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Assessment of Water Scarcity Levels in the Srepok River Basin

Le Van Linh[1], Tu Anh Nguyen[1*], Nguyen Anh Duc[1], Tran Van Tra[1], Nguyen Thanh Long[1], Dang Dinh Duc[2], Tran Duc Thinh[3], Nguyen Thi Bich[4]

[1]Water Resources Institute, Ministry of Natural Resources and Environment, Ha Noi, Viet Nam
[2]Center for Environmental Fluid Dynamics, VNU University of Science, Ha Noi, Viet Nam
[3]National Centre for Water Resources Planning and Investigation, Ministry of Natural Resources and Environment, Ha Noi, Viet Nam
[4]Institute of Geography, Viet Nam Academy of Science and Technology, Ha Noi, Viet Nam
Email: *tuanh.evp@gmail.com

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Abstract

Water scarcity has become a pressing global issue, worsening food security, hindering economic development, compromising environmental quality, and threatening human health and other fundamental societal needs. Viet Nam is among the countries severely affected by water scarcity. This study comprehensively assesses the extent and scale of water scarcity in the Srepok River Basin, considering the impacts of water resource allocation, balance, and environmental flows. The areas heavily affected by water scarcity include Ea Hleo, Ea Krong Ana, and several Srepok River branches, with water scarcity periods mainly concentrated in February, March, and April. The influence of climate change has increased the extent and level of water scarcity in the river, affecting an estimated 1.4 million people for at least one month and about 1 million for at least three months. The agricultural sector is significantly affected by water scarcity, with water shortages of 50% according to the baseline scenario and over 60% according to climate change scenarios.

Keywords

Water Scarcity Level, Water Balance, Climate Change, RCP 4.5, Srepok River Basin

1. Introduction

Water scarcity has become a pressing global issue, increasing pressure on food security [1] and affecting human health [2]. About 2.67 billion people face severe water scarcity for at least one month a year [3]. Climate change has made global water scarcity more severe, especially in major river basins around the world, such as the Indus, Ganges, and Mekong [1] [2] [4]. Responding effectively and proactively to water scarcity requires thorough information about high-risk areas and the severity of the situation. This information can identify appropriate evidence-based policies and measures to help mitigate the impacts of drought and water shortages and ensure sustainable water resources in a region.

Water scarcity is typically defined as a disparity between water availability and water demand [5]-[7]. The water scarcity index assesses the human impact on water resources in a river basin by comparing water demand and use with water supply [8], which can be more broadly described as a deficit in renewable freshwater resources relative to water demand [9]. Many water scarcity indices have been developed over the past three decades [10]. Currently, there are over 150 [11], ranging from simple thresholds of per capita freshwater availability [12] to more complex metrics that account for variability in demand (e.g., WTA) [10], adaptive capacity (e.g., SWSI) [13], environmental flows (e.g., WSI_{EWR}) [14], and socio-economic conditions (e.g., WPI) [15].

Many studies have assessed water scarcity at different scales at the global [3] [14] [16]-[19], regional [10] [20] [21], national [22]-[24], and river basin levels [25]-[30]. These assessments are often difficult and have many limitations because water scarcity depends on several factors, including input data, annual flow changes, changes in water demand over the years, climate change, and reservoir and irrigation works in the area. The nature of water scarcity is dynamic, changing over time within a year and from year to year [3]. In some areas, water scarcity occurs only in certain months of the year [16] and cannot be calculated accurately on an annual average [16] [31] since flow is very high during the flood season. Furthermore, reservoirs and irrigation projects also significantly impact water scarcity [8], regulating and allocating water resources between the flood and dry seasons. If these projects are designed and funded appropriately, they can reduce water shortages and scarcity in the dry season [32]-[34]. Water scarcity may also increase owing to climate change [9] [30] [31] [35] [36] and increased water demand [37]-[40]. Therefore, studies and assessments need to consider monthly flow changes, water storage capacity, flow redistribution of irrigation works [10] [31] [41], changes in water demand [16] [10], and environmental flows [8] [10] [14] [42].

Viet Nam is a developing country heavily dependent on water resources to ensure socio-economic activities, protect the environment, respond to climate change, and achieve sustainable development goals. With rapid urbanization, population growth, and the impact of climate change, this country faces many water resource problems, including drought and shortage. Water demand has increased even as water resources in some river basins have shown signs of decline in volume and quality [43]. Accordingly, with the current increase in water demand, water resource stress in the dry season will occur in 12 out of 19 major river basins in Viet Nam, including the Srepok River Basin. According to forecasts, with a flow scenario corresponding to 50% frequency, the Srepok River Basin will lack about 257 million m^3 of water by 2050 [43].

Although many studies related to water scarcity and shortage have been conducted in this basin, they have mainly focused on the impact of hydropower projects on water flow [44], the impacts of climate change on water resources, drought [45]-[48], water balance and allocation [48] [49], water stress level [50], and assessments of water poverty levels [30]. These studies have yet to comprehensively and precisely assess the risk and levels of water scarcity because they need to consider the allocation and balance of water resources and environmental flows in the area. Therefore, in this study, we use MIKE HYDRO BASIN and the water scarcity index (WSI) to consider environmental flows and climate change scenarios in order to assess the level of water scarcity in the Srepok River Basin of Viet Nam. The results will assist policymakers in identifying areas of high risk and water scarcity to develop appropriate policy interventions.

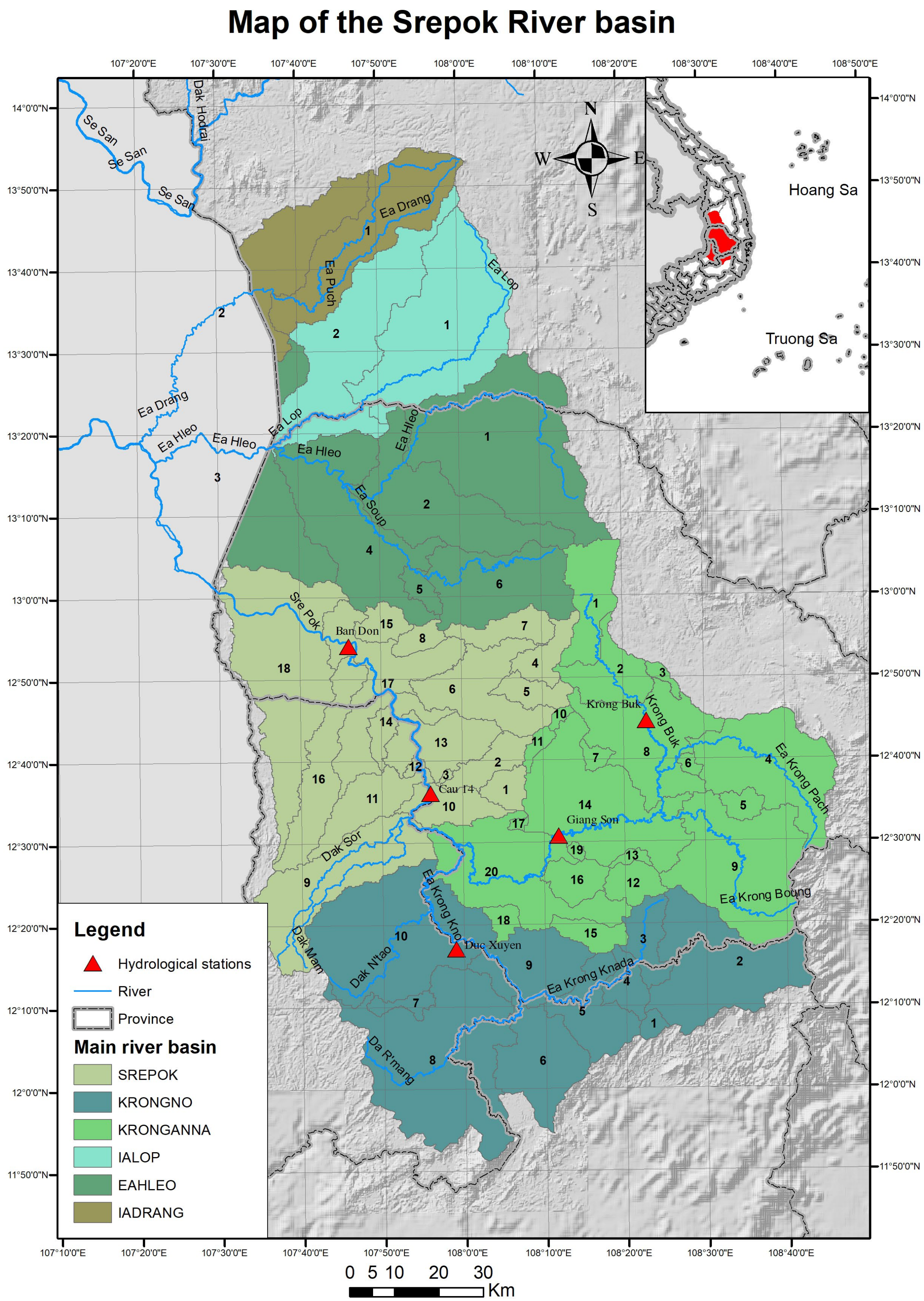
2. Srepok River Basin

The Srepok River Basin is one of the tributaries of the Mekong River, originating from the Central Highlands, flowing through Cambodia, and converging with the Mekong River at Stung Treng [49]. The total area of the river basin is about 31,000 km^2, about 18,230 km^2 of which is in Viet Nam (**Figure 1(a)**), including parts of Dak Lak, Dak Nong, Gia Lai, and Lam Dong provinces. The Srepok River Basin has five main branches: the Ia Drang River, Ia Lop River, Ea Hleo River, Ea Krong Ana River, Ea Krong No, and Srepok River. The average annual rainfall in the river basin is about 1823.6 mm, with the total rainfall in the rainy season accounting for 83.32% of the total annual rainfall and the dry season accounting for 16.68% [49]. The flood season spans June to November, and the total flow in the flood season accounts for 65% - 80% of the total annual flow [49]. The total average rainfall resources in the basin are about 33.5 billion m^3, and the total surface water resources are about 15.74 billion m^3 [49].

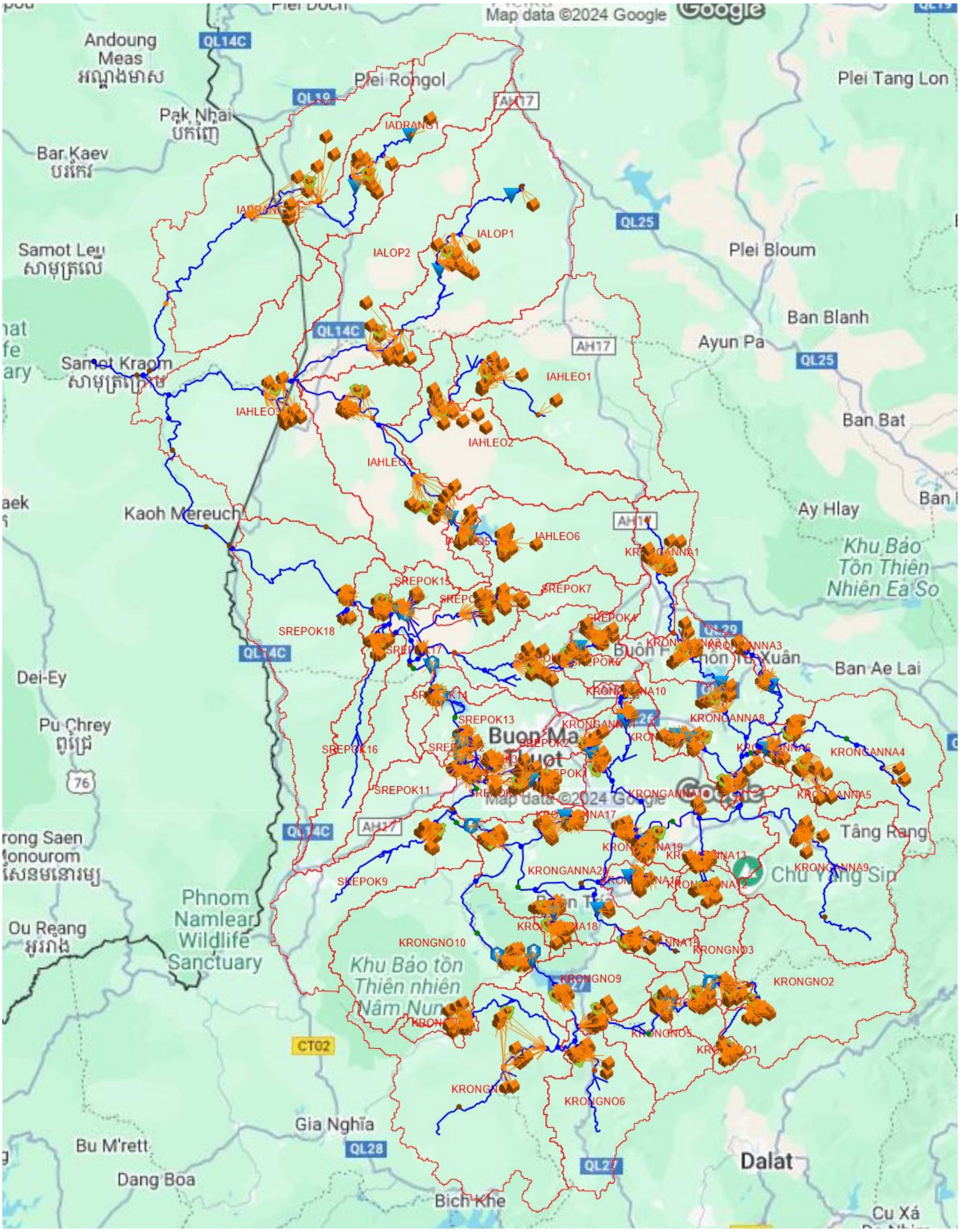
Currently, about 510 reservoirs in the area serve mainly agricultural, industrial, and hydroelectric purposes [49]. Hydroelectric reservoirs on the Srepok River (Buon Tua Srah, Buon Kuop, Srepok 3, and Srepok 4) and large reservoirs (Upper Ea Soup Lake, Lower Krong Buk Lake, etc.), when operated according to approved procedures, regulate, exploit, and develop water resources in the basin, contributing to flood reduction and water supply during the dry season.

According to statistical data from the Srepok River Basin Master Plan [49], the agricultural land area of the basin is about 758,897 ha, of which the annual crop area is about 404,829 ha; The winter-spring rice area is 49,467 ha, the main rice area is 81,512 ha, and dry crops are 170,741 ha. The perennial crop area is 354,265 ha, of which the coffee-growing area is 330,714 ha and fruit trees comprise 23,268 ha. There is about 9484 ha of aquaculture.

The total water demand in 2017 for the entire basin was about 2301 million m^3, of which agricultural irrigation accounted for the highest proportion at 1946 million m^3 (84.57%) and tourism for the smallest at 0.32 million m^3 (0.01%) [49].


Map of the Srepok River basin
Legend
Hydrological stations
River
Province
Main river basin
SREPOK
KRONGNO
KRONGANNA
IALOP
EAHLEO
IADRANG
Hoang Sa
Truong Sa
N
S
W
E
Se San
Dak Hodrai
Ea Drang
Ea Puch
Ea Lop
Ea Hleo
Ea Soup
Sre Pok
Ban Don
Krong Buk
Ea Krong Pach
Cau 14
Giang Son
Dak Sor
Ea Krong Kno
Ea Krong Boung
Dak Mam
Dak N'tao
Duc Xuyen
Ea Krong Knada
Da R'mang
0 5 10 20 30
Km

(a)



(b)

Figure 1. (a) Boundary of Srepok River Basin in Viet Nam. (b) Water balance model for Srepok River Basin.

3. Methods and Data

To assess the level of water scarcity in the Srepok River Basin according to monthly flow changes and the impact of hydropower projects, reservoirs, changes in water use, and environmental flows, this study uses the MIKE HYDRO BASIN model set combined with the water scarcity index and climate change scenarios project future water scarcity in the basin. Data on rainfall, flow, water demand, environmental flows, and the hydropower project and irrigation reservoir system are entered into the MIKE HYDRO BASIN model. The model results include net inflows to sub-basins, which can be combined with corresponding water demands and environmental flows to evaluate the extent of water scarcity in these areas. Figure 2 illustrates a framework for determining the Water Stress Index (WSI) across various sub-basins (sb-1, ..., sb-n) utilizing the MIKE HYDRO Basin model.

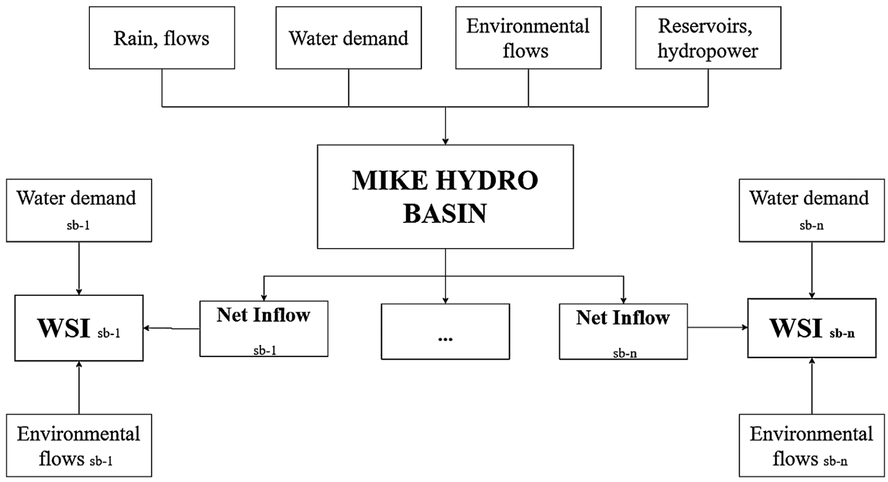


Figure 2. Research framework.

3.1. MIKE HYDRO Basin Water Balance Model

We use the MIKE HYDRO BASIN model developed by the Danish Hydraulic Institute (DHI) to assess the balance and allocation of water resources in the Srepok River Basin. This model was inherited from the Srepok River Basin Integrated Planning project [49]. The model's inputs include the water demand of sectors (including environmental flows), flow data in sub-basins, reservoir parameters, and hydropower works. These are operated according to the basin's inter-reservoir operation process, regulated under Decision No. 1201/QD-TTg, dated July 24, 2014, of the Prime Minister. The basin model includes 58 sub-basins and water used for domestic, industrial, irrigation, husbandry farming, aquacultural, and tourism purposes in Viet Nam (Figure 1). Water demand for domestic, industrial, livestock, aquacultural, and tourism purposes is calculated according to Viet Nam's standards and estimated for 2017, assuming this demand will stay the same over the years. Agricultural irrigation demand is calculated according to crop growth stages for rice and the FAO 56 Dual Crop Coefficient method for other crops (corn, sugarcane, potato, cassava, coffee, and fruit trees). Crop irrigation demands are established in the MIKE HYDRO BASIN model, depending on annual rainfall. The total water demand was about 2301 million m^3 in 2017 [49]. Environmental flows are approximately 10% of the water demand of all sectors, corresponding to approximately 230 million m^3 for 2017 [49]. Environmental flows are assumed to be constant across calculation years.

3.2. Water Scarcity Index

The water scarcity index is calculated using the following formula [14] [51].

$$WSI = \frac{WU}{MAR - EWR} \tag{1}$$

in which: WU: Water demand;

MAR: Total available quantity;

EWR: Environmental flow.

Accordingly, WSI ≥ 1 is considered scarce in raw water resources, which represents an over-exploited basin; 0.6 ≤ WSI < 1 is an environmentally stressed basin; 0.3 ≤ WSI < 0.6 is a moderately exploited basin; WSI < 0.3 is an environmentally safe basin.

3.3. Climate Change Scenarios

This study used the 2016 climate change scenarios of Viet Nam [52] to project the WSI of the basin for 2065. The period of 1986-2005 was used as the baseline to evaluate the level of water scarcity by month. The RCP4.5 scenario was employed to assess changes in streamflow using the MIKE NAM model derived from the water balance model set for the Srepok River Basin [49]. **Table 1** presents projected changes in seasonal rainfall in the basin under the RCP 4.5 scenario for the two periods, 2016-2035 and 2046-2065.

Water demand for the domestic, industrial, livestock, aquacultural, and tourism sectors was determined based on baseline year data and development scenarios for the respective periods [49]. The population is projected to increase by an average of 1.1% - 1.5%/year, the industrial production value is expected to grow at 14%/year, and the livestock growth rate is expected to be about 1%/year. Cultivation areas are projected to continue expanding until 2020 and then remain stable. Water demand for agricultural irrigation will fluctuate annually based on rainfall, assuming the cultivation area remains constant at the 2020 level.

4. Results and Discussion

4.1. Model Calibration and Validation

Using cultivation area data for 2017 and the water demand of the remaining sectors to calibrate and verify the MIKE HYDRO BASIN model for the basin, we set the calibration period to 2005-2010 and the verification period to 2011-2015. The monthly average flow series was calibrated and verified in the MIKE HYDRO BASIN model. Observed and simulated flow data at the Cau 14, Giang Son, and

Table 1. Seasonal rainfall changes in the Srepok River Basin under the RCP 4.5 scenario [52].

Province	Season	RCP4.5	
		Scenario 1 2016 - 2035	Scenario 2 2046 - 2065
Gia Lai	*Winter*	−8.1	7.3
	Spring	10.3	7.4
	Summer	0.7	−0.7
	Autumn	15.2	20.5
Dak Lak	*Winter*	3.2	2
	Spring	4.5	1.1
	Summer	1.3	−5.1
	Autumn	10.2	16.3
Dak Nong	*Winter*	13.4	20.9
	Spring	13.5	4.6
	Summer	4.9	12.1
	Autumn	2.9	12.5

Ban Don stations were used for the evaluation according to the criteria. The calibration and verification criteria were the Nash-Sutcliffe coefficient (NSE), BIAS, and the correlation coefficient (R).

$$\text{NSE} = 1 - \frac{\sum_{k=1}^{n}\left(X_k^{Sim} - X_k^{Obs}\right)^2}{\sum_{k=1}^{n}\left(X_k^{Obs} - \bar{X}^{Obs}\right)^2} \tag{2}$$

$$\text{Bias} = \frac{1}{n}\sum_{t=1}^{n}\left(X_{Sim,t} - X_{Obs,t}\right) \tag{3}$$

$$R = \frac{\sum_{t=1}^{n}\left(X_t^{Obs} - \bar{X}^{Obs}\right)\left(X_t^{Sim} - \bar{X}^{Sim}\right)}{\sqrt{\sum_{t=1}^{n}\left(X_t^{Obs} - \bar{X}^{Obs}\right)^2 \sum_{t=1}^{n}\left(X_t^{Sim} - \bar{X}^{Sim}\right)^2}} \tag{4}$$

A comparison of the simulated and observed results at the Cau 14, Giang Son, and Ban Don stations (Table 2) shows a strong correlation between the values.

Figure 3 presents the flow simulation results at Ban Don station, highlighting the similarity between the observed and simulated data. After calibration and

Table 2. Model calibration and validation statistics for Cau 14, Giang Son and Ban Don stations.

	Cau 14			Giang Son			Ban Don		
	NSE	BIAS	R	NSE	BIAS	R	NSE	BIAS	R
Calibration	0.91	−27.3	0.96	0.92	9.56	0.96	0.90	40.91	0.95
Validation	0.65	−22.54	0.88	0.78	6.96	0.97	0.84	18.86	0.95

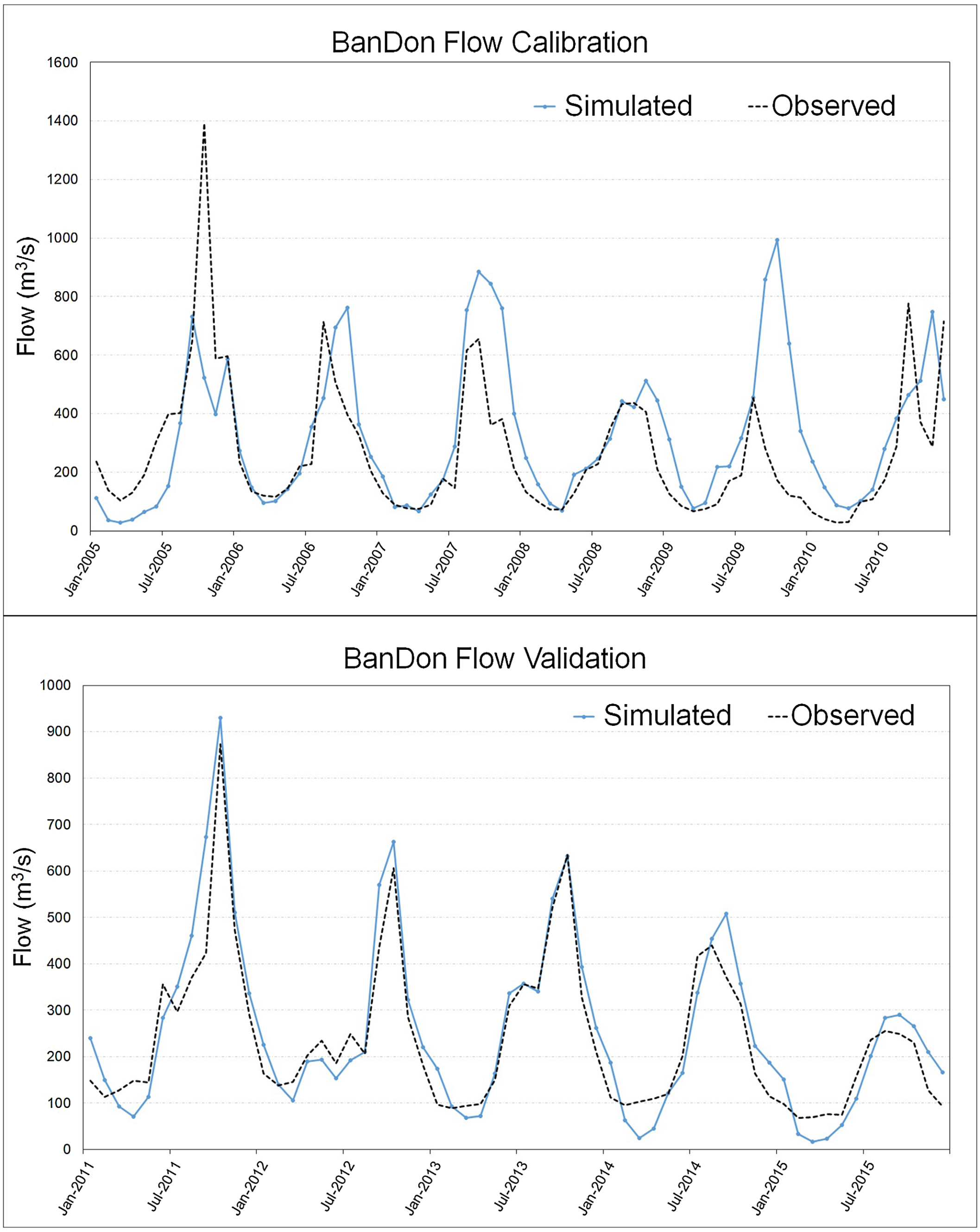


Figure 3. Monthly observed and simulated flow at Ban Don station.

verification, the model demonstrates good performance, making it suitable for simulating flow in the baseline period and two projected periods, 2016-2035 and 2046-2065, based on climate change scenarios.

4.2. Assessment of Water Scarcity

4.2.1. Baseline Scenario

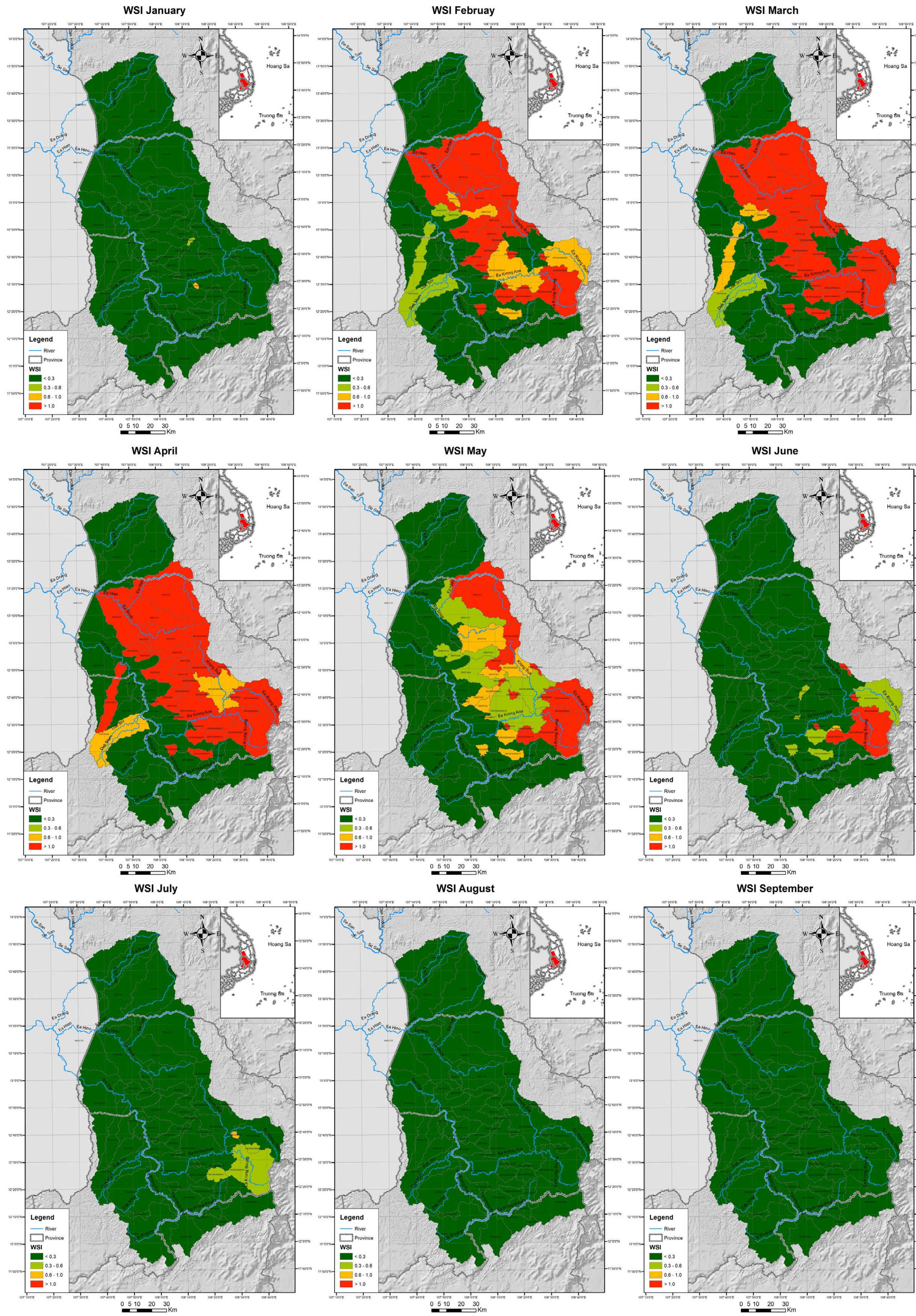
The baseline period for our calculations was from 1986 to 2005, with assessments conducted monthly. The level of water scarcity was estimated each month for each year within this timeframe. Average monthly values were used to determine the monthly water scarcity levels across the Srepok River Basin sub-basins during the baseline period (1986-2005) (**Figure 4**). The areas most affected by water stress ($0.6 \le WSI < 1$) and water scarcity ($WSI \ge 1$) are primarily located in the sub-basins of the Ea H'leo, Ea Krong Ana Rivers and part of the Srepok tributary, mainly within Dak Lak province. Water scarcity can be predominantly observed in February, March, and April, with the lowest average flow of the year.

During the 1986-2005 period, at least 32/58 sub-basins (0.83 million people) were affected by water scarcity on average for at least 1 month per year, and 25/58 sub-basins (0.65 million people) were affected by water scarcity for at least 3 months (**Figure 5**, **Table 3**), with about 0.83 million people (46% of the population) affected in total. These sub-basins belong to three main river branches: the Ea Hleo River, the Ea Krong Ana River, and the Srepok River. Water scarcity mainly occurs during the dry season, from late November to the end of April. In years with low flows in the dry season, the water scarcity level increases. For example, in 1995, 35/58 sub-basins had water scarcity for at least 1 month, and 31/58 sub-basins had water scarcity for at least 3 months; in 1998, 34/58 sub-basins had water scarcity for at least 1 month, and 29/58 sub-basins had water scarcity for at least 3 months; and in 2005, 35/58 sub-basins had water scarcity for at least 1 month, and 31/58 sub-basins had water scarcity for at least 3 months.

The proportion of water demand in the Srepok River Basin indicates that the agricultural sector had the most prominent water demand from 1986 to 2005, accounting for 95% of the total demand in the basin. The total water shortage in this period was about 839.1 million m^3, accounting for a 48.6% deficit, to which water shortage during the dry season contributed 51.6%. Agriculture experienced a significant water shortage of approximately 836 million m^3 (**Table 4**), presenting a shortfall of about 51.1%. Among 58 sub-basins, sub-basins in Ea Hleo River, Ea Krong Ana River, and Srepok River, which are characterized by intensive agricultural development, experienced the highest water shortage rates at 65.19%, 54.98%, and 26.19%, respectively (**Figure 6**).

These findings align with research conducted by Tran Van Ty and colleagues in 2012 [48], which indicated that most sub-basins in the Srepok River Basin had faced specific water shortage rates, especially in dry years from 1997 to 2007. The agricultural water deficit was high. However, the water shortage levels in that study were considerably lower than those in our findings, which revealed shortfalls of roughly 19.4% and 28.6% in the dry season. The difference between the two studies can be explained by two main factors: 1) Including environmental flow in our water scarcity assessment and 2) variations in the average dry season flow at Ban Don station. The average flow from 1997 to 2007 was 121.5 m^3/s, higher than the 106.2 m^3/s from 1986 to 2005.

On the one hand, this difference highlights the importance of considering environmental flow in water resource management to accurately reflect an area's total water requirements and emphasizes the need to balance economic development


WSI January
WSI Februay
WSI March
WSI April
WSI May
WSI June
WSI July
WSI August
WSI September
Legend
River
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< 0.3
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> 1.0
Hoang Sa
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0 5 10 20 30
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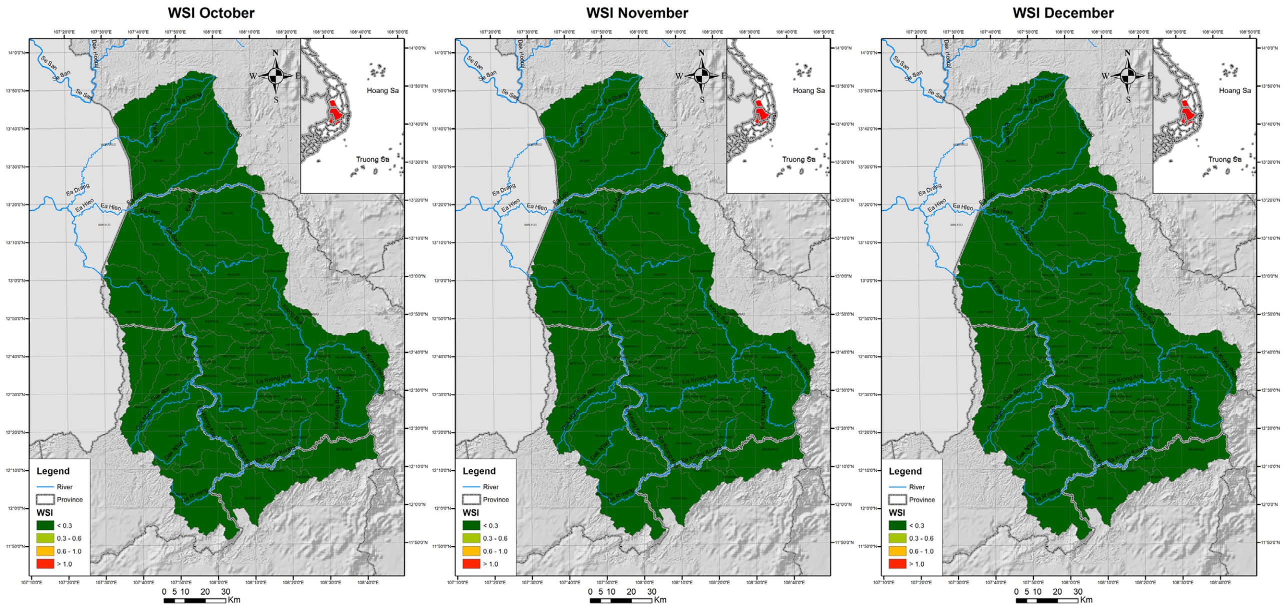

Figure 4. The level of water scarcity by month in the baseline scenario (1986-2005).

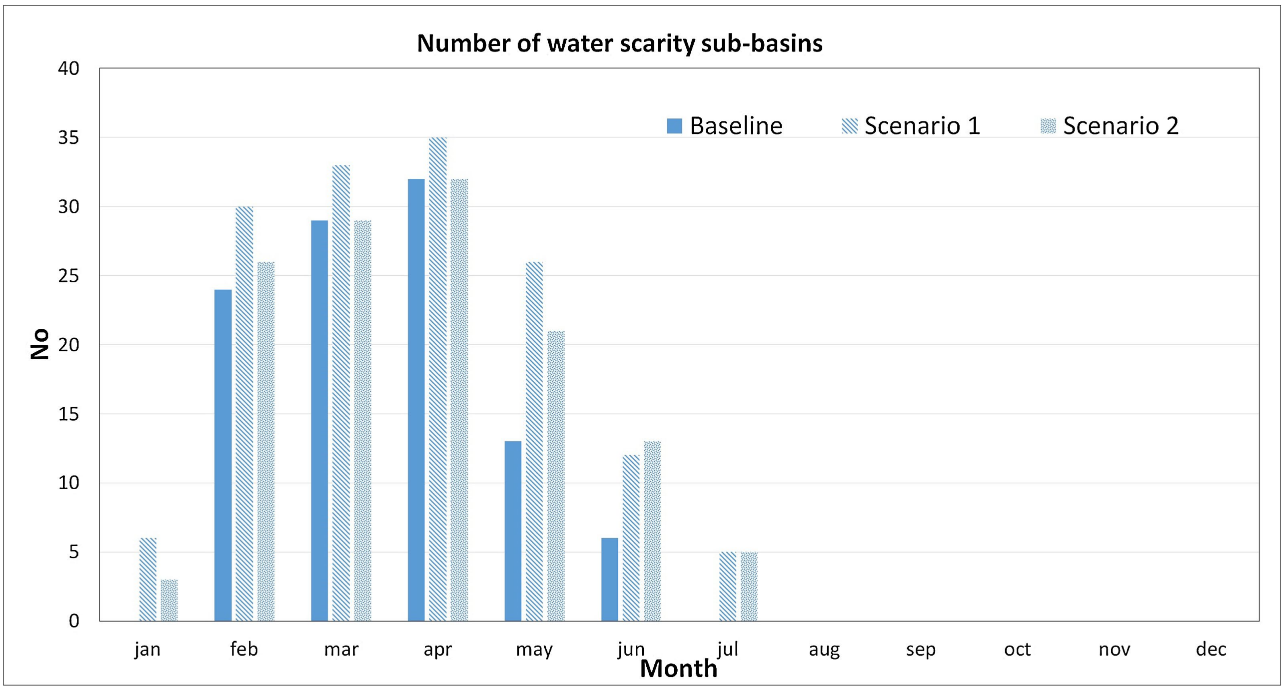

Figure 5. Number of sub-basins experiencing water scarcity according to scenarios.

Table 3. Number of sub-basins experiencing water scarcity for one and three months in the tributaries of the Srepok River.

River	Baseline		2016-2035		2046-2065	
	1 month	3 months	1 month	3 months	1 month	3 months
Ia Drang	0	0	0	0	0	0
Ia Lop	0	0	0	0	0	0
Ea Hleo	5	4	5	4	4	3

Continued

Ea Krong Ana	18	16	19	18	19	17
Ea Krong No	0	0	0	0	0	0
Srepok	9	5	11	7	9	7

Table 4. Projected water demand and shortage in the 2016-2035 and 2046-2065 periods.

	Baseline		Period 2016-2035		Period 2046-2065	
	Water demand	Water deficit	Water demand	Water deficit	Water demand	Water deficit
Domestic, tourism	53.66	0.59	103.65	1.38	123.27	1.00
Industry	21.4	0.24	355.93	4.07	1033.00	10.77
Agriculture	1636	836.05	2660.88	1787.24	2322.29	1406.75
Livestock	7.85	0.55	31.60	2.00	38.56	1.66
Aquaculture	15.2	1.65	224.70	27.77	284.27	24.61
SUM	1734.11	839.08	3376.76	1822.46	3801.39	1444.79

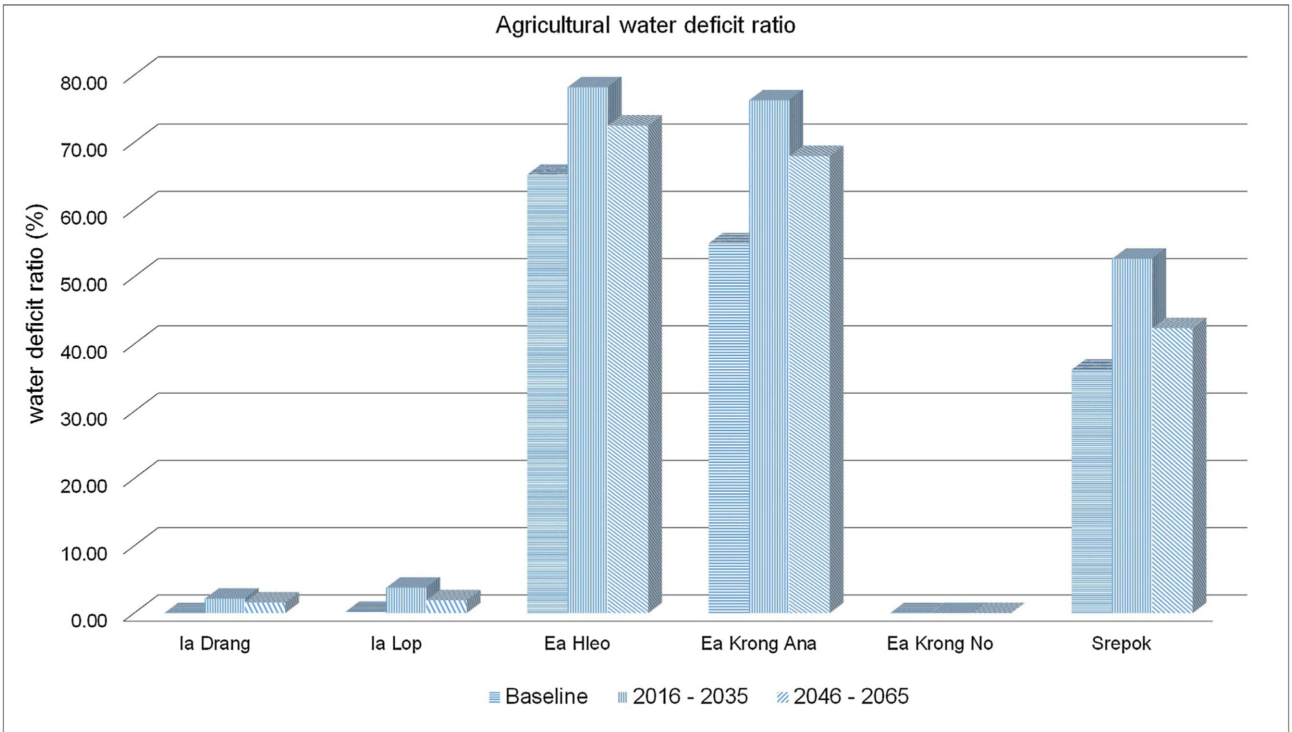

Figure 6. Water shortage rate for agriculture in tributaries according to scenarios.

with environmental conservation. On the other hand, the flow during the dry season significantly affects the water shortage rate. Therefore, integrating environmental flow requirements in water scarcity assessments with accurate dry season flow forecasts is crucial for developing effective strategies to address water scarcity. This holistic approach promotes sustainable water management and improves preparedness for future challenges related to water scarcity.

4.2.2. Climate Change Scenarios

We examined both the RCP4.5 Climate Change scenario for the two periods—2016 - 2035 and 2046 - 2065—and their associated socio-economic development scenarios to assess the level of water scarcity in the Srepok River Basin. Both periods project increased rainfall in the basin. From 2016 to 2035, rainfall increased by an average of 6%/year, and from 2046 to 2065, it increased by an average of 8.24%/year. Compared with the baseline period, the average annual flow increases by 15.3% from 2016 to 2035 (the dry season increases by 12.2%) and 29.4% from 2046 to 2065 (the dry season increases by 23.5%). Increased flow is more significant than increased rainfall in these two periods owing to construction and reservoirs that will increase this factor in the dry season [53] [54].

The two periods have different water use demands, altering the basin's flow and leading to changes in water scarcity. In both periods, water scarcity increases (**Figure 5**, **Table 4**). Water scarcity occurs in January and July in both periods, whereas there is no water scarcity during the baseline period. Areas with similar water scarcity levels in the baseline period are mainly concentrated in sub-basins of the Ea Hleo and Ea Krong Ana Rivers and part of the Srepok River branch. In both periods, about 1.4 million people are affected by water scarcity for at least one month, and about 1 million are affected for at least three months.

The total water demand also increases compared with the baseline period. In the 2016-2035 period, the demand is about 3376.76 million m^3/year (1.95 times), and in the 2046-2065 period, it is about 3801.39 million m^3/year (2.19 times) (**Table 4**). This change is due to variations in different socio-economic conditions for these periods. Water demand in the 2046-2065 period decreases compared with the 2016-2035 period because, in the former, the crop area does not change much, and increased rainfall in the basin reduces the demand for water for agriculture. The water shortage levels significantly rise in these two periods, of which the agricultural sector still accounts for the highest proportion (**Table 4**).

The total water shortage levels for the agricultural sector increase compared with the baseline in both periods: the 2016-2035 period has a shortage of 1787.24 million m^3 (67.2%), and the 2016-2035 period has a shortage of 1,406.75 million m^3 (60.58%) (**Table 3**). In the main river branches, the agricultural water shortage significantly increases compared with the baseline and is most severe in the 2016-2035 period (**Figure 6**).

The Srepok River Basin has experienced high-density agricultural intensification, resulting in significant water demand and a substantial water shortage. According to these climate change and socio-economic development scenarios, agricultural water shortages are estimated to exceed 60%. This water shortage significantly affects crop productivity and the socio-economic development of the region, so it is necessary to have measures and policies in place to minimize these impacts, such as water demand management strategies, water reuse, water storage measures, and construction (reservoirs and dams). We should also apply efficient water-saving irrigation technologies such as drip irrigation.

One limitation of our study is that our climate change scenarios do not consider the future development of reservoirs, hydropower projects, and new operating procedures, which may change water scarcity levels in the basin. In future studies, we will evaluate measures to reduce water scarcity and its damage to the socio-economic well-being of the Srepok River Basin. In addition, the impacts of irrigation, hydropower, and reservoir projects on water scarcity were not considered. We will supplement these assessments in subsequent studies.

5. Conclusions

This study assessed water scarcity levels in the Srepok River Basin of Vietnam over time and space and under the influence of climate change. Water scarcity levels were comprehensively and holistically considered in the assessments of the allocation and balance of water resources and environmental flows in this basin, and our assessment scale thus provides a clearer picture of the affected areas. In a river basin affected by many hydroelectric projects, reservoirs, and different water users, applying water scarcity scale calculations based on water balance and allocation problems is reasonable and appropriate [10].

Our results provide an overview of the water scarcity situation in the Srepok River Basin. Water scarcity occurs most frequently in February, March, and April, with affected areas concentrated in sub-basins of the Ea Hleo and Ea Krong Ana Rivers and part of the Srepok River. Analysis using monthly time steps provides insights into water scarcity by year, more clearly indicating when water scarcity will occur rather than relying on periods of the year.

In the socio-economic development and climate change scenarios we examined, water scarcity in the Srepok River Basin increases. It is estimated that over 1.4 million people will be affected by water scarcity for at least one month, and about 1 million will be affected for at least three months in the 2016-2035 and 2046-2065 periods.

From 2016 to 2035, water demand increases 1.95 times and water shortage increases 2.17 times compared with the baseline period. From 2046 to 2065, water demand increases 2.19 times and water shortage increases 1.72 times compared with the base period. The total water shortage for the agricultural sector also increases compared with the baseline period: from 2016 to 2035, the shortage is 1787.24 million m^3 (67.2%), and from 2046 to 2065, the shortage is 1406.75 million m^3 (60.58%).

Author Contributions

Conceptualization, Le Van Linh; Formal analysis, Le Van Linh and Tu Anh Nguyen; Investigation, Le Van Linh; Methodology, Le Van Linh and Tu Anh Nguyen; Software, Nguyen Thanh Long, Dang Dinh Duc, Tran Duc Thinh and Nguyen Thi Bich; Supervision, Tu Anh Nguyen, Nguyen Anh Duc and Tran Van Tra; Writing—original draft, Le Van Linh; Writing—review & editing, Tu Anh Nguyen, Nguyen Anh Duc and Tran Van Tra.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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