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Adapting to Climate-Change-Induced Drought Stress to Improve Water Management in Southeast Vietnam

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Abstract: In Southeast Vietnam, droughts have become more frequent, causing significant damage and impacting the region's socio-economic development. Water shortages frequently affect the industrial and agricultural sectors in the area. This study aims to calculate the water balance and the resilience of existing water resource allocations in the La Nga-Luy River basin based on two scenarios: (1) business-as-usual and (2) following a sustainable development approach. The MIKE NAM and MIKE HYDRO BASIN models were used for rainfall–runoff (R-R) and water balance modeling, respectively, and the Keetch–Byram Drought Index (KBDI) was used to estimate the magnitude of the droughts. The results identified areas within the Nga-Luy River basin where abnormally dry and moderate drought conditions are common, as well as subbasins, i.e., in the southeast and northeast, where severe and extreme droughts often prevail. It was also shown that the water demand for the irrigation of the winter–spring and summer–autumn crop life cycles could be fully met under abnormally dry conditions. This possibility decreases to 85–100% during moderate droughts, however. In contrast, 65% and 45–50% of the water demand for irrigation is met for the winter–spring and summer–autumn crop life cycles, respectively, during severe and extreme droughts. Furthermore, this study demonstrates that the water demand for irrigation could still be met 100% and 75–80% of the time during moderate, and extreme or severe droughts, respectively, through increased water use efficiency. This study could help managers to rationally regulate water in order to meet the agricultural sector's needs in the region and reduce the damage and costs caused by droughts.

Keywords: water allocation; water use; droughts; climate change; Southeast Vietnam

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1. Introduction

The water balance represents how much water is available in a hydrological system. The input into the system, i.e., precipitation, is equal to the output, which is the water leaving the system, such as evapotranspiration and runoff [1]. The latter primarily depends on the catchment's land use/land cover (LULC) [2]. LULC changes can notably increase the water demand through an increase in agricultural production and industrialization [3], potentially leading to competition amongst water users when the demand exceeds the available supplies [4,5]. Moreover, trends in hydroclimatic variables, including precipitation and temperature, through their impact on evapotranspiration [6] can affect the availability of water resources and agricultural water needs [7,8]. These trends can also increase the occurrence and intensity of droughts, often leading to competition among water users [9–11].

The land in the southeast region of Vietnam is fertile and is covered with commercial crops such as rubber, cashew, coffee, pepper, and fruit trees. The region experiences a tropical monsoon climate with distinct wet and dry seasons. Although the area receives between 1500 and 3000 mm of precipitation annually, it is highly variable both spatially and temporally [12]. For instance, the 2014–2016 El Niño exposed many localities to droughts, thereby increasing the number of wells drilled into in order to extract water for irrigation. The El Niño-induced drought affected Binh Thuan Province the most, with irrigation providing water to less than 16% of the cultivated land when it occurred. Agricultural production was consequently greatly affected, with 11,304 hectares of cropland being damaged [13,14]. Therefore, allocating water resources adequately is very important. This is particularly the case when there are many competing water users within a catchment. For instance, using water for industrial crops in upland areas often results in rivers and streams running dry yearly and the lowering of the water table, leading to dry wells or salinization of the water supply, thereby affecting water users downstream [15].

There has been rapid development in hydrological and hydraulic modeling in recent years [16], leading to improvements in the simulation of river flow and water balance modeling [17]. The choice of a numerical model depends on data availability [4,18], with commonly used models including SWAT [19–22], MIKE *Système Hydrologique Européen* (SHE) [23–25], MIKE Nedbor-Afstromings Model (NAM) [26,27], and MIKE HYDRO BASIN [28–32]. Santos et al. [21] used SWAT and MIKE HYDRO BASIN to model water allocation in the Sabor River in Portugal, while Yu et al. [32] used the latter model to develop sustainable agricultural water management practices in the Tarim River in northwestern China.

During the 2015–2016 winter–spring crop life cycle and the dry season of 2018–2019, many households in Binh Thuan Province lacked water for domestic use because the water supply from irrigation construction only met the water demand in Phan Thiet, Binh Hiep, Ma Lam, and Tuy Phong. Similarly, in 2018–2019, thousands of households lacked water for domestic use in the Ham Thuan Nam and Tanh Linh districts, and 1846 hectares of cropland were damaged due to a lack of irrigation water. Moreover, crops could not be grown on 13,215 hectares of arable land in the Duc Linh and Tanh Linh districts during the summer–autumn crop of 2019 due to a lack of water.

This study investigates changes in water availability for irrigation in southeastern Vietnam under different drought scenarios. It first calculates the water balance and, thus, the water resource potential of the La Nga and Luy river basins. Secondly, it simulates the effects of various drought categories on water resource availability and assesses the capability of water infrastructure development to mitigate these effects. The study also proposes a water use plan to enhance efficiency in response to droughts in Binh Thuan Province.

2. Methodology

2.1. Study Area

This study focuses on Binh Thuan Province's La Nga and Luy rivers. The source of the La Nga River is located near Di Linh-Bao Loc at an altitude of 1300–1600 m. The river flows along the western edge of Binh Thuan Province and meets the mainstream, covering 4100 km^2 of the watershed. The Luy River originates in a mountainous region, bordering the Da Quyeon basin of Lam Dong Province at 1623 m and flowing through the Bac Binh district, and its outlets are at Phan Ri (Figure 1). The river is 87 km long and has a basin area of 2004 km^2. The Luy River is vital to the region since its topography favors the construction of dams and reservoirs. The Luy River system also receives water from the Dong Nai River basin. However, these two basins often suffer from drought and severe water shortages during the dry season. Water resources in the study area are unevenly distributed in space and time. The total annual rainfall is an average of 1950 mm, equal to 61.4 billion m^3/year, with nearly 92% falling during the rainy season.

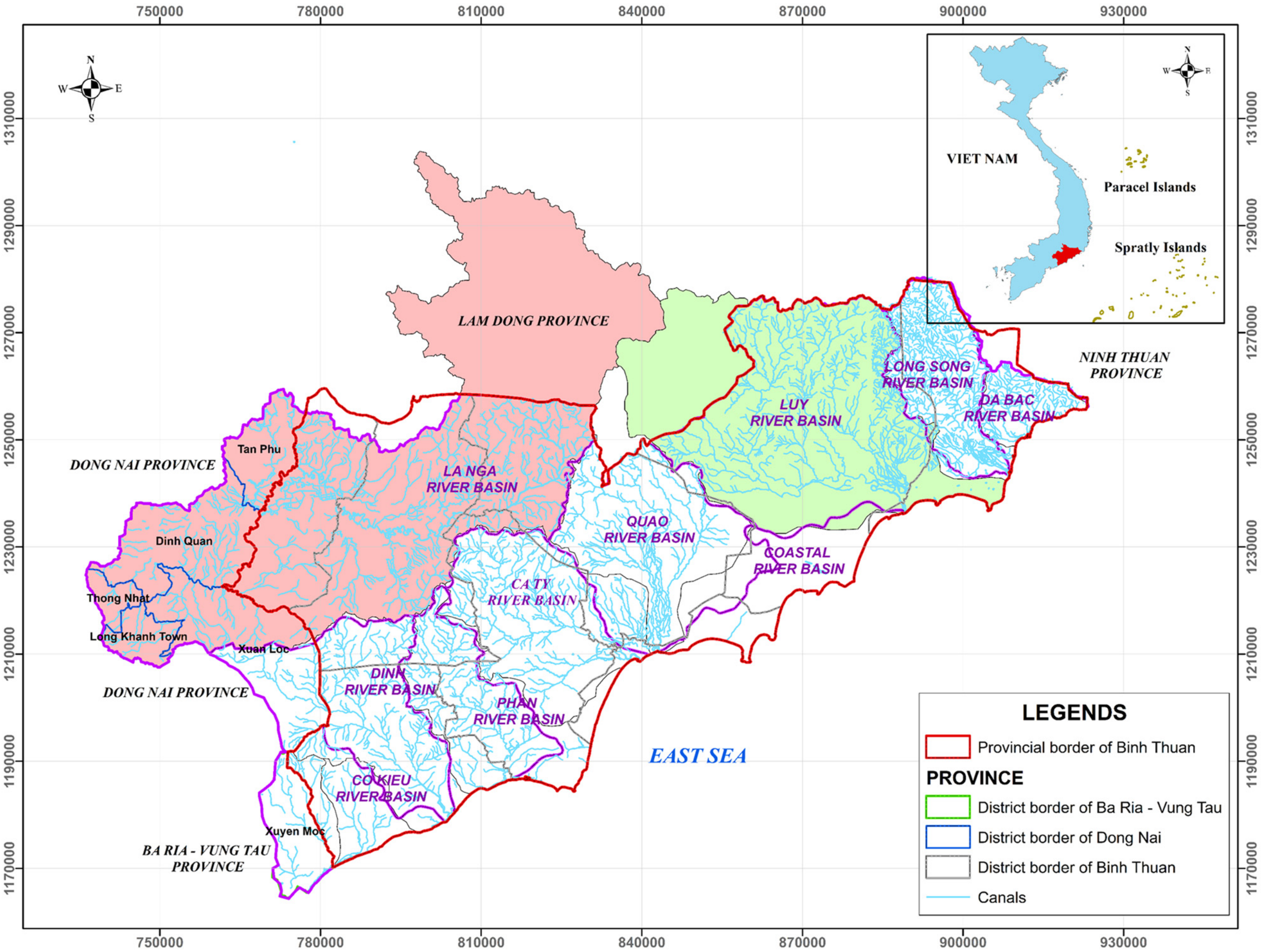

Figure 1. The La Nga and Luy River basins.

The water supply depends heavily on the outflow from the Ham Thuan and Da Mi hydroelectric reservoirs (La Nga River basin), as well as Dai Ninh (Luy River basin). In the first eight months of 2015, according to data from Phan Thiet, only 550 mm of rain fell over Binh Thuan Province, which was lower than the average rainfall for the same period (721 mm). The volume of water only fulfilled approximately 21.7% of the total capacity of the reservoirs. Some reservoirs were below the dead water level. In addition, the storage capacity of the Ham Thuan-Da Mi and Dai Ninh hydropower reservoirs had dropped to about 2.3 m^3/s, much lower than the average of many years, leading to water shortages.

2.2. Methodological Approach

This study used the MIKE NAM rainfall–runoff (R–R) and the MIKE HYDRO BASIN water balance model. The R–R model was calibrated and validated using discharge data from Ta Pao and Luy from 1988–1999. For the R–R model, the input data included hydrological data (i.e., rainfall, evaporation) and geographical data (i.e., river network, digital elevation model (DEM), land cover map, soil map), and for the MIKE HYDRO BASIN model, the input data included infrastructure (i.e., reservoir operation, hydraulic structure), water data (i.e., water demand, irrigation area and method, and streamflow time series).

We selected the two commonly used greenhouse gas (GHG) emission scenarios in our investigation of the impacts of climate change on water resources, thus allowing for a consideration of the uncertainties regarding such emissions. The two scenarios were (1) a business-as-usual scenario based on current trends and conditions (KB1) and (2) a scenario following a sustainable development strategy (KB2), i.e., representative concentration pathway (RCP) 4.5 and 8.5, respectively, from the Intergovernmental Panel on Climate Change (IPCC) (Figure 2). The output of the study consisted of the calculation results of water balance, water supply capacity, drought map, water flow distribution, and available water potential.

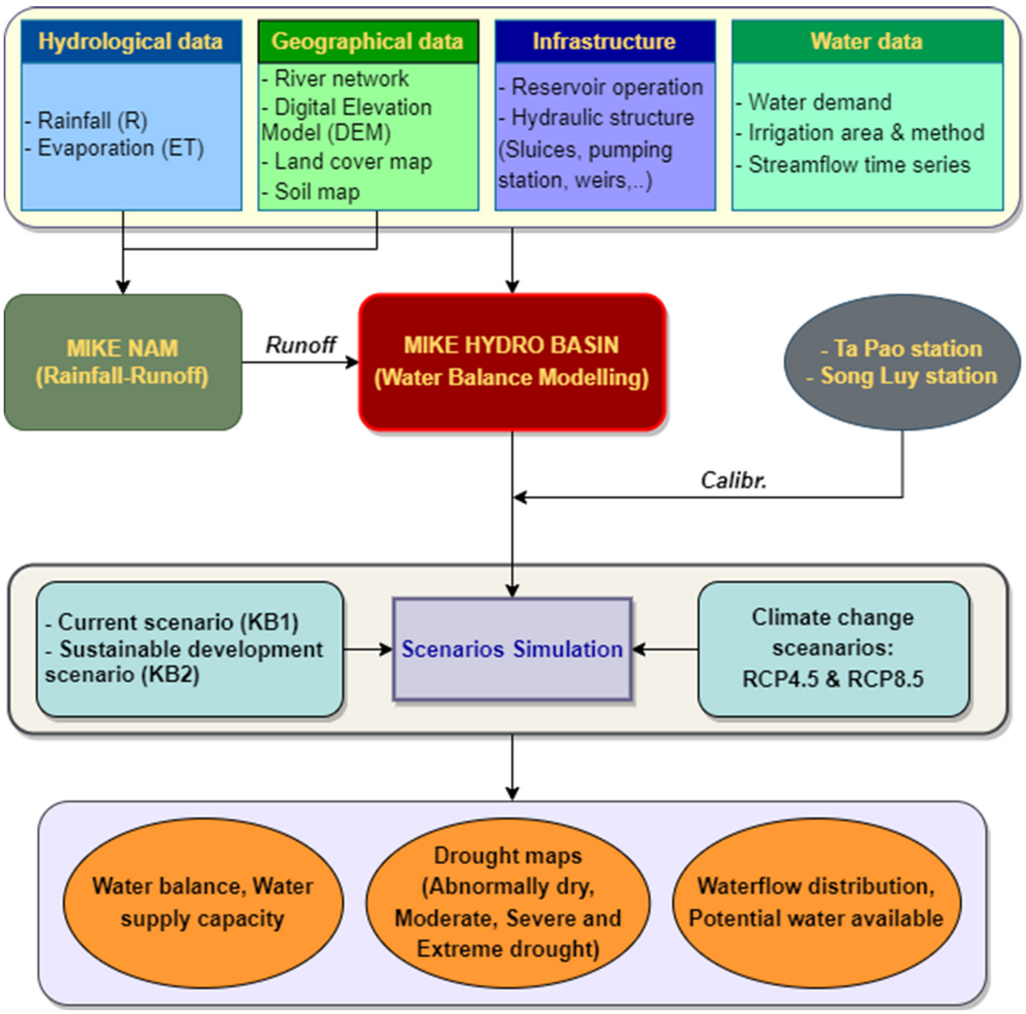

Figure 2. The methodological approach used in this study.

2.3. MIKE HYDRO BASIN

MIKE HYDRO BASIN was developed by the Danish Hydraulic Institute [33]. It has been used as a decision-support tool in water resource management and planning, including water allocation [34]. MIKE HYDRO BASIN is also used for rainfall–runoff modeling [35]. The MIKE HYDRO BASIN model incorporates information on the catchment characteristics, river network, water use, reservoir operation, and hydropower elements [33]. The model allows for the simulation of single- or multipurpose reservoirs using specified operating policies, sharing rights, and no-operation policies [34]. Figure 3 shows the river network and hydraulic works used in the MIKE HYDRO BASIN.

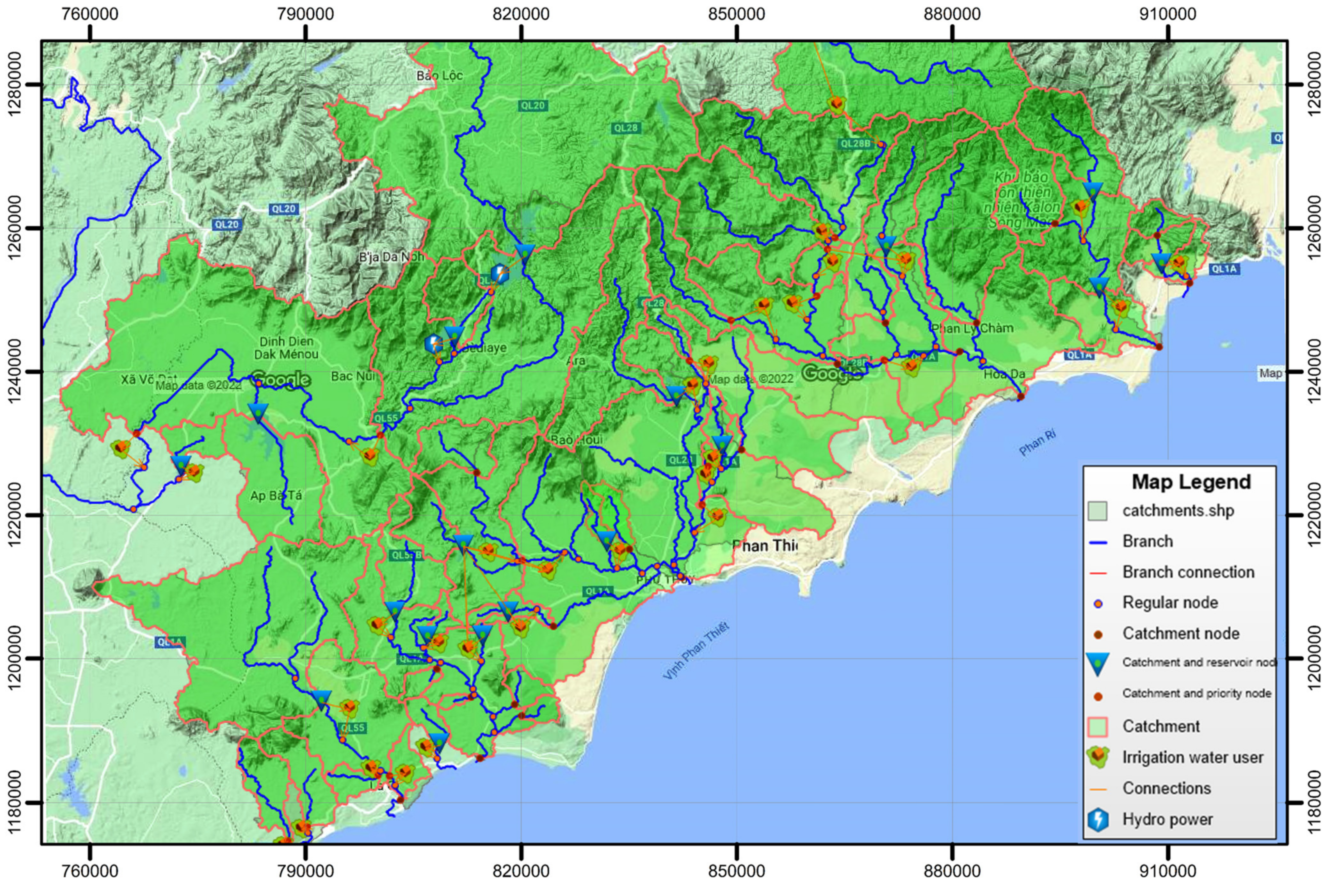

Figure 3. River network and hydraulic works used in the water balance modeling.

2.4. Input Data for MIKE Models

The allocation of water to different users and assessment of potential shortages and surpluses were investigated using the MIKE HYDRO BASIN model. The model used time series of precipitation, evaporation, and irrigation works to determine the water availability and refine the allocation and usage priorities. The rainfall time series at eight stations in the study area and the average monthly potential evaporation data were used as inputs into the MIKE HYDRO BASIN model to determine the basin's water balance.

The allocation of water to different users and the assessment of potential shortages and surpluses were investigated using the MIKE HYDRO BASIN model. The model used time series of precipitation, evaporation, and irrigation to determine the water availability. Daily rainfall time series from 1980 to 2017 at eight stations in the study area, i.e., Di Linh, Ta Pao, Dong Giang, La Gi, Lien Huong, Song Luy, Phan Thiet, and Song Mao, as well as average monthly potential evaporation data, were input into the MIKE HYDRO Basin model to determine the basin's water balance. Monthly evaporation was calculated at Phan Thiet and Ham Tan using the Penman formula based on the Piche evaporimeter at Phan Thiet.

The Penman equation combines radiative and radiation–aerodynamic factors to estimate evapotranspiration (ETo). This study used the FAO version of the equation from 1992, as described in [36,37]. Penman's original equation [38] and its subsequent modifications have been extensively employed for estimating evapotranspiration [39]. It is calculated using the following equation:

$$ETo = \frac{0.75\Delta(R_n - G) + 1.84\gamma\frac{900}{273+t}U_2(e_a - e_d)}{\Delta + \gamma(1 + 0.34U_2)}, mm/month \quad (1)$$

where t—mean monthly temperature (°C); Δ—the inclination of the temperature relationship curve with the saturated vapor pressure at temperature t (Kpa/°C), which is determined using the following:

$$\Delta = \frac{4098e_a}{(t+237)^2} \quad (2)$$

e_a—saturated vapor pressure (kPa):

$$e_a = 0.611\exp\left(\frac{17.27t}{t+237}\right) \quad (3)$$

R_n—deviant between increased radiation and decreased radiation of short and long waves (mm/month):

$$R_n = R_{ns} - R_{nL} \quad (4)$$

R_{ns}—retained solar radiation after reflection to the crop ground (mm/month):

$$R_{ns} = 0.77\left(0.19 + 0.38\frac{n}{N}\right)R_a \quad (5)$$

R_a— irradiance at the boundary layer of the atmosphere (mm/month)
R_a = 37.6dr ($\omega_s$sinψ sinδ + cos$\omega_s$cosψcosδ)
ω_s = arcos(−tanψtanδ), (rad)
ψ—geographical latitude angle
δ—deviation angle by day (rad):
δ = 0.409sin (0.0172J − 1.39)
dr—relative distance by month
dr = 1+ 0.033cos(0.0172J)
J—ordinal number by date of calculation

$$R_{nL} = \frac{118(t+273)^4 10^{-9}(0.34 - 0.044\sqrt{e_d}\left(0.1 + 0.9\frac{n}{N}\right)}{59.7 - 0.055t} \quad (6)$$

N—maximum number of hours of sunshine
N = 7.64W_s (h)
G—heat flux of the soil (MJ/m^2 month)
If we calculate G in days, then: G = 0.38(t_i − t_{i-1})
t_i, t_{i-1}—air temperature on day I and i−1, (°C)
If G is calculated according to the average temperature of the month, then: G = 0.14 (t_m − t_{m-1})
t_m, t_{m-1} — Average temperature of month m and m-1, (°C)

In 2018, Binh Thuan Province had 78 irrigation systems comprising 21 reservoirs, 35 weirs, 18 pumping stations, and 4 canals, with a total storage capacity of 303.7 million m^3 available to irrigate 70,360 hectares (Figure A1—Appendix A). There are 73 existing systems of irrigation constructions from the focal point to the in-field canal system, with a total design irrigation capacity of 49,047 hectares; 5 systems of hydraulic works have been invested in since 2010, with a total design capacity of 21,313 ha (Figure 3). Out of 73 constructions, 33 systems promote irrigation efficiency beyond design capacity, 16 promote irrigation efficiency from 70–100% of design capacity, and the remaining 24 effective irrigation systems reach less than 70% of design capacity.

2.5. Model Performance Evaluation

The simulated data were evaluated by comparison with the measured data using various statistical measures, such as relative bias [40], percentage of bias (BIAS(%)), the correlation coefficient (R), Nash–Sutcliffe efficiency (NSE) [16], root mean square error (RMSE), and mean absolute error (MAE) [41].

The formula used to calculate the indicators was as follows:

$$Relative\ Bias = \frac{\sum_{i=1}^{n}(O_i - P_i)}{\sum_{i=1}^{n} O_i} \tag{7}$$

$$BIAS(\%) = \frac{\sum_{i=1}^{n}(O_i - P_i) * 100}{\sum_{i=1}^{n} O_i} \tag{8}$$

$$R = \frac{\sum_{i=1}^{n}(O_i - \overline{O})(P_i - \overline{P})}{\sqrt{\sum_{i=1}^{n}(O_i - \overline{O})^2}\sqrt{\sum_{i=1}^{n}(P_i - \overline{P})^2}} \tag{9}$$

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \overline{O})^2} \tag{10}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i - P_i)^2} \tag{11}$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|O_i - P_i| \tag{12}$$

where O_i—the observed data at the time i; P_i—the simulated data at the time i; $\overline{O}$—the mean value of the observed data; and $\overline{P}$—the mean value of the simulated data.

2.6. Scenarios Simulations

The two scenarios that were simulated are described in Table 1. At the same time, the KB2 represents projected water use by 2030 based on socio-economic development and future water use by the different sectors, as approved by the government. The seasonal rainfall frequency scenarios are shown in Table A1, in the Appendix A, with two cases, namely, water excess and less water. Rainfall frequency is the probability of a rainfall event of defined characteristics occurring in any given year at a given location. If the rainfall frequency is less than 50%, it corresponds to the scenario of water excess. For the case of less water, rainfall frequencies of 50–75%, 75–85%, 85–95%, and over 95%, respectively, represent abnormally dry, moderate drought, severe drought, and extreme drought scenarios. Future precipitation changes were based on climate change scenarios (RCP 4.5 and RCP 8.5 greenhouse gas emissions) estimated for 2025 and 2035 (Table A3—Appendix A; Figure 4). Irrigation and hydropower infrastructure will be upgraded, repaired, and built according to the plan until 2025 and 2030.

Table 1. Characteristics of the two scenarios.

Factors	Simulation Scenarios	
	Business-as-Usual (KB1)	**Sustainable Development (KB2)**
Inflow scenarios	Scenario 1a: Magnitude 50% Scenario 1b: Magnitude 75% Scenario 1c: Magnitude 90%	RCP 4.5 and RCP 8.5 GHG emission scenario for 2035
Industrial water demand	Water demand in 2018	Water demand in 2030
Hydraulic works	Reservoirs, hydropower plants, and dams connected to the network in 2018	Planned hydraulic works, including reservoirs, hydropower plants, and weirs, in 2030

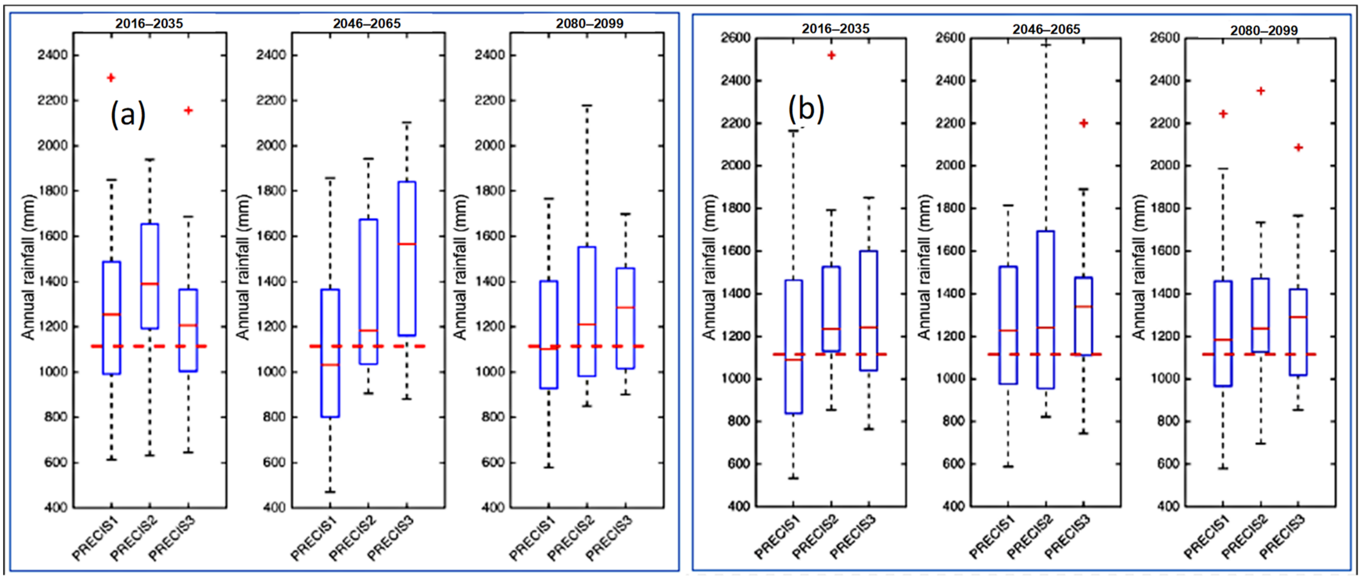

Figure 4. Total annual rainfall for three future twenty-year periods at Phan Thiet, according to three versions of the PRECIS Regional Climate Model, with the (**a**) RCP 4.5 and (**b**) RCP 8.5 scenarios developed by the Ministry of Natural Resources and Environment.

2.7. Quantifying the Magnitude of the Droughts

The magnitude of the droughts was assessed using the Keetch–Byram Drought Index (KBDI). John Keetch and George Byram developed the KBDI in 1965 based on soil moisture for the purpose of monitoring the risk of forest fires [42,43]. The values of the KBDI can range from zero, representing no-drought conditions, to a maximum of 800, the most severe drought category (Table 2). The KBDI index is calculated as follows:

$$KBDI_t = (KBDI_{t-1} - 100r) + dF \quad (13)$$

$$dF = \frac{[800 - KBDI_{t-1}]\left[0.968^{0.0486T} - 8.30\right]dt}{1 + 10.88e^{(-0.0441R)}}10^{-3} \quad (14)$$

where $KBDI_t$—current-day KBDI index; $KBDI_{t-1}$—the previous day's KBDI index; dF—drought factor (0.01 inch); r—daily rainfall (inch); dt—time increment (1 day).

Table 2. Categorization of droughts according to the KBDI index.

Values	Drought Level
0–200	No drought
201–400	Possibility of a drought
401–600	Occurrence of a drought
601–800	Severe drought

3. Results and Discussion

3.1. Model Calibration

The model parameters were calibrated using data from the Luy River at Luy and the La Nga River at Ta Pao (Table 3). The calibration was performed manually, and the model parameters were modified to obtain the smallest possible error between the simulated and measured data.

Table 3. Calibration of the MIKE HYDRO BASIN model over the study catchments.

Statistical Indicators	Ta Pao	Luy
Relative bias	2530	−2390
BIAS%	6%	8%
R	0.85	0.87
NSE	0.997	0.997
RMSE	349.5	84.8
MAE	0.025	0.023

The model parameters of the Luy River station in the coastal basin were used to simulate flow for construction routes in Long Song, Da Bac, the Quao Rivers, the Ca Ty Rivers, Co Kieu Streams, Phan, and the Dinh Rivers. Figure 5a,b illustrate the calibrated flow at Luy and Ta Pao and the associated rainfall over the catchment from 1988 to 1999. The observed and simulated discharge similarities are demonstrated by a bias of no more than 8% at each location and a correlation coefficient of 0.85 and 0.87 at Luy and Tao Pao, respectively (Table 3). Similarly, the correlation coefficient between the simulated and measured accumulative water volume at Luy and Tao Pao were both 0.999 (Figure 5c,d).

3.2. Water Availability and Allocation under Climate Change

The totals of the calculated potential water were 8.092 billion m^3, 6.447 billion m^3, and 5.609 billion m^3 for p = 50%, 75%, and 90%, respectively (Table 4). Of this estimate, the potential water volume in the North Binh Thuan region accounted for 24–26% of the total water volume of the province. The Luy River basin accounted for 71–75% of the water volume in the North Binh Thuan region. The potential water volume in the South Binh Thuan region accounted for 73–75% of the total water volume of the province. At the same time, the La Nga River basin accounted for 75–80% of the water in the South Binh Thuan region. The flood season tends to begin between June and November, and the flow accounts for 75–80% of the total annual flow. The dry season is usually from December to May. Most of the streams in the north of the province are almost dry. The transition time from the flood to the dry season is usually one month in both river basins.

Table 4. Potential water resources of the river basins of Binh Thuan Province with rainfall frequencies of p = 50%, 75%, 95%.

River Basin	Area (km^2)	Total Volume (106 m^3)		
		50%	75%	90%
Da Bac	85.9	14.640	7.230	4.72
Long Song	471.7	93.140	82.330	28.18
Luy (including discharge from the Dai Ninh hydropower plant)	1952.7	1404.18	1204.33	1057.1
Quao	1068.3	440.66	390	289.76
Ca Ty	840	565.150	175.82	85.85
Luy	533.5	214.500	131.77	73.67
Dinh	834.5	904.93	524.34	330.5
Co Kieu	74	58.390	8.730	5.63
Tram	63.7	53.66	55.14	50.98
La Nga (including discharge of Ham Thuan-Da Mi Hydropower)	3181	4343.69	3867,88	3683.41
Total		**8092.4**	**6447.6**	**5609.8**

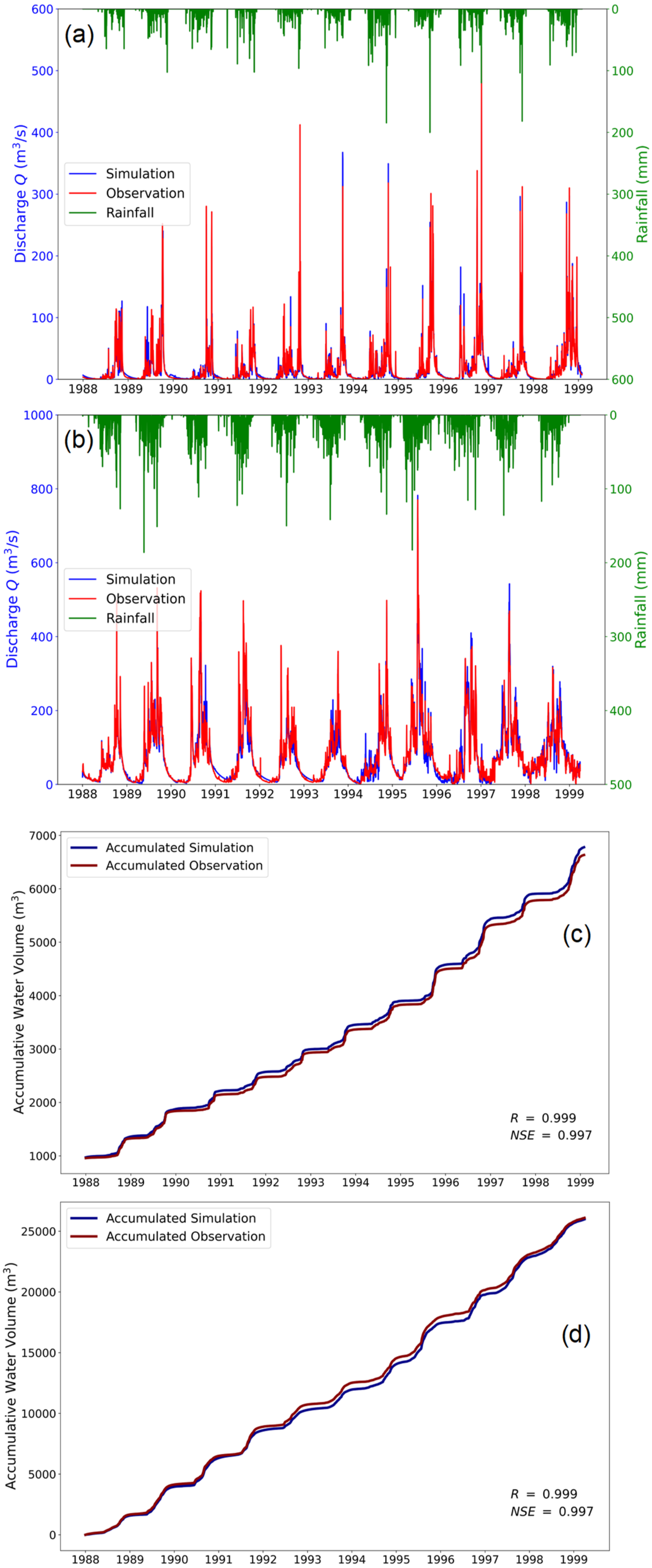

Figure 5. Calibrated daily discharge associated with rainfall intensity (**a**) at Luy station and (**b**) at Tao Pao station; accumulative water volume (**c**) at Luy station and (**d**) at Tao Pao station.

The province has only two regular flow monitoring stations to standardize the model parameters. The Luy River station represents the coastal plain, and Ta Pao station the mountainous area. In the condition of the existing observed data, we suggest using the Ta Pao model parameter set of the mountainous basin to simulate the flow of the sub-basins of La Nga, Tra Tan, and Bien Lac. In addition, the water in the river can suddenly decrease due to steep slopes and the high permeability of the basins. Especially in recent years, as the vegetation growth rates are declining, the ability of the land to hold and regulate water is also decreasing.

The rivers and streams in the La Nga river basin have a significant average annual rainfall, and this area is also the place with the most extensive flow module of about M = 0.040 $m^3/s.km^2$ in the province. The area with the second largest flow is the Phan River and Dinh River, which fluctuate by around 0.026 $m^3/s.km^2$. The site with the lowest flow, even from the Ca Ty River, is only 0.008–0.014 $m^3/s.km^2$.

We calculated the water resource potential of the two river basins according to climate change scenarios predicted for 2030. The results show that the total annual flow will increase by 2.4% by 2030. The total flow during the flood season will increase by 3.6%. The dry season flow assessment will show an average decrease of about 2.3%. Coastal basins will decrease more than mountainous areas, such as the Long Song and Luy River basins, with the highest reduction rates of 6.7% and 8.8%, respectively (Table 5). The La Nga and Dinh River basins will slightly decrease from 0.2–0.3%. It can be seen that climate change alters the flow pattern in the canal systems, with a tendency to increase the extremes. Thus, the flood season is expected to become more severe, and the dry season is expected to become more and more water-deficient. Therefore, the basins will have a greater risk of water shortage.

Table 5. Predicted water resources available in two river basins.

River Basin	Mean Annual Flow		Dry Season		Flooding Season		Change (%) (In Comparison to the Current Scenario)		
	Q_0 (m^3/s)	**W_0 (10^6 m^3)**	**Qk (m^3/s)**	**Wk (10^6 m^3)**	**Ql (m^3/s)**	**Wl (106 m^3)**	**Annual Average**	**Dry Season**	**Flooding Season**
Da Bac	0.69	21.76	0.14	4.42	1.21	38.16	+1.5	0.0	+2.4
Long Song	5.82	183.54	2.98	93.98	8.6	271.21	+0.5	−8.8	+3.4
Luy	54.56	1720.6	31	977.62	77.22	2435.21	+0.8	−6.7	+3.6
Quao	25.08	790.92	6.5	204.98	42.27	1333.03	+2.8	−1.4	+3.4
Ca Ty	16.83	530.75	3.71	117	29.22	921.48	+2.2	−1.1	+2.5
Phan	14.37	453.17	2.92	92.09	24.94	786.51	+3.1	0.3	+3.4
Dinh	21.59	680.86	3.57	112.58	38.28	1207.2	+3.1	−0.6	+3.4
La Nga	119.85	3779.59	49.33	1555.67	179.71	5667.33	+4.4	−0.2	+5.7
Total	**258.78**	**8161.2**	**97.7**	**3091.07**	**419.86**	**13,240.7**	**+2.4**	**−2.3**	**+3.6**

The results of the assessment of water demand for the economic sectors in 2030 in Binh Thuan Province are presented. Compared with the potential of the surface water, we can see that the province's water resources will be met in terms of water use needs. However, water resources are unevenly distributed among the river basins. The water resources of the South Binh Thuan and North Binh Thuan regions are mainly concentrated in the La Nga and Luy river basins.

3.3. Water Balance of the La Nga and Luy River Basins

Based on the availability of water sources in river basins and the water demand for socio-economic development, the water balance calculation must consider each river basin's water supply capacity in order to propose solutions and ultimately provide sufficient water for different economic sectors.

The outcomes of the water balance analysis are shown in Table 6 for each river basin. They represent the water supply capacity for: (i) water balance of river basins, scenario

1a—current—p = 50%); (ii) water balance of river basins, scenario 1—current—p = 75%); (iii) water balance of river basins, scenario 1c—current—p = 90%); (iv) water balance in river basins, scenario 2 (2030 plan + climate change).

The results of scenario 1a show that the total water shortage of the whole province is 24.089 million m^3, of which the Luy River basin and surrounding (Northern Binh Thuan region) account for about 68%. The lack of water is mainly in the Long Song, Quao, and Luy river basins (mainly in the irrigation area on the side of the Ca Tot dam). The La Nga River basin and its surrounding area (the South Binh Thuan region) account for 32% of the province's total water shortage. The water shortage is mainly concentrated in the irrigation areas of the Ca Ty and Co Kieu river basins, as well as the Tram River dam. In scenario 1b, the province's total water shortage is 85.072 million m^3, of which the Luy River basin and surrounding account for about 39.6% of the province's total water shortage. The Long Song, Quao, and Luy River basins (on the Ca Tot dam side) meet 75%, 95%, and 99% of the demand, respectively.

From December to April, the available water can only meet 35–60% of the demand. The La Nga River basin and the surrounding water shortage amount to 51.39 million m^3, accounting for 60.4% of the province's total water shortage. The water shortage is mainly concentrated in the irrigation areas of the Ca Ty and Co Kieu river basins, as well as the Tram River dam. In Weir's system, in the La Nga River basin pumping station, the response rate is only 45–55% of the demand in the dry season months from December to April. For scenario 1c, the province's total water shortage is 176.240 million m^3. The Luy River basin accounts for 57.1% of the water shortage in the region. The Long Song, Quao, and Luy River basins meet 63%, 74%, and 96.5% of the water demand, respectively. The water is available during the dry season from January to May, and in December, only 30–46% of the demand can be met.

The La Nga River basin and its surrounding areas account for 42.9% of the province's water shortage. The water shortage is mainly concentrated in the irrigation areas of the river basin, mainly in the Ca Ty, Co Kieu, Tram River Dam, Ta Pao Dam, and La Nga River Basin pumping stations. In the dry season months from December to April the response rate next year is only expected to meet 40–55% of the demand. For scenario 2, the province's total water shortage is 157.610 million m^3. The Luy River basin and its surroundings account for about 58.8% of the province's water shortage. The Long Song, Quao, and Luy River basins meet 63%, 80.5%, and 100% of the water demand, respectively. The water shortage occurs in the middle of the dry season from January to May, and in December, only 30–40% of the water demand can be met. The La Nga River basin and its surrounding areas account for 41.23% of the province's water shortage. The sources of the water shortage are mainly concentrated in the irrigation areas of the river basin, mainly in the Ca Ty, Co and Tram River Dam, Ta Pao Dam, and La Nga River basin pumping stations. During the dry season from December to April, the response rate is only 35–45% of the demand.

Table 6. The water supply capacity of the two river basins.

No	River Basin	Current Water Demand (m^3/s)	Inflow with p = 50%		Inflow with p = 75%		Inflow with p = 90%		Water Demand in 2030 (m^3/s)	Climate Change + 2030 Plan	
			Deficit Discharge (m^3/s)	% Supply Capacity	Deficit Discharge (m^3/s)	% Supply Capacity	Deficit Discharge (m^3/s)	% Supply Capacity		Deficit Discharge (m^3/s)	% Supply Capacity
I	Luy River basin										
1	**Da Bac**	2.138	0.564	**73.62**	0.726	**66.04**	1.025	**52.03**	2.523	0.697	**72.38**
2	**Long Song**	27.415	4.874	**82.22**	6.812	**75.15**	10.143	**63.00**	47.768	9.296	**80.54**
3	**Luy**	139.787	0.505	**99.64**	0.824	**99.41**	4.901	**96.49**	160.056	0	**100**
4	**Quao**	81.829	1.679	**97.95**	3.601	**95.60**	21.179	**74.12**	131.206	25.491	**80.57**
II	La Nga River basin										
1	**Ca Ty**	17.620	0.538	**96.95**	0.911	**94.83**	0.918	**94.79**	38.937	11.357	**70.83**
2	**Phan**	9.495	0	**100**	0.058	**99.39**	1.004	**89.43**	19.678	2.570	**86.94**
3	**Dinh**	18.375	0.585	**96.82**	0.671	**96.35**	0.811	**95.59**	63.547	10.240	**83.89**
4	**Co Kieu**	0.415	0.043	**89.65**	0.043	**89.65**	0.073	**82.43**	0.527	0.224	**57.53**
5	**Tram**	1.127	0.117	**89.61**	0.369	**67.25**	0.454	**59.70**	1.126	0.632	**43.84**
6	**La Nga**	184.837	0	**100**	17.703	**90.42**	25.049	**86.45**	236.929	0	**100**
	Total (Million.m^3)		**24.089**		**85.072**		**176.240**			**157.610**	

3.4. Drought Assessment and Prediction

This section presents the results of the future drought forecast with different scenarios, such as abnormally dry conditions, moderate drought, severe drought, and extreme drought, in 2030. Two scenarios are considered: the current situation and the sustainable development scenario. We classify drought according to the American classification [44–46].

3.4.1. Abnormally Dry Conditions

Figures 6 and 7 show the areas projected to experience abnormally dry conditions during the winter–spring crop season. In non-drought years, the reservoirs are filled with over 240 million m3 of water at the start of the winter-spring crop, which lasts throughout its life cycle. Additionally, the total rainfall during the Winter–Spring crop period is greater than 40 mm, and the water sources provide enough water to meet the demand. However, there are a few months during which the water in the reservoir can only meet 30–40% of the irrigation demand (Figure 6). At the beginning of the summer–autumn crop life cycle, less than 104 million m^3 of water is available in the reservoir, and the total rainfall in the summer–autumn crop period is 40 mm, which is more significant than in non-drought years. Drought and water shortages may occur locally in some reservoirs at the beginning of the production season (Figure 7). It is necessary to grasp the situation and the results of water resource forecasting in order to recommend forecasting water availability, as it can help people to adjust the cultivation areas and develop plans to change the crop structures.

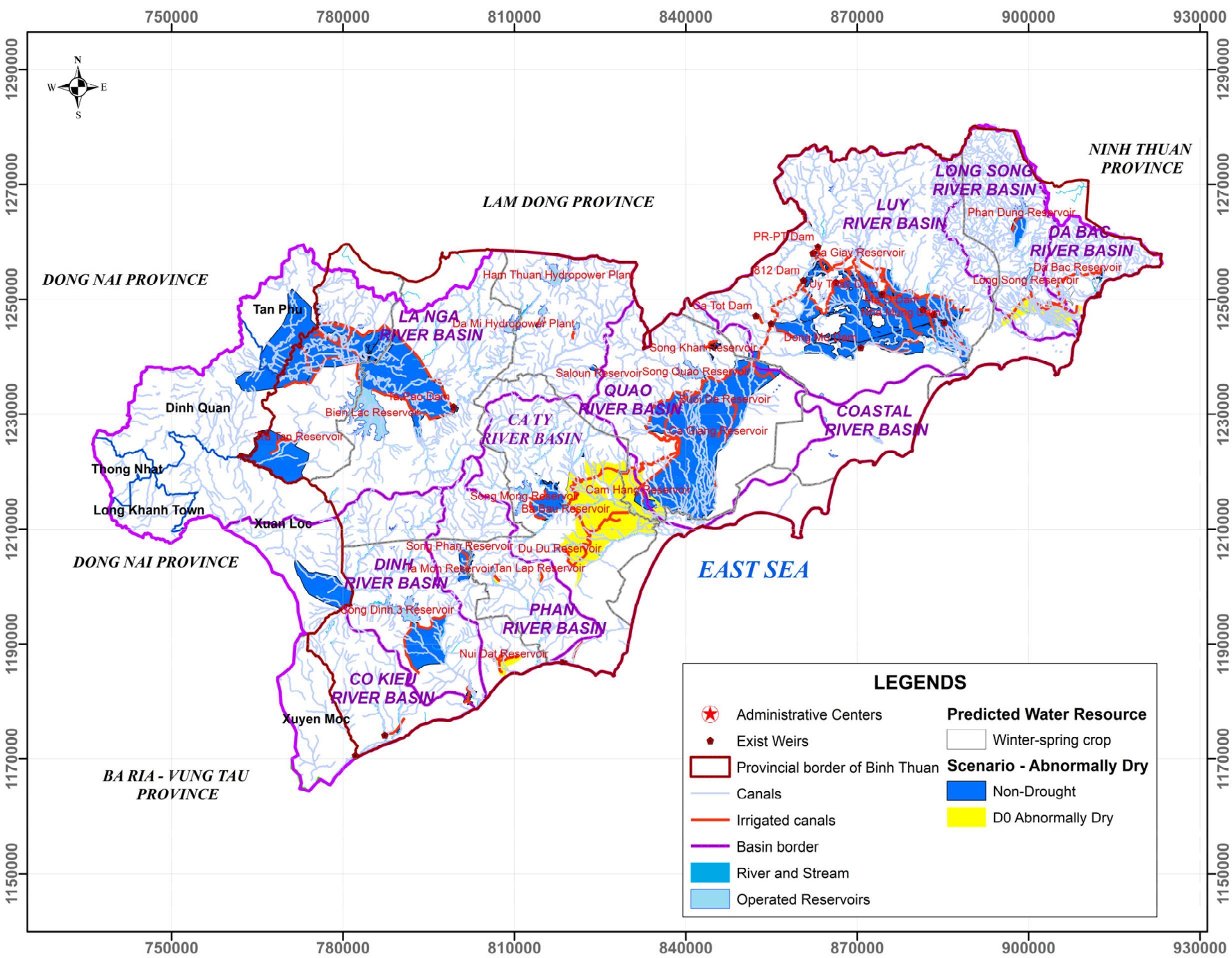

Figure 6. Areas projected to experience abnormally dry conditions during the winter–spring crop growing period.

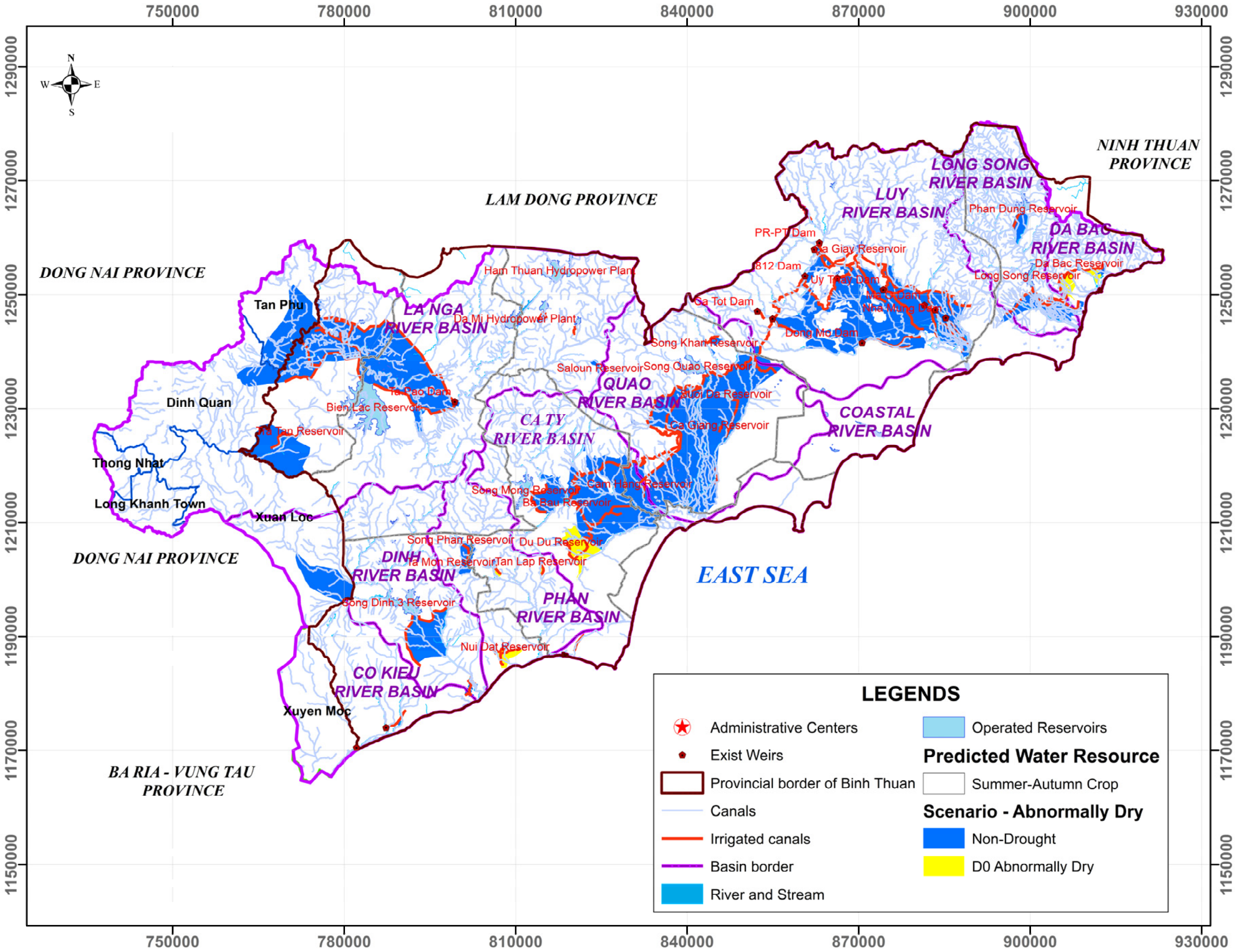

Figure 7. Areas projected to experience abnormally dry conditions during the summer–autumn crop period under two scenarios.

3.4.2. Moderate Drought Scenario

At the beginning of the winter–spring crop life cycle, 204 million m^3 of water or less is available in the reservoirs. The total rainfall is less than 35 mm in abnormally dry and moderate drought years. This implies that the water source meets 85% of the agricultural water demand. However, the water availability in some reservoirs at the beginning of the crop life cycle can only meet 25–35% of the irrigation needs (Figure 8). Reservoirs with additional water sources during the season can still ensure sufficient water supplies (e.g., Ca Giay reservoir). The water availability in the reservoir at the beginning of the summer–autumn crop life cycle is less than 60 million m^3, and the total rainfall is less than 450 mm in moderate drought years (Figure 9). This may lead to local droughts and water shortages in some reservoirs. However, reservoirs with supplementary water sources can remain productive during the season. As can be seen, the heavy reliance on reservoirs as the primary water sources for irrigation raises questions regarding the sustainability of this practice in the face of increasing water demand for agricultural, industrial, and domestic use.

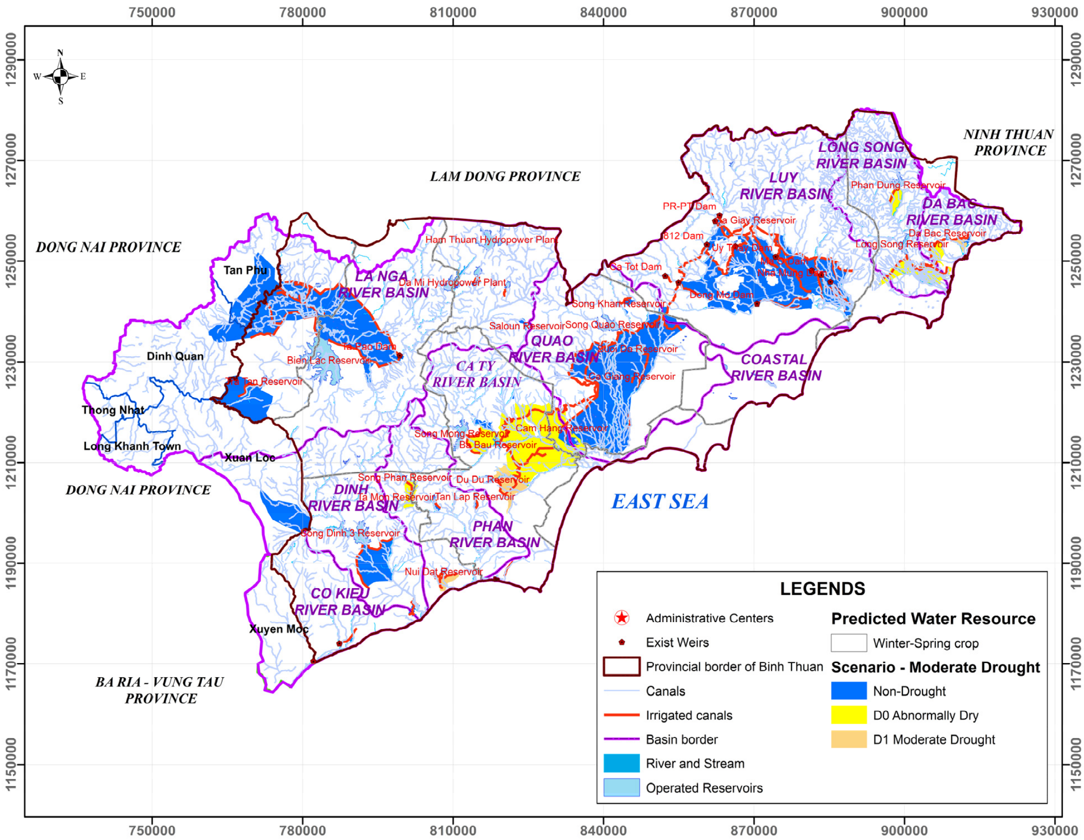

Figure 8. Areas projected to experience moderate droughts during the winter–spring crop period under two scenarios.

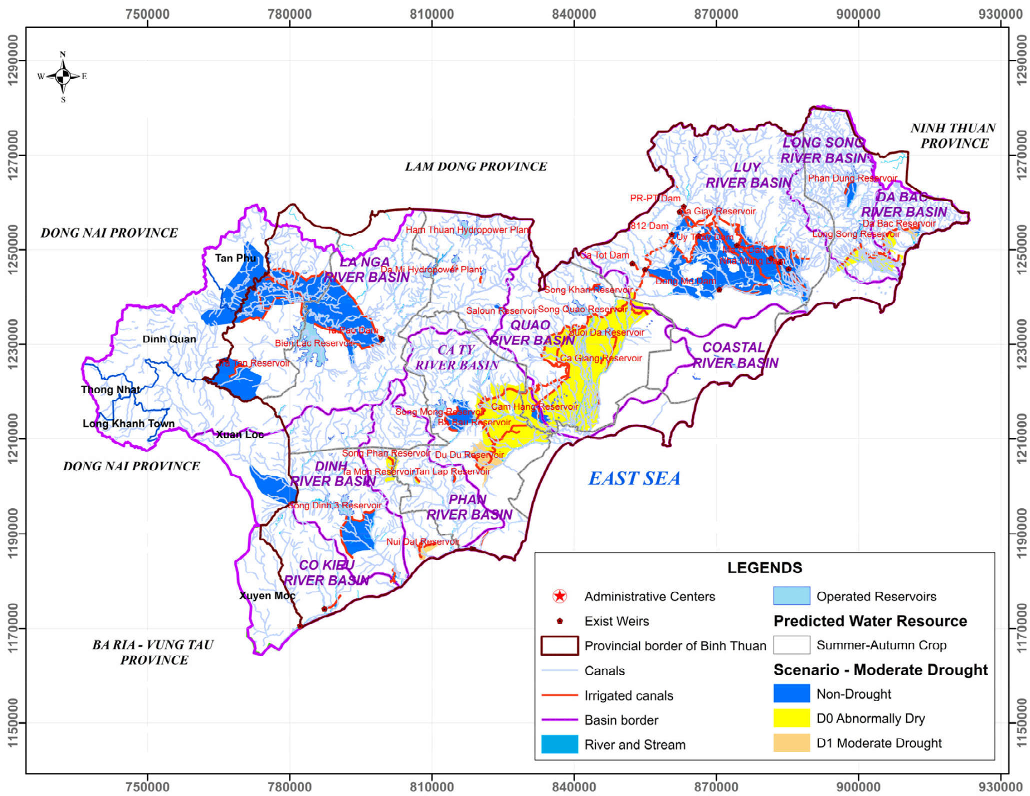

Figure 9. Areas projected to experience moderate droughts during the summer–autumn crop period under two scenarios.

3.4.3. Severe Drought Scenario

In the summer–autumn crop season, the reservoirs at the beginning of the crop life cycle contain less than 45 million m^3 of water, and the total rainfall is less than 400 mm in severe drought years. In these years, drought and lack of water are present in most reservoirs. During severe drought, the reservoirs at the beginning of the winter–spring crop life cycle contain less than 180 million m3 of water. The total rainfall in the summer–autumn crop season is less than 10 mm during years of moderate to severe drought. The water source meets 65% of the water demand. In some reservoirs, water availability at the beginning of the crop life cycle meets less than 25% of the water requirements for irrigation (Figure 10). Based on the results of the forecasts for drought occurrence and water source, local authorities in the affected areas should adjust the farming season or not allow crops to be grown.

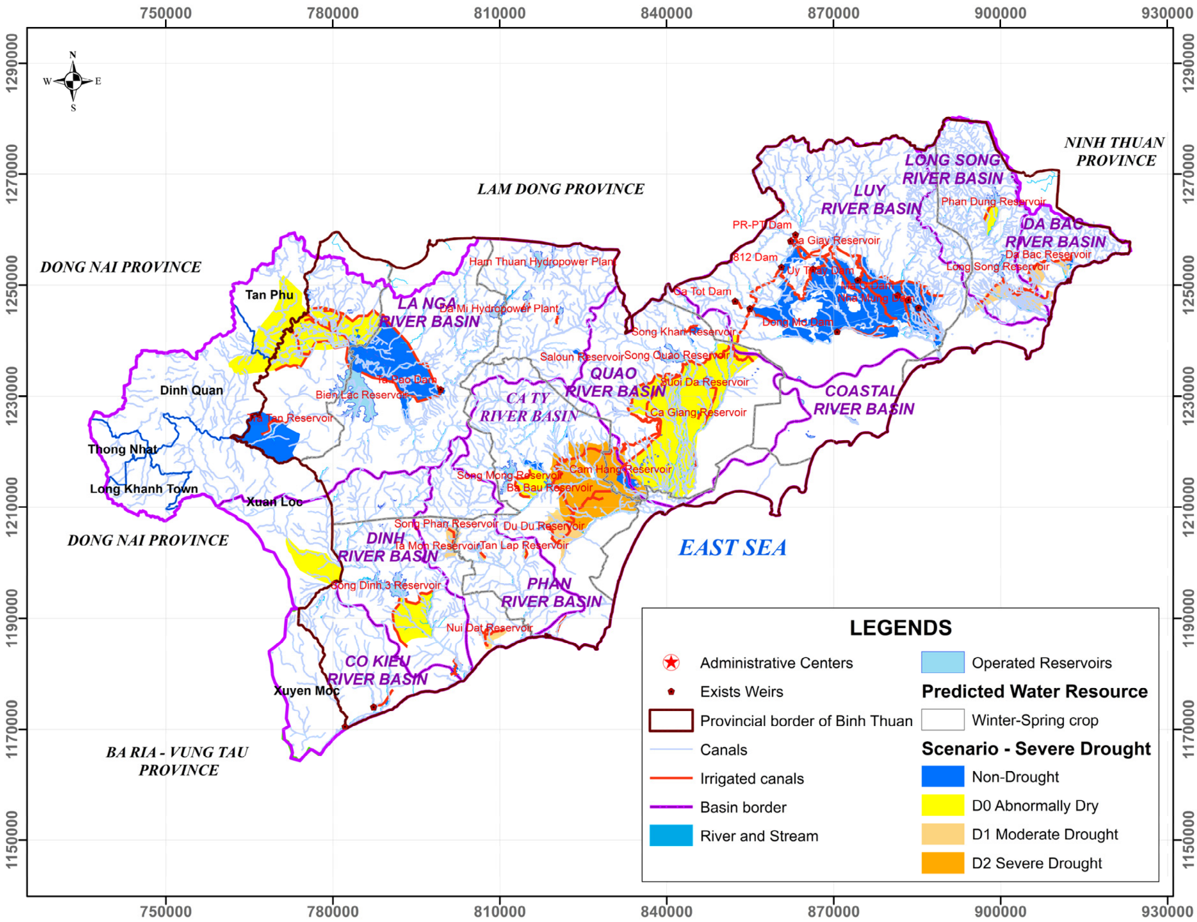

Figure 10. Areas projected to experience abnormally dry, moderate, and severe drought conditions during the winter–spring crop period.

Furthermore, the incoming water only meets 65% of the demand (Figure 11). At the beginning of the crop life cycle, it is necessary to plan production efficiently, adjust the season, and reduce the arable land area for reservoirs that can only meet 25–30% of the demand (e.g., Da Bac reservoir; Phan, Du Du, and Nui Dat Rivers). Preparing a backup pump system could reduce damage when a water shortage occurs.

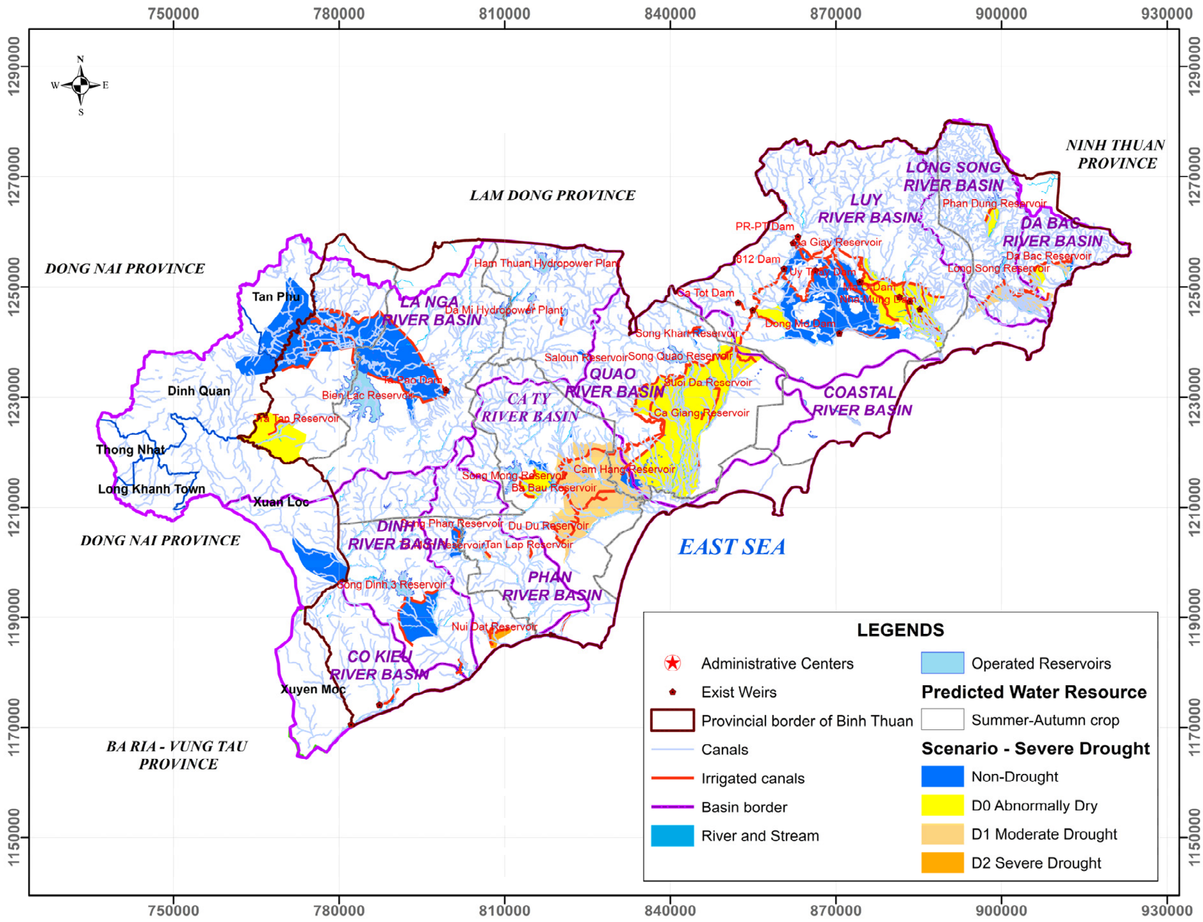

Figure 11. Areas projected to experience abnormally dry, moderate, and severe drought conditions during the summer-autumn crop period.

3.4.4. Extreme Drought Scenario

During an extreme drought (Figures 12 and 13), 160 million m^3 of water or less is available at the beginning of the winter–spring crop life cycle (Figure 12), and the total rainfall is less than 1 mm in severe and extreme drought years. Based on the results of the forecasts for drought occurrence and water resources, it is necessary to develop an efficient water use plan. The water source meets 50% of the water demand. The cropping area to be reduced compared to the program is 13,228 hectares. The water availability of some reservoirs at the beginning of the season can meet less than 20% of the water demand for irrigation. Some reservoirs, such as Mong, Quao, Phan, Da Bac, and Phan Dung, can supply water for domestic plants. This provides water for daily life and services for the population, then to livestock rearing, agricultural production, and other economic sectors. Preliminary calculations suggest that if an extreme drought occurs, the area affected by the drought and water shortages will be about 9344 hectares. For the summer–autumn crop (Figure 13), the water source for the reservoirs at the beginning of the crop life cycle consists of less than 25 million m^3, and the total rainfall is less than 300 mm in extreme drought years. With the drought, water shortage in most reservoirs, and the amount of incoming water only meeting 45% of the demand, the area must be reduced by nearly 17,000 hectares in comparison to the plan. From the beginning of the crop life cycle, it is necessary to plan production, adjust the season, and reduce the arable land area for reservoirs that can only meet 15–20% of the water demand.

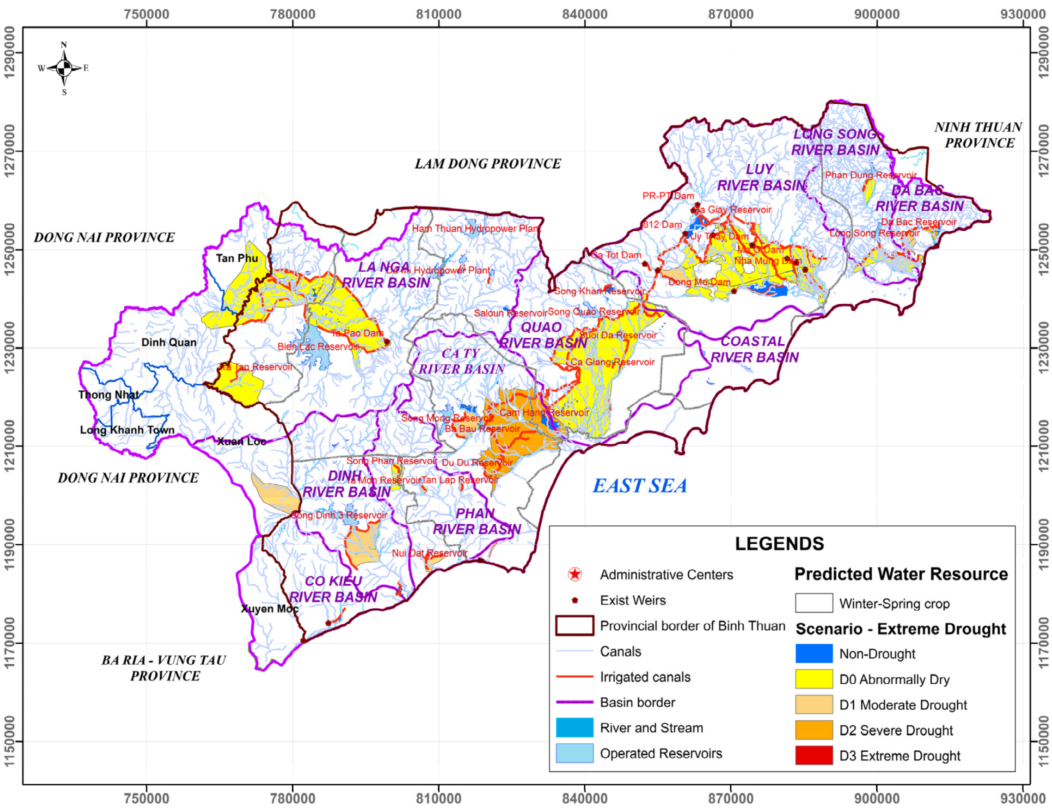

Figure 12. Areas projected to experience abnormally dry, moderate, severe and extreme drought conditions during the winter-spring crop period.

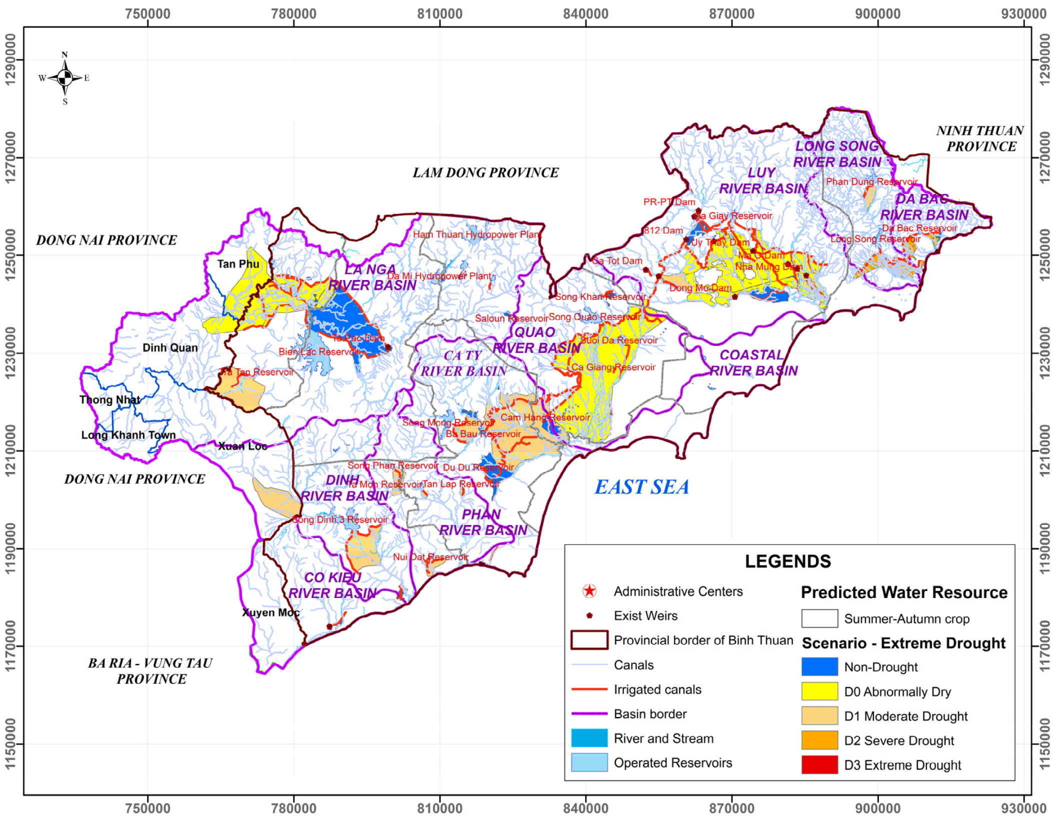

Figure 13. Areas projected to experience abnormally dry, moderate, severe and extreme drought conditions during the summer-autumn crop period.

The KBDI shows that droughts occur almost annually in the southeast provinces located in the south-central region (Binh Thuan, Dong Nai, and Ba Ria-Vung Tau provinces). The KBDI index at Dong Nai station from 2010 to 2018 shows that drought usually occurs from the end of January to the middle of May, while severe droughts typically happen in March and April. In 2010–2018, four relatively severe droughts (KBDI Index > 700) occurred for two consecutive months in the 2014, 2015, 2017, and 2018 dry seasons. In addition, the KBDI drought index shows that in the 2019 dry season, drought occurred unevenly in terms of space and time regions. The drought started in January and ended in May 2019, and the most significant drought occurred in March and April. In the northern and western areas, the drought appeared earlier, but also ended earlier than in the southern and eastern areas of the study area, with severe drought in the Binh Thuan, Dong Nai, and Ba Ria-Vung Tau provinces.

3.5. Assessing the Response of the Irrigation System to Different Drought Scenarios

Under the abnormally dry scenario (p = 50%), water is available for irrigation throughout the entire crop life cycle. However, drought occurs in some small reservoirs where the water source for winter–spring crops is guaranteed. Some areas of the Cam Hang and Du Du reservoirs experience abnormal and moderate droughts. For the summer–autumn cropping period, the incoming water source ensures the water use demand. Water shortage only occurs at the beginning of the Long Song reservoir season (June with a 75% response rate). The irrigation system of Phan Ri-Phan Thiet and Ta Pao dam ensures that 100% of the area is irrigated during each season (no drought). In the moderate drought scenario (p = 75%), some reservoirs in the winter–spring crop period experience abnormal drought conditions, such as the Da Bac reservoir, which lacks water at the beginning of the crop life cycle. For the Cam Hang reservoir, the amount of water at the beginning of the crop life cycle is only 26% compared to the requirement.

It has also been observed that abnormally dry and moderate droughts have occurred between February and April for many years. The Du Du reservoir reaches 32% compared to the requirement for a moderate water shortage from January to March. Moreover, abnormal drought is observed in the Nui Dat reservoir during March and April. The Ba Bau reservoir has only 28% of the required water at the beginning of the season, but the amount of water meets the irrigation demand. In the summer–autumn cropping season, some reservoirs have only 40–50% of the required water at the beginning of the season, but the amount of water can meet the demands because of rainfall. The Phan River reservoir has a mild water shortage at the beginning of the crop life cycle, with a supply rate of 56%. The Phan Ri-Phan Thiet irrigation system and the Ta Pao dam meet 100% of the irrigation demand in the moderate drought scenario. In the severe drought scenario (p = 85%), 188.05 million m^3 of water is available in the reservoirs at the beginning of the winter–spring crop life cycle. However, this decreases to 124.90 million m^3 by the end of January.

The water availability of the Cam Hang reservoir at the beginning of the cropping period is only 24% compared to the requirement. This amount of water is only enough for December and January. From February to April, a moderate to severe drought occurs. The Du Du and Nui Dat reservoirs experience an abnormally dry to moderate drought from January to April. The Quao reservoir requires more water to provide to the Phan Thiet water supply plant for domestic purposes. The Ba Bau reservoir has a moderate drought from December to January and a severe drought from February to April. The response rate is less than 40% of the requirement. The Phan Ri-Phan Thiet irrigation system can ensure that 80% of the water demand for the crop is met, and the Ta Pao dam can provide more than 90% of the water demand for the crop in the abnormally dry scenario. In the summer–autumn crop season, the Cam Hang, Du Du, and Nui Dat reservoirs need their capacity to meet the crop water demand to be improved. The Song Phan reservoir has a slight water shortage at the beginning of the summer–autumn cropping season, with a supply rate of 50%. The Nui Dat reservoir experiences moderate and severe drought in May, June, and July.

The Phan Ri-Phan Thiet irrigation system can meet all the required water demands for cropping during abnormally dry conditions, although this decreases to 76% for the Ta Pao reservoir. For the extreme drought scenario (p = 95%), the total capacity of irrigation reservoirs at the beginning of the winter–spring crop reaches 164.21 million m^3. By the end of January, only 75.90 million m^3 can be supplied. At the beginning of the cropping season, there are water shortages in the Da Bac, Ca Giay, and Ba Bau reservoirs. The reservoirs' water supplies are only able to meet the demand at the beginning of the cropping between December and January of the following year. From February to April, there is moderate to severe drought. In the extreme drought scenario, there is no rain at all. The amount of water at the end of the crop life cycle in March is about 51.41 million m^3. The Ba Bau, Du Du, and Ca Giay reservoirs can meet about 15%, 22%, and 31% of the water demand. The Song Mong and Song Quao reservoirs can ensure that the water demand is met for irrigation and domestic use. Moreover, the Song Quao reservoir can provide sufficient water for the domestic demand of the Phan Thiet water plants. Most small reservoirs experience severe droughts between January and April.

In the summer–autumn cropping season, the Cam Hang, Du Du, and Nui Dat reservoirs must improve their capacities to meet the water demand for cropping. The Phan River reservoir needs more water at the beginning of the summer–autumn cropping season, as its response rate is less than 50%. The Nui Dat reservoir experiences moderate and severe droughts in May, June, and July. In this scenario, in two seasons, the irrigation system of Phan Ri-Phan Thiet is 75% guaranteed, and abnormally dry conditions occur at Ta Pao dam (80% and 76%, respectively) (Table 7). However, moderate droughts can occur in the summer–autumn cropping season.

Table 7. Production plan.

No	Construction or Construction Group	Scenario Responsiveness							
		Winter–Spring				Summer–Autumn			
		Abnormally Dry	Moderate Drought	Severe Drought	Extreme Drought	Abnormally Dry	Moderate Drought	Severe Drought	Extreme Drought
I	Reservoir system								
1	Long Song	88%	100%	75%	65%	100%	100%	40%	12%
2	Da Bac	85%	65%	56%	40%	80%	65%	20%	11%
3	Phan Dung	100%	100%	100%	100%	100%	100%	100%	100%
4	Ca Giay	100%	75%	41%	32%	100%	64%	41%	15%
5	Song Quao	100%	100%	78%	73%	100%	79%	79%	75%
6	Suoi Da	100%	86%	86%	80%	100%	86%	84%	81%
7	Khan	100%	100%	100%	100%	100%	100%	100%	100%
8	Ca Giang	100%	100%	74%	71%	100%	100%	100%	77%
9	Mong	100%	100%	100%	100%	100%	100%	100%	100%
10	Cam Hang	40%	28%	24%	23%	60%	28%	35%	22%
11	Ba Bau	100%	85%	25%	15%	100%	100%	45%	35%
12	Du Du	42%	32%	31%	22%	51%	32%	30%	29%
13	Phan	100%	100%	86%	76%	100%	100%	25%	22%
14	Tan Lap	100%	76%	71%	69%	100%	76%	65%	65%
15	Ta Mon	100%	95%	81%	73%	100%	85%	77%	55%
16	Nui Dat	100%	65%	65%	63%	100%	65%	24%	20%
17	Dinh 3	100%	100%	100%	100%	100%	100%	100%	100%
18	Tra Tan	100%	100%	100%	100%	100%	100%	72%	65%
II	Weir system								
1	Phan Ri-Phan Thiet	100%	100%	80%	75%	100%	100%	100%	75%
2	Ta Pao	100%	100%	90%	80%	100%	100%	76%	76%

The average annual flow across the region is 0.025 m^3/s, with surface water resources in the study area comprising 25.3 billion m^3. This water source is relatively abundant, but needs to be more evenly distributed. In the dry season, the water can dry up. In the rainy season, floods can occur and cause loss of human life, destruction of crops, and loss of livestock. In some places, severe water shortages cause drought and a lack of water for production and daily life.

The water supply for the domestic, agricultural, and industrial sectors in 2017 was 9.0 billion m^3, accounting for 21.7% of the total annual flow. Agricultural production, domestic use, and industry accounted for 77.3% (cultivation, 65.6%; fishery, 11.6%), 8.4%, and 14.0% of the water supply, respectively. Considering climate changes, the results of the expected water demand by 2030 show that the total water demand will be about 13.42 billion m^3, which represents an increase of about 4.35 billion m^3 compared to the water demand in the year 2017. The agricultural sector accounts for much of the water use in the basin. Compared with the water available in the basin, the water demand for agriculture by 2030 will account for about 29.75% of the water use requirements. The water balance results of the current situation in 2017 show that in the dry season, most river basins experience water shortages. The water shortage in the region is about 1.35 billion m^3. This water shortage is mainly concentrated in the Tay Ninh, Saigon River, and coastal sub-basins. The prediction results of the water balance by 2030 under climate change show that the planned constructions, namely, the Dong Nai River and La Nga 3 reservoir works and the Ta Pao and Vo Dac irrigation systems, can help to improve the water supply systems in some sub-basins, especially upstream sub-basins. Although large reservoirs exist, the water supply is insufficient to meet the high demand. As a result, water shortages can occur in some drought years, especially for the sub-basins of the Saigon River and the coastal river basin because this area has limited storage facilities, unlike upstream regions.

The study demonstrates the feasibility and high applicability of using the MIKE HYDRO BASIN model and KDBI drought index to assess water resource management in Binh Thuan Province. The successful calculation of the KDBI's potential application in monitoring drought and predicting crop yield has previously been demonstrated in the Greater Mekong sub-region; the central highland regions of Vietnam; and neighboring countries, including Indonesia [47–51]. The findings of this study can potentially improve the identification and monitoring of drought conditions in Binh Thuan Province, and can provide an example for other studies in other regions affected by droughts and water availability constraints. With the latter, decision makers and stakeholders, including farmers and water resource managers, can more effectively plan and arrange for the cultivation of different crops when droughts are forecast, eventually establishing a rational irrigation plan. Moreover, the research could assist the irrigation department in determining the water supply capacity and the percentage of water deficit required to enhance their irrigation system, reservoirs, pumping stations, and canals, thus raising awareness for future investments in water infrastructure.

Despite the model's excellent performance, it is essential to acknowledge that limitations and uncertainties remain. Specifically, this study only accounts for surface water calculations and does not include groundwater. Additionally, the study focused on one drought index to assess the extent of the droughts. Other drought indices representing meteorological, hydrological, and agricultural droughts, such as the standardized precipitation index (SPI), standardized precipitation evapotranspiration index (SPEI), standardized runoff index (SRI), and the standardized soil water index (SSWI), could be examined as an extension to this study, in addition to assessing drought frequency and probability using artificial intelligence (AI) models.

As for all numerical models, there are uncertainties associated with the use of the MIKE MYDRO BASIN model, most notably in the model structure, the assumptions that the model makes, the values of the model parameters even after calibration [52–54], and the accuracy of the input data [52]. Furthermore, there are uncertainties regarding the use of the regional climate model and climate change scenarios [54]; modeling more than just uncertainties could lead to a solution that meets the need for irrigation water by 100% and 75–80% during moderate to extreme drought. Nonetheless, the results indicate that water shortages will occur in some drought years, but uncertainties are associated with future GHG emissions and the climate system's response to them [55]. However, this problem was previously solved using two greenhouse gas emission scenarios, including the lower and upper boundaries of projected future emissions.

4. Conclusions

Water shortages and the allocation of water resources are major issues in the southeast region of Vietnam, especially in the Luy-Nga River basin, where water resources are not evenly distributed in space and time and where droughts are a recurrent problem during the dry season. This study shows the predicted recurrence of abnormally dry and drought conditions in the basin until 2030, as well as the resilience of existing allocations of water resources, based on two climate change scenarios. Under unusually dry conditions, 100% of the water needs during both annual crop cycles can be met. However, this rate decreases to 85–100% during a moderate drought. Severe and extreme droughts, common in the east and northeast of the basin, reduce the percentage of the water demand for irrigation that can be met to 65% and 45–50%, respectively, albeit with some reservoirs meeting only 15–40% of the demand. The water availability will increase when the La Nga 3 reservoir and Ta Pao Vo Dac irrigation systems are completed.

This study demonstrates that improving water resources management can meet the need for irrigation water by 100% and 75–80% during moderate to extreme drought, respectively. It will act as the basis for developing and expanding approaches to water resource management in other rivers in the southeast region, helping to stabilize agricultural production, changing the structure of crops suitable for water resources in harsh weather conditions, and reducing the costs and damage caused by droughts.

Author Contributions: Conceptualization, V.N.D.; methodology, T.L.V., V.N.D., D.T.A. and P.N.T.; software, T.L.V., V.N.D., T.H.N. and N.T.P.; validation, V.N.D., D.T.A. and A.S.G.; formal analysis and data curation, V.N.D., T.T.M., T.H.N., N.T.P. and P.N.T.; investigation and resources, V.N.D., T.L.V.; T.T.M. and T.H.N.; writing—original draft preparation, V.N.D., P.N.T., D.T.A., P.D., A.S.G., Q.B.P. and W.L.; writing—review and editing, Q.B.P., D.T.A., W.L., P.D. and A.S.G.; visualization, N.T.P., P.N.T., W.L. and Q.B.P.; supervision and project administration, V.N.D. and D.T.A.; funding acquisition, V.N.D. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: Not applicable.

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Data Availability Statement: The datasets generated and analyzed in this study are available from the corresponding author upon reasonable request.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

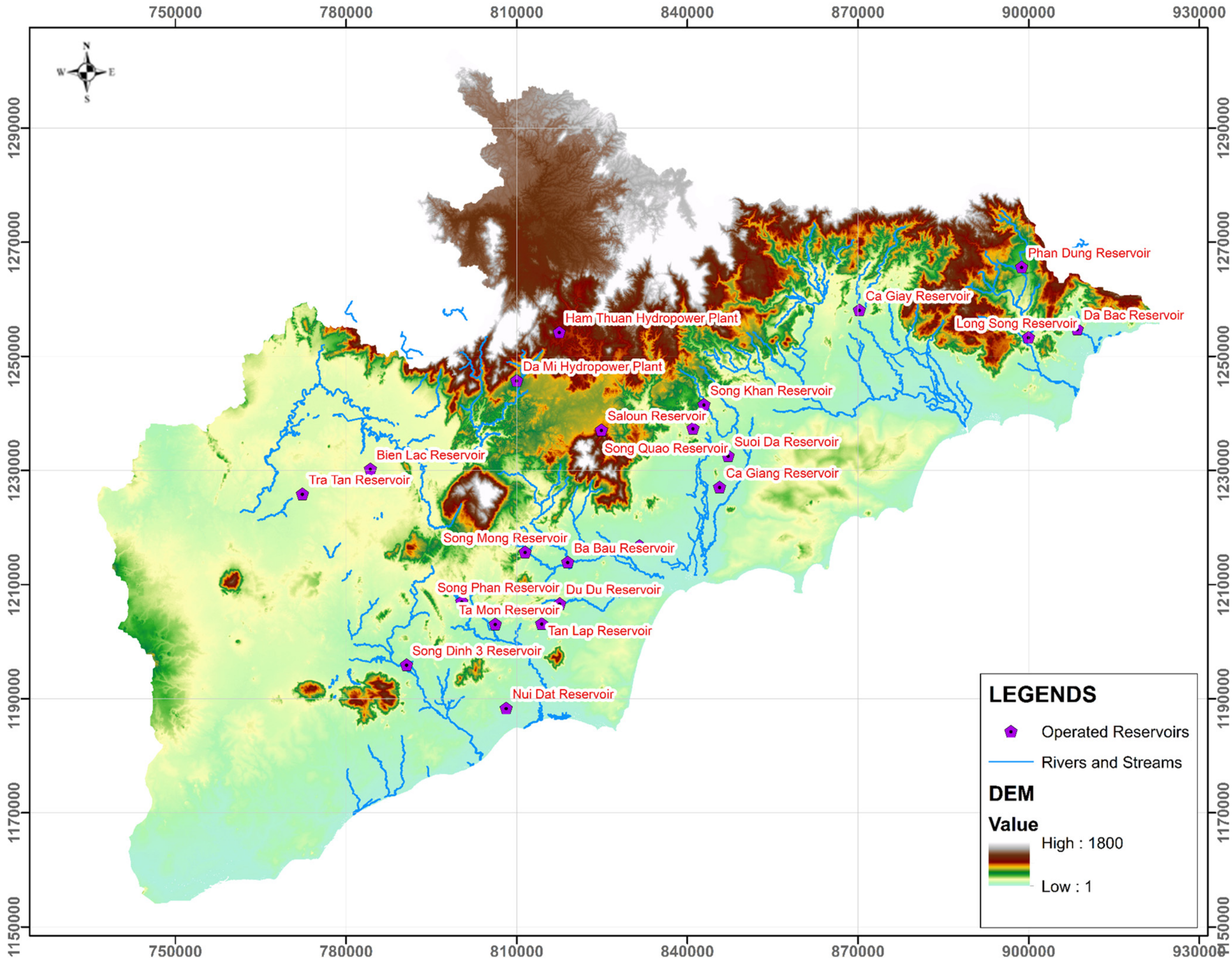

Figure A1. Digital elevation model (DEM) and location of critical reservoirs in the La Nga and Luy river basin of Binh Thuan Province.

Table A1. Drought scenario corresponding to rainfall frequency.

Case	Rainfall Frequency	Drought Scenario
Water shortage	<50%	No drought
Less water	From 50% to less than 75% From 75% to less than 85% From 85% to less than 95% Over 95%	Abnormally dry Moderate drought Severe drought Extreme drought

Table A2. Water use rates of different sectors in a sustainable development scenario (1000 m^3).

Year	Water Demand (Million m^3)	Ratio to Current	Cash Crop	Aquaculture	Domestic	Industry
2017	**9068.698** 100%	100%	5952.89 65.6%	1056.16 11.6%	762.83 8.4%	1296.81 14.0%
2030	**13,418.875** 100%	148%	8845.23 65.9%	969.34 7.2%	1327.89 9.9%	2276.39 17.0%

Table A3. Projected changes in mean annual temperature and total annual precipitation for different 20-year periods compared to the 1986–2005 period for RCP4.5 and RCP8.5.

Variable	RCP4.5			RCP8.5		
	2016–2035	**2046–2065**	**2080–2099**	**2016–2035**	**2046–2065**	**2080–2099**
Temperature	0.70 °C (0.4–1.3)	1.3 (0.9–2.1)	1.7 (1.1–2.6)	0.8 (0.5–1.2)	1.8 (1.3–2.6)	3.2 (2.7–4.1)
Rainfall	18.4% (8.3–28.0)	21.5 % (13.5–30.1)	23.2 % (13.4–33.2)	16.0 % (6.6–25.8)	17.8 % (6.2–28.9)	21.5 % (11.8–31.2)

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