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A Framework Using Applied Process Analysis Methods to Assess Water Security in the Vu Gia–Thu Bon River Basin, Vietnam

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Abstract: The Vu Gia–Thu Bon (VG–TB) river basin is facing numerous challenges to water security, particularly in light of the increasing impacts of climate change. These challenges, including salinity intrusion, shifts in rainfall patterns, and reduced water supply in downstream areas, are of great concern. This study comprehensively assessed the current state of water security in the basin using robust statistical analysis methods such as the Process Analysis Method (PAM), SMART principle, and Analytic Hierarchy Process (AHP). This resulted in the development of a comprehensive assessment framework for water security in the VG–TB river basin. This framework identified five key dimensions, with basin development activities (0.32), the ability to meet water needs (0.24), and natural disaster resilience (0.19) being the most crucial and water resource potential being the least crucial (0.11) according to the AHP methodology. The latter also highlighted 15 indicators, four of which are particularly influential, including waste resources (0.54), flood (0.53), water storage capacity (0.45), and basin governance (0.42). Furthermore, 28 variables with high weight factors were identified. This framework aligns with the UN-Water water security definition and addresses the global water sustainability criteria outlined in Sustainable Development Goal 6 (SDG6). It enables the computation of a comprehensive Water Security Index (WSI) for specific regions, providing a strong foundation for decision-making and policy formulation. It aims to enhance water security in the context of climate change and support sustainable basin development, thereby guiding future research and policy decisions in water resource management.

Keywords: water security framework; climate change; Vu Gia–Thu Bon river basin

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1. Introduction

Water is considered an essential natural resource; however, freshwater systems are currently under direct threat from human activities [1,2] and face an increasing risk due to climate change [3–5]. Ensuring water security is a multifaceted challenge that could jeopardize the lives and livelihoods of billions if left unaddressed [6–9]. Due to economic pressures, poverty, and urbanization trends [10], the growing concentration of people in densely populated coastal cities is expected to worsen water scarcity and increase vulnerability to water-related disasters [11]. This issue was highlighted in a study by Vorosmarty et al. (2000) [12], where population growth emerged as a significantly more influential factor than climate change in driving water scarcity.

The term "Water Security" is gaining prominence to encompass the numerous complexities linked to modern water resource management [13]. Water security is a defined concept that entails the maintenance of an acceptable level of risks related to water for both human populations and ecosystems, all while ensuring a sufficient supply of water that meets the required standards to support livelihoods, national security, human well-being, and ecosystem functions [14–16]. Awareness of the importance of water security is internationally recognized and included in specific action programs such as Goal 7 of the eight Millennium Development Goals (MDGs), which preceded the Sustainable Development Goals (SDGs) before 2015 [17], and the later SDG6, which aims at ensuring the availability and sustainable management of water and sanitation for all [18,19].

The measurement of water security is not a novel concept. However, most of the early research on water security was primarily conceptual, emphasizing defining the boundaries of water security [20]. One particularly impactful paper in this context is by Grey and Sadoff (2007) [15], who conceptualized water security by highlighting its relevance to human well-being and ecosystem health, emphasizing safeguarding against risks [20].

Currently, a highly favored and extensively employed approach for evaluating water security revolves around utilizing an assessment framework incorporating a set of criteria representing different characteristics of water security [21,22]. Several studies have followed this approach to urban [6,23–26], national [27,28], regional [29,30], and global scales [31,32]. The choice of assessment framework and criteria varies depending on the size and attributes of the system under investigation. In most cases, these assessment frameworks prioritize addressing the pivotal dimension that exerts the most significant influence on water security. Each of these frameworks has its advantages and limitations. These efforts are progressively moving towards more accurate assessments, aiding policymakers and decision-makers in formulating timely and appropriate water security policies.

In their assessment of the state of water security, researchers need to address the escalating complexity of the challenges stemming from economic downturns, disasters, and risks related to water resources. These challenges are exacerbated by adverse effects arising from human development activities and global climate change. Recent studies on water security have adopted a broader perspective, encompassing risks, disasters, the repercussions of ongoing climate change, and projections for the future across various dimensions and scales [20,25,33]. These include the four-dimensional framework in rural Alaska [34], the multi-criteria assessment framework for Bangkok (Thailand) [20] and Yulin City (China) [33], water security and zone adaptive management for arid and semi-arid regions of the Americas [35], and water security at the basin scale [25]. Current research often employs methods such as DPSIR (Driving Force–Pressure–State–Impact–Response) [20,25], System Dynamics Modeling (SDM) [28], and Process Analysis Methods (PAMs) [6,36]. Among these methods, PAMs are regarded as advantageous and more suitable compared with the other two approaches [6,37] when applied to construct a water security assessment framework.

The water agreement between Jordan and Israel, established as part of their 1994 peace treaty, provides a valuable case study in transboundary river water security. Over the past 25 years, both countries have upheld the detailed allocation terms outlined in the agreement. However, it is becoming increasingly clear that the terms may no longer be equitable, especially considering social, economic, and environmental changes within the region and the two nations. This highlights the dynamic nature of water security and emphasizes the necessity for ongoing evaluation and adaptation. This demonstrates how changes in water security can impact individuals and nations [38]. Another insight gained is also related to water security within the transboundary basin, which underscores the critical nature of hydro-politics in bringing attention to not only the political aspects of water-related decisions but also the fundamental assumptions of more traditional hydro-political analyses that tend to concentrate on conflicts and cooperation over water resources, with a strong focus on "the state" as the primary actor and scale of analysis [39].

In Vietnam, there are a limited number of studies on water security using assessment frameworks, and those conducted have not adequately addressed the impacts of climate change. Most research in this area has predominantly utilized the AWDO approach as its foundation [26,40] and UN-Water [41,42]. At the basin scale, assessments have been performed for the Red River [26]), Ma River [43], and Mekong River [42] Basins. Only Hanoi City [40], Quang Ngai Province, and Tra Vinh City [44] have been considered at the provincial and city scales. However, there is no comprehensive and direct research on assessing the level of water security in the VG–TB river basin (Figure 1) except for some studies indirectly addressing various aspects and individual factors related to ensuring the water security of the basin.

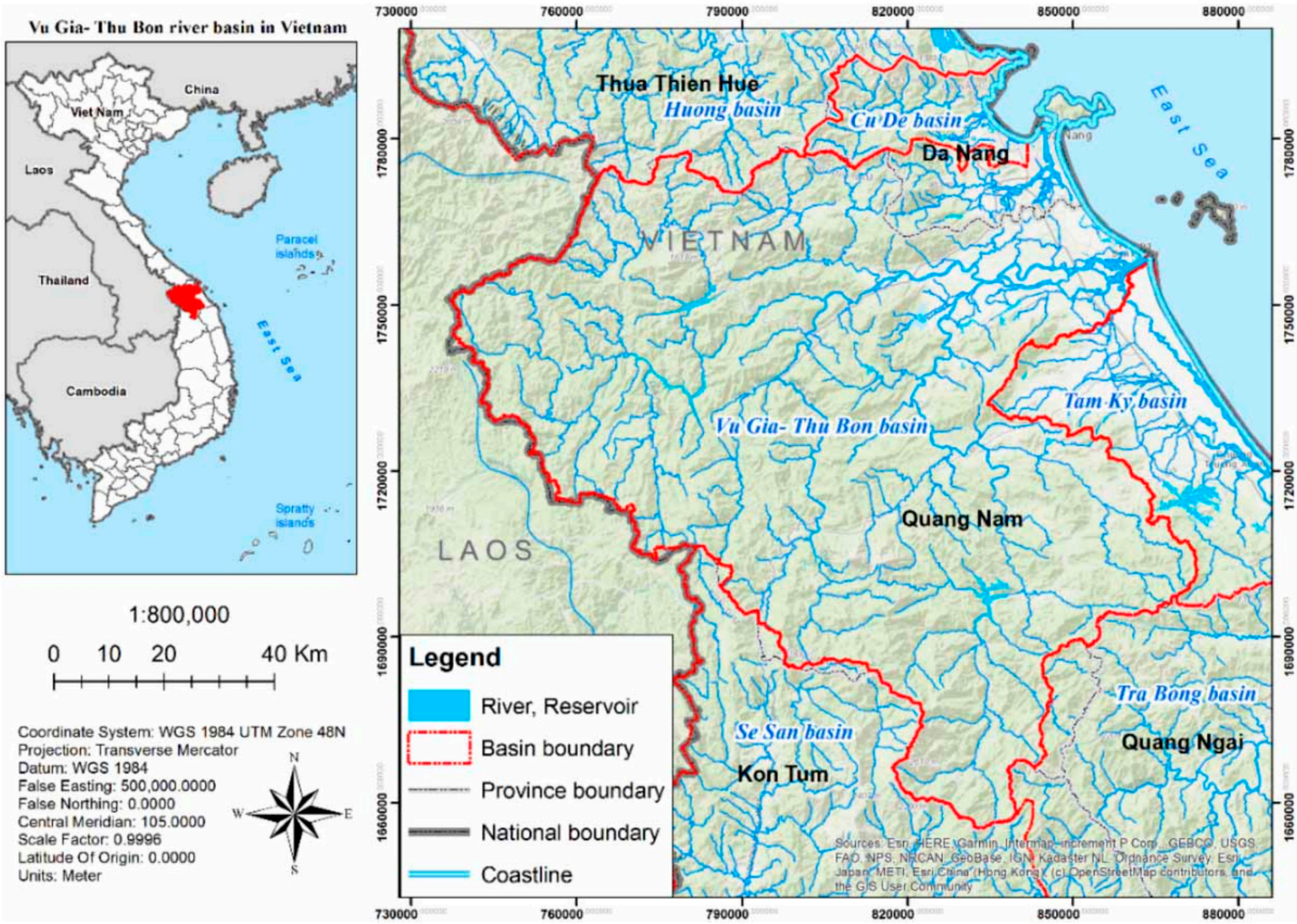

Figure 1. The study area: the VG–TB river basin [45].

The VG–TB river basin is confronted with various water security challenges, such as inequitable water distribution [46]; imbalanced water allocation and water transfer issues [47,48]; environmental flow violations and water pollution [49]; vulnerability to natural disasters [50,51]; salinity intrusion [52]; urbanization, deforestation, and other changes in vegetation cover, erosion, sedimentation [36]; the impact of tourism; and, particularly, the effects of hydropower operations on downstream water supply and flood control [53].

This study focused on establishing a robust framework for evaluating water security in the VG–TB river basin while considering climate change and socioeconomic activities. By combining the PAM–SMART–AHP methods, a comprehensive framework was devised to assess water security on a river basin scale. The SMART method was utilized to identify relevant criteria, while the AHP method was employed to determine the weight of each criterion. This framework provides a scientifically sound basis for policymakers to improve water security and formulate sustainable development strategies. It incorporates specific indicators from previous research and indicators tailored to the characteristics of the VG–TB river system while considering climate change and rapid growth in the basin.

2. Materials and Methods

2.1. Study Area

This study focused on the VG–TB river basin area, as shown in Figure 1. This region is home to Central Vietnam's most extensive river system, characterized by two primary rivers, Vu Gia and Thu Bon, originating in the Ngoc Linh Mountain and flowing towards the Cua Dai estuary [54,55]. Covering an extensive area of approximately 10,350 km^2, the VG–TB basin encompasses parts of Kon Tum, Quang Ngai, Quang Nam, and Da Nang City [55–57]. It is situated within a tropical monsoon climate zone where weather phenomena, including intense rainfall events and storms, occur complexly [58]. This region experiences substantial rainfall, averaging 2000 mm to 4000 mm annually, influenced by the basin's topography and shifting seasons [45,54]. The rainy season significantly contributes to the annual precipitation from September to December, accounting for 65–80% of the total. Conversely, during the dry season from January to August, rainfall sharply decreases, constituting only about 20–35% of the annual rainfall [45,54,58].

2.2. Framework Design for a Composite Model of Basin Sustainability

The proposed water security framework for sustainability in the VG–TB river basin encompasses several key elements (Figure 2): (1) ensuring access to safe and affordable drinking water to meet basic needs, including hygiene and sanitation, health, and well-being; (2) maintaining livelihoods and cultural values; (3) conserving ecosystems; (4) providing water for socioeconomic activities; (5) treating wastewater; (6) promoting international cooperation; (7) building resilience to water-related hazards; and (8) the responsible management of water resources, considering the interests of all stakeholders. All these components are crucial for sustaining essential ecosystem services, avoiding conflicts, and fostering stability in the region [1].

The process can be described step by step as follows:

- Step 1: Evaluate the overall water security situation in the VG–TB river basin, identify the issues that need to be addressed, and conduct an analysis and assessment of current water resources (quality and quantity), the capacity to meet water demands, water utilization activities within the basin, water-related risks, and the impact of basin development activities, as well as water management practices within the context of climate change.
- Step 2: Define the notion of water security (or define water security) to enable the selection of appropriate indicators. There are various definitions and approaches to water security worldwide. This study opts for the comprehensive description of water security provided by UN-Water, as it aligns with the practical conditions in Vietnam, specifically in the VG–TB river basin. While selecting indicators based on this definition, the research also considers the criteria of the SDG6 and the ADB approach to water security as presented in the AWDO reports.
- Step 3: Determine the boundaries of the assessment framework in terms of space and time. The study uses Water Security Index (WSI) indicators within the administrative boundaries of local areas (districts) in the basin, enabling a comparison of water security levels and facilitating solutions to improve water security for each locality. The period for assessing meteorological and hydrological variables is determined based on historical data. Socioeconomic data are collected for the most recent three-year period at the time of assessment. As for assessing the impact of climate change on water security in the basin, a mid-century period (2050) is chosen, along with corresponding scenarios. Steps 2 and 3 are elaborated and linked in Figure 3.
- Step 4: Establish the water security assessment framework. Based on the objectives of water security, spatial and temporal considerations, preliminary dimensions, indicators, and variables are selected. These aspects must align with the specific conditions

and characteristics of the VG–TB river basin. The chosen dimensions, indicators, and variables should effectively represent the impact of various factors on the well-being of the basin's residents. Water security in the basin is achieved when the population has access to water that meets the required standards in quantity and quality, sanitation facilities, convenient access to water sources, affordability, and safety during water-related disasters, all within acceptable levels. After the preliminary selection of evaluation variables, the SMART analysis method is used to determine the key variables for the assessment framework (Figure 4).

- Step 5: Consult with relevant stakeholders regarding the suitability of the variables and the assessment framework. The assessment framework, including dimensions, indicators, and variables determined using the specified methods and data, is evaluated for suitability through expert consultation and engagement with relevant parties. The dimensions, indicators, and variables should be a stakeholder consensus. If there are different opinions, it is necessary to discuss them to reach a consensus to unify the evaluation criteria.
- Step 6: Finally, the AHP algorithm (see in Figure 5) is applied to determine the weights of each criterion contributing to the framework. The weights are checked for consistency. Otherwise, the scores must be compromised with the stakeholder group until the final weights are accepted and the assessment framework is concluded.

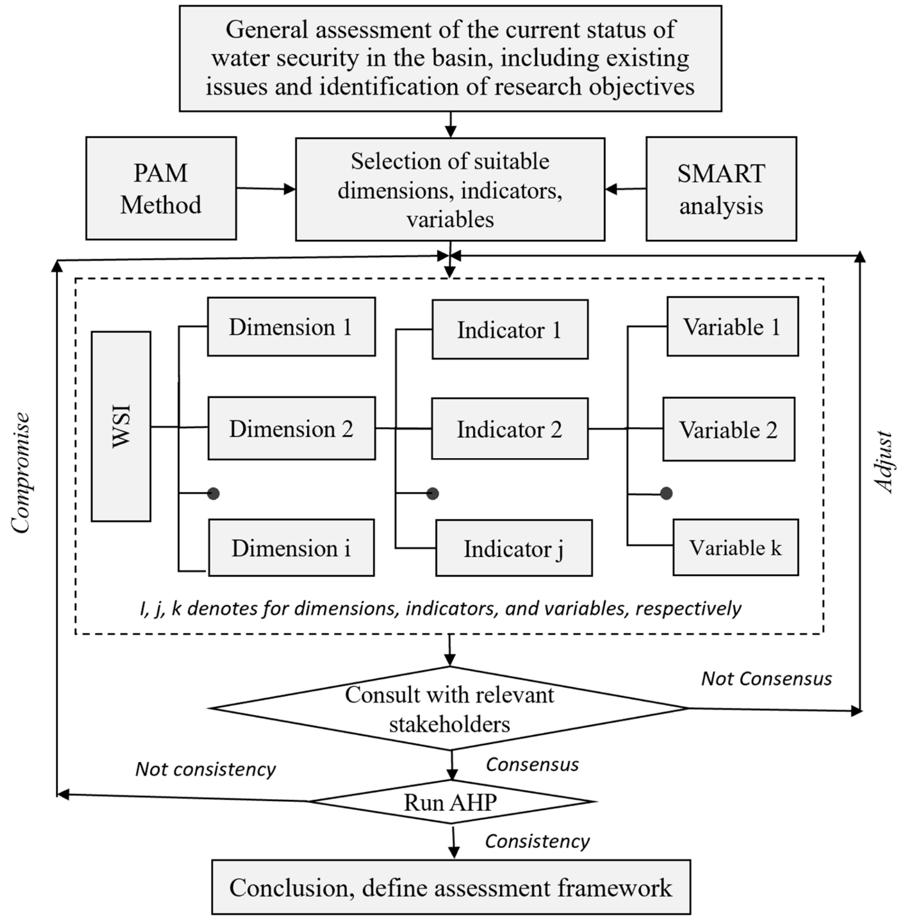

Figure 2. Process for developing the water security framework.

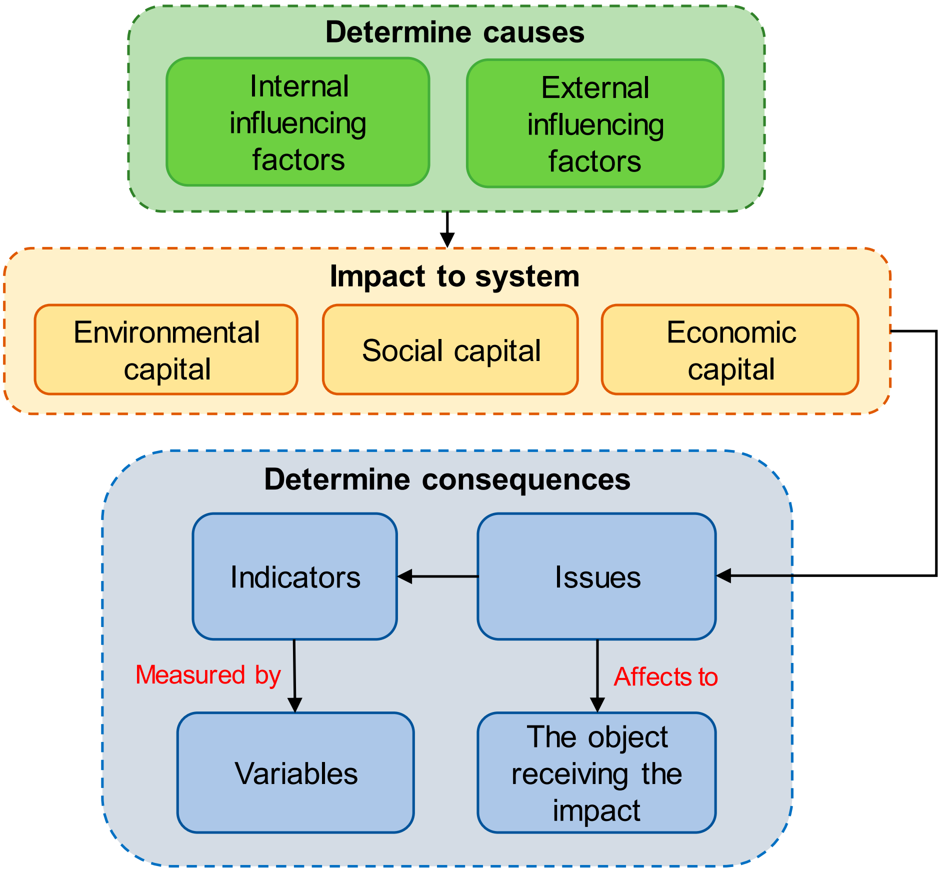

Figure 3. PAM's flowchart.

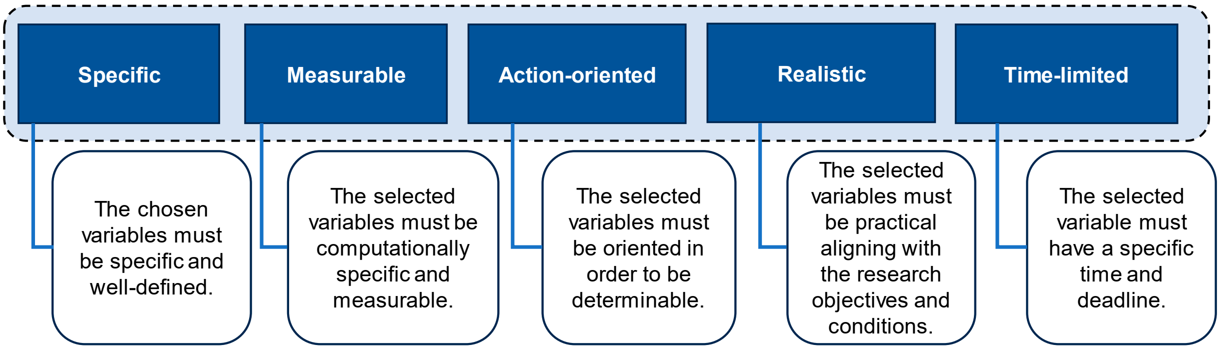

Figure 4. SMART's flow chart.

2.2.1. Process Analysis Method (PAM)

Developed by Tahir and Darton (2010) [37] and based on analyzing relationships among various factors, the PAM provides a procedure for selecting indicators to effectively assess a system's sustainability and resilience. It enables the creation of a comprehensive set of sustainability indicators and metrics tailored to a specific river system [59,60]. In this method, the impacts on the system are identified along with their underlying causes, referred to as the impacting agents [6]. Internal impacting agents pertain to activities within the watershed, such as water management, economic development, and societal factors, while external impact generators beyond the watershed's boundaries, such as meteorological conditions, hydrology, natural disasters, and climate change, serve as external driving forces. Both impacting agents contribute to water security within the watershed through critical dimensions. These impacts give rise to specific consequences for relevant entities, known as recipients of these impacts (including humans, the environment, and development activities within the watershed). These consequences are delineated through various aspects of indicators and are quantified using specific variables derived from statistical data and calculations. This process is depicted in Figure 3. In contrast to SDM, the PAM does not quantify causal relationships between causes, effects, and consequences. Instead, the selection of indicators through this method reflects a holistic understanding of a complex system by examining the literature and involving stakeholders while concurrently measuring specific factors [6]. With clear objectives, the advantage of the PAM approach is that it provides straightforward yet meaningful results. The PAM focuses on internal and external driving forces while identifying their impacts on the system through its analytical framework.

2.2.2. Principles for Selecting the Indicators (SMART)

Based on the analyses above, this study employed the PAM to construct a comprehensive framework for assessing water security in the VG–TB river basin. Subsequently, the SMART analysis method was used to select the key variables for this assessment framework. The SMART criteria are a popular technique to create robust indicators, examples of which abound in the literature [61]. Babel et al. (2020) developed a framework for measuring water security in the context of climate change adaptation [20]. SMART aids in identifying the most feasible and effective factors for achieving set evaluation objectives, ensuring that they are Specific, Measurable, Action-oriented, Realistic, and Time-limited. The process of establishing the SMART criteria is illustrated in Figure 4.

The selection of indicators for the proposed evaluation framework had to be relevant to the VG–TB river basin, ensuring the framework's appropriateness to the region under investigation. Still, it also had to ensure that the assessment was practical and maintained its scientific rigor. Therefore, whether creating new indicators or adopting existing water security indicators from previous studies, it was essential to adhere to the following principles: (1) The selected dimensions, indicators, and variables must align with the UN-Water definition of water security, taking into account the fulfillment of the criteria outlined in SDG6 [19] and the criteria ensuring water security as per the approach of the ADB in its AWDO reports [29,30]; (2) the selected indices must be clearly defined, verifiable, and not overly numerous [6]; (3) the selected indices can be measurable using a scientifically sound method within a cost-effective range; (4) the metrics should possess representativeness and appropriate synthesis in alignment with the evaluation objectives; (5) the metrics must be capable of reflecting future trend changes.

Applying these principles helped establish an evaluation framework and identify the best set of metrics under current conditions. However, in practice, the study bypassed certain principles while selecting water security indicators due to computational constraints, data collection limitations, and other factors.

2.2.3. Method for Determining Weights

There are several methods for determining the weights of different variables in decision-making in economics, transportation, education, resource allocation, planning, and integrated management [62]. Each method has advantages and limitations; for example, MicMac can simultaneously investigate multiple variables, but it does not give an overall priority score for each variable. On the other hand, the AHP only considers the direct impact of variables, but it provides an overall priority score for each variable [63]. The AHP has been a widely used multi-criteria decision-making (MCDM) method since the 1980s because of its simplicity and rationality [64]. In addition, the AHP is a structured decision and quantitative process that can be documented and replicated, it applies to decision situations involving multiple criteria and subjective judgment, it can deal with both qualitative and quantitative data, it can be used to check consistency of preference, and it is suitable for group decision-making [62].

To construct a highly reliable assessment framework that accurately reflects the level of water security in the basin, this study opted for the AHP methodology developed by [65] as its chosen method for analyzing the hierarchical system. Saaty (1987) [66] introduced the AHP as a measurement theory to establish ratio scales through discrete and continuous paired comparisons, aid decision-makers in prioritizing tasks, and optimize decision-making [67]. An AHP comparison matrix is created by systematically evaluating pairs of indicators using Saaty's scale, which ranges from 1 to 9 (Table 1) [68]. Assigning weights to the criteria plays a vital role in evaluating water security. The AHP method employs expert assessments, incorporating both quantitative and qualitative analyses, to determine the relative importance of each criterion [69].

Table 1. The scale of relationships between elements of the AHP [65].

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Weak importance of one over another	Experience and judgment slightly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance is demonstrated in practice.
9	Absolute importance	The evidence favoring one activity over another is of the highest possible order of affirmation.
2, 4, 6, 8	Intermediate values between adjacent scale values	When compromise is needed

Several techniques, such as geometric mean, arithmetic mean, row sum of the adjusted Saaty matrix, reverse sums of Saaty matrix columns, row sums of the Saaty matrix, and the Saaty method, are used to calculate the eigenvectors in the AHP for setting criteria. The Saaty method is the most complex and difficult, while the geometric mean and average mean methods are the simplest. Nonetheless, the Saaty method has been proven to be the most accurate [70]. Therefore, the Saaty method was selected in this study.

A flowchart for determining the weights of criteria according to the AHP was developed by Dang et al. (2011) [62], as can be seen in Figure 5. Matrix A = [a_{ij}] was established following the rule that is positive and reciprocal. Coefficients of the matrix were formed from the scoring of pairwise comparisons of dimensions, indicators, and variables of water security through group discussions of experts. Then, the relative weights of components were derived from the mathematical processing of the matrix using the AHP algorithm. The desired weights were computed as the matrix's principal right eigenvector (or Perron right vector), which was accomplished by raising matrix [A] to grow power k. The increasing power k of matrix [A] was iterated until the difference of priority weight vector of the two last repetitions was less than the permitted error. For each iteration, the weights were always normalized to sum to one for convenience. Ultimately, the maximum eigenvalue (λmax) of matrix [A] was then defined [62].

The AHP algorithm is developed as follows:

(1) Set up matrix [A] according to the principles of the AHP and the main elements taken from pairwise scores from experts' analysis results.
(2) Multiply matrix [A] with column vector (e) to get column vector (b).
(3) Multiply the column vector (b) with the row vector (eT) to get one value (c).
(4) Divide the column vector (b) by the value (c) to get the column vector of weight (w_1) for the iteration k = 1.
(5) Repeat a second time with k = k +1.
(6) Calculate matrix [A] by multiplying with itself.

(7) Repeat the computation process from (2) to (6) with k increases until the total absolute error between the two latest iterations is ≤ 0.00001, then exit the loop and record the preliminary result of the weights of the criteria.
(8) Determine the pairwise comparison matrix's consistency index (CI).

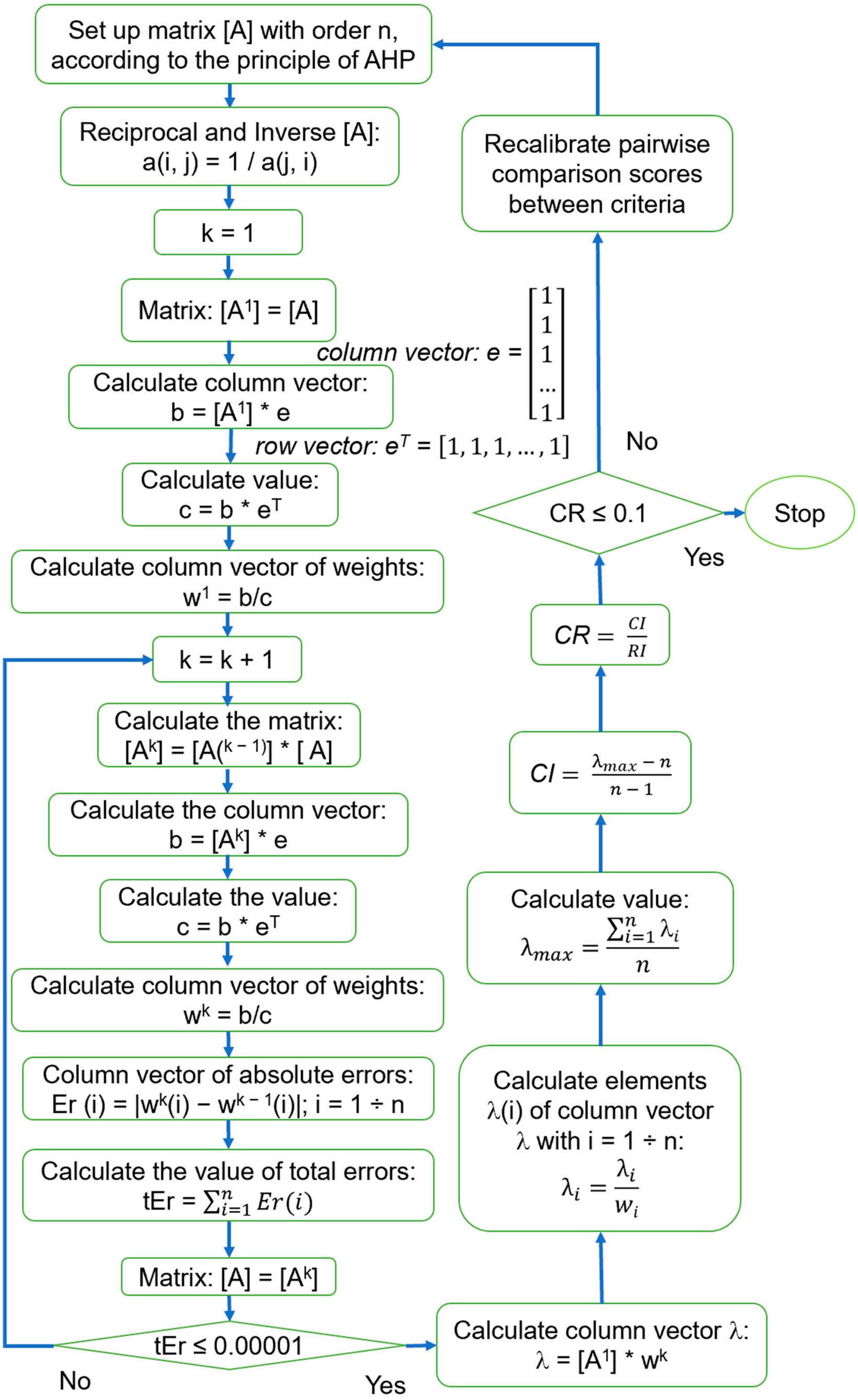

Figure 5. Diagram for determining the weights of factors according to the AHP (k is iteration; i and j are the numerical orders of the row and column of the matrix or vector) (modified from [62]).

Saaty (1980) emphasized that the calculated indices should consistently fall within an acceptable range of 0.0 ± 0.1 or less than 10% and apply to all types of problems [67]. The CI only has meaning for some criteria in the reciprocal matrix (order of the matrix, $n \geq 3$), and its minimum is zero. CR indicates the probability that the matrix judgments were generated randomly and remained consistent [71]. This means that only about 10% or less of the responses are random and inconsistent, while most responses are highly confident and certain. Conversely, if $CR \geq 10\%$, it indicates a situation where responses are hesitant and inconsistent in assessing pairwise comparisons within matrix [A]. In such cases, it is necessary to recalibrate the evaluations with experts to reach a consensus [68].

To ensure the reliability of a pairwise comparison matrix, it is essential to assess it using a consistency ratio CR, which is determined through the following calculations:

$$CR = \frac{CI}{RI} \tag{1}$$

where CI is the consistency index and RI is the random inconsistency index defined by using a function of the number of comparison criteria of the reciprocal matrix (n) proposed by Saaty (1980) [65], as shown in Table 2.

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{2}$$

where λ_{max} is the largest eigenvalue of the pairwise comparison matrix. It is important to note that $\lambda_{max} \geq n$, and if λ_{max} is closer to n, it indicates a higher level of consistency in expert evaluations. The value of λ_{max} is calculated as the average of the elements in the consistent column vector (λ) as below:

$$\lambda_{max} = \frac{\sum_{i=1}^{n} \lambda_i}{n} \tag{3}$$

in which λ_i is a value of an element (i) of the consistent column vector (λ) with a total of n elements; each element λ_i is determined by the following formula:

$$\lambda_i = \frac{\lambda_i}{\mathrm{w}_i} \text{with i} = 1 \div \text{n} \tag{4}$$

where w_i is a value of an element (i) of the column vector of weights (w) that is computed and satisfies the total permission error in step (7).

The consistent column vector (λ) is produced by multiplying matrix [A] with vector w:

$$\lambda = [\text{A}] \times \text{w} \tag{5}$$

where [A] is the pairwise comparison matrix and w is the column vector of weights.

Table 2. The relationship between the order of the matrix (n) and RI is used in the AHP.

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
RI	0.0	0.0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

3. Results and Discussion

3.1. Identification and Selection of the Water Security Assessment Indicators

Our research identified several fundamental factors for constructing an accurate and effective water security assessment framework for the VG–TB river basin. These factors encompass the natural characteristics and socioeconomic development activities in Quang Nam province and Da Nang City, as well as the increasing pressure on water supply due to population growth, tourism, water pollution sources, and existing challenges in managing and utilizing water resources. The study proposes an evaluation framework that utilizes five key dimensions, 15 indicators, and 34 variables, ensuring a comprehensive and detailed understanding of the water security situation in the VG–TB river basin.

Based on an analysis of the available data sources and input from expert consultations and relevant stakeholders, the study excluded six variables that did not meet the SMART criteria: (1) residue of pesticides and fertilizers in agricultural production, (2) incidence of diseases related to digestive and dermatological health due to the use of unsanitary water sources, (3) economic water scarcity (the extent of river extraction), (4) compliance of hydroelectric plants with reservoir operation processes, (5) water loss due to "virtual water" in agricultural production, and (6) local governments' attention to water security in their decision-making and governance.

The developed framework consists of 28 variables. Each variable's data was normalized before combining the variables relevant to each indicator. This involved scaling the data to a uniform range to eliminate differences in units and magnitude. The aggregation process also factored in the weight of each variable, which was determined using the AHP methodology. Similarly, the weight of each indicator from the AHP methodology was utilized to aggregate the indicators within each dimension of the WSI. The WSI provides a quantifiable measure of the level of water security in each locality and the overall water security status in the VG–TB river basin. The components, significance, and methods for determining the variables in the assessment framework are detailed, ensuring a robust and reliable evaluation of water security.

3.1.1. Water Resource Potential Dimension (WSI_1)

As a fundamental factor, water resources are inextricably linked to water security. The higher the volume of water in a basin, the greater the level of water security. This underscores the importance of the water resource potential dimension (WSI1) in our evaluation framework. This dimension is directly linked to the total water supply to the basin. This study meticulously examined the key potential sources, including rainfall, surface water, and groundwater. Based on data collected from meteorological and hydrological stations, as well as groundwater measurements, the potential water resources are determined using variables such as annual flow module, low flow module, coefficient of variation for low flow (Cv-dry), average annual rainfall, groundwater exploitation capacity, and reservoir capacity. For WSI1, water resources are evaluated spatially and in terms of time. The potential for new water resources only reflects the balance (surplus/deficit) and does not consider the ability to extract and efficiently use water resources (loss and wastage) (Table 3).

Table 3. Composition and determination of the water resource potential dimension.

Indicators	Variables	Determination	Data Source	Objective of Variables in Water Security Assessment
Surface water potential (WSI_{1-1})	Annual flow module (WSI_{1-1-1})	Calculate the daily flow from the mathematical model. Based on this data series, determine Q_0 and Q_{dry} for each year. Calculate the average M_0 and M_{dry} for many years.	Central Regional Hydrometeorological Station, Department of Natural Resources and Environment of Quang Nam province, Da Nang City	It demonstrates the basin's ability to produce water. Larger M_0 values represent the abundance and availability of water resources and higher water security levels.
	Dry season flow module (WSI_{1-1-2})			It demonstrates the ability to produce water in the basin during the dry season. The smaller the M_{dry}, the higher the level of water shortage. The larger the M_{dry}, the higher the level of security.
	Level of dry season flow fluctuation (WSI_{1-1-3})	Establish the low flow series and the low flow Cv from the average flow in each year's dry season.		The larger the $Cv\text{-}_{dry}$, the greater the dispersion of the dry season flow data series and the higher the possibility of extreme drought events. The higher the $Cv\text{-}_{dry}$, the lower the water security level.
Rainwater potential (WSI_{1-2})	Average annual rainfall (WSI_{1-2-1})	Rainfall distribution in localities is determined from the annual rainfall isometric map.		The larger the amount of water coming from rain distributed in localities, the higher the level of water security.

Table 3. *Cont.*

Indicators	Variables	Determination	Data Source	Objective of Variables in Water Security Assessment
Groundwater potential ($WSI_{1\text{-}3}$)	Underground water reserves can be exploited ($WSI_{1\text{-}3\text{-}1}$)	Determine groundwater reserves from groundwater potential reports.	Quang Nam Environmental Monitoring Center, Da Nang	The greater the ability to replenish water sources from groundwater, the greater the groundwater potential and the higher the level of water security.
Water storage capacity ($WSI_{1\text{-}4}$)	Total capacity of reservoirs ($WSI_{1\text{-}4\text{-}1}$)	Determine from statistics the capacity of all reservoirs from the Irrigation Departments and hydroelectric reservoir owners.	Department of Agriculture and Rural Development, Irrigation Engineering Company, Hydroelectric plants	In an area with many reservoirs (irrigation/hydropower), the ability to retain water in the basin is higher, and the benefiting area has a high level of water security.

3.1.2. The Water Quality Dimension (WSI_2)

The water quality dimension has the most pronounced impact on the water security level of a basin. This dimension is determined through indicators that include emissions from agricultural and aquaculture activities, surface water quality, groundwater quality, and the extent of water quality improvement within the basin. This group of indicators is represented by variables such as agricultural land area, total livestock and poultry population, aquaculture area, the number of lodging establishments, the number of times water quality standards are exceeded, access to clean water sources, and the ability to ensure environmental sanitation conditions (Table 4).

Table 4. Composition and determination of the water quality dimension.

Indicators	Variables	Determination	Data Source	Objective of Variables in Water Security Assessment
Waste sources ($WSI_{2\text{-}1}$)	Agricultural cultivation activities ($WSI_{2\text{-}1\text{-}1}$)	Ratio of land area used for agricultural cultivation/total natural area	Department of Agriculture and Rural Development of Quang Nam and Da Nang provinces	The more farming activities, the greater the water use and loss level and the more fertilizer and pesticide residues pollute water sources.
	Cattle raising activities. ($WSI_{2\text{-}1\text{-}2}$)	Total livestock herd (head) of each locality		The lower the water security level, the more livestock farming activities lead to surface water and groundwater pollution.
	Poultry farming activities. ($WSI_{2\text{-}1\text{-}3}$)	Total poultry herd (thousands of birds) in each locality		The lower the water security level, the more poultry farming activities lead to surface water and groundwater pollution.
	Aquaculture activities ($WSI_{2\text{-}1\text{-}4}$)	Ratio of aquaculture area of each locality/total natural land area of the locality		The larger the aquaculture area, the more drug residues and leftover food lead to pollution and fertility problems. A large amount of seawater is introduced to create a brackish water environment, increasing salinity. The more this activity, the lower the water security level.
	Tourism service activities ($WSI_{2\text{-}1\text{-}5}$)	Total number of accommodation rooms serving tourism in each locality	Department of culture, sports and tourism of Quang Nam and Da Nang provinces	The total number of accommodation rooms represents the need to serve large numbers of tourists, causing local pressure on water supply needs and water pollution from wastewater and garbage discharge activities in localities where these activities occur. The more tourism activities, the lower the water security level.
Surface and underground water quality (rivers, lakes, wells) ($WSI_{2\text{-}2}$)	Number of times exceeding the allowable threshold of water quality indicators/year ($WSI_{2\text{-}2\text{-}1}$)	The number of times in the year that 12 basic indicators exceeded the allowable threshold level B1 (QCVN 08 MT: 2023/BTNMT)/the total number of monitoring times	Water quality monitoring report from environmental monitoring centers of Quang Nam and Da Nang provinces	The number of times 12 basic indicators exceed the allowable threshold level B1 (QCVN 08-MT:2023/BTNMT) at monitoring locations during the year represents the pollution level of the local water environment. The more passes, the lower the water security.
Level of water quality improvement ($WSI_{2\text{-}3}$)	Percentage of communes with common domestic wastewater systems ($WSI_{2\text{-}3\text{-}1}$)	Number of communes with shared domestic wastewater systems/total number of communes (%)	Quang Nam and Da Nang statistical yearbook	The more communes have common domestic wastewater systems, the better the wastewater is collected, minimizing water pollution, and the higher the water security level.
	Percentage of communes with waste collection in the area ($WSI_{2\text{-}3\text{-}2}$)	Number of communes with waste collection in the area/total number of communes (%)	Quang Nam and Da Nang statistical yearbook	The more communes with waste collection on the ground, the better the amount of waste collected and treated, minimizing water pollution from surface waste and increasing water security.
	Ability to supply clean water according to QCVN 02:2009/BYT ($WSI_{2\text{-}3\text{-}3}$)	Percentage of households provided with clean water according to Standard 02/total number of households (%)	Quang Nam and Da Nang Statistical Yearbook	According to Standard 02, the more households are provided with clean water, the better the water supply system, the more people can access clean water, and the better the water security.

3.1.3. Disaster Dimension (WSI_3)

The impact of water-related disasters is a significant factor in ensuring water security; this dimension considers a community's resilience to the effects of natural disasters. For the VG–TB river basin, typical natural disasters significantly affecting economic and social life include floods, droughts, and saltwater intrusion. The more significant the impact of natural disasters, the lower the level of water security. This dimension is assessed through indicators of flood level, the SPI drought index, and river water salinity due to saltwater intrusion. Compared with other elements that humans heavily influence, the impacts of natural disasters on the basin are issues that we cannot fully actively control (Table 5).

Table 5. Components and determination of the water disaster dimension.

Indicators	Variables	Determination	Data Source	Objective of Variables in Water Security Assessment
Flood (WSI_{3-1})	Flood depth (WSI_{3-1-1})	Flood map of a frequently occurring flood (P = 5–10%, flood protection standards designed for the basin)	Irrigation Department	The level of flooding corresponding to floods that are likely to occur frequently reflects the negative impact of flooding on the basin; the deeper the level of flooding, the lower the level of water security.
Drought (WSI_{3-2})	12-month drought index SPI_{12} (WSI_{3-2-1})	SPI_{12} index is determined as: $SPI_{12} = \frac{R-\overline{R}}{\sigma}$ R: calculated annual CHIRPS rainfall; $\overline{R}$: documented average CHIRPS rainfall; σ: standard deviation of document list	Global CHIRPS satellite rain data	Localities with high levels of drought have their water supply severely affected, and the damage caused by drought is large. The higher this index, the lower the water security.
Saline intrusion (WSI_{3-3})	Salinity (WSI_{3-3-1})	Salinity S (‰) is determined from mathematical model results	Environmental monitoring centers of Quang Nam and Da Nang provinces	The greater the salinity S (‰), the higher the level of salinity intrusion, the greater the damage, and the lower the water security level.

3.1.4. Dimension of Ability to Meet Water Demand (WSI_4)

This is a highly crucial dimension that determines the level of water security. This dimension reflects water scarcity within a basin or the level of water shortage due to insufficient or untapped water resources to meet the water demand at various times. Current assessments indicate that the water potential in the VG–TB basin is substantial due to total annual precipitation. However, the level of water shortage is primarily due to the temporal distribution of rainfall (which is concentrated during the rainy season) and the system's inability to harness all the water generated in the basin during the rainy season. This dimension is determined by calculating the balance between the water inflow and demand of various water-consuming sectors within the basin (Table 6).

Table 6. Components and determination of the ability to meet water demand dimension.

Indicators	Variables	Determination	Data Source	Objective of Variables in Water Security Assessment
Level of water demand satisfaction (WSI_{4-1})	Level of water shortage (water scarcity) (WSI_{4-1-1})	Calculate the water balance between incoming water volume and the total water demand of sectors in the basin	Central Region Hydrometeorological Station, Department of Agriculture and Rural Development, Department of Industry and Trade of Quang Nam and Da Nang	The greater the water resource shortage, the less the ability to exploit and use water resources efficiently. Not meeting the water demand for industries leads to low water security.

3.1.5. Basin Development Dimension (WSI_5)

This dimension is considered based on the impacts of development activities on a basin. This dimension is challenging to determine because the variables include many dimensions and are difficult to quantify. This study evaluated the impact of development activities on the basin based on economic, social, environmental, policy, and institutional criteria. Hydropower exploitation, forest area conversion, and urbanization significantly impact the basin's water security. The transfer of water from the Vu Gia River to the Thu Bon River due to the operation of hydroelectric plants is also a notable issue in this basin. The water transfer has caused a water shortage downstream of the Vu Gia River, leading to continuous saltwater intrusion in the dry season in recent years since the hydroelectric system was put into operation. Salinity has dramatically affected the supply of water for agriculture and domestic use in the downstream areas of Quang Nam province and Da Nang City (Table 7).

Table 7. Components and ways to determine the basin development dimension.

Indicators	Variables	Determination	Data Source	Objective of Variables in Water Security Assessment
Water transfer in the basin ($WSI_{5\text{-}1}$)	Give/receive water ($WSI_{5\text{-}1\text{-}1}$)	Total amount of water transferred (to)/total amount of natural water arriving in that basin (%)	Calculated from the model, Dak Mi 4 hydropower plant operating parameters	The total water outflow from the basin (only considering dry season water supply and excluding the flood season) increases due to the influence of hydropower projects; this will affect the downstream area of the basin and the water security level of the downstream region (post-construction), making the water security level lower. Conversely, the portion of the basin that receives water will have the opposite effect.
Socioeconomic ($WSI_{5\text{-}2}$)	Level of awareness and propaganda about water security in the community ($WSI_{5\text{-}2\text{-}1}$)	Total number of teachers at schools (primary and middle, high school) of each locality/10,000 people (teachers/10,000 people)	Quang Nam and Da Nang Statistical Yearbook	A high ratio of high school teachers in the population represents a high proportion of educational establishments or the number of students in the locality, representing the number of people being educated about the awareness of saving and protecting water resources. A high ecological environment and water security level will be high and vice versa.
	Average income per capita ($WSI_{5\text{-}2\text{-}2}$)	Average income (Thousand VND/person/month)	Quang Nam and Da Nang statistical yearbook	Localities with high per capita income demonstrate their ability to withstand adverse impacts from natural disasters (floods, droughts, etc.) and improve their quality of life and living environment. They also have a good ability to pay for water supply services. The higher the average income, the better the level of water security.
	Health services ($WSI_{5\text{-}2\text{-}3}$)	Total number of hospital beds of medical facilities in the area (beds)	Quang Nam and Da Nang statistical yearbook	The greater the number of hospital beds in medical facilities in the area, the better the living conditions and resilience to the negative impacts of natural disasters related to the water environment.
Urbanization ($WSI_{5\text{-}3}$)	Level of decline in green area ($WSI_{5\text{-}3\text{-}1}$)	Determine the index from remote sensing images over time to determine the level of decline in the tree area	Data from remote sensing image source Sentinel 2	The more significant the decline in the green area, the greater the reduction in the basin's land cover and buffer surface. This affects the ability to store water and prevent erosion. High levels of urbanization and heavy forest exploitation activities pressure the water environment. The greater the level of degradation, the lower the water security.
	Population density ($WSI_{5\text{-}3\text{-}2}$)	Population density of localities (people/km^2)	Quang Nam and Da Nang statistical yearbook	The larger the population of localities, the higher the demand for water supply and the higher the level of waste discharge (wastewater and garbage), which will negatively impact the water environment. The higher the population density, the lower the level of water security response.
Basin governance ($WSI_{5\text{-}4}$)	Investment capital for water supply, waste and wastewater management, and treatment activities ($WSI_{5\text{-}4\text{-}1}$)	Investment capital for water supply, management, waste, and wastewater treatment activities in localities (million VND)	Quang Nam and Da Nang Statistical Yearbook	The larger the investment capital allocated to water supply, waste management, and wastewater treatment activities in local areas, the more enhanced the water supply capacity and the ability to manage and control water environmental pollution. A higher level of investment capital correlates with higher water security.
	Infrastructure development in rural areas ($WSI_{5\text{-}4\text{-}2}$)	Percentage of communes meeting new rural standards/total number of communes in the locality (%)	Quang Nam New Rural Office, Da Nang	The more communes that meet new rural standards, the better the rural infrastructure system, including good water supply and wastewater treatment systems, living environment conditions, and accessibility such as guaranteed water sources, educated people, high standards of living (meets 19 new rural criteria). A locality with a high rate means a good level of water security.
	The proportion of field managers in state management agencies (districts) with appropriate expertise ($WSI_{5\text{-}4\text{-}3}$)	Number of people with expertise in water resources field/number of district People's Committee officials (%)	People's Committees of districts in Quang Nam Province and Da Nang City	The more people with expertise in water resources in the local management and administration apparatus, the better the advice will be for the management and direction of local authorities to ensure water security issues, as well as the ability to propagate and raise awareness about water security in local communities. The higher this ratio, the better the water security level.

3.2. Determining the Weights of Factors According to the AHP

After selecting the water security assessment framework for the VG–TB river basin, including dimensions, indices, and variables as synthesized in Section 3.1, the AHP was employed to establish comparison matrices. Eight tables were designed for pairwise comparison of water security factors. The scores were first given by authors and arranged as matrices for the AHP. Experts in different groups (scientists, managers, technicians, water resources, hydropower, irrigation, water supply, sociologists, economics, and environment) discussed and compromised to consensus scores. These experts have been working for at least 15 years in related the invited fields and come from different institutions of government, provinces, districts, communes, and enterprises. The final scoring is shown in Tables 8–15, which is also matrix [A] as an input for the AHP. In each table, the integer number is from the scoring following the AHP rule, and the remaining number is just the inverse of the integer number. These tables are formed as reciprocal matrices.

Table 8. Pairwise comparison of the five dimensions of water security.

Dimensions	Water Resource Potential (W_1)	Water Quality (W_2)	Water Disaster (W_3)	Ability to Meet Water Demand (W_4)	Basin Development (W_5)
Water resource potential (WSI_1)	1	1/5	1/9	1/8	1/3
Water quality (WSI_2)	5	1	1/3	1/6	1/3
Water disaster (WSI_3)	9	3	1	1	3
Ability to meet water demand (WSI_4)	8	6	1	1	3
Basin development (WSI_5)	3	3	1/3	1/3	1

Table 9. Pairwise comparison of the four indicators of the water resource potential dimension (WSI_1).

Indicators	Surface Water Potential ($WSI_{1\text{-}1}$)	Rainwater Potential ($WSI_{1\text{-}2}$)	Groundwater Potential ($WSI_{1\text{-}3}$)	Water Storage Capacity ($WSI_{1\text{-}4}$)
Surface water potential ($WSI_{1\text{-}1}$)	1	5	3	1/4
Rainwater potential ($WSI_{1\text{-}2}$)	1/5	1	1/5	1/9
Groundwater potential ($WSI_{1\text{-}3}$)	1/3	5	1	1/5
Water storage capacity ($WSI_{1\text{-}4}$)	4	9	5	1

Table 10. Pairwise comparison of the three variables of the surface water potential indicator ($WSI_{1\text{-}1}$).

Variables	Annual Flow Module ($WSI_{1\text{-}1\text{-}1}$)	Dry Season Flow Module ($WSI_{1\text{-}1\text{-}2}$)	Level of Dry Season Flow Fluctuation ($WSI_{1\text{-}1\text{-}3}$)
Annual flow module ($WSI_{1\text{-}1\text{-}1}$)	1	1/8	3
Dry season flow module ($WSI_{1\text{-}1\text{-}2}$)	8	1	9
Level of dry season flow fluctuation ($WSI_{1\text{-}1\text{-}3}$)	1/3	1/9	1

Table 11. Pairwise comparison of the three indicators of the water quality dimension (WSI_2).

Indicators	Waste Sources ($WSI_{2\text{-}1}$)	Surface and Underground Water Quality (Rivers, Lakes, Wells) ($WSI_{2\text{-}2}$)	Level of Water Quality Improvement ($WSI_{2\text{-}3}$)
Waste sources ($WSI_{2\text{-}1}$)	1	7	4
Surface and underground water quality (rivers, lakes, wells) ($WSI_{2\text{-}2}$)	1/7	1	1/3
Level of water quality improvement ($WSI_{2\text{-}3}$)	1/4	3	1

Table 12. Pairwise comparison of the five variables of the waste indicator ($WSI_{2\text{-}1}$).

Variables	Agricultural Cultivation Activities ($WSI_{2\text{-}1\text{-}1}$)	Cattle Raising Activities ($WSI_{2\text{-}1\text{-}2}$)	Poultry Farming Activities ($WSI_{2\text{-}1\text{-}3}$)	Aquaculture Activities ($WSI_{2\text{-}1\text{-}4}$)	Tourism Service Activities ($WSI_{2\text{-}1\text{-}5}$)
Agricultural cultivation activities ($WSI_{2\text{-}1\text{-}1}$)	1	1/7	1/5	2	1/8
Cattle raising activities ($WSI_{2\text{-}1\text{-}2}$)	7	1	3	5	1/3
Poultry farming activities ($WSI_{2\text{-}1\text{-}3}$)	5	1/3	1	3	1/3
Aquaculture activities ($WSI_{2\text{-}1\text{-}4}$)	1/2	1/5	1/3	1	1/9
Tourism service activities ($WSI_{2\text{-}1\text{-}5}$)	8	3	3	9	1

Table 13. Pairwise comparison of the three variables of the level of improvement in water quality ($WSI_{2\text{-}3}$).

Variables	Percentage of Communes with Common Domestic Wastewater Systems ($WSI_{2\text{-}3\text{-}1}$)	Percentage of Communes with Waste Collection in the Area ($WSI_{2\text{-}3\text{-}2}$)	Ability to Supply Clean Water According to QCVN 02:2009/BYT ($WSI_{2\text{-}3\text{-}3}$)
Percentage of communes with common domestic wastewater systems ($WSI_{2\text{-}3\text{-}1}$)	1	3	1/7
Percentage of communes with waste collection in the area ($WSI_{2\text{-}3\text{-}2}$)	1/3	1	1/9
Ability to supply clean water according to QCVN 02:2009/BYT ($WSI_{2\text{-}3\text{-}3}$)	7	9	1

Table 14. Pairwise comparison of the three indicators of the water disaster dimension (WSI_3).

Indicators	Flood ($WSI_{3\text{-}1}$)	Drought ($WSI_{3\text{-}2}$)	Saline Intrusion ($WSI_{3\text{-}3}$)
Flood ($WSI_{3\text{-}1}$)	1	6	9
Drought ($WSI_{3\text{-}2}$)	1/6	1	2
Saline intrusion ($WSI_{3\text{-}3}$)	1/9	1/2	1

Table 15. Pairwise comparison of three indicators of the basin development dimension (WSI_5).

Indicators	Water Transfer ($WSI_{5\text{-}1}$)	Socioeconomics ($WSI_{5\text{-}2}$)	Urbanization ($WSI_{5\text{-}3}$)	Basin Governance ($WSI_{5\text{-}4}$)
Water transfer ($WSI_{5\text{-}1}$)	1	2	2	1/5
Socioeconomics ($WSI_{5\text{-}2}$)	1/2	1	1/5	1/9
Urbanization ($WSI_{5\text{-}3}$)	1/2	5	1	1/5
Basin governance ($WSI_{5\text{-}4}$)	5	9	5	1

The scoring tables include qualitative numbers; it is therefore essential to convert them into quantitative values and test for the consistency of such matrices [62]. The consistency of expert ratings was evaluated through the CR, and calculations were performed to determine the weights of the components of specific variables, indicators, and dimensions, as shown in Table 16. This table presents the weight values for different dimensions, indicators, and variables. The AHP results depend on the weights assigned to the criteria.

Table 16. AHP weights for water security dimensions in the VG–TB river basin.

Dimensions		Indicators		Variables	
Main Dimensions	AHP Weight	Sub-Dimensions	AHP Weight	Sub-Dimensions	AHP Weight
Water resource potential dimension (WSI_1)	0.11	Surface water potential ($WSI_{1\text{-}1}$)	0.28	Year flow module ($WSI_{1\text{-}1\text{-}1}$)	0.62
				Dry season flow module ($WSI_{1\text{-}1\text{-}2}$)	0.24
				Fluctuating level of flow in the dry season ($WSI_{1\text{-}1\text{-}3}$)	0.14
		Rainwater potential ($WSI_{1\text{-}2}$)	0.16	Average annual rain ($WSI_{1\text{-}2\text{-}1}$)	1.00
		Groundwater potential ($WSI_{1\text{-}3}$)	0.11	Ability to exploit groundwater ($WSI_{1\text{-}3\text{-}1}$)	1.00
		Water storage capacity ($WS_{1\text{-}4}$)	0.45	Reservoir capacity ($WSI_{1\text{-}4\text{-}1}$)	1.00
Water quality (WS_2)	0.14	Waste sources ($WS_{2\text{-}1}$)	0.54	Agricultural cultivation activities ($WS_{2\text{-}1\text{-}1}$)	0.18
				Cattle farming activities ($WS_{2\text{-}1\text{-}2}$)	0.12
				Poultry farming activities ($WS_{2\text{-}1\text{-}3}$)	0.06
				Aquaculture activities ($WS_{2\text{-}1\text{-}4}$)	0.22
				Tourism service activities ($WS_{2\text{-}1\text{-}5}$)	0.42
		Surface and groundwater quality ($WSI_{2\text{-}2}$)	0.16	Number of times exceeding the allowable threshold of criteria/year ($WS_{2\text{-}2\text{-}1}$)	1.00
		Level of improvement in water quality ($WSI_{2\text{-}3}$)	0.30	Percentage of communes with shared domestic wastewater systems ($WSI_{2\text{-}3\text{-}1}$)	0.32
				Percentage of communes with waste collection in the area ($WSI_{2\text{-}3\text{-}2}$)	0.08
				Ability to supply clean water according to Regulation 02—2009 BYT, Vietnam ($WSI_{2\text{-}3\text{-}3}$)	0.60

Table 16. *Cont.*

Dimensions		Indicators		Variables	
Main Dimensions	AHP Weight	Sub-Dimensions	AHP Weight	Sub-Dimensions	AHP Weight
Natural disaster (WS_3)	0.19	Flood ($WSI_{3\text{-}1}$)	0.53	Flood depth ($WSI_{3\text{-}1\text{-}1}$)	1.00
		Drought ($WSI_{3\text{-}2}$)	0.14	Standardized Precipitation Index (SPI) ($WSI_{3\text{-}2\text{-}1}$)	1.00
		Salinity intrusion ($WSI_{3\text{-}3}$)	0.33	Salinity (S‰) ($WSI_{3\text{-}3\text{-}1}$)	1.00
Ability to meet water needs (WSI_4)	0.24	Level of water demand met ($WSI_{4\text{-}1}$)	1.00	Water shortage (water scarcity) ($WSI_{4\text{-}1\text{-}1}$)	1.00
Basin development (WSI_5)	0.32	Water transfer ($WSI_{5\text{-}1}$)	0.17	Giving/receiving water ($WSI_{5\text{-}1\text{-}1}$)	1.00
		Socioeconomic ($WSI_{5\text{-}2}$)	0.14	Public awareness (number of teachers per 10,000 people) ($WSI_{5\text{-}2\text{-}1}$) Average income per capita ($WSI_{5\text{-}2\text{-}2}$) Health services ($WSI_{5\text{-}2\text{-}3}$)	0.12 0.65 0.23
		Urbanization ($WSI_{5\text{-}3}$)	0.27	Reduced green area ($WSI_{5\text{-}3\text{-}1}$) Population density ($WSI_{5\text{-}3\text{-}2}$)	0.30 0.70
		Basin Governance ($WSI_{5\text{-}4}$)	0.42	Investment capital for water supply, waste and wastewater management, and treatment activities ($WSI_{5\text{-}4\text{-}1}$) Infrastructure ($WSI_{5\text{-}4\text{-}2}$) Water resource management ($WSI_{5\text{-}4\text{-}3}$)	0.33 0.41 0.26

In brief, the comparison of five aspects that determine water security in the VG–TB river basin revealed that the dimension of basin development activities (WSI_5) has the most significant influence on the water security level of the basin with weight w = 0.32. Next is the dimension of ability to meet water demand (WSI_4), which also has a significant influence with weight w = 0.24. This shows that the state of water security is mainly due to the impact of human development activities in the basin and the ability to effectively exploit and use available water resources. Three other dimensions contribute to the basin's water security: the weights of natural disasters, water quality, and water resource potential are 0.19, 0.14, and 0.11, respectively.

In the water resource potential (WSI1) dimension, the indicator of water storage capacity ($WSI_{1\text{-}4}$) exerts the most substantial influence, carrying an AHP weight of 0.45. Notably, the variable of reservoir capacity ($WSI_{1\text{-}4\text{-}1}$) stands out with the highest AHP weight of 1.00, underscoring its pivotal role in shaping water resource potential. This implies that reservoir construction and regulation upstream are significant in contributing to water security in the VG–TB river basin. There is only one variable calculated for each indicator of rainwater (weight of 0.16) and groundwater (weight of 0.11), so the variable weight is also 1.0. The second influence indicator is surface water potential with a weight of 0.28.

Transitioning to the water quality dimension (WSI_2), significant contributions arise from the indicator of waste sources ($WS_{2\text{-}1}$) with an AHP weight of 0.54. Among these sources, the noticeable impact of tourism service activities ($WS_{2\text{-}1\text{-}5}$) is evident, boasting a considerable AHP weight of 0.42 and emphasizing its role in influencing water quality. The following indicator is the level of improvement in water quality ($WSI_{2\text{-}3}$, weight of 0.3), which is mainly contributed by a variable of ability to supply clean water ($WSI_{2\text{-}3\text{-}3}$) with a weight of 0.6. The lowest contribution indicator is surface and groundwater quality ($WSI_{2\text{-}2}$, weight of 0.16), with only one variable calculated.

Within the natural disaster dimension (WSI_3), paramount importance is assigned to the indicator of flood ($WSI_{3\text{-}1}$), carrying a substantial AHP weight of 0.53. Specifically, only one variable assessed, flood depth ($WSI_{3\text{-}1\text{-}1}$), takes precedence with the highest AHP weight of 1.00, underscoring its crucial role in evaluating the consequences of floods. The second influence indicator is salinity intrusion (weight of 0.33) because the sea level is rising in the VG–TB river system. Due to the occurrence of drought being underestimated in the basin, the last indicator is the drought factor ($WSI_{3\text{-}2}$, weight of 0.14) computed via SPI.

Turning to the dimension of the ability to meet water needs (WSI_4), the primary contributor was identified as the variable of the level of water demand met ($WSI_{4\text{-}1}$), boasting a noteworthy weight of 1.00. Water shortage ($WSI_{4\text{-}1\text{-}1}$) is notable, commanding a total weight of 1.00 and signifying its indispensable role in determining the basin's capacity to fulfill water needs.

The last dimension, which is the dimension with the most contribution to the goal of WSI in the basin, is the basin development factor (WSI_5), which includes five indicators. The most significant contributing indicator relates to basin governance ($WSI_{5\text{-}4}$) with a weight of 0.42, in which there are three main variables of infrastructure ($WSI_{5\text{-}4\text{-}2}$, weight of 0.41), water works investment ($WSI_{5\text{-}4\text{-}1}$, weight of 0.33), and water resource management ($WSI_{5\text{-}4\text{-}3}$, weight of 0.26). This proves that water infrastructure construction and management are significant for water security in the VG–TB river basin.

Furthermore, the urbanization process ($WSI_{5\text{-}3}$) is the second most significant indicator (weight of 0.27) due to variables of dense population, pressure on water use, and the collection and treatment of waste and wastewater ($WSI_{5\text{-}3\text{-}2}$, with significant weight of 0.7); moreover, urbanization also leads to changes of land use and topographic structure, reductions in the area of natural and green cover, and variations in the hydrological regime ($WSI_{5\text{-}3\text{-}1}$, weight of 0.3).

The third indicator assesses the influence of water transfer works ($WSI_{5\text{-}1}$, weight of 0.17), which is accounted for by only one variable for both the giving and receiving water systems. The "last but not least" indicator is the level of socioeconomic development in the basin ($WSI_{5\text{-}2}$, weight of 0.14); the variable of capital income is highly appreciated with a weight of 0.65, while health services and public awareness are weighted for 0.23 and 0.12, respectively.

3.3. Discussion

The water security assessment framework for the VG–TB river basin was developed with the PAM and SMART method and includes five dimensions, 15 indicators, and 28 variables. The weights of these dimensions, indicators, and variables were computed using the AHP method. The framework provides an overarching view of the current status and changes in water security within the basin. It also allows for the determination of the WSI for individual regions (sub-basins and districts) and an aggregated WSI for the entire basin. The impact of climate change on water security in the basin could be assessed via the variables relevant to temperature variation, sea level rise, and changes in rainfall patterns. These variables are examined with the following dimensions: potential water resources (WSI_1), natural disasters (WSI_3), and ability to meet water needs (WSI_4). The impact of the socioeconomic and infrastructure development level on water security in the basin is assessed through the variables of the water quality (WSI_2) and basin development (WSI_5) dimensions. Consequently, water security maps in the basin will be conducted using this framework to provide WSIs for individual sub-basins or districts. This will be a reference for authorities and stakeholders to improve water security and to plan to adapt to climate change and development activities in the basin.

This study excluded six variables (as mentioned in Section 3.1) considered relevant for assessing water security within the basin due to limitations in data availability and calculation constraints. Furthermore, some variables had to be indirectly calculated through other indicators, which might not best represent the assessment objectives. Although the weights of water security criteria in the VG–TB river basin, as outlined in Table 16, provide an overall picture of water security, inputs from complex water resource models can be utilized to calculate specific indicator parameters, especially when applying probability and uncertainty associated with mathematical expressions [72]. These are challenges that need to be addressed in further research endeavors.

Previous studies on the WSI have not considered the weights between criteria contributing to the overall WSI but assumed that the criteria have equal contributions and the same weights. This article researched the connection of the PAM–SMART–AHP methods to quantitatively calculate the weights based on analyzing the experts' scores. Consequently, the importance of each criterion to the comprehensive WSI was analyzed and computed; this can demonstrate the physical and practical meaning of the river basin.

This is the first study to develop a set of water security assessment indicators for the VG–TB river basin. The basin has complex characteristics, including a harsh climate, frequent natural disasters, and unstable water demand. Therefore, determining an evaluation framework requires a comprehensive review and approach that considers the interactions between factors. This article proposed a framework for assessing water security in the VG–TB river basin, following its unique characteristics.

Although this study successfully applied the linked PAM–SMART–AHP methods, there are still two limitations. As mentioned in Section 2.2.3, using the AHP has a limitation in that the algorithm assumes independence between criteria during pairwise comparisons and considers the direct impact of variables. However, during the development of the WSI assessment framework, the linked PAM–SMART–AHP methods helped select five dimensions, 15 indicators, and 28 variables to be independent and set up eight tables of pairwise comparison matrices. Further studies could consider using other methods to relax the postulation of the independent criteria in the AHP, e.g., the Analytic Network Process or another technique that incorporates the discrete Markov Random Fields into the AHP framework developed by Huang and Chen (2024) that enhances decision-making by effectively and sensibly capturing interdependencies among criteria, reflecting actual weights [64]. Another limitation of the study is the need for more data for AHP computation. Section 3.1 excludes six variables that are also helpful and related to the WSI in the basin and nine indicators with only one variable. Nevertheless, the framework is sufficient, with 28 variables covering almost all fields, and could be accepted for computing the WSI in the VG–TB river basin.

This study's AHP relied on expert evaluations during pairwise comparisons; therefore, experts from different groups were carefully selected, as mentioned in Section 3.2. It is concluded that experts' perspectives and understanding of the analyzed parameters were independent and certain and did not change the final results.

When selecting influence variables for the WSI, it's essential to consider their direct impact on the WSI indicator. Six variables have been identified based on their weight contribution to the WSI: population density (0.70), average income per capita (0.65), annual flow (0.62), ability to supply clean water (0.60), tourism service (0.42), and infrastructure (0.41). However, to make better decisions for enhancing water security in the VG-TB river basin, evaluating each variable's performance and contribution to the overall WSI for the entire basin is essential. As a result, the priority variables are water shortage (1.0), flood depth (1.0), reservoir capacity (1.0), tourism service (0.42), and infrastructure (0.68). This holistic approach considers the integration of weights from the fundamental components to the final WSI. This highlights one of the advantages of the AHP method, as detailed in Section 2.2.3.

4. Conclusions

This article utilized the PAM method to construct an assessment framework for water security for the VG–TB river basin. The framework encompasses five dimensions, 15 indicators, and 28 variables, aligning with the UN-Water definition of water security and addressing the SDG6 criteria for global water sustainability. Additionally, it adheres to the ADB approach to assessing water security, as outlined in the AWDO reports.

The assessment framework offers a comprehensive overview of the factors influencing water security in the basin. In addition to the inherited indices, the research proposes dimensions, indicators, and indices that reflect significant influences on the basin's water security level. These influences include tourism exploitation, water transfers within the basin due to hydroelectric activities, urbanization, and overall developmental activities. These impacts are represented through the development of the basin, waste emissions, water transfers within the basin, urbanization, basin management, variables related to tourism service activities, rural infrastructure development, the ratio of specialized personnel in state management agencies, and others. Furthermore, several variables, such as reservoir capacity, cattle farming activities, poultry farming activities, annual exceedances of water quality standards, 12-month SPI, and public awareness, are calculated using new methods suitable for the available data conditions in the basin.

The novelty from this study are the weights of the different components of the framework arising from the AHP methodology. Five key dimensions significantly contribute to the WSI of the basin: the basin development activities (0.32) and the ability to meet water needs (0.24) are the most important, while water resource potential is the least (0.11). Four noticeable indicators are waste resources (0.54), flood (0.53), water storage capacity (0.45), and basin governance (0.42). Five priority variables for improving the WSI in the VG–TB river basin are water shortage (1.0), flood depth (1.0), reservoir capacity (1.0), tourism service (0.42), and infrastructure (0.68).

The framework can assess the impacts of climate change and basin development activities on water security using variables related to water resources, natural disasters, ability to meet water demands, and water quality. The weights of water security criteria will be used to create subregion-based water security maps.

The study's results could support decision-making to enhance the water security situation in sub-basins and the basin, adapt to climate change and development activities, propose appropriate solutions to overcome the weaknesses of WSIs, and formulate plans and policies to facilitate sustainable basin development.

For further study, other techniques (e.g., multidisciplinary analysis, MicMac, and Markov Random) could be applied to define water security dimensions, indicators, and variables. This may overcome the limitation of the AHP methodology, which assumes independence between criteria during pairwise comparisons.

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