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Application of decision analysis module in water resources allocation of inter-provincial river basins: A case study at the Bang Giang - Ky Cung river basin, Vietnam

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Abstract:

The analytic hierarchy process (AHP) method has been widely applied in numerous studies related to water allocation worldwide. However, in Vietnam, very few works have addressed the determination of priority orders and water allocation proportions using this method. This paper focuses on the application of AHP, integrated into the decision analysis module for Excel tool (DAME), to determine the priority order and proportion of water resource allocation for the Bang Giang - Ky Cung river basin using various input data, such as water usage, production values, growth rates, etc. The results, based on scenarios of socio-economic growth up to 2025 for Cao Bang, Lang Son, and Bac Kan provinces, taking into account four main water user categories (industry, livestock, agriculture, aquaculture), and considering the entire basin, indicate that the highest proportion of water resource allocation is for the agriculture, approximately 34%, followed by livestock at 33%, industry at 22%, and finally aquaculture at 11%. The findings of this paper can serve as a reference for near-future planning to promote the development of water sectors, increase production capacity, and effectively manage water resources to meet socio-economic development targets for the period from 2021 to 2025 in the provinces located within the basin.

Keywords: **AHP, DAME, Bang Giang - Ky Cung river basin, water resources allocation.**

Classification numbers: **2.1, 7**

1. Introduction

Water resources are a pivotal factor, playing a crucial role in ensuring food and energy security, as well as supporting the processes of industrialisation and urbanisation. In recent years, Vietnam has witnessed a notable increase in droughts and water shortages. The conflicts arising from competing water demands, particularly between hydropower plants and the agricultural sector downstream, have become more pronounced. Thus, it becomes imperative to establish a quantifiable framework for determining the priority order and allocation proportions of water resources among various sectors.

Multi-Criteria Analysis methods (MCA) have gained widespread adoption across various disciplines worldwide. AHP has been applied extensively, incorporating stakeholder participation, in the domain of water resources management Examples include works such as "A review of the AHP: An approach to water resource management in Thailand" [1, 2]; "Analytical hierarchical process as a decision support tool in water resources management" [3]; "An improved analytic hierarchy process method for the evaluation of agricultural water management in irrigation districts of North China" [4]; and "Making choices in the water allocation for the Lam Pao reservoir Kalasin by analysis hierarchy process" [5]. Additionally, AHP has been utilised for selecting rainfall forecasting models and evaluating alternative management solutions for urban water supply systems through MCA [6, 7].

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However, studies and research on analytical hierarchy and water allocation proportions in Vietnam remain relatively scarce. Most studies have primarily focused on water resource allocation based on efficient water utilisation. The determination of priority order and water allocation proportions, especially in the context of droughts and water shortages, has only been briefly addressed in Article 23 of Circular No. 04/2020/TT-BTNMT, issued on 03/6/2020 by the Ministry of Natural Resources and Environment, which pertains to technical regulations governing the general planning of inter-provincial river basins and water sources.

The AHP method, integrated into the DAME, builds upon the principles of analytical hierarchy by incorporating various criteria (input data) to produce priority orders and allocation proportions for different scenarios and integrated scenarios. This approach introduces a novel perspective on water resources allocation, enabling the quantification of priority orders and proportions in the context of droughts and water shortages, particularly for critical inter-provincial river basins and transboundary river basins.

In this paper, we employ the AHP method, integrated into the DAME, to determine the priority order and allocation proportions among water users in the Bang Giang - Ky Cung river basin. This represents the central objective of our study. Ultimately, the findings of this work can contribute to the socio-economic development of the relevant provinces, alleviate poverty, and enhance social security within the territorial regions. The results presented in this paper will provide valuable support to decision-makers and planners in formulating policies, ensuring water security, and advancing the socio-economic well-being of both the affected provinces and the entire river basin.

2. Study area and input data

2.1. Overview of the study area

The Bang Giang river, also known as the Bang river, originates from Guang Xi province, China, and flows in a northwest-southeast direction into Cao Bang province, Vietnam, near the Soc Giang Border gate, Soc Ha commune, Ha Quang district, before returning to Guang Xi province, China (Fig. 1). In China, it merges with the Ky Cung river, giving rise to the Ta Giang river (Fig. 1). This river spans a total length of 90 km and encompasses a basin area of 4,000 km^2. Furthermore, the Bang Giang river basin boasts an annual water volume of approximately 4.34 billion m^3. In the dry season, it contains 1.17 billion m^3, constituting 27% of the annual volume, while the wet season sees about 3.17 billion m^3, accounting for 73%.

The Ky Cung river, situated in Lang Son province, is one of the prominent rivers in the region (Fig. 1). Its source lies in the high mountain region of Bac Xa, within Dinh Lap district, Lang Son province, before it flows into China. The Ky Cung river serves as a major tributary of the Ta Giang river (Fig. 1). In Vietnam, this river spans a total length of 243 km and encompasses a basin area of 6,660 km^2. It is the sole river in Northern Vietnam that flows in a southeast-

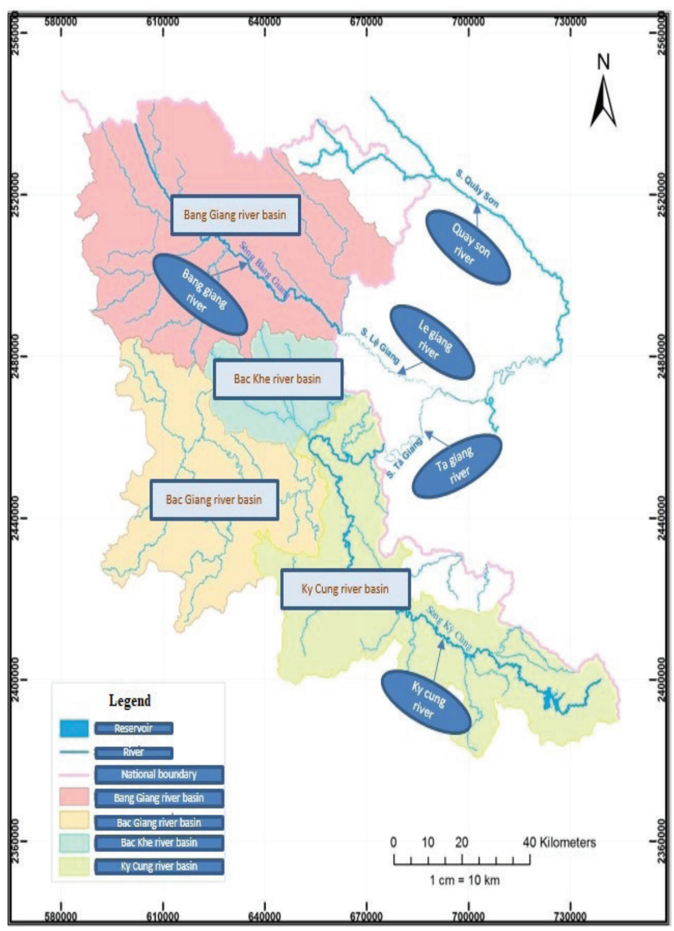

Fig. 1. Map of Bang Giang - Ky Cung river basin.

northwest direction into China. The river comprises three primary tributaries: Bac Giang, Bac Khe, Ba Thin rivers. The Ky Cung river basin has an annual water volume of approximately 1.8 billion m^3. During the dry season, it contains 0.39 billion m^3, accounting for 21.6% of the yearly volume, while the wet season sees approximately 1.41 billion m^3, constituting 78.4% of the annual volume.

With a relatively high potential for water resources, approximately 10.000 m^3 per capita, the Bang Giang - Ky Cung river basin ranks among Vietnam's abundant river basins, based on the average water volume per person. Nevertheless, annual water resources are distributed unevenly throughout the basin, particularly during the wet season when water volume ranges from 65-80% of the total yearly water volume. Additionally, groundwater resources are limited and challenging to exploit within this river basin. Situated in a developed economic zone, the basin experiences a significant increase in water demand across various sectors and provinces. The current water demand stands at approximately 465 million m^3, with projections indicating a rise to 576 million m^3 by 2050, representing a 1,24-fold increase over the present demand. Consequently, effective water resource allocation within this basin is imperative to balance current and future water demand.

2.2. Input data

In this article, we have taken into account the socio-economic development plans up to 2025 for three pertinent provinces: Lang Son, Cao Bang, and Bac Kan. The baseline year selected for our analysis is 2021, aligning with the Integrated Water Resources Plan for the Bang Giang - Ky Cung river basin, which extends from 2030 to 2050. Our study encompasses four primary water sectors: agriculture, livestock, industry, aquaculture.

Based on the data collected from the river basin situated within the three aforementioned provinces, with particular emphasis on Lang Son and Cao Bang as the principal areas, we have identified four criteria for our analysis. Table 1 provides details pertaining to the four criteria for the four principal water sectors:

- Water utilisation patterns across all water sectors up to 2025 [8].
- Production values associated with diverse fields (water sectors) up to 2025 [9-11].

Table 1. Input data used for the DAME tool.

Province	Criteria/Sector	Water use (mil.m^3)	Production value 2025* (mil VND)	Proportion 2025 (%)	Growth rate 2025 (%)
Cao Bang	Agriculture	142.04	2,571,156.49	11.3	4.7
	Livestock	3.47	2,395,704.06	7.1	4.4
	Aquaculture	4.14	19,824.66	0.1	3.6
	Industry	24.7	531,653.90	36.7	16.7
Lang Son	Agriculture	179.76	7,379,303.57	10.4	5.3
	Livestock	1.8	4,535,644.13	8.7	5.2
	Aquaculture	9.36	80,423.56	1	4.4
	Industry	37.6	1,414,174.71	23.1	20
Bac Kan	Agriculture	55.89	4,168,607.17	20.5	5.1
	Livestock	0.6	1,896,911.17	13.3	4.7
	Aquaculture	5.98	90,174.75	0.3	3.9
	Industry	3.7	811,252.44	22	6.9

*Production values of water sectors based on the equation of economic growth $Yn=Y0(1+Ga)^n$. n: number of criteria.

• The distribution of various water sectors as per the socio-economic development plans of the relevant provinces up to 2025 [12-14].

• The growth rates characteristic of different water sectors, as outlined in the socio-economic development plans of the related provinces up to 2025 [12-14];

3. Method

AHP stands out as one of the most widely employed and popular multi-criteria methods (Fig. 2). AHP is a method that leverages mathematics and psychology to organise and analyse intricate decisions. It was originally developed by T.L. Saaty (1980) [15] in the 1980s and has undergone refinements over time. AHP comprises three essential components: the overarching goal or problem under consideration, the array of potential solutions referred to as alternatives, and the criteria against which the alternatives are to be assessed. AHP furnishes a logical framework for making necessary decisions by quantifying the criteria and alternative options and establishing their relationship with the overarching objective. Rather than relying on extensive datasets, AHP can utilise expert opinions or judgements for analysis. Furthermore, AHP typically entails three core steps: analysis, assessment, and integration. The AHP method facilitates the resolution of questions such as "What are the available alternatives?" or "Which alternative is the most suitable?".

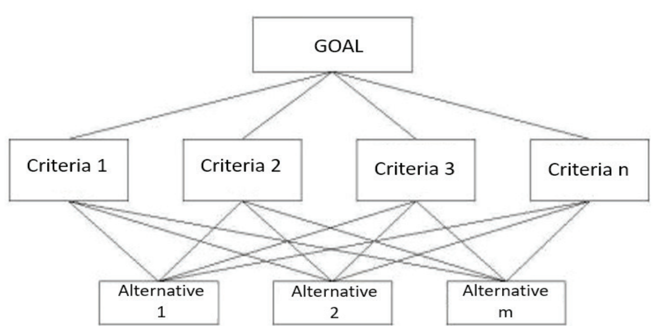

Fig. 2. Schematic representation of analytic hierarchy.

The application of this methodology entails determining the relative weights to be assigned to the criteria in defining the overarching goal. This stage involves pairwise comparisons of the criteria and the assignment of preference. Additionally, priority levels corresponding to the pairwise criteria comparisons encompass values ranging from 1 to 9, or the inverses of these values (Table 2). Accordingly, two preference values are associated with each pair of criteria, depending on which value takes precedence.

Table 2. Preference levels and corresponding values.

Preference level	Numerical value
Equally preferred	1
Equally to moderately preferred	2
Moderately preferred	3
Moderately to strongly preferred	4
Strongly preferred	5
Strongly to very strongly preferred	6
Very strongly preferred	7
Very strongly to extremely preferred	8
Extremely preferred	9

As mentioned earlier, the DAME is a tool that supports the analytical hierarchy in the decision-making process. DAME has the capability to accommodate a variety of scenarios and decision-makers. The tool provides a display of all calculations conducted during the AHP (Fig. 3). Users can structure their models into three primary levels: scenario, criteria, and variant. These levels can be evaluated using weights or pairwise comparisons. Three distinct methods are available for weighing the criteria, variants, and scenarios, including: the method proposed by T.L. Saaty (1980) [15]; the geometric mean; and the method proposed by B. Agarski [16].

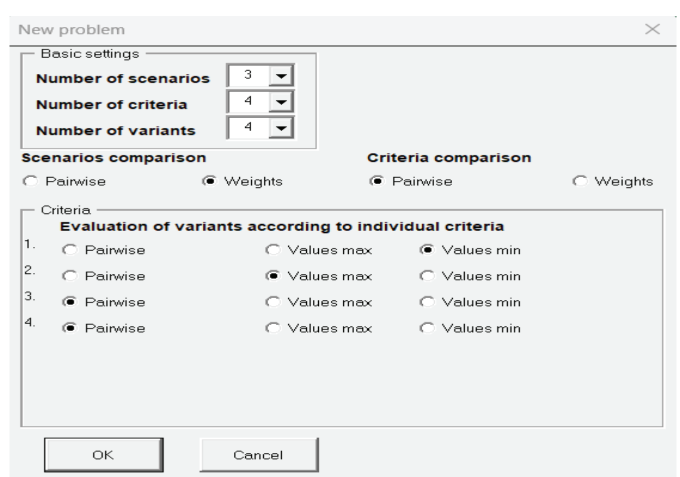

Fig. 3. DAME interface used for entering input data.

Figure 3, displayed above, illustrates the fundamental configurations of the tool, including the number of scenarios, criteria, and variants. If users opt not to utilise the scenario feature, they should specify the number of scenarios as 1. In Fig. 3, users can establish scenarios and criteria comparisons either through a pairwise matrix or by directly assigning weights. Furthermore, users have the flexibility to choose how they want to evaluate the variants in accordance with individual criteria, with three options available: pairwise - wherein each individual pair of variants is compared; value max - which shows maximisation based solely on value (e.g., price) for each individual variant; value min - which indicates minimisation based solely on value (e.g., cost) for each individual variant. DAME is seamlessly integrated into the Microsoft Excel platform, rendering it user-friendly and facilitating the resolution of multi-criteria problems.

In the criteria comparison section, users can select values (located in yellow cells) using the drop-down menu, as illustrated in Table 3. It is important to note that values in the other cells are calculated and assigned automatically. If criteria in the rows hold greater significance than those in the columns, users can input values ranging from 2 to 9 (higher values signifying greater importance). Conversely, if criteria in the rows are less significant than those in the columns, users can input values from 1/2 to 1/9 (lower values indicating lesser importance).

Table 3. Criteria comparison setting in DAME.

Criteria	Crit 1	Crit 2	Crit 3	0.000	*Criteria weights*
Crit 1	1				0.333333
Crit 2	0	1			0.333333
Crit 3	0	0	1		0.333333

If criteria in the rows are of roughly equivalent importance to those in the columns, users can input a value of 1 or leave it at the default setting. Additionally, it is crucial to ensure that the conflict index, situated in the upper right corner of the matrix, remains below 0.1. If it surpasses this threshold, adjustments are necessary. Apart from the criteria matrix, the criteria weights must also be specified. This column displays the weight assigned to each individual criterion, based on the values designated in the matrix. Consequently, the weights are computed using the following equation:

$$w_k = \frac{\left(\prod_{j=1}^{n} a_{kj}\right)^{1/n}}{\sum_{i=1}^{n}\left(\prod_{j=1}^{n} a_{ij}\right)^{1/n}}, \quad k = 1,2,\ldots,n$$

where w_k is the weight of criterion k (variant), a_{ij} is value of the matrix of pairwise comparison, n is the number of criteria (variants), a_{kj} is value of criterion k in the matrix of pairwise comparison.

The global conflict index (GCI) index is computed as below:

$$GCI = \frac{2}{(n-1)(n-2)}\sum_{i<j}\log^2\left(a_{ij}\cdot\frac{w_j}{w_i}\right)$$

where n is the number of criteria, W_i: weight of criteria in the i-th row, W_j: weight of criteria in the j-th column, a_{ij}: value in the pairwise comparison of the i-th row, j-th column.

Once values are entered into the matrix of pairwise comparison, all the weights are recalculated immediately, enabling a clear observation of the impacts of individual pairwise comparisons. The tool also provides matrices and graphs of total variants. The vector of weights of variants Z is computed using the following equation:

$$Z = W_{32}W_{21}$$

where W_{21} is the matrix of dimensions n*1 (vector of criteria weights)

$$W_{21} = \begin{bmatrix} w(C_1) \\ \vdots \\ w(C_n) \end{bmatrix}$$

and W_{32} is the weight matrix of dimensions m*n

$$W_{32} = \begin{bmatrix} w(C_1,V_1) & \cdots & w(C_n,V_1) \\ \vdots & \cdots & \vdots \\ w(C_1,V_m) & \cdots & w(C_n,V_m) \end{bmatrix}$$

where $w(C_i)$ is the weight of criterion C_i and $w(C_i,V_j)$ is the weight of criterion C_i corresponding to variant V_j.

4. Results and discussion

4.1. Water allocation criteria requirements

The criteria for water allocation, intended to determine the priority order and allocation proportions, were established based on the water requirements and socio-economic development plans of the relevant provinces within the Bang Giang - Ky Cung river basin. These criteria serve as the constraints guiding the primary objective, which is the equitable and optimal allocation among water users. Table 4 provides an overview of the criteria and constraints configured within DAME.

Table 4. Allocation criteria and constraints set up in DAME.

Criteria	Water use	Production value	Water sectors proportion	Water sector growth rate
Objective function	Minimum	Maximum	Pairwise comparison	Pairwise comparison

4.2. Results of water allocation rights

To assess water allocation rights and water distribution within the Bang Giang - Ky Cung river basin, considering the perspectives and opinions of the provinces, three planning scenarios were formulated for the 2020-2025 period. These scenarios revolved around (1) Cao Bang province, (2) Lang Son province, (3) Bac Kan province, with the scenario weights being computed based on the Provincial Competition Index (PCI) (Table 5). This index encompasses ten sub-indices employed to evaluate the weights: 1. Market enrolment, 2. Land use approach and stability, 3. Transparency, 4. Time cost, 5. Other costs, 6. Proactive and pioneering characteristics of leaders, 7. Fair competition, 8. Support service for business, 9. Labour training, and 10. Governance. Fig. 4 illustrates the Decision Analysis module for calculating scenario weights. The Saaty method was utilised to assess criteria weights. The table below presents the outcomes of the weights and the PCI index for the scenarios.

Table 5. Scenario weights and the PCI of scenarios.

Scenario	Weight	PCI
Lang Son	0.35	67.88
Cao Bang	0.31	59.58
Bac Kan	0.34	65.15

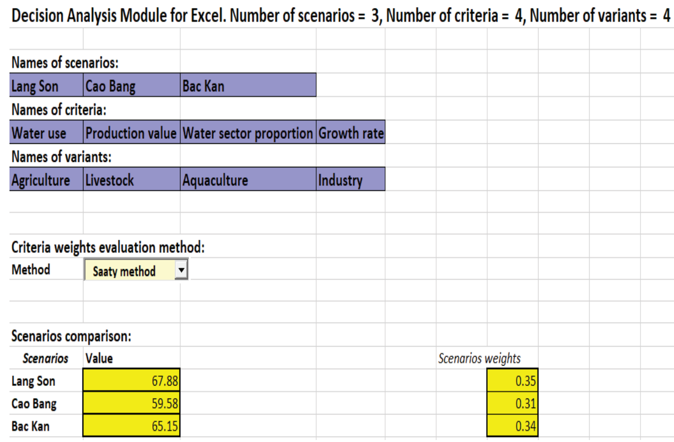

Fig. 4. Screenshot of the Decision Analysis module in DAME.

The results indicate that Lang Son province achieved the highest PCI index among the three provinces, with a score of 67.88. Consequently, the water allocation right for this province is 0.35. Bac Kan secured the second position with a PCI of 65.15 and a water allocation right of 0.31. Finally, Cao Bang recorded a PCI of 59.58, accompanied by a water allocation right of 0.31. These results demonstrate that the three provinces within the Bang Giang - Ky Cung river basin obtained similar water allocation rights for the 2020-2025 period. This can be attributed to their shared natural characteristics and socio-economic conditions.

4.3. Results of priority order and water allocation proportion

4.3.1. Results of priority order

After establishing the criteria for comparison and calculating the priority order and water allocation proportions in line with the socio-economic development plans up to 2025 of the three provinces, this information was incorporated into the DAME Tool. It facilitated the computation of water allocations and sharing ratios for water users situated within the Bang Giang - Ky Cung river basin.

The input data integrated into the DAME model for scenario determination of priority objects and optimal allocation and sharing rates included the following:

- Primary water users: cultivation, livestock, industry, aquaculture.

- Evaluation criteria: 1. Water consumption; 2. Production value; 3. Water sector proportion; 4. Growth rate.

The paired criteria for prioritisation utilised an expert-based approach, with representatives from the Departments of Natural Resources and Environment, the Department of Agriculture and Rural Development, and the Department of Industry and Trade. These experts were consulted to collect their opinions and to compare criteria based on the current status and the developmental orientation of each province within the Bang Giang - Ky Cung river basin up to 2025. The following section presents the results of this expert-based comparison (Tables 6, 7).

Table 6. Weights of criteria for three related provinces (Lang Son, Cao Bang, and Bac Kan)*.

Criteria	Lang Son				
	*LDN***	*GTSX****	*TT*****	*TDTT******	*Weight*
LDN	1	1	1/3	1/3	0.14
GTSX	1	1	1	1	0.24
TT	3	1	1	1	0.31
TDTT	3	0	1	1	0.31
	Cao Bang				
	LDN	*GTSX*	*TT*	*TĐTT*	*Weight*
LDN	1	1/3	1/2	1/3	0.11
GTSX	3	1	1	1	0.30
TT	2	1	1	1	0.28
TDTT	3	1	1	1	0.30
	Bac Kan				
	LDN	*GTSX*	*TT*	*TĐTT*	*Weight*
LDN	1	1	1/2	1/3	0.16
GTSX	1	1	2	2	0.34
TT	2	0.5	1	1	0.23
TDTT	3	0.5	1	1	0.27

*The evaluation form includes three pairwise comparison evaluation forms representing three departments: the Department of Natural Resources and Environment, the Department of Agriculture and Rural Development, and the Department of Industry and Trade in Cao Bang, Bac Kan, and Lang Son.

**Water use

***Production value

****Water sector proportion

*****Growth rate

Table 7. Results of water users versus setup criteria in DAME .

Water user	Lang Son			
	Water use (Minimum)	*Production value (Maximum)*	*Water sector proportion (Pairwise comparison)*	*Growth rate (Pairwise comparison)*
Agriculture	0.008	0.550	0.284	0.331
Livestock	0.800	0.338	0.203	0.241
Aquaculture	0.154	0.006	0.040	0.241
Industry	0.038	0.105	0.474	0.188
	Cao Bang			
Agriculture	0.012	0.466	0.253	0.336
Livestock	0.499	0.434	0.225	0.205
Aquaculture	0.418	0.004	0.044	0.231
Industry	0.070	0.096	0.478	0.227
	Bac Kan			
Agriculture	0.013	0.598	0.370	0.289
Livestock	0.705	0.272	0.224	0.289
Aquaculture	0.111	0.013	0.035	0.246
Industry	0.172	0.116	0.370	0.175

4.3.2. Results of priority order and water allocation proportion

Figure 5 displays the outcomes regarding the priority order and water allocation proportion, encompassing three scenarios aligned with the planning of the three provinces in the basin, as well as a general scenario designed for the entire basin, as defined in DAME.

The results based on the priority order and allocation proportion, considering four criteria (water use, production value, water sector proportion, and growth rate), unveil specific allocations for each province and the basin as a whole. Lang Son province, with its distinctive agricultural economic structure, is gradually shifting towards increasing the proportion of livestock while reducing agriculture, resulting in a priority allocation of 33% for livestock, followed by 32% for agriculture, 24% for industry, 11% for aquaculture. Cao Bang province, with promising opportunities in agriculture, particularly for high-value endemic crops (for example, chestnuts, squash, tea, essential oil products, honey, wild mushrooms, sticky rice), assigns the highest priority of 32% to agriculture, followed by 31% for livestock and the remainder for industry. Bac Kan province, endowed with natural characteristics conducive to agriculture and forestry, allocates priority orders of 37% for agriculture, 34% for livestock, 20% for industry, and 10% for aquaculture. Lastly, for the Bang Giang - Ky Cung river basin, the priority order for water allocation is 34% for agriculture, 33% for livestock, 22% for industry, 11% for aquaculture.

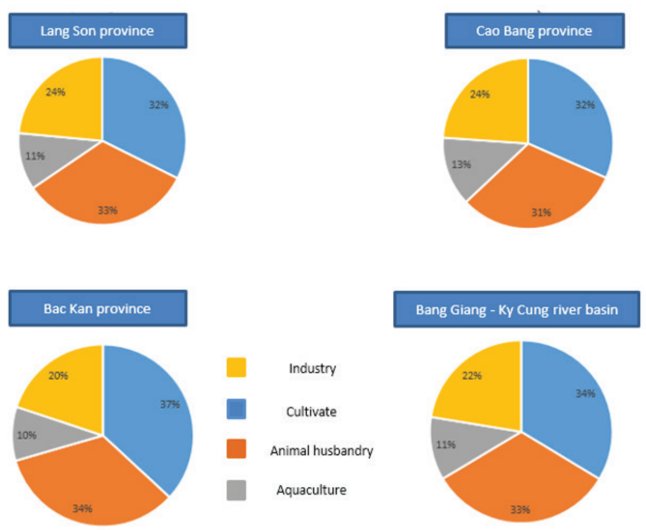

Fig. 5. Results of water allocation proportion corresponding to different scenarios in the Bang Giang - Ky Cung river basin.

In summary, the Bang Giang - Ky Cung river basin is acknowledged as one of the most water-abundant river basins, boasting an approximate water availability of 10,000 m^3 per capita. Nevertheless, it is imperative to frequently update the water allocation proportions to align with the socio-economic development objectives of the related provinces and to adapt to the challenges posed by climate change. The basin faces the complexities of climate phenomena such as El Nino and La Nina, which can significantly impact its hydrological dynamics in the present and future.

5. Conclusions

This paper has presented various scenarios and employed DAME tool, underpinned by the multi-criteria analysis AHP method within the Excel platform, to determine the priority order and allocation proportion for water resources. These scenarios have been tailored to the unique natural characteristics and socio-economic development orientations of the three local provinces, encompassing industry, agriculture, livestock, and aquaculture sectors.

The results derived from the water allocation scenarios for the entire basin have underscored the need to accord the highest priority to agriculture at 34%, followed closely by livestock at 33%, industry at 22%, and aquaculture at 11%. Consequently, to effectively utilise water resources and align with the socio-economic development orientations of each province for the five-year period spanning 2021 to 2025, it is imperative to formulate policies that foster the robust growth of agriculture and livestock production, as well as other productive cultivation and water sectors.

However, it is essential to acknowledge the inherent uncertainty in this method, which may not yield entirely optimal evaluation results. To address these limitations, various studies have proposed solutions that integrate AHP with fuzzy logic, giving rise to the Fuzzy Analytic Hierarchy Process (F-AHP) for pairwise comparisons. These advanced methodologies offer promising avenues for further research and exploration.

CRediT author statement

Hung Anh Nguyen: Conceptualisation, Methodology, Revising; Quoc Viet Tran: Writing - Reviewing, and Editing, Xuan Manh Trinh: Writing - Reviewing, and Editing, Duc Quy Luong: Conceptualisation, Methodology.

COMPETING INTERESTS

The authors declare that there is no conflict of interest regarding the publication of this article.

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