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Assessment of Climate Change Impacts on the Water, Food, and Energy Sectors in Sittaung River Basin, Myanmar

Uttam Ghimire [1,*], Thanapon Piman [1,2], Manish Shrestha [3], Anil Aryal [4] and Chayanis Krittasudthacheewa [1,2]

1 Stockholm Environment Institute, Asia Center, Chulalongkorn University, Bangkok 10330, Thailand
2 Environmental Research Institute, Chulalongkorn University, Bangkok 10330, Thailand
3 International Centre for Integrated Mountain Development, Lalitpur 44700, Nepal
4 Water Engineering and Management, Asian Institute of Technology, Pathum Thani 12120, Thailand
* Correspondence: uttam.ghimire@sei.org

Abstract: The Sittaung river basin (SRB) remains one of the least studied basins of Myanmar in terms of the assessment of the impact of climate change. As several reservoirs already exist in the basin, much research is needed to understand how projected climate change impacts rainfall, temperature, flows, domestic and agricultural demands, and hydropower generation. Given the limitation in observed data on the ground, a combination of satellite-derived meteorological data and digital elevation data is used to generate inputs to a Water Evaluation and Planning (WEAP) model. Five CMIP5 GCMs are used in the WEAP to assess the impact of climate change on the water, food, and energy production of the SRB for the baseline (BL: 1985–2014), near future (NF: 2021–2050), and far future (FF: 2051–2080) periods. The results indicate that the average temperature and rainfall are likely to increase in the future for the SRB. December and January are expected to be drier and warmer, whereas rainy months are expected to be wetter and warmer in the future. The BL flows (1091 m^3/s) are expected to increase by 7–10% during NF and by 16–19% during FF at the basin outlet. Meanwhile, the unmet domestic demand during BL (1.3 MCM) is expected to decrease further by approximately 50% in the future. However, the unmet agricultural demand (667 MCM) for food production is estimated to increase from the BL by 11–15% during NF and by 14–19% during FF. Similarly, the total energy generation of nine hydropower projects (4.12 million MWh) is expected to increase by 9–11% during NF and by 16–17% during FF. Thus, the riverine flows are expected to increase in the future, thus positively impacting the domestic and hydropower sectors, whereas the unmet demands in the agricultural sector likely remain unsatisfied. These results will help the water, agriculture, and energy sectors to develop strategies to maximize benefits and cope with the impacts of climate change in the near and long-term future.

Keywords: climate change; Myanmar; Sittaung river basin; WEAP; water–food–energy

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1. Introduction

Myanmar has been identified as one of the most vulnerable countries to the extreme shifts in climate [1–4]. Climate change impacts many sectors, such as water resources, agriculture, health, energy, and the ecosystem [5,6]. Thus, the possible impacts of climate change must be understood for the proper adaptation and mitigation plans for any geographical region [4]. Myanmar is projected to experience an increase in average temperature from 23.3 °C in 1986–2005 to 24.4 °C (24.5 °C) and 25.1 °C (26.0 °C) in 2021–2050 and 2051–2080, respectively, under representative concentration pathways (RCP4.5 and RCP8.5) emission scenarios of the multi-model ensemble of Coupled Model Intercomparison Project 5 (CMIP5) global climate models (GCMs) [7]. Similarly, the annual rainfall of the country is expected to increase from 1375 mm to 1449 mm (1419 mm) and 1507 mm (1500 mm) in 2021–2050 and 2051–2080, respectively, under RCP4.5 (RCP8.5) scenarios. Ayeyarwady, the largest river basin in the country, is likely to experience an increase in flows by 8.0–45.0%

in the future [8], which is expected to translate into significant floods [9] and can impact existing agriculture practices [10]. The Chindwin River basin is also expected to experience floods and morphological changes in the future under climate change scenarios [11]. The Salween (Nu) river basin is also reported to experience an increase in flows under climate change scenarios [12]. The impacts of climate change have been thoroughly studied in many river basins in Myanmar, including Ayeyarwady [8,9,13–15], Chindwin [11,16–19], Bago [18,20–23], and Salween [12,24–27]. However, the Sittaung river basin (SRB), the fourth major river in the country [28], remains the least researched basin for climate change impacts on water resources, agriculture, and energy compared with the other major river basins. Yamashita and Aung [29] used a single climate model and a hydrological model to estimate flows for 22 years (2014–2035) and reported that floods are likely to increase in the future in the basin. Similarly, Kyi et al. [30] estimated the projected changes in rainfall in the SRB using an ensemble of five CMIP5 GCMs and reported that rainfall in the future (2046–2061) is expected to increase by 14.7% compared with the baseline (1990–2005). An assessment of climate change impacts on agriculture water uses and hydropower energy production has yet to be conducted in the basin.

The primary reason for the lack of research on the SRB is the unavailability of long-term meteorological and hydrological data [29,31,32]. This limitation also poses a challenge for the statistical downscaling of climate change variables such as rainfall and temperature in the basin. Myo Lin et al. [31] and Yamashita and Aung [29] used TRMM 3B42 [33] satellite-estimated rainfall data for hydrological modeling in the SRB. Similarly, Kyi et al. [30] performed the calibration and validation of the Rainfall Run-off Inundation (RRI) model for the Sittaung basin using surface-observed information for 2012–2015 only. In addition, the Asian Precipitation—Highly-Resolved Observational Data Integration Towards Evaluation (APHRODITE) rainfall and temperature datasets [34,35] have been used in multiple studies in Myanmar [36–38]. However, their usage in the SRB has not been reported. APHRODITE data are available for a relatively long period (1951–2015) at a 0.25° spatial resolution and could be a potential data source to complement the scarce meteorological information in the basin. Additionally, 21 reservoirs exist within the SRB, with a total estimated storage capacity of 7100 million cubic meters (MCM) [32]. Several hydropower and irrigation reservoirs either exist or are planned in the SRB in its Paung Luang, Ka Baung, Chaung, Taung Ye Khat, Phyu Chaung, Kun Chaung, Shwegyin, Ye New, Bawgata, and Bilin tributaries [39]. The information on the storage change, inflows, outflows, and rule curves of these reservoirs is not available to the public, thus limiting the capability of water resources and hydropower modeling in the SRB. To overcome this limitation, the Water Evaluation and Planning (WEAP) model [40] can help by simulating reservoirs and hydropower generation using a relatively small set of data. Several studies [41–43] have used the digital elevation model (DEM) of the Shuttle Radar Topography Mission (SRTM) to generate information on the reservoir area elevation volume with satisfactory accuracy in data-limited regions. Moreover, studies have used the model further in hydrological applications. Thus, the ability of techniques incorporating satellite data (DEM) to capture the reservoir influences in riverine flows of the SRB satisfactorily must be verified.

The SRB is home to approximately 10% of the country's total population, of which 30–40% are engaged in rice farming [44]. Livelihoods in the lower part of the basin are highly dependent on natural resources, with mostly wetlands, including marshes, mangroves, mudflats, and oxbows, characterizing the region. The agriculture sector has substantial unexploited potential, which can add value to the country's economic development and food security [45]. However, climate changes are expected to impact agriculture in the region negatively [46]. Similarly, the coverage of safe drinking water in Myanmar was reported to be very low compared with the global standards set by the Water Environment Partnership in Asia [47]. The National Water Resources Committee in Myanmar adopted the National Water Framework Directive in 2014, whose first principle is to achieve "good status" for all ground and surface water as clean and sufficiently stored water in the country [48]. Thus, further research is necessary to determine whether local water supplies in the SRB are sufficient under changing climates [49,50]. Hydropower is considered to have a large untapped potential in Myanmar [51], which is directly impacted by the changes in rainfall and flows to the reservoirs. Presently, the potential impacts of climate change on hydropower and energy generation in the SRB are unknown. Normally, the impact assessments of climate change on water, food, and energy have been studied separately [52,53] and lack an integrated approach [54,55]. Similarly, the majority of these assessments pertain to the river basins, where most of the data are available [56–58]. Therefore, this study aims to assess the impact of climate change on the water, food, and energy in the SRB by using an integrated approach of a hydrological model, remote sensing, and GIS techniques to fill the knowledge gaps and address the limitation in the long-term observed hydro-met information and reservoir characteristics to improve planning and management in the water, agriculture, and energy sectors for climate change adaptation.

2. Methodology

2.1. Study Area

The SRB drains a cumulative area of 34,195 km^2 to the flow station Madauk in the central-southern part of Myanmar (Figure 1). Bound within the geographic domain of 95.17–97.2° E longitude and 17.27–20.58° N latitude, it is surrounded by the forested mountains of Bago in the west and the steep Shan Plateau in the east. It lies between the lower Ayeyarwady and the Thanlwin rivers and has an average flow of 1000 m^3/s [39]. Of the total river reaches, 82% lie in the broadleaf forest region at a low elevation and floodplains, 13% lie in the dry broadleaf forest region with floodplains and sediment, and 5% lie in the low-elevation karst region [39]. The river is navigable throughout the year for 40 km in the dry season and 90 km during the rainy season. In the coastal zone, the Sittaung river meets the Gulf of Mottama, resulting in the Sittaung estuary region with powerful tidal surges and coastal erosion [59]. Vilder [60] reported that annual rainfall in the basin ranges from 889 to 3810 mm, with low rainfall in the upper parts and high rainfall in the lower part (Supplementary Figure S1).

2.2. Data Used

To assess the impacts of climate change on flows, hydropower production, domestic water demands, and agricultural water demands for food production, large amounts of data are required. Monthly observed data for rainfall, temperature, relative humidity, wind speed, solar radiation, and flows for the baseline period are needed for the calibration and validation of the hydrological model. Moreover, the reservoir's physical characteristics, including latitude, longitude, storage capacity, commissioning date, area elevation curves, top of the conservation zone, top of the inactive zone, buffer coefficient, top of the buffer zone, maximum turbine flow, tailwater elevation, plant factor, and generation efficiencies, are necessary to simulate the hydropower potential. To estimate the domestic demands, the per capita water usage characteristics and the historical and future population are required. To estimate agricultural demands, land use data that categorize rainfed and irrigated lands are needed with a crop calendar for major crops within the basin. A 30 m SRTM digital elevation model was used for the basin delineation and the estimation of reservoir characteristics. The sources of data used in this study are presented in Table 1.

Table 2 presents information on the observed rainfall and flow locations and the reservoirs used in this study. The rainfall and flow information for the corresponding periods was taken from an operational flood forecasting system developed for Myanmar [61]. The meteorological and hydrological data were collected at a monthly time step.

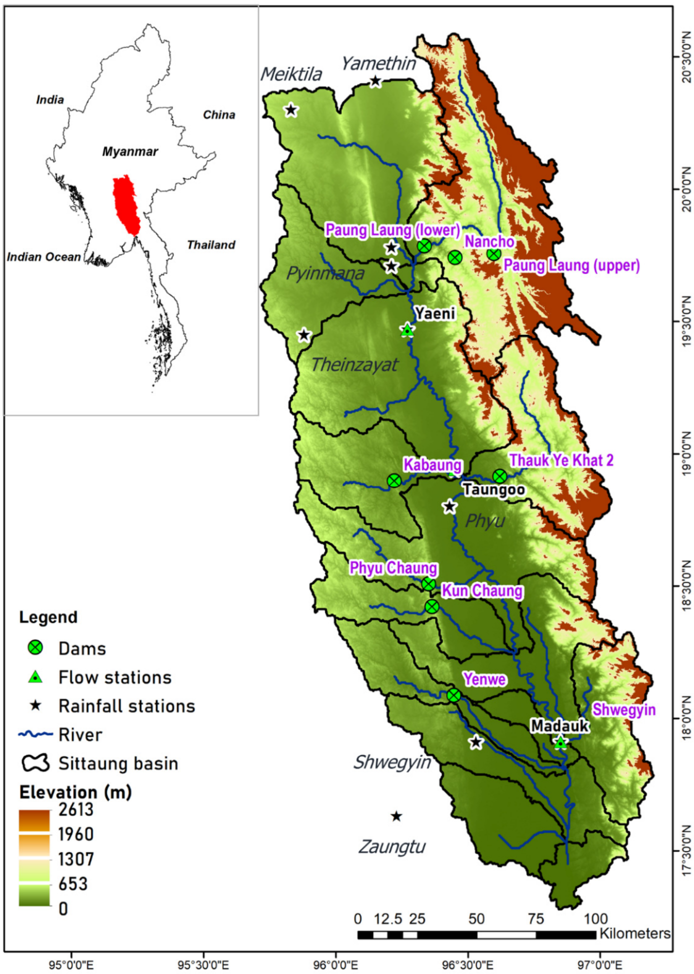


Figure 1. Sittaung river basin and the location of rainfall, discharge stations, and dams in the study area.

Table 1. Data used in this study and their sources.

Data	Type	Source	Reference
Rainfall	Observed	Department of Meteorology and Hydrology, Myanmar	Agarwal et al. [61]
	Gridded	APHRODITE	Yatagai et al. [35]
Flows	Observed	Department of Meteorology and Hydrology, Myanmar	Agarwal et al. [61]
Temperature	Gridded	APHRODITE	Yatagai et al. [35]
Relative humidity	Gridded	Climate Forecast System Reanalysis (CFSR)	Saha et al. [62]
Wind speed	Gridded	CFSR	Saha et al. [62]
Solar radiation	Gridded	CFSR	Saha et al. [62]
CMIP5 GCMs	Gridded	The Earth System Grid Federation (ESGF) data portal	Cinquini et al. [63]
Land use	Gridded	European Space Agency	Arino et al. [64]
Domestic water consumption	Discrete	Japan International Cooperation Agency (JICA) report 2019	Japan International Cooperation Agency [65]
Crop calendar	Discrete	A Master's Thesis in the Bago-Sittaung region	Phue and Chuenchooklin [66]
Digital elevation model	Gridded	Shuttle Radar Topographic Mission (SRTM)	Yang et al. [67]
Reservoir Physical information	Discrete	Strategic Environmental Assessment report	International Finance Corporation [68]
Reservoir Area/Volume Elevation Curve	Discrete	Estimated using SRTM and python scripting	Biswas et al. [42]

Table 2. Location of hydro-met stations and reservoirs used in the SRB.

Hydro-Met Stations				
Station	**Lat.**	**Lon.**	**Type**	**Data Period**
Taungoo	18.94	96.45	Rainfall, Flow	2000–2013
Madauk	17.91	96.85	Rainfall, Flow	2000–2013
Meiktila	20.30	95.83	Rainfall	2000–2013
Yamethin	20.41	96.15	Rainfall	2000–2013
Pyinmana	19.71	96.21	Rainfall	2000–2013
Phyu	18.48	96.43	Rainfall	2000–2013
Dothaung	18.80	96.43	Rainfall	2000–2013
Shwegyin	17.91	96.53	Rainfall	2000–2013
Theinzayat	19.45	95.88	Rainfall	2000–2013
Yezin	19.78	96.21	Rainfall	2000–2013
Yaeni	19.47	96.27	Flow	2000–2013
Reservoirs				
Project (Type)	**Lat.**	**Lon.**	**Storage cap (MCM)**	**Commission Year**
Kabaung (MP)	18.90	96.22	1468	2008
Kun Chaung (MP)	18.42	96.36	1467.8	2012
Nancho (HP)	19.74	96.45	9	2013
Lower Paung Laung (MP)	19.79	96.34	690	2005
Upper Paung Laung (HP)	19.76	96.60	1286	2015
Phyu Chaung (MP)	18.51	96.35	779.57	2015
Shwegyin (HP)	17.97	96.94	2080	2011
Thauk Ye Khat 2 (HP)	18.91	96.62	444.06	2014
Yenwe (HP)	18.09	96.45	149.38	2007

2.3. Methodology

The overall methodology adopted in this study is presented in Figure 2.

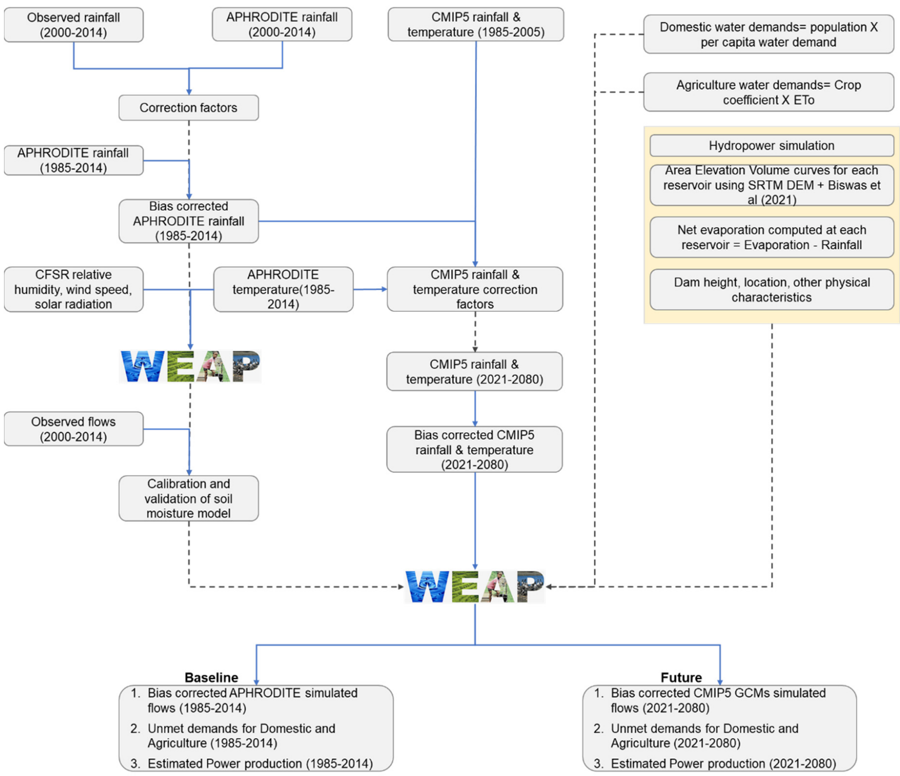


Figure 2. Overall methodology adopted in this study [42].

The World Meteorological Organization (WMO) recommends a 30-year standard reference period to reflect the changing climate [69] as the baseline better. As the observed rainfall data were not long enough to cover a 30-year period (Table 2), the baseline rainfall was estimated at each sub-basin using APHRODITE gridded data [34,35]. To reflect the observed precipitation in the SRB better, the gridded APHRODITE rainfall was corrected using observed rainfall at the sub-basin level using 2000–2014 data. For this purpose, monthly bias correction factors of APHRODITE rainfall were generated using the linear scaling technique [70]. As the observed temperature data were unavailable for the basin, the average temperature from APHRODITE was used as a baseline temperature for 1985–2014.

The other meteorological variables, including relative humidity, wind speed, and solar radiation, were used to calculate evapotranspiration using the Penman Monteith technique. As these data were unavailable from the surface observations, we used CFSR gridded data [62] at a 0.38 degree spatial resolution. These data were used as their mean monthly average values and were kept consistent for both baseline and future periods. The baseline in this study was defined as a 30-year period from 1985 to 2014. The future periods were defined as the near future (NF) from 2021 to 2050 and as the far future (FF) from 2051 to 2080, respectively. Similarly, the monsoonal months in the study area were defined as May to October, and the non-monsoonal months were defined as November to April [9].

2.3.1. WEAP Modeling

The Water Evaluation and Planning (WEAP) [40] software was used for the integrated water resources modeling in this study. Developed by the Stockholm Environment Institute (SEI), WEAP can be set for a complex river basin system with several sources of supplies, demands, and sectors [71–73]. It accounts for demands from the agriculture and population sectors in the SRB and supplies from the surface water system modeled within the WEAP. A similar setup of WEAP for water allocation in the Bago river basin, which is adjacent to the SRB, has been studied by Phue and Chuenchooklin [74]. This setup has been found to be effective in simulating a water resources system.

In this research, the SRB was delineated into 17 sub-basins with a mean area of 2011.5 km^2 and a standard deviation of 1,438.1 km^2, with a standard terrain processing technique in ArcMap 10.1 [75]. Then, these delineated sub-basins (green nodes in Figure 3, right) and river tributaries (17) were exported to WEAP to generate the schematic of the river basin system. Figure 3 (right) illustrates the schematic of the WEAP model set for the SRB in this study. Each sub-basin in WEAP was a source of supply of water and a potential demand node depending on the presence of irrigated land. Each sub-basin had discrete meteorological inputs and land use classes. Moreover, the local flows generated by the sub-basin met the agricultural and domestic demands within itself. While agricultural demands were specified within the sub-basin node, separate nodes were created for domestic demands (red nodes in Figure 3, right), which supplied water using transmission links in WEAP. Accordingly, 17 domestic demand nodes were created in WEAP, with 17 transmission links from the local rivers and 17 return flow links returning the unconsumed water to the river system. The three flow stations (Table 2) were also included in the model for the calibration and validation of the monthly flows within the river system.

To estimate the surface water in the SRB, the Soil Moisture (SM) method inherently built within WEAP was used. The SM method provides a simple yet realistic way of modeling hydrological processes in a basin with semi-physical representation. Although this method is data-intensive and relatively more complex than a few other models within WEAP [76], it was needed in this study to incorporate the impact of reservoirs in the mainstream and tributaries and to estimate the irrigation demands. The SM method is based on an algorithm of the 1D-two-soil-layer conceptual model to calculate evapotranspiration, surface runoff, interflow, and deep percolation for a defined unit of study [77]. The top layer considers evapotranspiration losses, considering rainfall and irrigation on agricultural and non-agricultural land uses, runoff and interflow, and changes in soil moisture. The second layer simulates the baseflow and soil moisture changes [40]. A simplified illustration of the Soil Moisture model in WEAP is presented in Figure 3 (left).

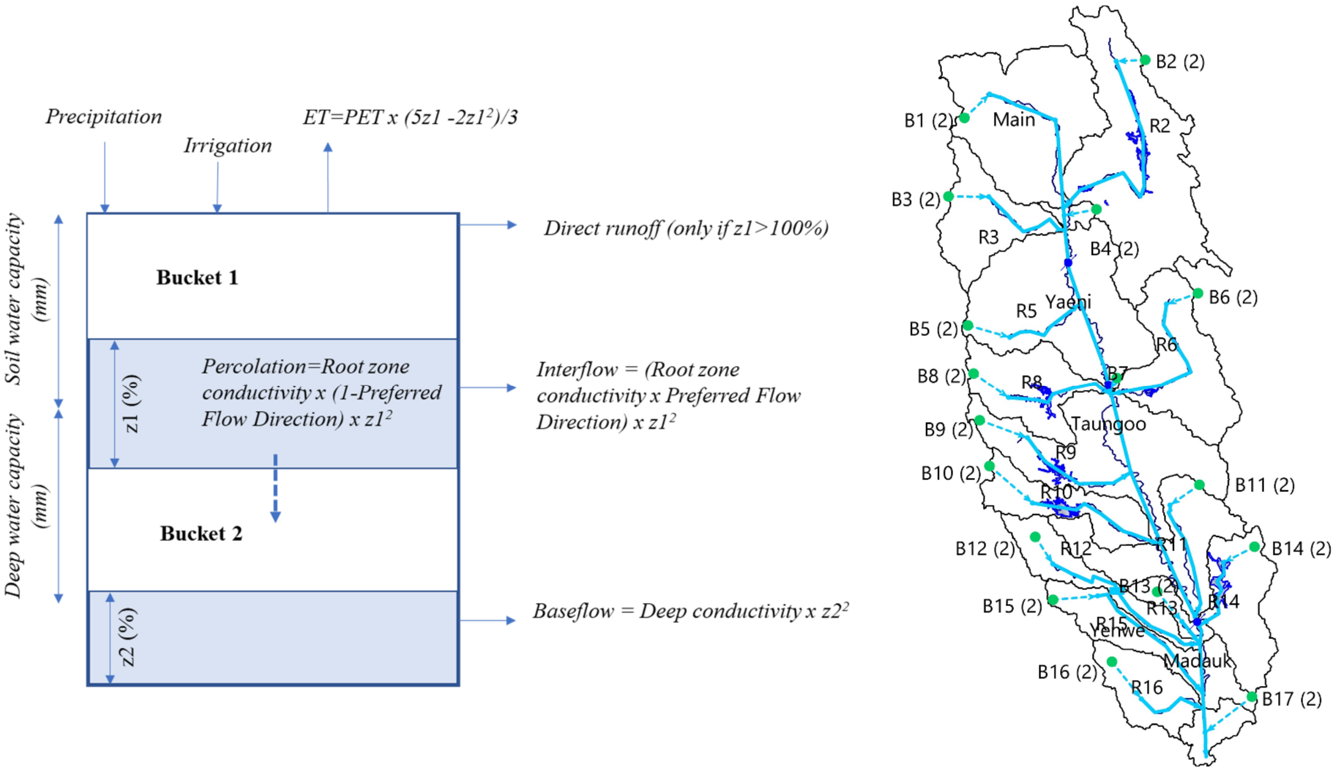


Figure 3. Soil Moisture method used in the WEAP model set for the Sittaung river basin.

The parameters of the SM model for each subbasin were calibrated to match the observed monthly flows at three locations in the SRB (refer to Table 2) using a WEAP calibration tool [78]. The period 2000–2009 (10 years) was used for calibration, while 2010–2013 (4 years) was used for the validation of the set model. Nash Sutcliffe Efficiency (NSE) and Percentage Bias (PBIAS) were selected as the model performance indicators in this study to evaluate model performance at the monthly time step [79]. Once calibrated and validated satisfactorily, the SM model was used to simulate the baseline flows (1985–2014) and future flows for 2021–2050 and 2051–2080, respectively.

2.3.2. Climate Models, Scenarios, and Bias Correction

Based on the past usage of CMIP5 GCMs in the study area [29,30] and recommendations from Ghimire et al. [70], five GCMs were selected to project rainfall and temperature in the SRB (Table 3). These data were accessed from https://esgf-node.llnl.gov/search/cmip5/ on 22 March 2021, and their brief information is presented in Table 3.

Table 3. CMIP5 rainfall and temperature data used in this study.

Model	Resolution (Lon ∗ Lat)	Research Center	Data Period
CNRM-CM5	1.40 × 1.40°	CNRM	1985–2080
GFDL-CM3	2.50 × 2.00°	NOAA GFDL	1985–2080
GISS-E2-H	2.50 × 2.00°	NASA-GISS	1985–2080
HadGEM2-AO	1.87 × 1.25°	NIMR-KMA	1985–2080
MIROC5	1.40 × 1.40°	MIROC	1985–2080

Since WEAP cannot handle gridded meteorological data without pre-processing them, sub-basin estimates of rainfall and temperature were calculated using the areal average technique in the R programming language. The customized scripts generated daily time-series of GCM rainfall and temperature at each of the 17 subbasins for the baseline scenario of 1985–2005 and the RCP4.5 and RCP8.5 scenarios from 2006 to 2080. It is also notable that the spatial resolution of climate models might affect the performance of the model they are used to drive [80,81]. The baseline rainfall and temperature (visualized in Figure 2) were used to generate rainfall and temperature correction factors for the individual GCMs using a common period of 1985–2005. The linear scaling technique recommended by Ghimire et al. [70] and Shrestha et al. [82] was used to correct the rainfall and temperature from 2021 to 2080. For the future, the near future (NF: 2021–2050) and the far future (FF: 2051–2080) periods of the RCP4.5 and RCP8.5 scenarios were thus evaluated against the baseline (BL: 1985–2014) climatology and hydrology.

2.3.3. Domestic Demands

Domestic demands in this study are defined as the amount of water needed by people living in the basin to meet their daily consumption needs. The Japan International Cooperation Agency [65] reported that the per capita water consumption in Yangon City, Myanmar is likely to range from 150 to 200 L per capita per day (LPCD). Accordingly, this study assumes a domestic demand of 65 m^3/year (~175 LPCD) for the population in the SRB during the baseline and the future (NF and FF) scenarios. While many studies have reported increasing domestic demands for the future, we argue that future water-saving technologies can help in the reduction of demands, thus providing a basis for the same domestic demands for the baseline and the future periods in the SRB. The annual domestic demand in each sub-basin is calculated as Equation (1).

$$\text{Domestic demand } (m^3) = \text{Per capita water consumption } (m^3/\text{year}) \times \text{Population}. \quad (1)$$

The population in the SRB is estimated from the 2014 country census report [83] and the trend during the baseline (1985–2014), and the future (till 2080) is estimated from https://worldpopulationreview.com/countries/myanmar-population on 1 June 2021. Figure 4 presents the information on the projected population in the sub-basins of the SRB.

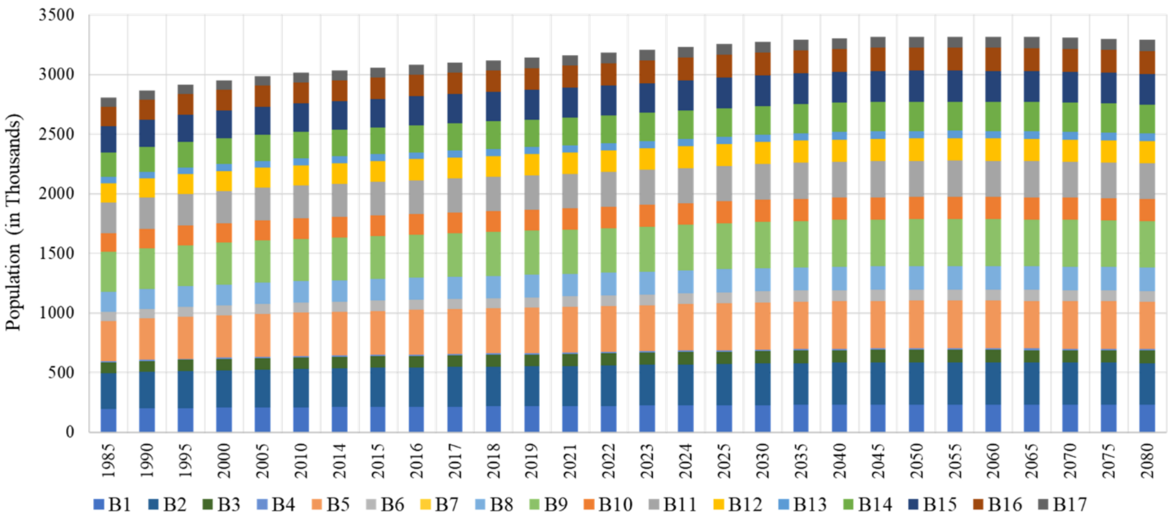
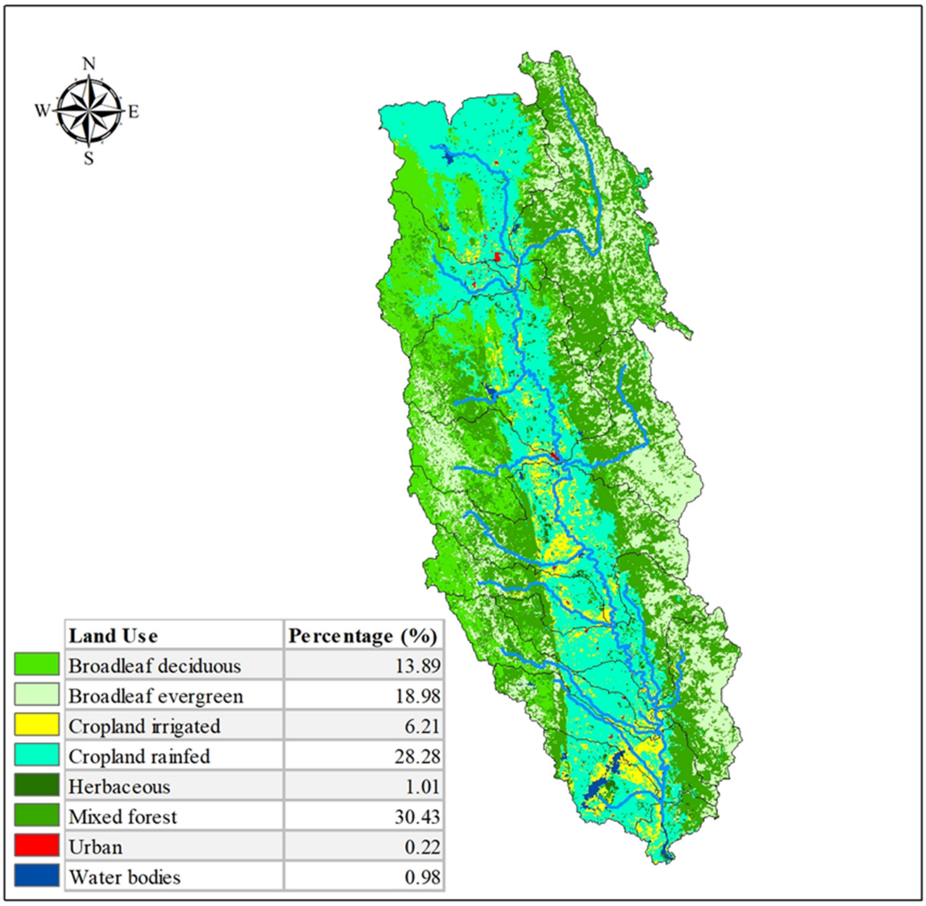


Figure 4. Observed (1985–2014) and projected (2015–2080) population in 17 sub-basins of the SRB.

The domestic demand is expected to be influenced by the average temperature of each sub-basin (i.e., hotter months have a higher demand of water). Accordingly, January (6.9%), February (7.8%), March (9.1%), April (10.1%), May (8.8%), June (8.5%), July (8.5%), August (8.5%), September (8.5%), October (8.5%), November (7.5%), and December (7.2%) are expected to have corresponding levels of water demand.

2.3.4. Agriculture Demands

To estimate agricultural demands in the SRB, the land use map of the European Space Agency [84], accessed from http://maps.elie.ucl.ac.be/CCI/viewer/download.php on 1 June 2021, was used. The land use information, available at a 300 m spatial resolution, identified the rainfed and irrigated croplands of the SRB (Figure 5).



Crop Type	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Remark
Wet season rice													Transplanting
Dry season rice													Transplanting

Figure 5. Land use information in 2015 derived from the European Space Agency (ESA) and crop calendar used in the study.

In WEAP, each of these land use classes (Figure 5) was defined at the sub-basin level. Crop coefficient (Kc) factors were defined for each class, which estimated the evapotranspiration from each land use class compared with the reference evapotranspiration (ETo) estimated by the model using the Penman Monteith equation. The ETo was the evapotranspiration occurring from a hypothetical reference crop with an assumed height of 0.12 m, a fixed surface resistance of 70 s/m, and an albedo of 0.23 [40]. The Penman Monteith equation made use of the maximum and minimum daily temperature, relative humidity, wind speed, solar radiation, and latitude of each sub-basin in the WEAP. For other land uses, except cropland, the crop coefficient values were set to default values within the model. Typically, a crop coefficient curve would fluctuate in response to the actual sowing, growing, maturity, and harvest phases of a given crop. Rice and pulses were the major crops in the study area [85], and the majority of the rice production in the country happened in the Ayeyarwady, Yangon, and Bago regions. Therefore, only rice was considered as the main crop during both the dry and wet seasons in the SRB. The rice crop calendars of the dry and wet seasons (Figure 5) were adopted from Phue and Chuenchooklin [74]. Respective Kc values were assumed for the transplanting, growing, maturity, and harvest phases of rice in the SRB for rainfed croplands in the SRB. For the irrigated croplands in each sub-basin, we assumed a crop coefficient of 1, indicating the full possibility of potential evapotranspiration.

WEAP primarily catered to the crop demand (Monthly Kc * ETo) using the monthly rainfall in the basin and, if unmet, would extract the remaining water from the river system (through the transmission links). Thus, the agricultural demands in this study indicated the demands arising from irrigated croplands currently not receiving adequate rainfall. If the local sources of water were also not enough to meet these needs, this scenario would be understood as the unmet agricultural demand in this study. Given that water was allocated in WEAP as per their allocation order of demand priorities and supply preferences [40], both the domestic and agriculture sectors were given equal weightage in the WEAP model for the SRB.

2.3.5. Reservoir Modeling

The information about the reservoirs in the SRB was collected through secondary literature, mostly from the Strategic Environment Assessment report 2017 [39,68]. The list of reservoirs, their installed capacity and firm power, and their basic characteristics are presented in Table 4. In the table, installed capacity means the maximum production capacity of the hydropower depending on the turbines and design discharge. Similarly, firm power or capacity is the power available at all times, which is always less than the installed capacity due to the efficiency of the machines, the amount of water available, and other technical constraints.

Table 4. Hydropower characteristics of the reservoirs selected in this study.

Project	Installed Capacity (MW)	Firm Power (MW)	Type	Dam Height (m)	Reservoir Area (km^2)	Reservoir Length (km)
Nancho	40	12.6	Run-off-River	72	0.3	3
Paunglaung Lower	280	104	Storage	131	17	16
Paunglaung Upper	140	84	Storage	98	61	50
Kabaung	30	13.69	Storage	61	150	16
Kun Chaung	60	17.5	Storage	73	150	23
Phyu Chaung	40	28.4	Storage	75	24	27
Shwegyin	75	50.6	Storage	57	58	35
Thauk Ye Khat 2	120	101	Storage	94	14	22
Yenwe	25	14.04	Run-off-River	77	77	36

For the hydropower simulation in WEAP, reservoir-specific data, such as net evaporation at the reservoirs, storage capacity, initial storage, volume elevation curve, top of active and inactive storage, and startup year for reservoir simulations, were needed. The net evaporation in each reservoir was estimated using the potential evapotranspiration from the air temperature data and the rainfall in the sub-basin nearest to the reservoir. The volume-elevation-area curve of each reservoir was estimated using the SRTM digital elevation model [86], the reservoir polygon extracted from the Google Earth engine, and a customized Python script (Supplementary Table S1). A similar technique was used to understand reservoir characteristics in the Lower Mekong countries by Biswas et al. [42] and Das et al. [87]. The accuracy of this technique in estimating the volume elevation curve was found to be satisfactory, as shown in Supplementary Figure S3. To understand the impacts of climate change on hydropower production in the SRB, all reservoirs were assumed to be in operation from 1985 onward, and the production of hydropower for the baseline and the future scenarios was examined.

3. Results and Discussion

3.1. Climate Projections

Based on the ensemble of five CMIP5 GCMs, the baseline average annual rainfall of 2389 mm was expected to increase to 2516 (2605) and 2656 (2722) mm during the NF and FF of the RCP4.5 (RCP8.5) scenarios, respectively. This increase corresponded to the 5.3% (9.0%) increase in NF and the 11.2% (13.9%) increase in FF under the RCP4.5 (RCP8.5) scenario. The uncertainty (presented as bands in Figure 6), calculated as the standard deviation among the GCMs, remained distinct, especially under the RCP8.5 scenario. The mean baseline rainfall in the basin may increase by almost 75% and reach as high as 4000 mm in certain years in the future, as projected by selected GCMs. A general increase in annual rainfall for the basin could be potentially beneficial for different water user sectors. A study in northeast Thailand reported that an increase in rainfall stimulated the economic growth in agriculture sectors and sub-sectors [88]. Changes in rainfall and climate have been known to drive the civilization in Southeast Asia [89]. A neighboring basin of SRB, the Bago River Basin connected via the Moeyingyi wetland, is also expected to experience higher rainfall and temperature compared to its baseline period [90]. An increase in rainfall may also increase flood risks and damage in the basin for extreme rainfall events. Such damages not only pertain to the human settlement but also to the agricultural croplands. In the Bago region, a study suggested that when the croplands were subjected to a 2.3 m depth of flood for two weeks in the reproductive stage, the yield losses were more than 50% [91].

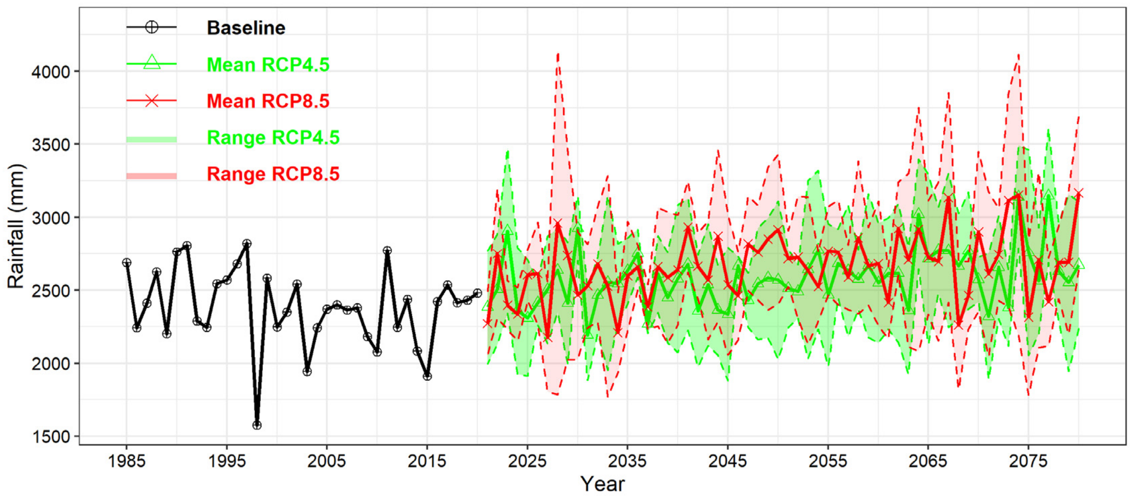


Figure 6. Baseline and projected mean annual rainfall for RCP4.5 and RCP8.5 scenarios in the SRB.

While the annual rainfall was expected to increase under climate change scenarios in the SRB, not all months were expected to experience such increase. Table 5 presents the monthly baseline rainfall of the SRB and the projected mean and variability in terms of the standard deviation under the RCP4.5 (RCP8.5) scenarios for the NF and FF periods. Additionally, it also presents the agreement among the five CMIP5 GCMs for the direction indicated by the mean change.

Dry months such as December and January would likely experience a decrease in mean rainfall, and a minimum of three GCMs agreed to this change. August and September showed an increase in mean rainfall, and a minimum of four GCMs agreed to this change for all scenarios. Interestingly, April was expected to experience an increase of 3.5% during the FF of RCP4.5. However, among the five GCMs, only one GCM was causing this increase, while the remaining four indicated drier future scenarios. While the magnitude and timing of rainfall was observed to change in the future, its geo-spatial characteristics were found, such as that of BL, with the lower southern sub-basins expecting low rainfall and the upper northern sub-basins expecting high rainfall (Supplementary Figure S1). Projected increases in rainfall were expected to increase river flows and subsequently provide more water supply for both rainfed and irrigated croplands. Conversely, this increase might negatively impact the water security of both the domestic and agriculture sectors, as increased rainfall intensity and extremes had been known to lead to water redistribution between green and blue water, increase soil erosion, and reduce water security [92]. Moreover, it could lead to increased floods in the basin [30].

Table 5. Baseline monthly rainfall (mm) in Sittaung, the projected mean and standard deviation monthly rainfall (mm) for RCP 4.5 and RCP8.5 scenarios, and agreement among the number of GCMs in the direction of change. The arrows in agreement indicate the direction of change with up arrow indicating increase and down arrow indicating decrease from baseline values.

Month	Baseline (mm)	RCP4.5 (NF)		RCP8.5 (NF)		RCP4.5 (FF)		RCP8.5 (FF)	
		Mean ± STD	Agreement	Mean ± STD	Agreement	Mean ± STD	Agreement	Mean ± STD	Agreement
Jan	2.6	1.7 ± 1.1	4 ↓	2.8 ± 1.8	3 ↑	1.8 ± 0.9	4 ↓	1.7 ± 0.3	5 ↓
Feb	5.1	9.4 ± 5	4 ↑	6.3 ± 1.7	4 ↑	15.6 ± 9.1	5 ↑	9.8 ± 5.1	5 ↑
Mar	6.5	7.9 ± 2.4	3 ↑	7 ± 1.5	3 ↑	10.5 ± 3.5	5 ↑	10.3 ± 5.1	4 ↑
Apr	37.5	27.6 ± 10.6	4 ↓	40.2 ± 18.8	3 ↑	38.8 ± 11.6	1 ↑	34 ± 9.5	3 ↓
May	217.4	247.4 ± 43.5	4 ↑	216.4 ± 81	2 ↓	259.6 ± 72.1	4 ↑	228.8 ± 45	4 ↑
Jun	450.4	469.7 ± 40.9	3 ↑	504.3 ± 59.5	5 ↑	529.4 ± 23.5	5 ↑	503.4 ± 49.1	4 ↑
Jul	547.2	528.8 ± 20.7	4 ↓	551.5 ± 44.1	2 ↑	533 ± 22.3	4 ↓	568.5 ± 24.3	5 ↑
Aug	588.7	648.3 ± 50.5	4 ↑	677.3 ± 30.8	5 ↑	667.2 ± 51.9	4 ↑	721.5 ± 40.3	5 ↑
Sep	311.8	355.5 ± 29.3	5 ↑	365 ± 26.3	5 ↑	365.3 ± 39.8	5 ↑	398.2 ± 44.1	5 ↑
Oct	159.7	155.2 ± 25.9	3 ↓	158.2 ± 7.6	3 ↓	162 ± 13.5	3 ↑	163.1 ± 36.2	3 ↑
Nov	57.9	60.1 ± 17.5	4 ↑	72.1 ± 7.7	5 ↑	68.5 ± 17.7	4 ↑	78.3 ± 31.4	3 ↑
Dec	4.3	4.1 ± 1.6	4 ↑	4.2 ± 1	2 ↑	4.5 ± 1.8	4 ↑	4.9 ± 2.4	4 ↑
Annual	2389.2	2515.7 + 248.9	5 ↑	2605.2 + 281.8	5 ↑	2656.2 + 267.5	5 ↑	2722.4 + 292.8	5 ↑

Similarly, the average temperature of the SRB was expected to increase from 25.9 °C during BL to 27.0 °C (27.1 °C) during NF and to 27.7 °C (28.4 °C) during FF of the RCP4.5 (RCP8.5) scenario. The uncertainty among GCMs was roughly around 1 °C in NF, which increases to around 2 °C in FF, as presented in Figure 7.

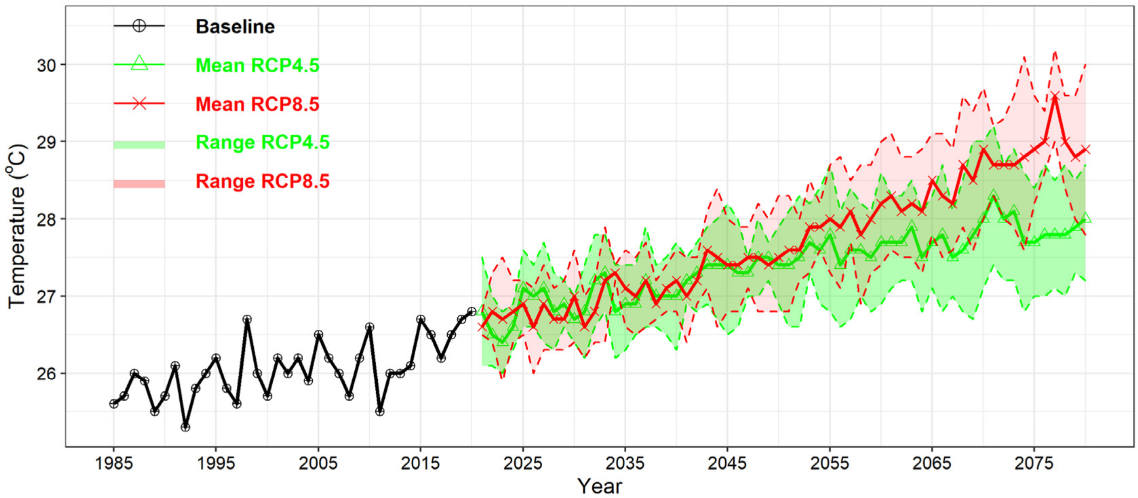


Figure 7. Baseline and projected mean annual temperature for RCP4.5 and RCP8.5 scenarios in the SRB.

The highest increase in mean monthly temperature was expected for the dry season (November to April), particularly for the RCP8.5 scenario during FF (Table 6). Thus, the non-monsoonal months such as December and January might become drier and warmer in the future, whereas the monsoonal months were expected to become wetter and warmer. The presence of reservoirs in the SRB could be useful in such situations where the monsoonal months were expected to experience an increase in rainfall and the non-monsoonal months became drier.

Table 6. Baseline (°C) and projected mean and standard deviations of basin temperature (°C) changes (°C) under RCP4.5 and RCP8.5 scenarios for near and far future and agreement among the GCMs for the direction of change. The arrows in agreement indicate the direction of change with up arrow indicating increase and down arrow indicating decrease from baseline values.

Month	Baseline (°C)	RCP4.5 (NF)		RCP8.5 (NF)		RCP4.5 (FF)		RCP8.5 (FF)	
		Mean ± STD (°C)	Agreement	Mean ± STD (°C)	Agreement	Mean ± STD (°C)	Agreement	Mean ± STD (°C)	Agreement
Jan	21.9	23.1 ± 0.5	5 ↑	23.2 ± 0.5	5 ↑	23.9 ± 0.9	5 ↑	24.7 ± 0.8	5 ↑
Feb	24.1	25.3 ± 0.5	5 ↑	25.2 ± 0.6	5 ↑	26.1 ± 0.8	5 ↑	26.7 ± 0.7	5 ↑
Mar	27.4	28.8 ± 0.5	5 ↑	28.6 ± 0.2	5 ↑	29.5 ± 0.8	5 ↑	30 ± 0.6	5 ↑
Apr	29.9	31.4 ± 0.6	5 ↑	31.2 ± 0.6	5 ↑	32 ± 1	5 ↑	32.5 ± 0.9	5 ↑
May	28.6	29.8 ± 0.5	5 ↑	29.9 ± 0.4	5 ↑	30.4 ± 1	5 ↑	31.1 ± 0.8	5 ↑
Jun	26.8	27.6 ± 0.2	5 ↑	27.8 ± 0.5	5 ↑	28.1 ± 0.5	5 ↑	29 ± 0.6	5 ↑
Jul	26.2	27.2 ± 0.2	5 ↑	27.3 ± 0.4	5 ↑	27.7 ± 0.6	5 ↑	28.4 ± 0.6	5 ↑
Aug	26.2	27.1 ± 0.4	5 ↑	27.1 ± 0.4	5 ↑	27.7 ± 0.6	5 ↑	28.3 ± 0.7	5 ↑
Sep	26.6	27.5 ± 0.3	5 ↑	27.6 ± 0.4	5 ↑	28.1 ± 0.6	5 ↑	28.8 ± 0.7	5 ↑
Oct	26.7	27.7 ± 0.4	5 ↑	27.7 ± 0.3	5 ↑	28.4 ± 0.6	5 ↑	29 ± 0.6	5 ↑
Nov	24.8	25.9 ± 0.3	5 ↑	25.9 ± 0.5	5 ↑	26.8 ± 0.8	5 ↑	27.4 ± 0.7	5 ↑
Dec	22.2	23.3 ± 0.4	5 ↑	23.4 ± 0.4	5 ↑	24.1 ± 0.7	5 ↑	24.9 ± 0.6	5 ↑
Annual	26.0	27.1 + 0.4	5 ↑	27.1 + 0.4	5 ↑	27.7 + 0.7	5 ↑	28.4 + 0.7	5 ↑

A higher agreement was observed among GCMs toward the change in temperature than that in rainfall. All GCMs for the future were projecting an increase in monthly temperatures in the SRB. The spatial variability of the average temperature in the SRB was also less pronounced than that of the annual rainfall (Supplementary Figure S2). Most of the sub-basin had a baseline temperature of 26–27 °C during BL, which increased to 27–28 °C (27–29 °C) during NF and to 28–29 °C (28–29 °C) during FF of the RCP4.5 (RCP8.5) scenario. While these numbers provided some estimate of expected changes in the mean temperature, the changes in minimum and maximum temperatures and the compounding impacts on hot days, cool days, growing degree days, heat waves, and cold waves [93] might be more significant and warrant further investigation. An increase in temperature compounded with a change in rainfall may also affect the livestock by changing the quantity and quality of available feed, available water, metabolism and milk production, potential infection, diseases, etc. [94]. Similarly, an increase in temperature during the growing period of cereal crops in Myanmar has been reported to reduce the crop yield significantly (e.g., a 1 °C increase during the growing period, resulting in a 3.8 million-ton reduction in yield) [95]. Similarly, increased temperature and still-water systems may result in potential outbreaks of water- and vector-borne diseases for a longer transmission season [96].

The mean temperature could also be non-linearly linked with the extreme weather events related to heavy rainfall and temperature. Knutti et al. [97] reported that the number of hot days exceeding a percentile-based threshold increased sixfold for a 1 °C warmer world, while such number for a 2 °C warmer condition increased by 20-fold. The corresponding increase in temperature translated to an increase in the evapotranspiration potential of the basin, which can further reduce the available soil moisture [98].

3.2. WEAP Calibration and Validation

The WEAP model, when initially tested with raw APHRODITE rainfall from 2000 to 2013, yielded a lower rainfall and hence a lower discharge during the monsoon seasons (Figure 8). Similar results were also observed in other studies [99,100]. However, when APHRODITE was bias-corrected with reference to the observed rainfall within the basin, the results improved considerably. APHRODITE has been reported for its good performance in the simulation of observed rainfall in Myanmar in Ayeyarwady and has been used in multiple studies as observed rainfall itself [36,38,98–100]. While APHRODITE has merited its usage in the SRB, improvements can be expected with relevant statistical corrections, as observed in this study and other studies [100]. Figure 8 presents a visual comparison of APHRODITE (with and without bias correction) simulated flows at the three flow stations within the SRB. The statistics such as NSE, PBIAS, and R^2, estimated using bias-corrected APHRODITE-simulated flows and observed flows for the three stations, showed that WEAP was satisfactorily able to simulate monthly flows in the study area. The computed statistics during the calibration and validation periods within the SRB are presented in Table 7.

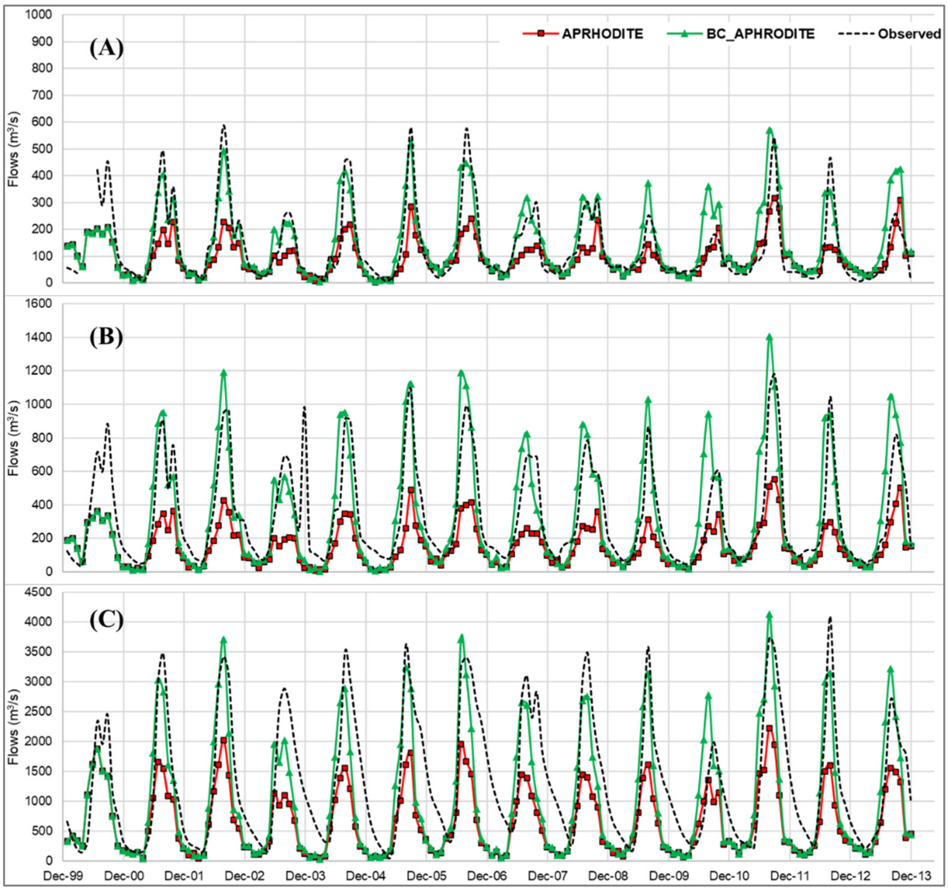


Figure 8. Simulation of monthly flows at (**A**) Yaeni, (**B**) Taungoo, and (**C**) Madauk stations using APHRODITE and bias-corrected APHRODITE (BC_APHRODITE).

Table 7. Calibration and validation statistics estimated using bias-corrected APHRODITE in the Sittaung river basin.

Station	Calibration (2000–2009)			Validation (2010–2013)		
	R^2	Bias	NSE	R^2	Bias	NSE
Yaeni	0.84	−0.06	0.78	0.69	0.38	0.51
Taungoo	0.73	−0.04	0.73	0.69	0.16	0.67
Madauk	0.63	−0.33	0.47	0.63	−0.16	0.59

WEAP was able to simulate the monthly flow with satisfactory accuracy [79] in the upstream locations (Yaeni and Taungoo). However, while the impacts of reservoirs existing in the SRB were cumulated, the flows at the outlet of the basin were considerably altered, which was visible in the low model performance statistics and the inability to capture the low flows appropriately.

Once the flows were calibrated, the hydropower generated from the reservoirs was tuned in the model (calibrating the model and plant efficiency and tailwater elevation). The required area elevation curves were estimated using SRTM DEM and the technique of Biswas et al. [42]. The volumetric errors computed using the estimated curve and the observed curve for Upper Paung Luang, Kun Chaung, and Yenwe were around 7%, 12%, and 14%. For Shwegyin, the error was around 28%. Thus, this technique of generating reservoir physical characteristics was assumed to be satisfactory for the selected reservoirs in Sittaung and was thus used in the model. The visual comparison of the estimated volume elevation curve with the observed information at these four reservoirs is presented in Supplementary Figure S3.

Figure 9 presents the summary of the WEAP-simulated hydropower and the observed firm power in the existing reservoirs in the SRB. The comparison of other reservoirs was not possible, as three of them commenced their operation in 2015.

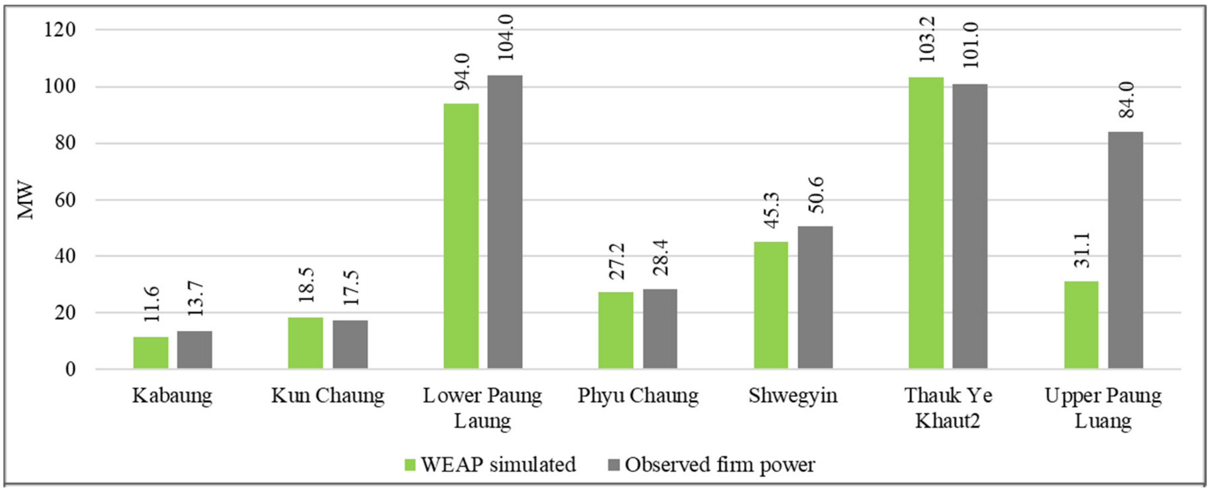


Figure 9. WEAP-simulated and observed firm power in the selected hydro-powers of the SRB.

3.3. Flow Projections

The mean flows in the basin were projected to increase from a BL value of 1092 m^3/s to 1174.5 m^3/s (1192 m^3/s) in NF and 1271.5 m^3/s (1302.2 m^3/s) in FF of the RCP4.5 (RCP8.5) scenario, as presented in Figure 10. This increase corresponded to 7.5% (9.6%) and 16.4% (19.2%) for the RCP4.5 (RCP8.5) scenario during the NF and FF periods. However, the inter-annual variability within different GCMs was still high, as could be seen from the band plots of the RCP4.5 (green) and the RCP8.5 (red) color in Figure 10. For example, in 2050–2080, at least three years had flows exceeding 100% of the baseline mean under the RCP8.5 scenario, which signified that the future remained uncertain. Moreover, a small decrease or heavy increase might occur in annual flows, depending on the selected GCM scenarios.

While the mean of all GCMs exhibited a general increase in annual flows in the basin for both RCP4.5 and RCP8.5 scenarios, the monthly mean flow projections of the GCMs showed that some months, such as July and October, might experience some decrease (Table 8). This expectation was due to the decrease in rainfall during these months (Table 5). However, flows increased in December and January (nearly 100%) under all scenarios of climate change, whereas the rainfall during these months was expected to go under the baseline due to the presence of reservoirs in the basin. Moreover, the agreement among GCMs was very high (Table 8) in predicting the direction of the change of flows during non-monsoonal months, and relatively less agreement was observed among GCMs in predicting the change in monsoonal months.

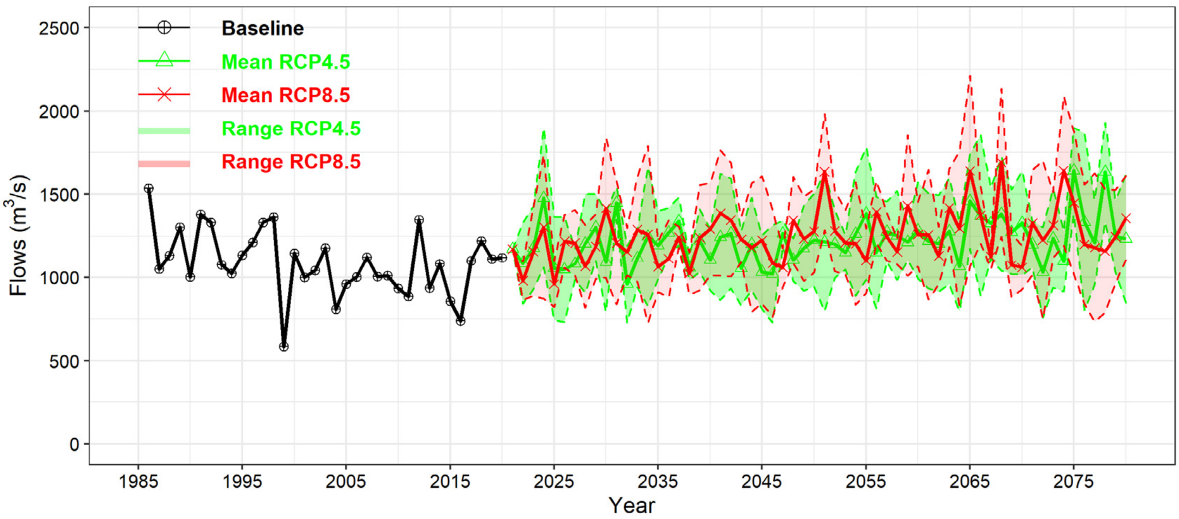


Figure 10. Baseline and projected mean annual flows at the outlet of Sittaung under RCP4.5 and RCP8.5 scenarios.

Table 8. Mean monthly baseline and future flows (m^3/s) in the Sittaung river basin. The arrows in agreement indicate the direction of change with up arrow indicating increase and down arrow indicating decrease from baseline values.

Month	Baseline (m^3/s)	RCP4.5 NF		RCP8.5 NF		RCP4.5 FF		RCP8.5 FF	
		Mean (%)	Agreement	Mean (%)	Agreement	Mean (%)	Agreement	Mean (%)	Agreement
Jan	195.4	95.5	5 ↑	99.5	5 ↑	96.0	5 ↑	95.6	5 ↑
Feb	146.3	132.5	5 ↑	130.2	5 ↑	154.5	5 ↑	136.5	5 ↑
Mar	132.6	84.1	5 ↑	83.0	5 ↑	89.2	5 ↑	90.8	5 ↑
Apr	169.1	56.6	5 ↑	58.9	5 ↑	83.4	5 ↑	81.6	5 ↑
May	550.9	48.9	5 ↑	39.3	5 ↑	76.1	5 ↑	51.6	5 ↑
Jun	1746.5	4.2	3 ↑	9.6	4 ↑	29.8	3 ↑	24.0	4 ↑
Jul	2758.3	−6.8	4 ↓	−5.4	3 ↓	−2.7	4 ↓	−0.1	3 ↓
Aug	3460.5	−0.3	3 ↓	2.0	4 ↑	5.4	2 ↑	14.2	4 ↑
Sep	2022.1	1.7	3 ↑	2.4	3 ↑	5.2	3 ↑	16.3	3 ↑
Oct	1070.3	−5.9	4 ↓	−4.1	4 ↓	−1.7	4 ↓	−2.8	4 ↓
Nov	572.8	10.0	4 ↑	21.4	5 ↑	18.4	4 ↑	25.7	5 ↑
Dec	278.6	82.4	5 ↑	84.7	5 ↑	85.1	5 ↑	86.0	5 ↑
Annual	1092.0	7.6	5 ↑	9.6	5 ↑	16.4	5 ↑	19.3	5 ↑

The projected increase in mean monthly flows might increase floods in the river basin as well. Kyi et al. [30] reported that the SRB has already been plagued with floods and is expected to experience even more of an increase in extreme flood discharges in the future (2046–2061). The SRB region has been studied for flood depth inundation and its impact on crop losses [91]. The increase in monsoonal flows indicated a possibility of frequent and intensified flood inundations, which could easily transform to a loss of yield and further aggravate food insecurity. Many cases of flooding in Sittaung have been reported in the recent past [101–103], which have dislocated tens of thousands of people from their residences. Such events may be more frequent in the future. Aside from the floods, the decreased flows in July and October may affect crop water availability and the crop yields, which need relevant adaptation plans and measures. A majority (85%) of the rural population is dependent on climate-sensitive sectors for their livelihoods [104]; the increases in temperature, wet season rainfall, and floods are likely to adversely impact the people and their livelihoods in the SRB as well.

3.4. Domestic Water Demand Projections

The population was expected to increase in the basin until 2050, after which it would start plateauing and even decrease by 2080 (Figure 3). Furthermore, the average domestic water demands were expected to increase for both future periods compared with the BL. The basin domestic water demand in the BL was 190.8 MCM, of which only a minimal demand of 1.35 MCM remained unmet. The domestic water demands were higher in April and March and relatively similar during other months, as discussed in the methodology section.

In future periods, domestic water demands were not affected by the change in climate but by the population change, which was assumed to be consistent for both RCP4.5 and RCP8.5 scenarios. Thus, the average domestic demand increases to 213.1 MCM during the NF period and to 215.2 MCM during the FF period. As the basin was expected to experience an increase in rainfall, the unmet demands are reduced even further from 1.4 MCM to 0.8 (0.7) and 0.7 (0.8) MCM in the NF and FF periods of the RCP4.5 (RCP8.5) scenario. The distribution of unmet demands during the BL and future periods is presented in Figure 11.

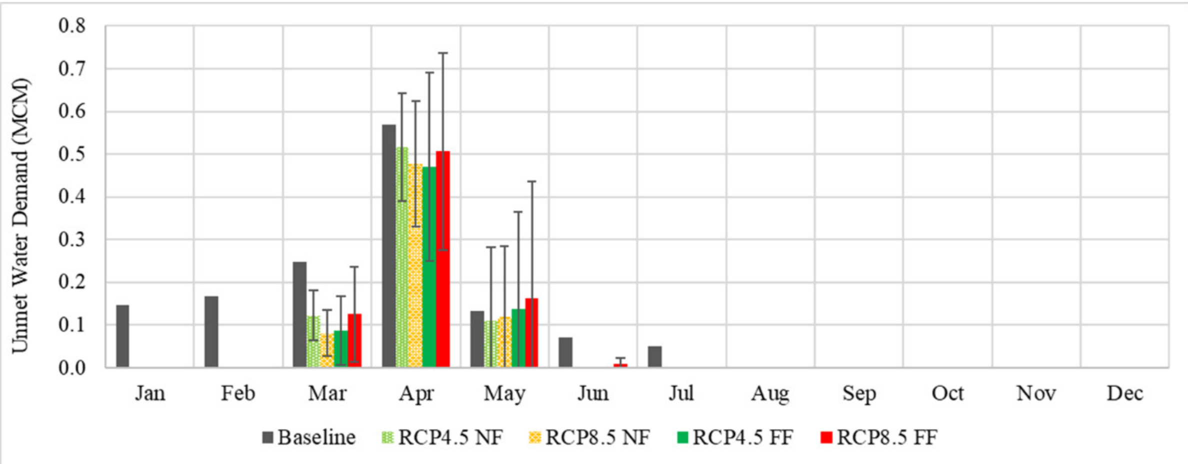


Figure 11. Unmet domestic demands in the SRB for baseline and future scenarios.

January and February, which previously had some unmet domestic demands during BL, were projected to be satisfied with the local water supplies in future scenarios. This satisfaction was due to the increase in flows in the local river, as seen in Table 8. April and May were likely to have some of their demands unmet, mostly due to the increase in the water requirement in these months by the domestic sector. In Myanmar, the water services do not reach a large proportion of the urban population [105], and for the rural population, such access is even more limited. Thus, in most cases, people adapt to their environment and self-improvise with the local water systems and rainwater. Accordingly, SRB is also likely to provide domestic water to its inhabitants in the future with its own local water systems.

3.5. Agriculture Water Demand Projections

A considerable interannual variability was observed in the agricultural water demands within the SRB for both the BL and future periods (Figure 12). The BL demand of 1390.2 MCM was expected to increase to 1577.4 MCM (1553 MCM) in the NF and to 1567.9 MCM (1635.9 MCM) in the FF under the RCP4.5 (RCP8.5) scenario. This expectation corresponded to the increase in the baseline agricultural water demand by 13.5% (11.8%) in the NF and by 12.8% (17.7%) in the FF under the RCP4.5 (RCP8.5) scenario. As the croplands remain unchanged, the agriculture water demand was projected to increase due to an increase in the mean temperature (thereby increasing the evapotranspiration) and a change in the monthly rainfall amounts in the SRB.

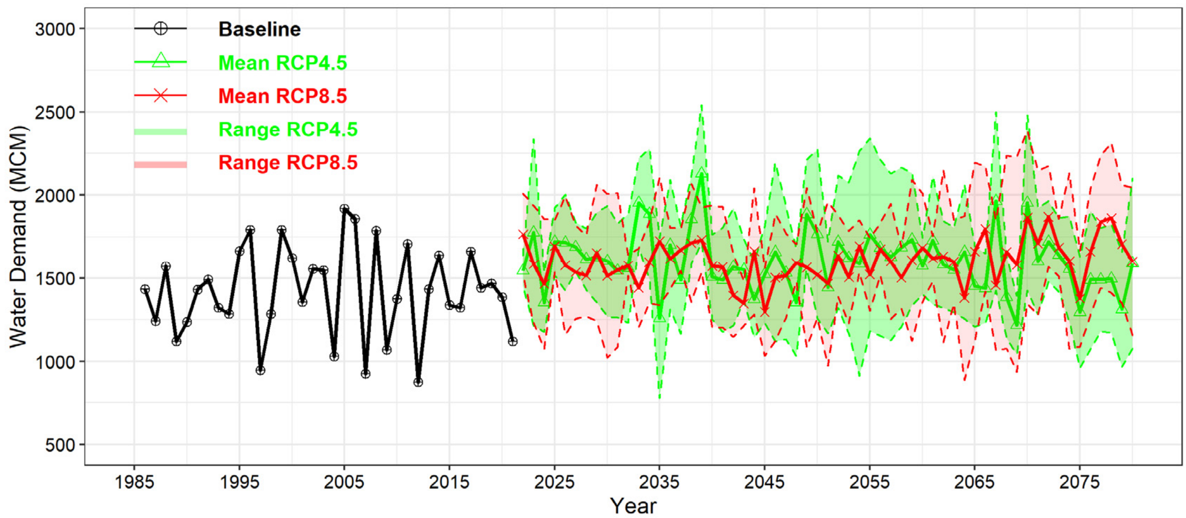


Figure 12. Annual baseline and projected agricultural water demands (MCM) in Sittaung under RCP4.5 (green) and RCP8.5 (red) scenarios.

From December to May, water demand from the agriculture sector was observed, whereas the other months (June–November) had enough rainfall to meet the evapotranspiration needs of the croplands. Under climate change scenarios, this trend was expected to continue with the prominent relative increase in water demand in May. The variation among the GCMs, presented as the error bars in Figure 13, also indicated significant variability among the projections of the GCMs.

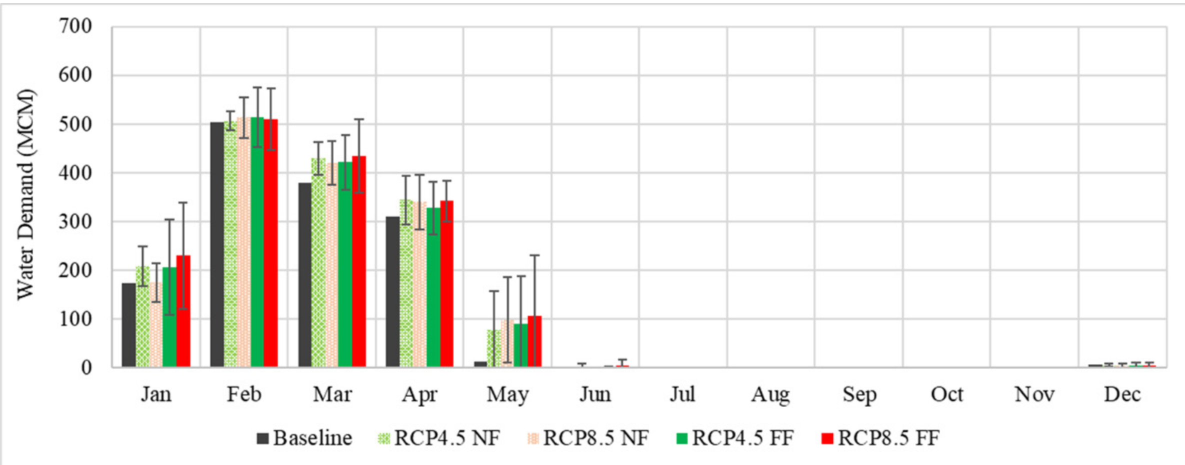


Figure 13. Agricultural water demands in the SRB. Error bars in the figure show a standard deviation between the GCMs.

Of these agricultural water demands, the local river supplies could meet almost half for these dry months (January–April) during BL. During BL, the unmet agricultural demand was 668 MCM, which was expected to increase to 771.4 (743.4) during NF and to 762.2 (797.7) during FF under the RCP4.5 (RCP8.5) scenario (Figure 14). This expectation indicated that, even though the rainfall was likely to increase in the SRB for the future, the existing water resources hinted at unmet agricultural water demands, particularly during the dry months. Compared with the other months, May exhibited a prominent increase in agricultural water demands, most of which remained unmet in the future (Figures 13 and 14).

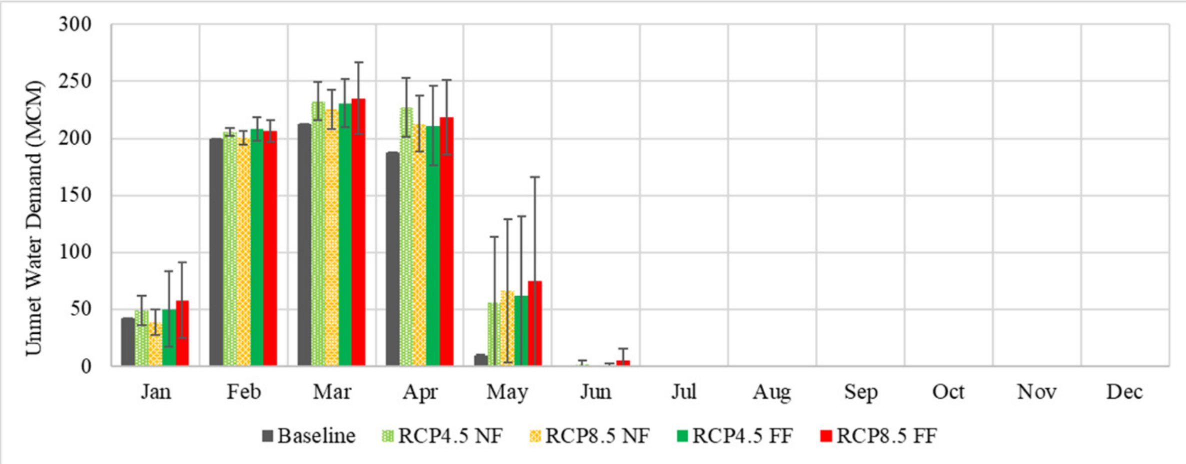


Figure 14. Unmet agricultural water demands (MCM) in the SRB during baseline and future scenarios. Error bars show the standard deviation among the GCMs.

The Food and Agriculture Organization (FAO) summarized that climate change has direct consequences on food security [106] due to the loss of rural livelihoods and income, food insecurity, the breakdown of food systems, and many other reasons. Likewise, the first regions to be impacted and the most-impacted regions are regions that are arid in nature, vulnerable regions, landlocked regions, and small island nations. Myanmar is already known to be vulnerable to climate change. When coupled with an increase in temperature, changes in rainfall patterns and increases in agricultural water demands are likely to exacerbate food insecurity in the SRB. People at the highest risk of food insecurity are those who depend on agriculture and natural resources, those whose livelihoods are highly exposed to the impacts of climate change, and those who have a limited capacity to respond to it. Understandably, the changes in rainfall and temperature characteristics change the quantity of the crop produced. However, climate change may also decrease the nutritional value of the food [107]. Higher concentrations of carbon dioxide in plants have been reported to reduce their protein, zinc, and iron contents. Thus, by 2050, 175 million people globally may develop zinc deficiency, and 122 million people may develop protein deficiency by then. In addition to the impact on agricultural crops, the increase in temperature also affects the livestock and fish populations, which is characteristic in the southeast Asian region.

3.6. Hydropower Projections

As the reservoirs were assumed to be operational from 1985 onward for this analysis, a comparison of hydropower generation potential during the baseline and future climate change scenarios was carried out, as presented in Figure 15. In the BL, the average annual potential for hydropower generation was 4.12 million MWh, which increased by 9.0% (11.6%) in the NF and by 16.2% (16.4%) during the FF under the RCP4.5 (RCP8.5) scenario.

All months were expected to experience an increase in hydropower generation in the future, and a larger agreement was observed among the GCMs (Table 9). Compared with the rainfall and flows, the agreement among GCMs was higher for the projected change, mostly due to the combined impact of the increase in rainfall, flows, and the presence of the reservoirs.

Currently, The Myanmar National Electrification Plan aims to achieve 95% electrification of the country by 2030 [105], and the potential increase in power in the SRB is likely to contribute to this plan. The SRB lies within the Mandalay (13% of households connected to national grid) and Bago (7%) regions of the country and can be expected to have more households connected to the national grid in the future. While establishing new connections might have its own technical constraints, it can be expected that the existing connections will become more stable. Additionally, the generation of hydropower was not solely dependent on the available water but was also reliant on other factors such as the availability of physical units of power turbines, their design discharge, and other generation efficiencies. Thus, this analysis should be taken as an observation of the linear relationship between the available water and the power production potential, which might not ideally exist in real world conditions.

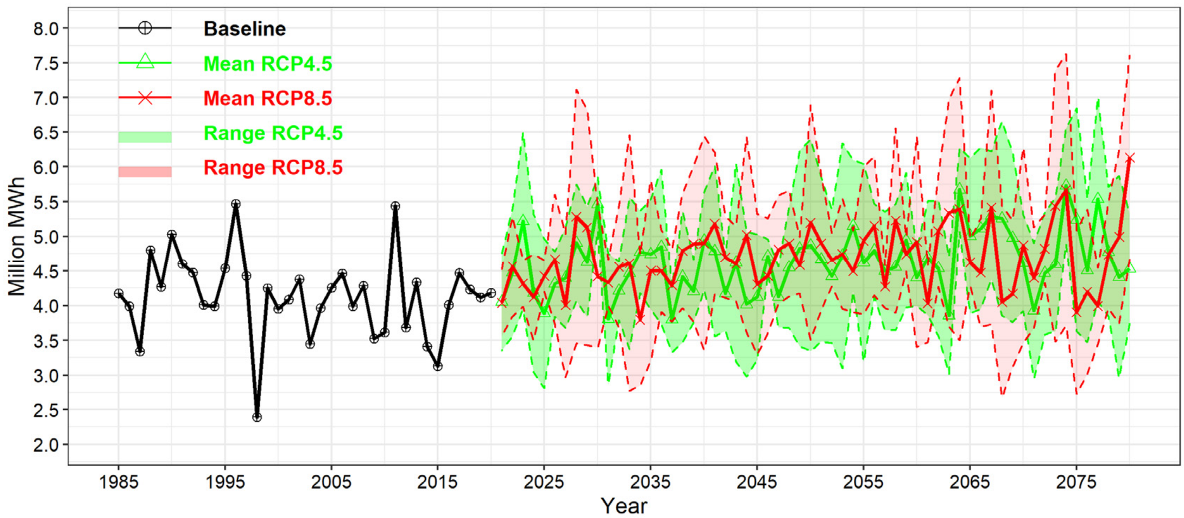


Figure 15. Potential hydropower generation in Sittaung (million MW-H) from the reservoirs in Sittaung for the baseline and future under RCP4.5 (green) and RCP8.5 (red) scenarios.

Table 9. Projected monthly changes in hydropower generation (in thousand MWh) under RCP4.5 and RCP8.5 emission scenarios of near and far futures and agreement among GCMs for the change. The arrows in agreement indicate the direction of change with up arrow indicating increase and down arrow indicating decrease from baseline values.

Month	Baseline (Thousand MW-H)	RCP4.5 NF		RCP8.5 NF		RCP4.5 FF		RCP8.5 FF	
		Mean (%)	Agreement	Mean (%)	Agreement	Mean (%)	Agreement	Mean (%)	Agreement
Jan	226.5	5.3	5 ↑	7.9	5 ↑	7.5	5 ↑	8.5	5 ↑
Feb	177.0	11.3	5 ↑	10.6	5 ↑	17.9	5 ↑	12.2	5 ↑
Mar	122.4	6.7	5 ↑	6.5	5 ↑	12.5	5 ↑	11.0	5 ↑
Apr	122.2	1.4	2 ↑	9.5	3 ↑	9.6	4 ↑	8.4	5 ↑
May	219.9	18.7	4 ↑	11.1	3 ↑	27.9	4 ↑	13.7	4 ↑
Jun	326.7	15.1	5 ↑	20.9	5 ↑	31.3	5 ↑	21.1	4 ↑
Jul	479.1	5.9	4 ↑	10.7	3 ↑	14.6	4 ↑	12.3	4 ↑
Aug	599.2	14.5	5 ↑	18.7	5 ↑	22.4	4 ↑	24.1	4 ↑
Sep	561.9	20.2	5 ↑	22.7	5 ↑	27.5	5 ↑	36.1	5 ↑
Oct	529.6	6.8	4 ↑	6.5	5 ↑	12.5	4 ↑	13.4	4 ↑
Nov	362.0	9.8	4 ↑	17.6	5 ↑	16.3	5 ↑	23.9	5 ↑
Dec	311.0	4.9	5 ↑	6.6	5 ↑	7.5	5 ↑	9.1	5 ↑
Annual	4037.7	11.1	5 ↑	13.8	5 ↑	18.5	5 ↑	18.7	5 ↑

4. Conclusions

Despite being one of the four major river basins of Myanmar, the SRB has yet to be researched for climate change impact assessments. As such, the possible changes in rainfall, temperature, and flows in the basin, as well as the impacts of climate change on the water, food, and energy production, must be understood and investigated. An ensemble of five CMIP5 GCMs for RCP4.5 and RCP8.5 scenarios were used in the WEAP model to assess the impacts of climate change. Given the meteorological data scarcity in the basin, satellite data from APHRODITE and CFSR were used to estimate rainfall, temperature, and other meteorological data in the area. The linear scaling bias correction technique was used to correct both the APHRODITE rainfall and the GCM rainfall and temperature in the basin. We applied remote sensing and GIS techniques in combination with SRTM DEM to estimate reservoir physical characteristics for reservoir modeling in the WEAP model, where data were missing. The impact assessment was conducted between the baseline (BL: 1985–2014) period and the near future (NF: 2021–2050) and far future (FF: 2051–2080) periods for the RCP4.5 and RCP8.5 scenarios.

The average temperature in the basin is expected to increase from 25.9 °C by 1.0 °C (1.1 °C) and 1.8 °C (2.4 °C) in the NF and FF of the RCP4.5 (RCP8.5) scenario, respectively. Compared with the BL rainfall of 2389 mm, the NF is expected to experience a 5.3% (9.0%) increase, and the FF is expected to experience an 11.1% (13.9%) increase under the RCP4.5 (RCP8.5) scenario. In the future, the basin is projected to have drier and warmer non-monsoonal months (December and January) and wetter and warmer monsoonal months. While the magnitude of rainfall and temperature is likely to change in the future, their baseline spatial variability is expected to be retained. Annual flows are expected to experience an increase of 7.5% (9.6%) and 16.4% (19.2%) in the NF and FF, respectively, under the RCP4.5 (RCP8.5) scenario from the baseline value of 1,091.9 m^3/s.

Domestic water demands in the basin are expected to increase from a baseline value of 190.8 to 213.1 and 215.2 MCM in the NF and FF, respectively, due to the increase in the population. The unmet domestic water demands are minimal for the BL (1.3 MCM), which even further reduces in the future by almost 50% due to an increase in rainfall and flows. Agriculture water demands during BL (1390.2 MCM) are expected to increase in the future to 1577.4 MCM (1553 MCM) and 1567.9 MCM (1635.9 MCM) in the NF and FF of the RCP4.5 (RCP8.5) scenario, respectively. This change is due to the increase in evapotranspiration from the increased temperatures, mostly during non-monsoonal months. Compared with the BL, hydropower generation is also projected to increase by 9.0% (11.6%) in the NF and by 16.2% (16.4%) in the FF under the RCP4.5 (RCP8.5) emission scenario. Thus, the domestic and hydropower sectors are likely to be positively impacted by climate change in the SRB, while agriculture water demands are likely to remain unmet in the future. These study results will help the water, agriculture, and energy sectors to develop strategies to maximize benefits and cope with the impacts of climate change in the near and long-term future.

It is recommended that future studies incorporate the more recent climate projections of CMIP6 GCMs [108] for the assessments of the impact of climate change. The crop water requirements of specific crops grown in the SRB need to be included to simulate the water demands of the agriculture sector. All crops grown in the SRB need to be included in future modeling by estimating their crop water requirements and specifying their sources of supply. Similarly, future studies are encouraged to include detailed reservoir operation, inflows, and outflows to simulate flows in the SRB realistically. There is a need to adopt integrated modeling approaches in future studies, with a better representation of rainfall runoff, crop modeling, reservoir modeling, and power generation processes, rather than assessing such impacts individually. The integrated approach can also be applied to evaluate the interconnection of the water–food–energy nexus and the robustness of adaption measures under uncertainties. Hence, this study should be taken as the first undertaking toward the assessment of the impacts of climate change in the SRB and a guide for such studies in data-scarce catchments.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w14213434/s1, Supplementary Figure S1: Baseline (1985–2014) and projected future rainfall for RCP4.5 and RCP8.5 scenarios in Sittaung river basin, Supplementary Figure S2: Baseline (1985–2014) and projected future average temperature for RCP4.5 and RCP8.5 scenarios in Sittaung river basin, Supplementary Figure S3: Observed and estimated volume elevation curves at the selected reservoirs in Sittaung, Supplementary Table S1: Python script to generate reservoir volume elevation curve.

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