resources in the group of water resource assessment

Based on the scientific basis mentioned above, the research team decided that water resources need to be evaluated via the three basic characteristics of quantity, quality and dynamics. Water quantity is a characteristic that indicates the abundance of water resources in a territory. Water quality is the characteristics of the dissolved substance content in the water that serves a specific water use requirement in terms of benefits and harms, according to the standards of water users. To accurately assess water resources, we need to evaluate the main factors: quantity, quality and dynamics of water in the study area. Overall, water and land resources maintain a close relationship with each other, interacting with each other in the process of movement. The characteristics of land resources affecting water resources are as follows: Soil thickness; Topographic; Soil structure; The composition of the soil; Proportion of soil; Reaction of the soil, etc. The research team realized that the natural cover index of the land has included these above factors that can represent land resources in the water resource assessment group.

Therefore, the research team proposes a set of indicators for sustainable use of water and land resources in the water resource assessment group, including: The total amount of surface water resources; the quality of surface water; the total amount of groundwater resources; the quality of groundwater; the amount of surface water transferred to the basin; natural cover index of the land.

3. Results and Discussion

3.1. Calculation results of the water resource assessment index in the Southern Hau River area

With its special location, the SHRB is greatly affected by saline intrusion and complicated hydrological regimes, so it is very difficult to assess the quantity of surface water resources, which causes big challenges for the planning of sustainable use of water resources in the region. This is also the reason why it is necessary to consider the groundwater reserve in the regional water resource allocation planning since the groundwater is an important water source that can ensure the essential needs of water users. Therefore, within the scope of the article, the research team selects a number of indicators in the water resource assessment group for a pilot calculation for the SHRB: The total amount of surface water resources; The total amount of groundwater resources; The amount of surface water transferred to the basin (the amount of endogenous water).

3.2.1. Total amount of surface water resources

The entire hydraulic network system of rivers and canals was calculated in the model with the time period. The calculation results have determined the flow process and water level on nodes along the main canals of the SHRB. These results extracted from the model were outputs to calculate the average monthly flowrate value in the period 2000–2019.

The results show that the average amount of surface water from Hau River supplying to the entire SHRB in the dry season months (I–VI) is about 487 million m^3/month, of which the surface water mainly flows along the axis canals of the Long Xuyen Quadrangle and a number of canals in the Can Tho and Hau Giang areas to supply the Ca Mau Peninsula area. The calculation results of the total average amount of water for many years are presented in Table 4.

Table 4. The total monthly average volume of water at the beginning of the main canals taking water from the Hau River to the SHRB (million m^3).

River	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Average Drought season (I–VI)	Average year
Vinh Te	37.8	30.4	25.4	18.9	15.6	-10.0	-528.1	-2169.1	-3443.7	-3175.5	-1282.9	-202.6	**19.7**	**-820.3**
Muoi Chau Phu	9.9	6.9	5.6	4.2	3.6	6.4	9.6	14.9	16.3	6.9	5.7	10.0	**6.1**	**8.4**
Dao	9.2	6.4	5.1	3.8	3.5	4.8	-19.8	-73.8	-100.6	-114.4	-57.4	-7.2	**5.5**	**-28.4**
Can Thao	9.8	6.8	5.5	4.1	3.7	5.8	-6.1	-30.3	-44.8	-55.9	-29.0	2.0	**6.0**	**-10.7**
Chac Bang	-75.7	-61.5	-68.3	-65.8	-44.6	-49.0	-43.8	9.5	16.7	-39.9	-63.3	-79.8	**-60.8**	**-47.1**
No. 1	58.2	51.4	53.7	47.2	25.3	-5.4	-25.4	-29.4	-28.1	-21.7	21.1	49.1	**38.4**	**16.3**
Ba Chieu	32.7	23.6	20.1	15.9	10.2	11.5	19.1	47.8	79.7	74.5	49.8	39.5	**19.0**	**35.4**
Thom Rom	72.4	60.2	60.3	50.9	42.7	43.9	60.4	87.3	106.5	110.2	95.2	83.7	**55.1**	**72.8**
Thot Not	17.5	12.8	10.8	8.3	2.4	-0.5	-3.0	9.6	19.2	6.4	16.0	18.8	**8.6**	**9.9**
Chac Ca Dao	125.3	89.3	75.6	58.4	53.4	96.1	197.7	367.0	458.6	427.7	266.4	177.5	**83.0**	**199.4**
Tri Ton	95.4	67.8	56.5	42.5	37.3	68.2	105.5	172.4	216.5	160.8	89.7	103.1	**61.3**	**101.3**
Ba The	61.6	43.5	35.8	26.7	23.4	45.2	84.9	145.9	179.6	158.3	99.5	77.7	**39.4**	**81.9**
Tron	19.8	14.5	12.5	10.0	7.2	10.1	19.3	39.4	67.2	61.2	32.7	24.4	**12.4**	**26.5**
Nang Mau	8.8	7.0	6.3	5.6	1.8	0.2	-0.8	3.8	9.6	8.8	8.4	8.7	**5.0**	**5.7**
O Mon	122.7	92.5	84.3	71.6	44.3	46.7	73.5	152.8	214.8	198.1	175.5	148.6	**77.0**	**118.8**
Rach Gia Long Xuyen	22.9	20.6	18.4	15.3	5.6	-4.8	-43.4	-134.5	-190.6	-170.3	-58.5	4.0	**13.0**	**-42.9**
Dai Ngai	27.4	17.7	13.8	11.9	-4.0	-6.4	-0.3	13.7	32.7	22.0	32.7	32.6	**10.1**	**16.1**
Cai Con	36.6	21.4	11.9	4.6	-23.0	-26.8	-17.2	13.1	45.4	29.5	43.6	45.7	**4.1**	**15.4**
Mac Can Dung	14.2	9.3	7.6	5.9	5.3	10.0	29.1	74.4	102.4	82.3	40.2	22.6	**8.7**	**33.6**
Cai San	78.9	57.6	49.4	39.2	27.9	39.3	74.4	166.2	255.5	245.8	146.9	101.2	**48.7**	**106.8**
KH8	6.0	3.7	2.8	2.1	1.2	2.8	7.2	15.6	21.8	20.8	14.0	9.3	**3.1**	**8.9**
KH9	33.7	28.7	25.6	20.3	15.9	16.3	22.2	30.0	35.1	37.1	36.0	36.0	**23.4**	**28.1**

River	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Average Drought season (I–VI)	Average year
Quan lo–Phung Hiep	-27.5	-22.7	-23.0	-17.0	-6.1	-0.8	7.9	14.4	10.3	-3.1	-21.2	-26.0	**-16.2**	**-9.6**
Quan lo–Phung Hiep	-13.2	-11.1	-11.5	-10.0	-4.7	1.9	6.1	7.6	4.5	3.1	-6.5	-12.8	**-8.1**	**-3.9**
Kien Hao	89.0	65.2	55.2	42.3	36.8	64.3	116.3	202.8	248.9	209.8	132.5	108.6	**58.8**	**114.3**
Can Tho	-77.9	-57.6	-50.4	-43.7	-11.6	-2.1	-1.7	-26.3	-55.8	-56.1	-74.5	-82.3	**-40.5**	**-45.0**
C. Lang thu 7	2.5	1.8	1.6	1.8	3.6	5.7	10.9	12.9	13.0	17.4	8.4	4.5	**2.9**	**7.0**
Total	**825.0**	**610.5**	**518.6**	**401.7**	**258.7**	**304.6**	**14.9**	**-1073.7**	**-1930.1**	**-1927.6**	**-317.6**	**705.2**	**486.5**	**-64.1**

3.2.2. The total amount of groundwater resources

The results of calculating the total amount of groundwater including saltwater and freshwater in the SHRB are shown in Table 5; and the results of the total amount of groundwater resources for freshwater are in Table 6. In which, the total amount of groundwater resources including freshwater and saltwater is 88.9 million m^3/day, of freshwater is 42.1 million m^3/day (accounting for 47% of the total water volume). Details of the modular map of the total exploitable amount of groundwater are shown in Figure 4.

Table 5. The total groundwater resources in the SHRB (saltwater and freshwater) (m^3/day).

Region	Total of saltwater and freshwater (m^3/day)							
	qh	**qp_3**	**qp_{2-3}**	**qp_1**	**n_{2-2}**	**n_{2-1}**	**n_{1-3}**	**Total**
N1	111278	1814233	3409345	2709881	1882600	2052550	810487	12790375
M3	198474	886165	1975837	1767120	2598646	2722782	1101243	11250267
L1	22060	386848	952755	920791	1181145	884639	227607	4575845
M1	8901	205623	384512	321012	113906	85908	0	1119862
M2	584084	1919270	5400694	4038280	5019888	6375347	899539	24237103
N4	372125	2966739	4375352	4605879	2190091	5230813	2122419	21863419
L2	226677	1130740	2309181	2056924	2772262	2927494	1657792	13081072
Total	**1523600**	**9309618**	**18807678**	**16419889**	**15758539**	**20279533**	**6819087**	**88917943**

Table 6. The total groundwater resources in the SHRB (freshwater) (m^3/day).

Region	Total of freshwater (m^3/day)							
	qh	**qp_3**	**qp_{2-3}**	**qp_1**	**n_{2-2}**	**n_{2-1}**	**n_{1-3}**	**Total**
N1	15373	144448	1081316	546536	302882	14920	810487	2915962
M3	43981	443337	1563195	1371107	930790	474414	1101243	5928067
L1	0	0	891581	767917	735450	464714	227607	3087267
M1	0	0	2282	0	0	0	0	2282
M2	0	0	3047078	2487622	1735494	1818395	991790	10080379
N4	310	1141842	3074336	2217133	850108	3723651	2122419	13129799
L2	0	189328	1856024	1067605	1032582	1169629	1657792	6972961
Total	**59663**	**1918955**	**11515812**	**8457920**	**5587306**	**7665723**	**6911338**	**42116717**

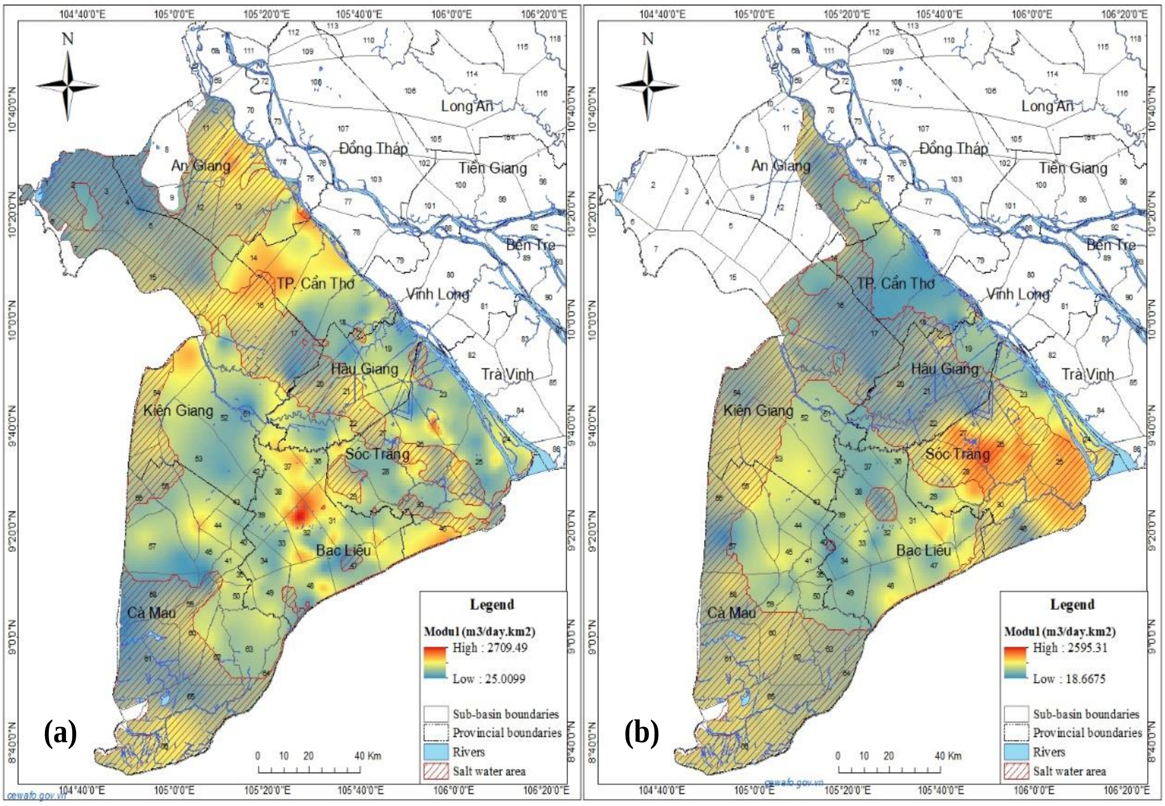

Figure 4. A modular map of total groundwater volume TCN qh(a) and qp3(b).

3.2.3. The amount of surface water transferred to the basin

The calculation results from the NAM model show that the total amount of surface water resources from endogenous rain in the above 66 sub–basins in the SHRB is 19.95 billion m^3. In which, the area M2 with 7.98 billion m^3 accounts for the largest proportion with 40% of the total water volume of the whole region; the area M1 has the lowest total amount of endogenous water from the rain with only 0.64 billion m^3 accounts for 3% of the total water volume of the whole region (Figure 5).

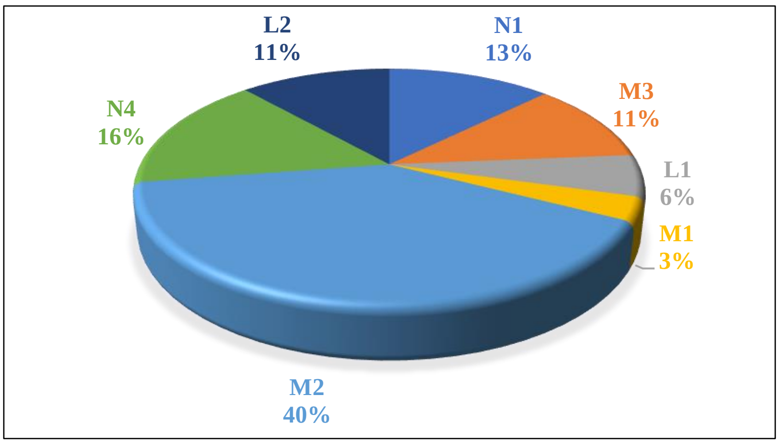

Figure 5. The percentage of total calculated water volume across regions.

Statistical data also show that there is a large difference in total water volume between the dry season and the flood season in the SHRB. Specifically, the amount of water volume in the dry season accounts for only 19% of the total annual water amount, equivalent to 3.8 billion m^3, while in the flood season, it accounts for 81% of the total annual water amount with a volume of 16.19 billion m^3 (Figure 6).

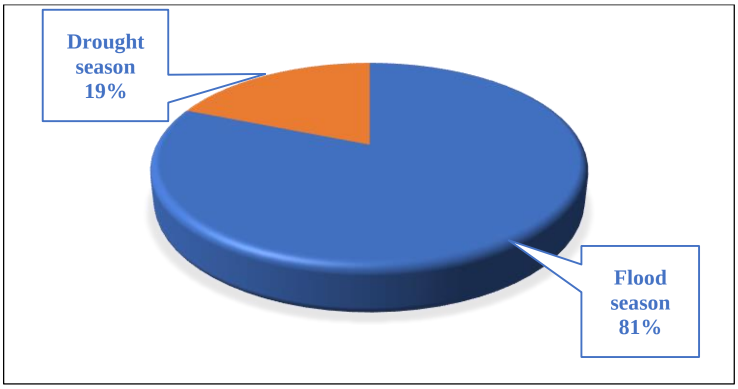

Figure 6. The percentage distribution of the total water volume in the dry–flood season in the region.

3.2. Result of index hierarchy

3.2.1. Index of total surface water resources

According to the viewpoint of the International Water Resources Association (IWRA), in the countries with average water resources, the average standardized amount of water is 10,000 m^3/person/year. Thus, the total water volume per capita of Vietnam is lower than the standard level; specifically, even if the calculation is taken the amount of endogenous water in the territory, each Vietnamese person will only have about 3,222 m^3/year. While nearly two–thirds of Vietnam's surface water flows from abroad, in the case that upstream countries do not have a fair share and reasonable use of water resources in inter–national rivers, Vietnam will face the risk of water crisis, which threatens its stable economic and social development, food security and water security [20–24].

Thus, if based on the viewpoint of the International Water Resources Association (IWRA), but now, if the total water resources per person of 3,222 m^3/year or more is considered sufficient, and the level below this threshold is considered a water shortage status, there is a hierarchy of sustainability levels. This study implemented a hierarchy of sustainability levels of total water according to the Falkenmark indicator. The levels of hierarchy are clearly shown in Table 7.

Table 7. The classification of total surface water resources index.

No.	Water level per capita	Rating of water resources
1	> 4000 m^3/person/year	Threshold of water sufficiency for using
2	1700–4000 m^3/person/year	The upper threshold of insufficiency when it happens sporadically or only locally
3	1000–1700 m^3/person/year	Water shortage threshold
4	500–1000 m^3/person/year	Threshold of water scarcity, restrictions on economic development, human health and social welfare
5	< 500 m^3/person/year	Life threatening threshold

3.2.2. Surface water quality index

There have been many in–depth studies on surface water quality index in the country and the world [25–26]. Almost studies have shown that the WQI surface water quality index hierarchies are representative and reliable. Since the research topic determines the index of sustainable use of water and land resources in the southern area of Hau River, the team focused on examining and evaluating the existing studies on the hierarchy of water quality indicators in the country.

Decision No.1460/QD–TCMT on the promulgation of Technical Guidelines for the calculation and publication of Vietnam's water quality index by the Vietnam Environment Administration has specified the method of calculating the water quality index as well as provided an assessment of water quality in the context of Vietnam. Therefore, the research team decided to choose the hierarchical level of water quality classification used in the study as the level given in Decision No. 1460/QD–TCMT.

Table 8. WQI Water Quality Index Hierarchy.

WQI Value	Rating of water quality	Color
91–100	Well–used for domestic water supply purposes	Blue
76–90	Used for domestic water supply purposes but need appropriate treatment measure	Green
51–75	Used for irrigation and other equivalent purposes	Yellow
26–50	Used for navigation and other equivalent purposes	Orange
0–25	Severely polluted water that needs future treatment measures	Red

In Table 8, the water quality index is calculated on a scale from 0 to 100 with five specific levels of assessment and alarming.

3.2.3. Index of the total amount of groundwater resources

This index can rank the degree of sustainability for potential reserves through the change in groundwater reserves per capita [7]. This index represents the change of the amount of groundwater resources (shown in potentially exploitable reserves) during the study period. The specific calculation formula is:

$$A = (Q_{kttn\ nc} - Q_{kttn\ nn})/Q_{kttn\ nn} \times 100 \quad (1)$$

where A is the level of change; $Q_{kttn\text{-}nc}$ is the potentially exploitable reserves per capita in the study period (m^3/day); $Q_{kttn\ nn}$ is the potentially exploitable reserves per capita over a period of many years (m^3/day).

The data on groundwater reserves over a period of many years were collected from reports on groundwater resources at the National Center for Water Resources Planning and Investigation. The population data were collected from the Statistical Yearbook in the SHRB. Figure 7 shows the variation of the parameter from the smallest to the largest range towards the mean value over a multi–year period for that parameter.

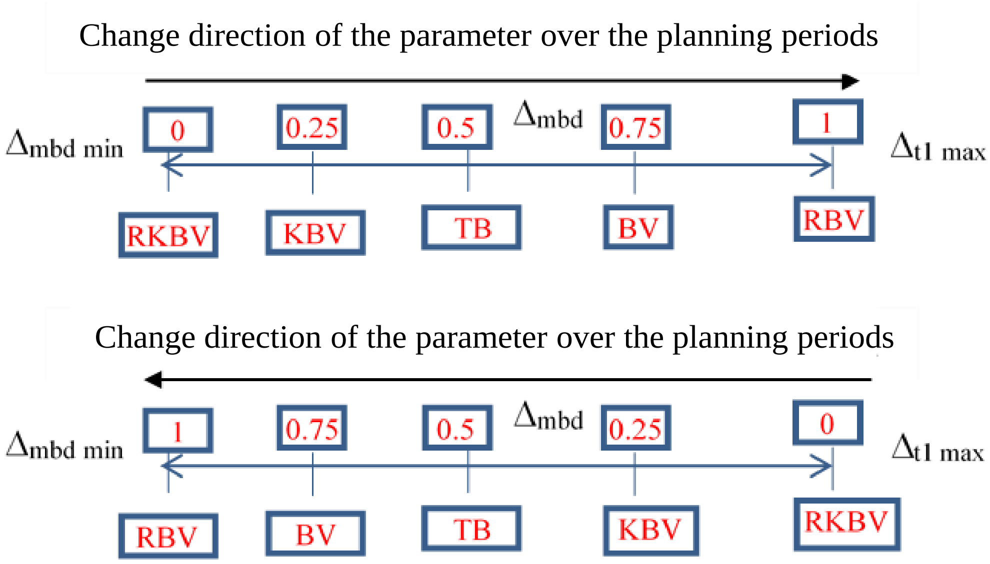

Figure 7. The hierarchy of the total groundwater resource index.

Abbreviated term: RKBV: very unsustainable; KBV: less sustainable; TB: average; BV: sustainable; RBV: very sustainable.

This "variable level" hierarchy was divided into 4 equal levels from the smallest to the largest with scores of 0.25, 0.5, 0.75, 1, respectively, depending on the specific value and the changing tendency of the parameters over the planning period to score the parameters. If this level of change achieves the "expected value" (that is the value of the parameter given in the planning period), that means the value is considered sustainable when it satisfies the needs and wants for the following years.

3.2.4. Groundwater quality index

According to Circular No. 19/2013–BTNMT dated July 18, 2013, regulating techniques for monitoring groundwater resources, types of groundwater quality samples include comprehensive analysis samples, iron samples, microscopic samples and samples with organic pollution origins and a number of other groundwater quality parameters. Since it is not possible to consider all the groundwater quality parameters within the scope of the study, only one representative parameter was selected to examine the level of groundwater quality change. Depending on the characteristics of groundwater resources of each specific study area, the appropriate representative parameters are determined. For the SHRB, the selected representative parameter was the pH index, since the pH data at the groundwater resource monitoring works are complete, easy to collect, measurable and able to demonstrate the sustainability of the groundwater quality. The pH is the acidity of the water, and the pH value is also the representation value for the presence of H+ ions in the groundwater environment. Water source with the pH > 7 often contains many carbonate and bicarbonate ions as it flows through many layers of limestone soil; Water source with the pH < 7 often contains many acid–based ions. If the pH is too small (below 6.0) or too large (above 8.5), health problems will occur, affecting daily life activities, irrigation, agriculture, fisheries... The most obvious evidence of the relationship between the pH and health is that a prolonged usage of water with high or low pH will cause growth retardation, stunting and susceptibility to disease for both humans and organisms. When the water has the pH > 8.5 with the presence of organic compounds, the disinfection with chlorine will form trihalomethane compounds that cause cancer. According to the standard, the pH of the water for domestic usage is 6.0–8.5 and that of drinking water is 6.5–8.5. Thus, if the pH parameter that is between 6.0 and 8.5 is considered to be sustainable; the pH that is either below 6.0 or above 8.5 is considered unsustainable. The groundwater quality index was also used a quantitative assessment method of water quality based on the RQ_2 ratio, which was calculated by the average concentration through the measured pH parameters over a period of many years and the pH level limit which is determined according to the national technical regulation on groundwater quality QCVN 09:2015–MT/BTNMT. If the RQ_2 coefficient is between 0.01 and 0.1, the groundwater quality is considered to be good. If the value of this ratio is greater than 1, it demonstrates that the quality of groundwater is poor, exceeding the allowable standard.

Table 9. The classification of groundwater index.

Index	Threshold	Score	Existing research
Ground water quality index	$RQ_2 \geq 1$	0.25	EPA [12]
	$0.5 \leq RQ_2 < 1$	0.50	
	$0.1 \leq RQ_2 < 0.5$	0.75	
	$0.01 \leq RQ_2 < 0.1$	1.00	

4. Conclusions

This study has conducted an overall water resources assessment for the SHRB as proposing a set of indicators of sustainable use of water and land resources. These indicators were estimated by using a range of the hydrological-hydraulic- and groundwater model.

- The set of indicators for sustainable use of water and land resources includes six indicators: (i) the total amount of surface water resources; (ii) the quality of surface water; (iii) total amount of groundwater resources; (iv) the groundwater quality; (v) the amount of surface water transferred to the basin; (vi) the natural cover index of the land.

- With a special geographical position, the hydrological regime in the SHRB is directly affected by the upstream flow. Therefore, the assessment of the quantity of surface water resources is very difficult, which causes big challenges for the planning of sustainable use of water resources in the region. It is also the reason why it is necessary to consider the groundwater reserve in the regional water resource allocation planning since this is an important source of water that can ensure the essential needs of water users.

- Within the scope of this study, we selected a number of indicators in the group of water resources assessment to conduct the pilot calculation for the SHRB. The results showed that the total amount of surface water from the Hau river supplying for the entire SHRB in the dry season months (I–VI) reached the average of about 487 million m^3/month; The total amount of groundwater including freshwater and saltwater is 35.5 million m^3/day, only 16.7 million m^3/day of freshwater; The total amount of surface water resources from endogenous rain in the SHRB is 19.95 billion m^3, of which that of the Ca Mau Peninsula area is 16.8 billion m^3, accounting for 84.2% of the total water volume of the whole region; The Long Xuyen Quadrangle area has the lowest total amount of endogenous water from the rain with only 3.15 billion m^3, accounting for 15.8% of the total amount for the whole region. There is a large difference in total water volume between the dry season and the flood season in the SHRB; in particular, the water volume in the dry season accounts for only 19% of the total water volume, equivalent to 3.8 billion m^3, while the water volume in the flood season accounts for 81% of the total water volume with a value of 16.19 billion m^3.

Although the models have been established to ensure the most reliable results for the years of calibration and verification, the errors in the calculation of water resources in the area are unavoidable as the direction of the flow is not clearly determined yet, the hydrological data is not long enough, it is not possible to ensure the appropriateness for the entire multi–year data series due to the fluctuations of the riverbed and reservoir topography, and the regulation and activity coordination process of irrigation works and canals in the region are still inadequate and difficult to control when the activity operations in many locations are still spontaneous. Therefore, in order to improve the quality of calculations, it is necessary to include the measured additional cross–sections for the hydraulic models of the flow and updated rules of reservoir operation and irrigation works in the area.

Author’s contribution: Developing research ideas: L.T.M.V., B.T.B.N.; Selecting of research methods: L.V.M.V., B.T.B.N.; Collecting, analyzing, calculating and processing of data: Writing the draft paper: N.H.A., B.T.B.N., L.T.M.V., D.Q.T.; T.V.C; D.H.H; Editing the final paper: N.H.A., B.T.B.N., L.T.M.V., D.Q.T; L.M.H; T.V.H.

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Disclaimer: The authors declare that this paper is the work of the research team, has not been published anywhere, and has not been copied from previous studies; there is no conflict of interest among the author group.

References

1. Chaves, H.M.L.; Alipaz, S. An integrated indicator based on basin hydrology, environment, life, and policy: The watershed sustainability index. *Water Resour. Manage.* **2007**, *21*, 883–895.
2. Catano, N.; Marchand, M.; Staley, S.; Wang, Y. Development And Validation Of The Watershed Sustainability Index (WSI) For The Watershed Of The Reventazón River, 2009, pp. 67.
3. Mititelu–Ionuș, O. Watershed Sustainability Index Development and Application: Case Study of the Motru River in Romania. *Pol. J. Environ. Stud.* **2017**, *26(5)*, 2095–2105.
4. Department of Water Resources Management. Report on Vietnam Water Sector Assessment Project, 2009.
5. Ministry of Natural Resources and Environment. Master plan for socio–economic development in the Red River Delta in the period 2010–2013, 2013.

6. Y, T.V.; Tri, N.D.; Can, L.T.; Chi, T.T.; Chinh, N.T.; Hau, N.X.; Hieu, N.V.; Tuan, D.Q.; Thinh, N.V.; Tuan, N.T.; Hennessy, J. Establishing a sustainable development indicator set including economic, social, and environmental fields in Tay Nguyen provinces. *VN J. Earth Sci.* **2014**, *36*, 241–251.
7. Hoan, H.V. Research on assessing the sustainability of groundwater resources in Ho Chi Minh City, Binh Duong and Dong Nai, 2012.
8. Van, L.T.M. Research on determining the sustainability index of the river basin and its pilot application in the Cau River basin. Ministry of Natural Resources and Environment, 2016.
9. Huong, H.T.L. Research on the scientific basis and propose solutions for integrated management of water resources in the Lo River basin. Hanoi Water Resources University, 2009.
10. Dung, N.K. Research on scientific and practical basis to determine content, methods of calculation, synthesis and statistics of water resource indicators, 2012.
11. Southern Institute of Water Resource Planning. The Mekong Delta Irrigation Master Plan in the context of climate change and sea–level rise, 2009.
12. Chuong, H.V.; Mai, L.Q. Evaluation of multi–criteria land for the development of land use types for rubber trees in the hilly areas of Huong Tra district, Thua Thien Hue province. *J. Soil Sci.* **2012**, *39*, 123–127.
13. Dinh, L.C. Integration of GIS and multi–criteria group decision analysis in land adaptation assessment. *J. Agric. Rural Dev.* **2011**, 82–89.
14. Trang, N.T.T. Research on sustainable land use in Ba Lat estuary area, Giao Thuy district, Nam Dinh province. Hanoi University of Agriculture, 2013.
15. Binh, N.V. Assessment of the current status to propose directions for sustainable agricultural land use in Huong Tra town, Thua Thien Hue province. Hue University, 2017.
16. Tuan, T.V.; Huan, N.C.; Thu, D.T.T.; Chinh, N.T.; Nhu, T.T.Q. Research and evaluation of land use system for sustainable agricultural land use planning (Case study: Dai Thanh commune, Quoc Oai district, Hanoi city). *VNU Sci. J. Earth Environ. Sci.* **2015**, *31*, 24–35.
17. Vietnam Mekong River Commission. Study of the Impacts of Hydroelectric Plants on the Mainstream of the Mekong River, Main Report, 2016.
18. Chinh, N.H. and et al. The results of groundwater monitoring in the Southern Delta in the National Monitoring Project – Southern Federation of Hydrogeology–Engineering Geology, 2000.
19. Dung, N.H. and et al. Project Result Report: N–Q stratigraphic division and study of the geological structure of the Southern Delta. General Department of Geology and Minerals of Vietnam, Archives Library of the Southern Federation of Hydrogeology–Engineering Geology, 2004.
20. Dung, N.Q. et al. Result Report: Result of water survey in the Remoted Southern region. General Department of Geology and Minerals of Vietnam, Archives Library of the Southern Federation of Hydrogeology– Engineering Geology, 2003.
21. DHI. Research Project on Impacts of Hydroelectric Plants on the Mainstream of the Mekong River, Volume 1–Model–Design and Simulation, 2016.
22. Vietnam Institute of Meteorology Hydrology and Environment. Impact of climate change on water resources and adaptation measures in the Mekong Delta, 2010.
23. Thai, T.H. Research on the effects of climate change on the change of water resources in the Mekong Delta, 2013.
24. Develop a plan for sustainable irrigation management in the Mekong Delta. Institute of Irrigation & Environment– University of Water Resources, 2013.
25. Report on the formulation of water resources planning tasks in the Mekong River Basin. National Center for Planning and Investigation of Water Resources, 2018.
26. Chaurasia, A.K.; Pandey, H.K.; Tiwari, S.K.; Prakash, R.; Pandey, P.; Ram, A. Groundwater Quality assessment using Water Quality Index (WQI) in parts of Varanasi District, Uttar Pradesh, India. Journal of the Geological Society of India, **2018**, *92(1)*, 76–82. https://doi.org/10.1007/s12594–018–0955–1.