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Evaluation of Stream Flow and Water Demand due to Climate Change in the Katha Basin Using Water Evaluation and Planning (WEAP) Model

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Abstract

This study addresses the critical issue of assessing climate change impacts on streamflow and water demand in the Katha basin using the WEAP hydrological simulation model with the Soil Moisture (SM) method. The Katha basin, situated within Ayeyarwaddy River basin, faces variability in stream flow due to changing climatic conditions, impacting water availability for agriculture and domestic use. Through WEAP modeling, calibrated and validated against observed data from 2000-2012, the study projects an increase in annual flows under future scenarios (SSP245 and SSP585). Results indicate potential decreases in monsoonal flows, affecting water availability for agriculture and domestic use, necessitating adaptive management strategies. Model performance assessed by Nash Sutcliffe Efficiency (NSE) and Coefficient of Determination (R2) shows satisfactory agreement with observed data. The study underscores the urgency of integrated water resource management to sustainably address water demands amid climate variability, highlighting implications for agricultural productivity and water security in the region.

A. Introduction

Water is an important resource that drives economies and social well-being of human societies. Understanding the processes that control the existence of water resource, its variability in time and space, and the ability to quantify its availability is important for its sustainable management and efficient allocation among competing users [1]. There is a need to find a solution to water reservation and allocation disputes in developing and developed countries. Applying an integrated strategy that considers the environment, ecological processes, and human activities in catchment areas is essential for the efficient management of water resources. For water resources, an equitable and sustainable water allocation assessment of their many uses in a catchment via a long-term streamflow study is essential [2]. Among the most crucial elements in hydrological systems, streamflow exhibits both geographical and temporal variability. It is crucial for managing and accessing water resources. To accurately estimate the hydrology of a watershed, it is essential to comprehend the features of a streamflow [3].

Non-availability of water has the potential to retard desirable economic and social development in a given society. Conflicts over future water allocations for various purposes have been reported both in advanced countries and the developing countries. Therefore analysis and quantification of water availability, water use and water management are key issues. Water availability is simply the supply of water in excess of that currently allocated for consumptive use in a particular basin; that is, the amount of water available for new development. It is one of the most important indicators of sustainable development in modern society. According to Tidwell [4], population growth coupled with industrial and agricultural expansion brings about new demands for water, further putting more stress on water availability. As observed by Barlow [5], water availability and use greatly depends on the basin hydrology, climate, use characteristics, legal and regulatory institutions, and personal values of the basin inhabitants. Characterizing water availability requires data on both water availability and the dynamics of water resources use in a region.

Ayeyarwaddy, the largest river basin in the country, is likely to experience an increase in flows by 8.0–45.0% in the future, which is expected to translate into significant floods and can impact existing agriculture practices [6]. The Katha Basin itself includes expansive fluvial plains formed by sediment deposition from the Ayeyarwaddy River. These plains are fertile and support agriculture, particularly rice cultivation. The river in this region shows typical braided and meandering patterns. Seasonal variations in water flow significantly impact sediment transport and deposition. Numerous tributaries join the Ayeyarwaddy in this basin, contributing to its hydrological complexity. The fertile plains are heavily utilized for agriculture, primarily rice paddies, which are crucial for the local economy. Towns such as Myitkyinā, Bhamo and Katha serve as administrative and trade centers, influencing the local land use patterns.

Currently, there are many different models that have been used to simulate hydrological processes and human interactions with the environment to develop water allocation plans and water resource management strategies, for example, MIKE BASIN and WEAP. Water Evaluation and Planning (WEAP) is a software tool that is based on water balance and can simulate some elements of rainfall–runoff, water demand and supply system. Additionally, WEAP is the instrument for global integrated water resource management (IWRM) that is utilised the most frequently [7].

The Katha basin heavily relies on the Southwest Monsoon, which brings the majority of annual rainfall between June and October. Rising temperatures associated with climate change can increase evapotranspiration rates, potentially reducing the effective water availability in the basin. The flow of the Ayeyarwaddy River in the Katha Basin has shown variability in recent years. Recent years have seen varying rainfall patterns, with some years experiencing above-average precipitation leading to floods, while others have faced below-average rainfall resulting in drought conditions. Conversely, droughts have been reported, particularly during years with weak monsoon activity. These droughts stress agricultural production and domestic water supply. Understanding the quantity and quality of the available water resources in great detail is essential for effective integrated water resource management. To address this issue, a model of the Katha basin's streamflow characteristics, and available water resources can be developed.

Therefore, this study aims to assess the impact of climate change on streamflow and water demand in the Katha basin using hydrological simulation model, namely the WEAP system via the soil moisture method. The model covers the entire river basin and is physically continuous, with areas constructed and grouped as subcatchments.

B. Research Method

Study Area and Data Collection

The Katha Basin is situated within the upper Ayeyarwaddy (Irrawaddy) River basin in Myanmar. This area lies approximately between 24° to 25° North latitude and 96° to 97° East longitude, it is surrounded by the western foothills of the Shan Plateau in the east and the central plains in the west. The Katha basin area is 132662 km^2.

To assess the impacts of climate change on flows, 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. Table 1 shows the data sources used in the Katha Basin–WEAP model.

Table 1. Data used in this study and their sources

Data sources used in the Katha Basin – WEAP model			
Data Type	**Scale**	**Description**	**Source**
Meteorology	Daily (2000-2023)	Precipitation, wind speed, humidity, temperature	Department of Meteorology and Hydrology, Myanmar
River Flow	Daily (2000-2012)	River discharge	Department of Meteorology and Hydrology, Myanmar

CMIP6 GCMs	2024-2100	CNRM	NASA Earth Exchange Global Daily Downscaled Projections
Land use	1992 -2015	Gridded	European Space Agency
Digital Elevation Model		Gridded	Shuttle Radar Topographic Mission (SRTM)

By using WEAP's rainfall–runoff modeling approach, four sub-basins made up the main Katha Basin. In this research, simulated and observed monthly stream flow are measured at two gauging stations (GS) namely Myitkyinā-GS and Katha-GS for the purpose of calibration and validation.

WEAP Modeling

The Water Evaluation and Planning (WEAP) 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 [8]. WEAP can automatically delineate catchments and rivers (using digital elevation data), calculate land area (disaggregated by elevation band and land cover), download historical climate data for each catchment (by elevation band) and create a climate summary background map layer. This will greatly simply the process of setting up and modeling catchment hydrology. Figure 1 illustrates the schematic of the WEAP model set for this study.

To estimate the surface water in the basin, 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. 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. 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 [9]. A simplified illustration of the Soil Moisture model in WEAP is presented in Figure 2.

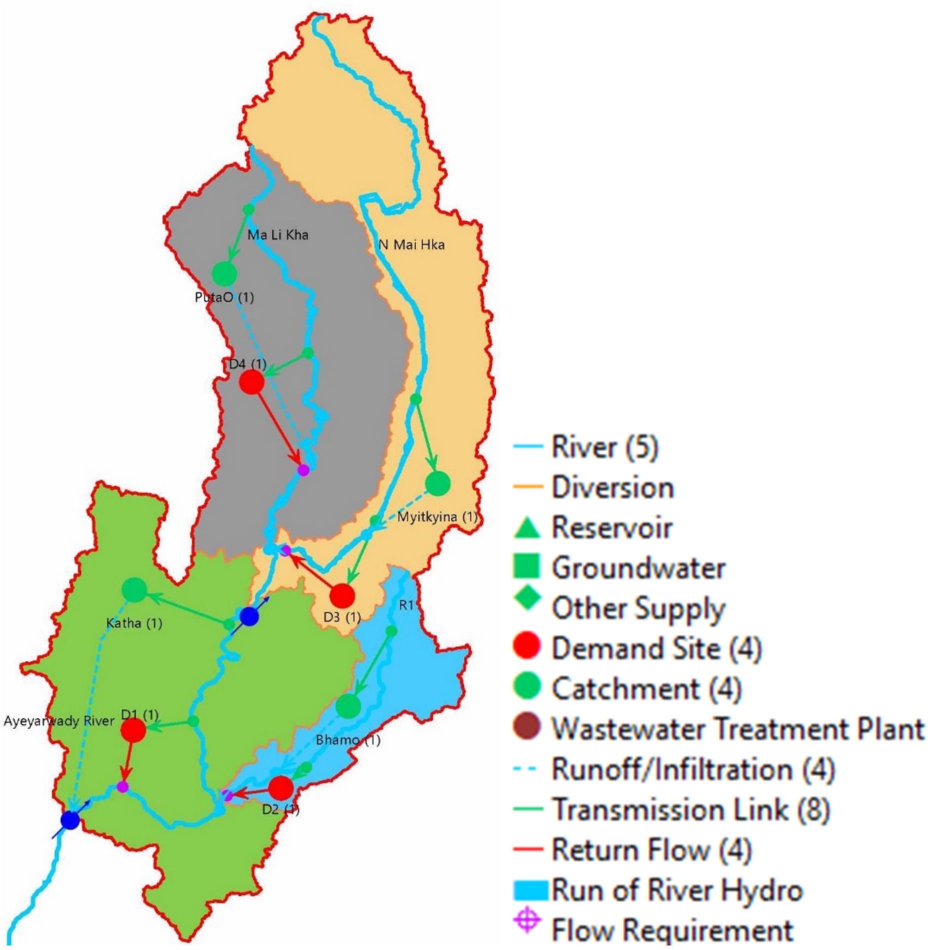

Figure 1. The schematic of the WEAP model for Katha Basin

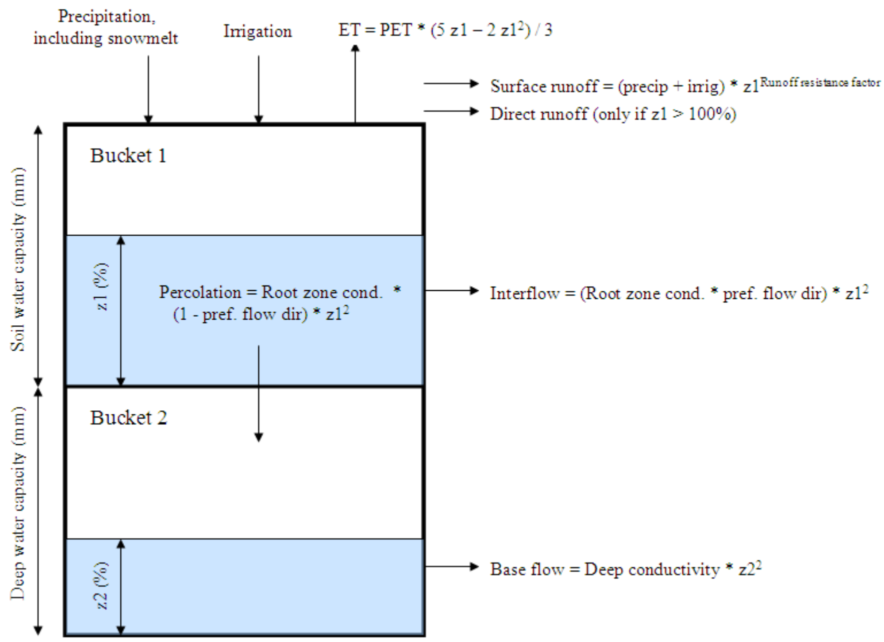

Figure 2. The Soil Moisture Method used in WEAP model

WEAP Model Performance

The parameters of the SM model for each subbasin are calibrated to match the observed monthly flows at two locations in the basin using a WEAP calibration tool. The period 2000–2009 (10 years) is used for calibration, while 2010–2012 (3 years) is used for the validation of the set model. Nash Sutcliffe Efficiency (NSE) and Coefficient of Determination (R^2) are selected as the model performance indicators in this study to evaluate model performance at the monthly time step [10]. Once calibrated and validated satisfactorily, the SM model is used to simulate the baseline flows (2000–2012) and future flows for 2024–2100, respectively. Data and parameters are initially defined in WEAP model. Following the calibration of the model parameters, the model is setup by employing a "Key Assumption" of the physical characteristic values for each sub-basin. Table 2 provides a summary of the descriptions, certain parameters, and related default values.

Table 2. WEAP default values and parameters range

SN	Parameter	Code	Unit	Range of Values			Optimal Range
				Minimum	Maximum	Default	
1	Soil Water Capacity	SWC	mm	0	>0	1000	0-400
2	Deep Water Capacity		mm	0	>0	1000	
3	Runoff Resistance Factor	RRF	-	0	1000	2	0-12
4	Root Zone Conductivity	RZC	mm/month	0	>0	20	14-80
5	Deep Conductivity	DC	mm/month	0.1	>0.1	20	20
6	Preferred Flow Dirction	PF	-	0	1	0.15	0.33-0.8
7	Initial Z1	-	%	0	100	30	-
8	Initial Z2	-	%	0	100	30	-
9	Crop Coefficient	Kc	-	-	-	-	0-0.987

Nash–Sutcliffe Efficiency (NSE)

A common statistic called Nash–Sutcliffe efficiency (NSE) is used to assess how much the residual difference deviates from the variance of the observed data.

$$NSE=1-\frac{\sum_{i=0}^{n}(Q_{0i}-Q_{si})^2}{\sum_{i=1}^{n}(Q_{0i}-\overline{Q_0})^2} \quad (1)$$

Coefficient of Determination (R^2)

The coefficient of determination (R^2), which reflects how well the regression model fits the data observed, is a measure of how well the two variables are related or fit together.

$$R^2=\left(\frac{(\sum_{i=1}^{n}(Q_{0i}-\overline{Q_0})(Q_{si}-\overline{Q_s}))}{\sqrt{\sum_{i=0}^{n}(Q_{0i}-\overline{Q_0})^2}\sqrt{\sum_{i=0}^{n}(Q_{si}-\overline{Q_s})^2}}\right)^2 \quad (2)$$

Q_{oi} = is observed discharge;
Q_{si} = is simulated discharge;
$\overline{Q_0}$ = is mean of the observed discharge;
$\overline{Q_s}$= is the mean of the simulated discharge.

Validation and Classification Criteria

The validation and classification criteria for hydrological models are illustrated in Table 3. The observed and simulated streamflow are made comparison by checking of the accuracy of the model using NSE and R^2 values.

Table 3. Hydrological model categorization and validation standards

Goodness-of-Fit	NSE	R^2
Very good	0.75<NSE≤1	R^2 ≥0.75
Good	0.6<NSE≤0.75	0.7< R^2 ≤0.75
Satisfactory	0.5<NSE≤0.6	0.6< R^2 <0.75
Unsatisfactory	NSE<0.5	R^2 >0.6

C. Result and Discussion

Stream Flow

Understanding the seasonal and annual variability in stream flow is crucial for effective water supply planning. Ensuring adequate water storage during high flow periods can help manage supplies during dry seasons. Reservoirs and dams can be optimized to balance flood control with water storage, providing a reliable water supply throughout the year. The WEAP model, when initially tested with observed meteorological data from 2000 to 2012, yield annual and monthly streamflow presented in Figure 3. The flow data from Katha consistently exhibits the highest peaks, often reaching values above 8,000 Mcm. Puta-O and Myitkyinā follow, with moderate peaks ranging between 2,000 Mcm to 6,000 Mcm, while Bhamo records the lowest peaks, generally below 2,000 Mcm.

The Table 4 presents monthly stream flow data (measured in million cubic meters, Mcm) for four sub-catchment areas (Bhamo, Katha, Myitkyinā, and Puta-O) over a comprehensive period. During the initial months of the year, stream flows are relatively low across all stations. The total flow starts at 221.22 Mcm in January, increasing slightly to 252.32 Mcm in February and rising significantly to 589.56 Mcm in March. Stream flows begin to increase more substantially in April, reaching 1123.96 Mcm, and continue to rise dramatically in May (2618.45 Mcm) and June (6011.60 Mcm). This period marks the onset of the rainy season, with significant contributions from monsoon rains. The peak flow period occurs from July to September, with total flows reaching their highest values. July records a flow of 9497.67 Mcm, which further increases to 10242.67 Mcm in August. September data appears to follow a similar high trend. Stream flows begin to decline after September, reflecting the end of the monsoon season. October records a flow of 5383.46 Mcm, which decreases to 554.59 Mcm in November and further drops to 171.15 Mcm in December.

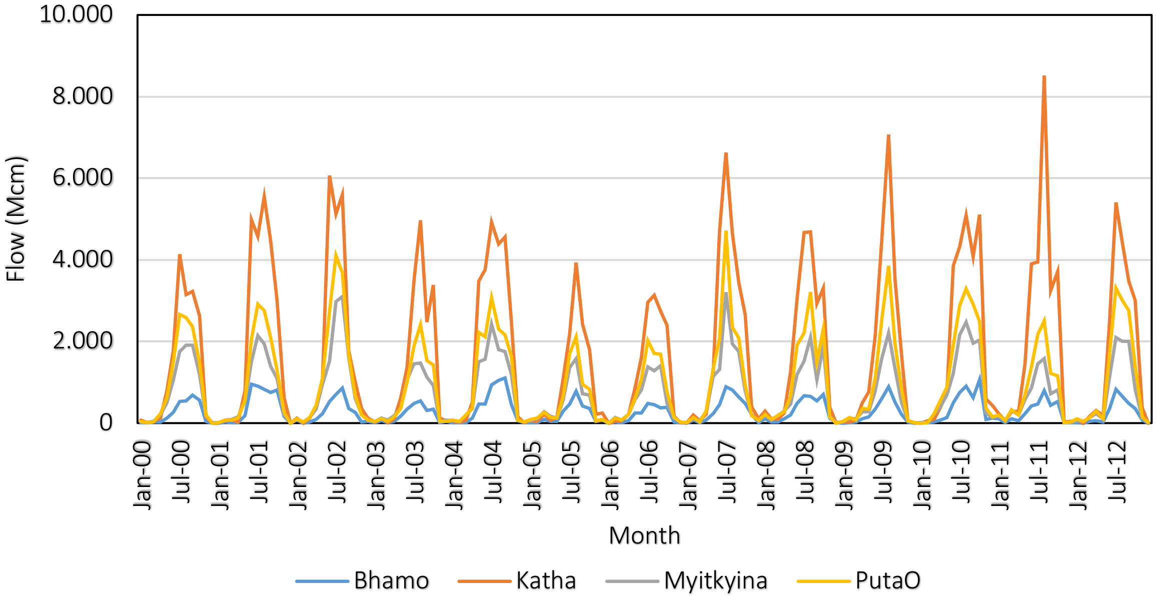

Figure 3. Baseline annual stream flow in sub-catchments

Table 4. Monthly streamflow (Mcm) (2000-2014)

Branch	Puta-O	Myitkyinā	Bhamo	Katha	Sum
Jan	67.4	62.87	25.14	65.82	221.22
Feb	83.35	87.93	21.86	59.18	252.32
Mar	234.89	218.78	32.78	103.11	589.56
Apr	412.08	409.05	61.19	241.63	1123.96
May	813.74	678.13	175.51	951.07	2618.45
Jun	1583.3	1105.78	405.57	2916.94	6011.6
Jul	2666.98	2079.99	642.22	4108.47	9497.67
Aug	2695.44	1927.9	750.18	4869.14	10242.67
Sep	1903.01	1429.32	556.93	3223.76	7113.02
Oct	1263.82	948.64	481.92	2689.08	5383.46
Nov	127.24	116.64	62.58	248.13	554.59
Dec	40.19	36.21	22.54	72.21	171.15
Sum	11891.45	9101.26	3238.42	19548.55	43779.67

WEAP Model Performance: Validation and Classification Critria

The results for monthly data calibration and validation at each measurement station and calibration parameters of sub-catchments are summarised in Table 5. The performance test results from the model simulation it is observed that the model shows a satisfactory match. For both values calibration 0.79 and 0.72 validation (Myitkyina Guage) and calibration 0.72 and 0.62 validation (Katha Guage), respectively, the coefficient of determination (R^2)

represents the streamflow variations at acceptable levels. While the NSE values are also at the acceptable level.

Table 5. Statistically monthly data calibration and validation

Station	Calibration(2000-2008)		Validation(2009-2012)	
	R^2	NSE	R^2	NSE
Myitkyina	**0.79**	**0.78**	**0.72**	**0.51**
Katha	**0.72**	**0.73**	**0.62**	**0.67**

Flow projection

The flows in the basin are projected to increase from a BL value of 642,137.04 Mcm to 2,711,761.49 Mcm in the SSP245 (Figure 4) and 2,395,845.08 Mcm in the SSP585 (Figure 5) scenarios. This increase corresponds to 3.22% SSP245 scenario and 2.73% SSP585 scenario. While the GCMs exhibits a general increase in annual flows in the basin for both SSP245 and SSP585 scenarios, the monthly mean flow projections of the GCMs show that some months, such as December to April, might experience some decrease according to Figure 6 and Figure 7. The projected decreases in mean monthly flows might decrease floods in the river basin. The decrease in monsoonal flows can lead to decreased water availability for agriculture and domestic use, which could easily transform to a loss of yield and further aggravate food insecurity. Aside from the floods, the decreased flows in November to February may affect crop water availability and the crop yields, which need relevant adaptation plans and measures.

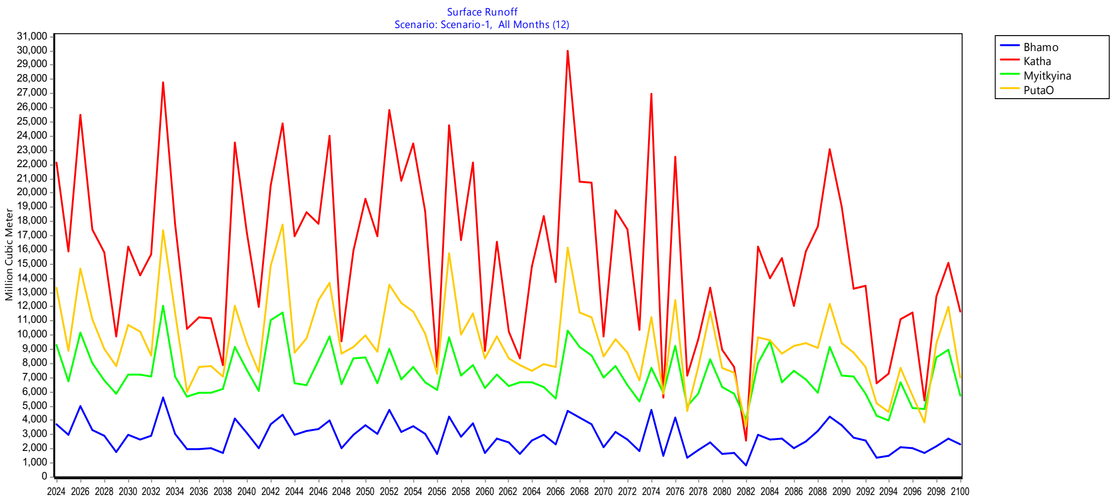

Figure 4. Projected stream flow for SSP245 scenario

The substantial unpredictability in annual flows, particularly around peak years, needs effective flood risk mitigation approaches. Improved forecasting, barriers to flooding, and emergency response strategies are critical for mitigating the effects of extreme flow events. Understanding long-term unpredictability in stream flows is essential for sustainable water supply planning. The findings underscore the importance of adaptive management options for addressing the effects of climatic variability and change on stream flows. The unpredictability of stream flows has important ramifications for aquatic ecosystems and biodiversity.

Maintaining environmental flows and safeguarding important habitats are critical to sustaining ecosystem health and resilience in the face of shifting flow patterns.

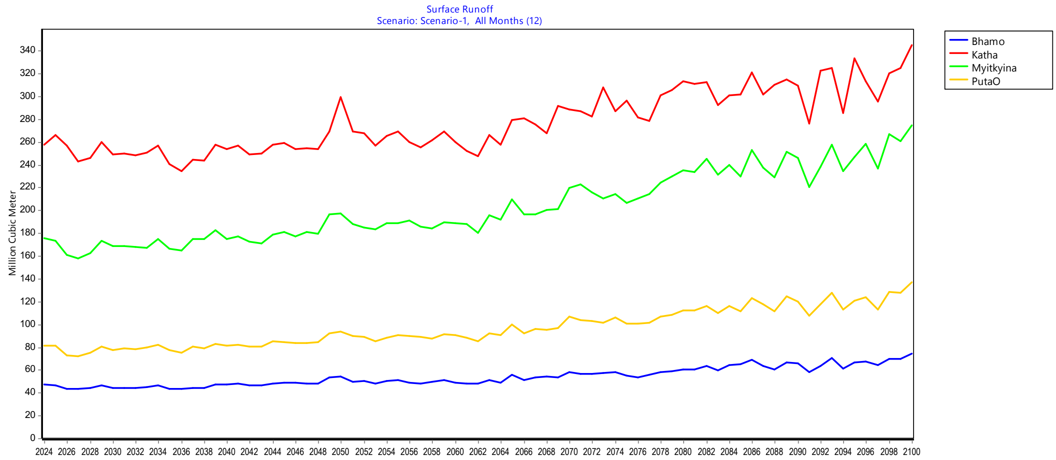

Figure 5. Projected stream flow for SSP585 scenario

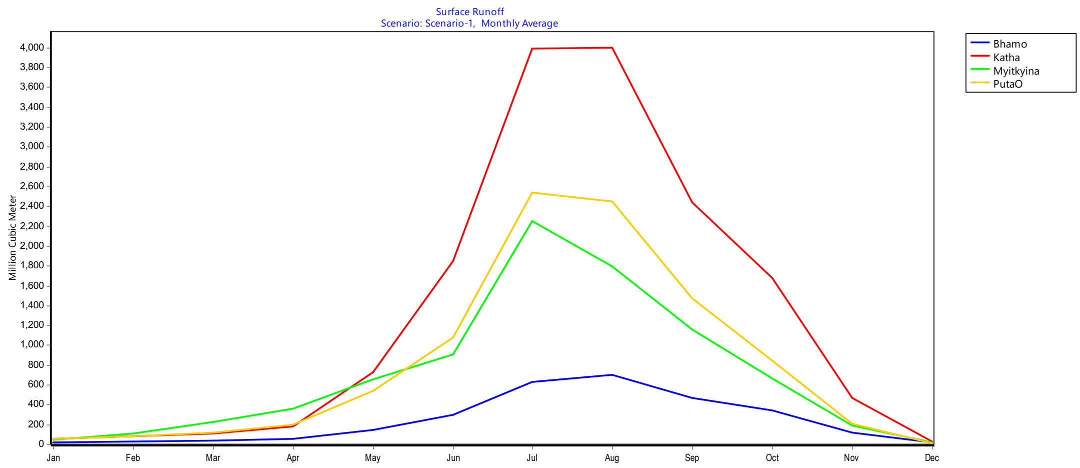

Figure 6. Projected monthly stream flow for SSP245 scenario

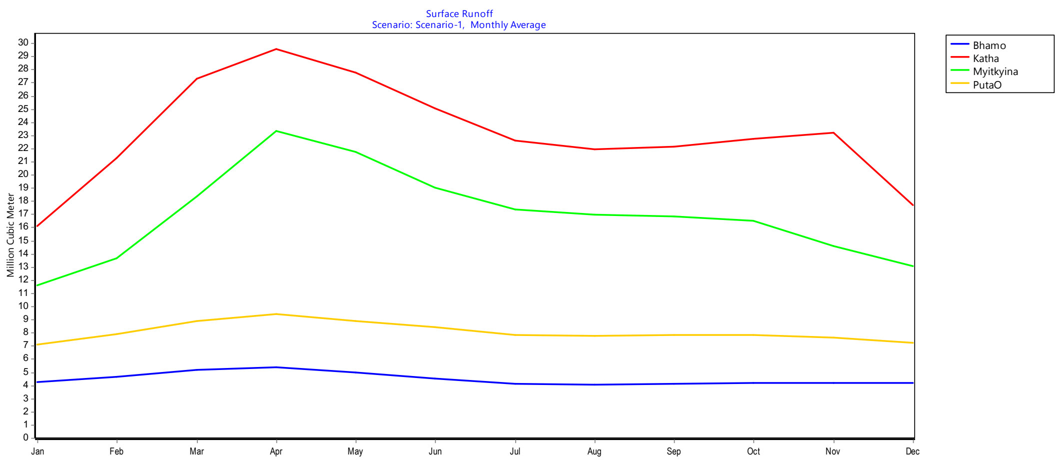

Figure 7. Projected monthly stream flow for SSP585 scenario

Domestic Demands

The amount of water required by individuals residing in the basin to satisfy their daily consumption needs can be quantified by examining their domestic demand. For the purposes of this analysis, a domestic demand is assumed 60 cubic meters per year per person. To calculate the annual domestic demand in each sub-basin, we use the following equation:

Domestic demand (m^3) = *Per capita water consumption* $(m^3/year)$ × *Population* (3)

In this equation, per capita water consumption is multiplied by the population of the sub-basin. Population estimates are derived from the 2014 country census report. Additionally, the population growth trend observed during the baseline period from 2000 to 2014 is considered to project future population figures up to the year 2100. This approach provides a comprehensive estimate of future water demands based on both historical data and projected population growth trends.

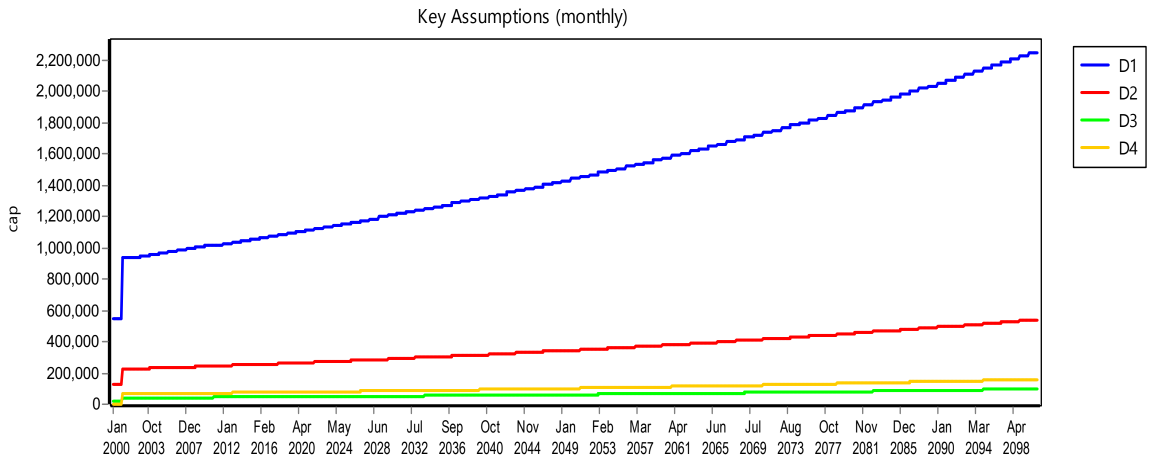

Figure 8. Observed (2000-2014) and Projected (2015-2100) Population of sub-basins

Analysis of water demand (Tabel 6) and unmet domestic demand (Figure 9) from 2000 to 2014 shows significant discrepancies among Katha, Bhamo, Myitkyinā, and Puta-O. Katha constantly satisfies its increasing water demand, which ascends from 33 Mcm in 2000 to 78 Mcm in 2014, for a total of 661 Mcm, with no unmet demand during the period. In contrast, Bhamo experiences increasing unmet demand, ranging from 7.86 Mcm in 2000 to 18.68 Mcm in 2014, for a total unmet demand of 158.93 Mcm, despite an increase in demand from 8 Mcm to 19 Mcm during the same period.Myitkyinā has very modest and constant demand (1 Mcm to 3 Mcm, totaling 29 Mcm), while unmet demand has increased from 1.42 Mcm to 3.36 Mcm, totaling 28.62 Mcm. Puta-O follows a similar pattern, with demand increasing from 2 Mcm to 6 Mcm (total 42 Mcm) and unmet demand increasing from 2.32 Mcm to 5.51 Mcm (total 42.10 Mcm). Optimizing water resource management in Bhamo, Myitkyinā, and Puta-O is essential in order to meet increasing demand and assure for years supply.

Table 6. Annual Water demand (Mcm)

Branch	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	Sum
Katha (D1)	33	37	37	38	38	38	38	38	38	38	38	47	57	67	78	661
Bhamo (D2)	8	9	9	9	9	9	9	9	9	9	9	11	14	16	19	159
Myitkyinā (D3)	1	2	2	2	2	2	2	2	2	2	2	2	2	3	3	29
Puta-O (D4)	2	1	1	2	2	3	3	3	3	3	3	3	4	5	6	42
Sum	44	48	49	50	51	51	52	52	52	52	52	64	77	91	105	891

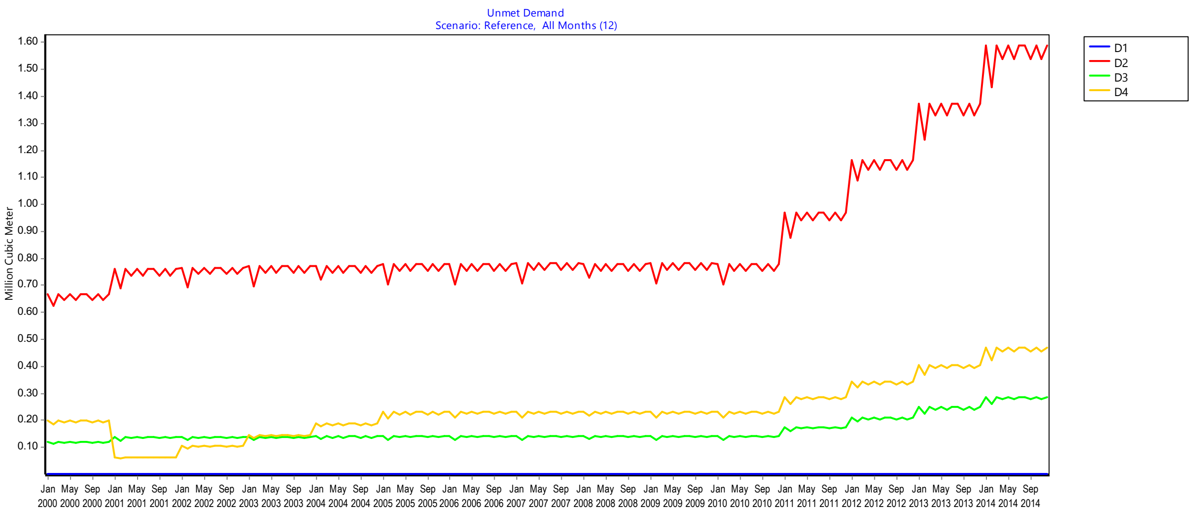

Figure 9. Baseline unmet domestic demand

The Figures 10 and 11 provide represent the unmet domestic demand for two different scenarios, SSP585 and SSP245, from 2024 to 2100. SSP585 and SSP245 scenarios both depict the future unmet demand for four demand sites (Katha, Bhamo, Myitkyinā, and Puta-O). Both scenarios show no unmet demand for Katha, and the total unmet demand across all sites is very similar for both scenarios. The comparison of unmet domestic demand between the SSP585 and SSP245 scenarios reveals remarkably similar trends and values. This similarity suggests that both scenarios, despite representing different socioeconomic pathways and climate futures, project nearly identical pressures on resources or supply chains in terms of unmet domestic demand for the given sites. Katha remains unaffected in both scenarios, indicating that the conditions leading to unmet demand do not impact this site under either scenario. Bhamo, Myitkyinā, and Puta-O show a consistent increase in unmet demand over time, reflecting a growing strain on resources. The yearly increase and total unmet demand are almost identical between the two scenarios, with minor numerical differences.

The domestic water demands are higher in March and May, mostly due to the increase in the water requirement in these months by the domestic sector and relatively similar during other months. In future periods, domestic water demands are not affected by the change in climate but by the population change. The unmet demands are increased to 69.63 Mcm in both scenarios. Katha Catchment, which previously had no unmet domestic demands during BL and local supply is sufficient for the future. Accordingly, Katha Basin is also likely to provide domestic water to its inhabitants in the future with its own local water system.

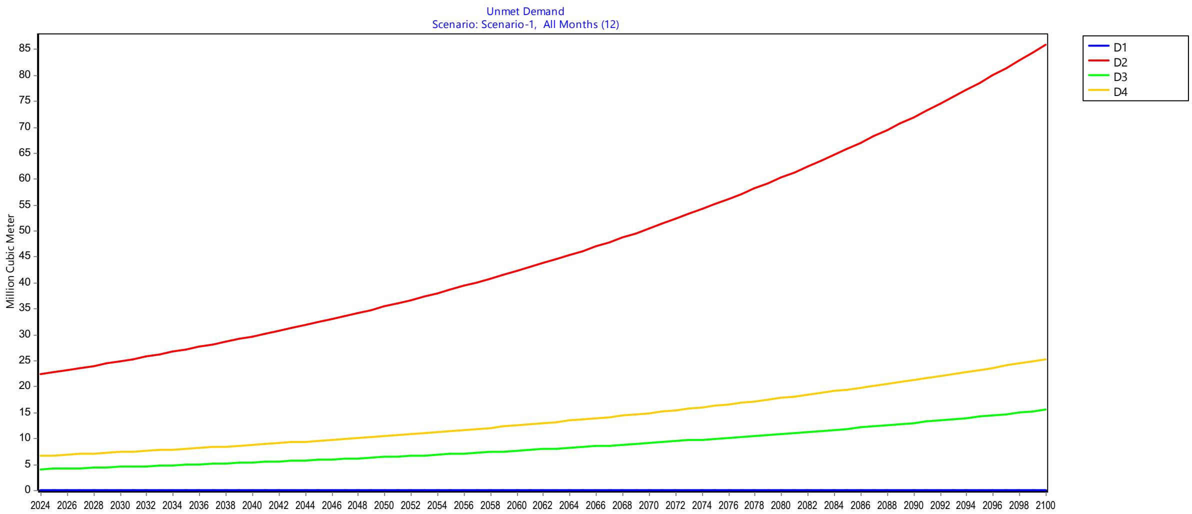

Figure 10. Unmet annual domestic demand for SSP245 scenario

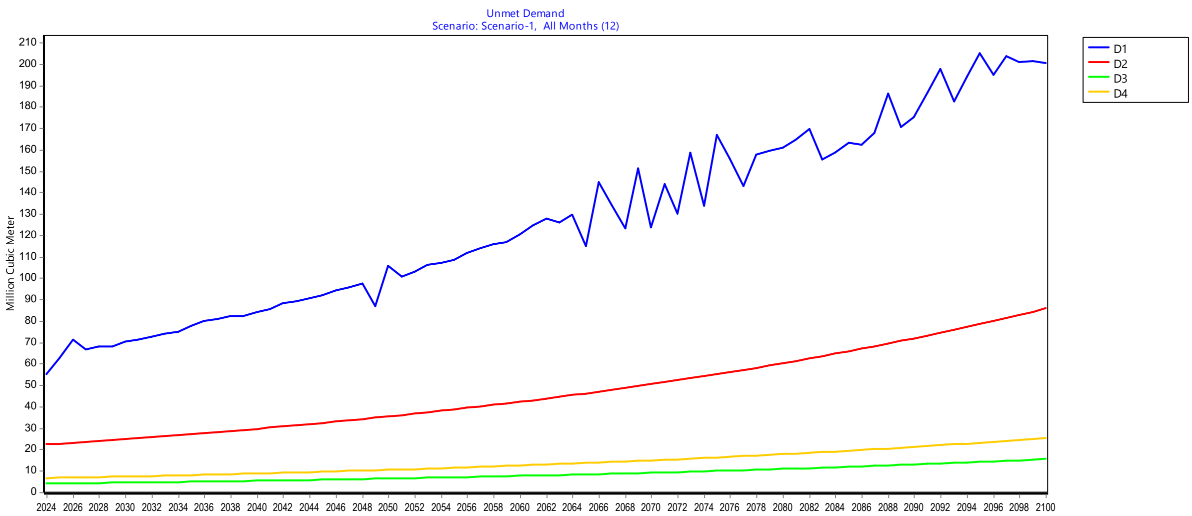

Figure 11. Unmet annual domestic demand for SSP585 scenario

Agriculture Demands

Katha has the largest catchment area of 7,722,929 ha. It also has significant rain-fed (402,590 ha) and irrigation cropland (75,472 ha), but the percentages are relatively low (5.2% and 1%, respectively). Bhamo has a much smaller catchment area (707,729 ha) compared to Katha, but it has a higher percentage of both rain-fed (9.9%) and irrigation cropland (3.1%). Myitkyinā has a catchment area of

2,504,166 ha with a very low percentage of rain-fed (0.9%) and irrigation cropland (0.3%). Puta-O has a catchment area of 2,331,386 ha with the lowest percentages for rain-fed (0.6%) and irrigation cropland (0.1%) among the regions listed. These figures indicate that Katha has the largest area devoted to both types of cropland in absolute terms, while Bhamo has the highest percentages of its catchment area used for cropland. Myitkyinā and Puta-O have relatively small proportions of their land used for agriculture are displayed in Table 7.

Table 7. Land used information in Katha Basin

Catchment (ha)	Rain fed Cropland (ha)	Irrigation Cropland (ha)
Katha (7722929)	402590 (5.2%)	75472 (1%)
Bhamo (707729)	70048 (9.9%)	22054 (3.1%)
Myitkyinā (2504166)	22871 (0.9%)	8716 (0.3%)
Puta-O (2331386)	14797 (0.6%)	2891 (0.1%)

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

Figure 12. Crop calendar used in Katha Basin

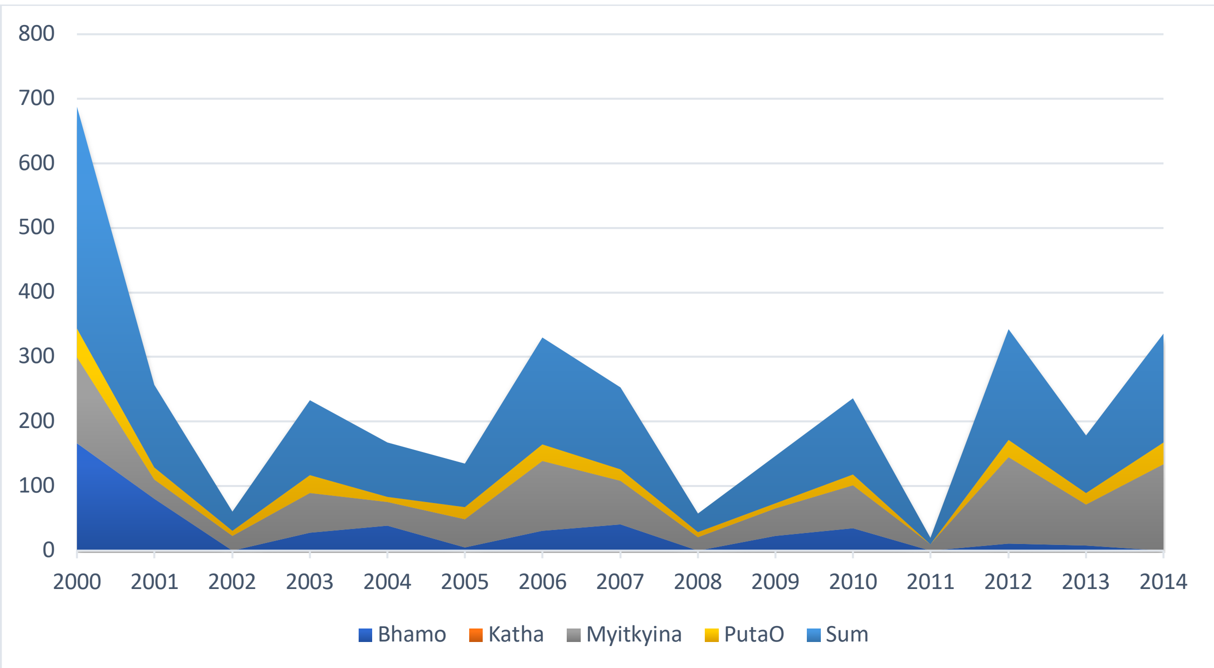

Figure 13. Baseline unmet agricultural demand

In Figure 13, Bhamo catchment shows varying levels of unmet agricultural demand over the years, ranging from 0 Mcm in some years to 166 Mcm in 2000.

Myitkyinā also exhibits fluctuations in unmet demand, with the highest demand recorded in 2013 (134 Mcm) and varying from year to year. The total unmet demand for Myitkyinā over the entire period is 976 Mcm, the highest among the sites listed. PutaO's unmet demand varies similarly, with the highest demand of 44 Mcm in 2000. The total unmet demand for Puta-O over the entire period is 279 Mcm. The total unmet agricultural demand across all sites and years sums up to 1721 Mcm. This total represents the gap between agricultural water demand and available water resources (including storage). The data shows that each site has experienced periods of both high and low unmet agricultural demand, which could be influenced by factors such as climate variability, water management practices, and agricultural production patterns.

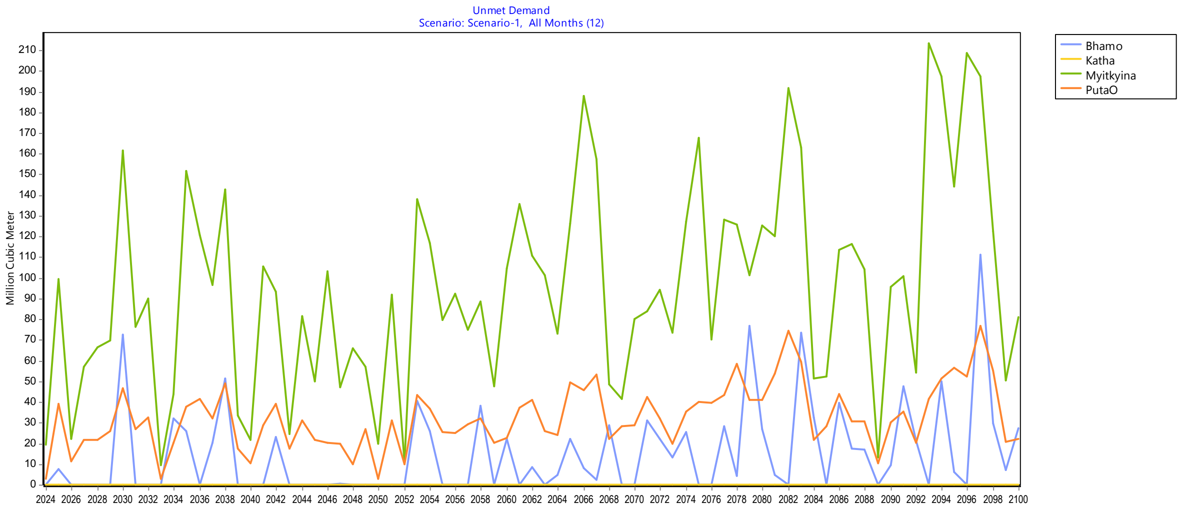

Figure 14. Unmet agricultural demand for SSP245 scenario

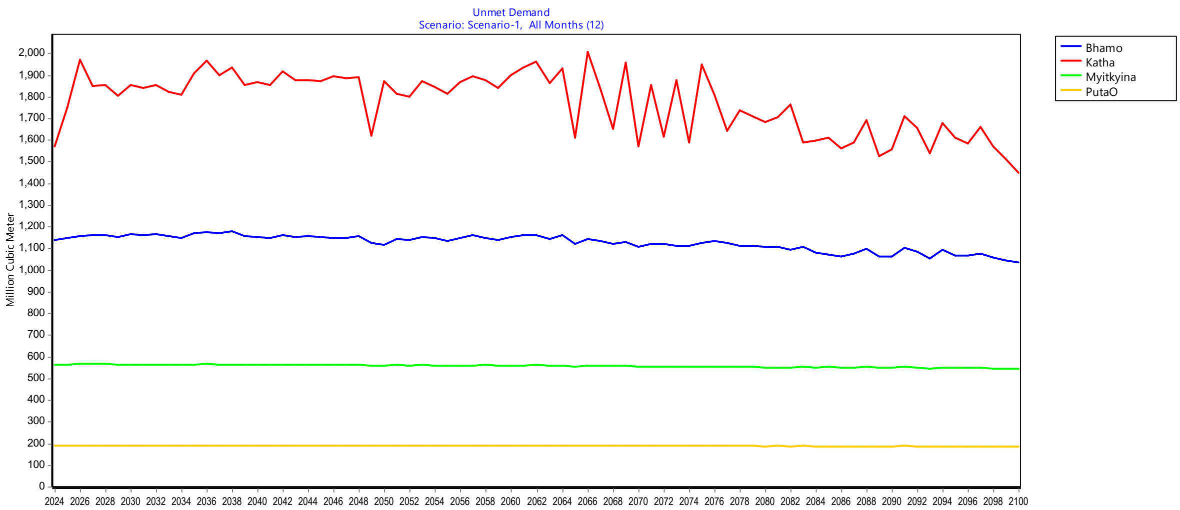

Figure 15. Unmet agricultural demand for SSP585 scenario

Both scenarios exhibit significant seasonal variation in water demand. For instance, in Myitkyinā (a representative site), demand peaks during the dry season months of March to May in both scenarios, reflecting higher agricultural water needs during planting and early growth stages. SSP585 generally shows higher total unmet agricultural water demand across all sites compared to SSP245. This indicates more severe water stress under the SSP585 scenario, likely due to higher population growth and economic development assumptions leading to increased water demand. Bhamo catchment shows relatively lower unmet water demands compared to other sites in both scenarios, except for April in SSP245 where it peaks. Myitkyinā catchment demonstrates the highest absolute unmet water demand among the sites, indicating potentially higher agricultural activity or less available water resources relative to demand. Puta-O and Katha catchments generally exhibit moderate to low unmet water demands across months and scenarios. SSP585 reflects more severe impacts of climate change and socio-economic development on water resources, leading to increased water stress and potentially compromising agricultural productivity. In the comparison between SSP245 and SSP585 scenarios underscores the critical influence future development pathways and climate change mitigation efforts on regional water availability and agricultural sustainability. It highlights the need for adaptive water management strategies to mitigate water stress and ensure food security in the face of evolving environmental conditions.

D. Conclusion

This study has demonstrated the significant implications of climate change on water resources management in the Katha basin, Myanmar, using the WEAP hydrological model with the Soil Moisture (SM) method. The projections under SSP245 and SSP585 scenarios highlight potential shifts in streamflow dynamics, particularly indicating a decrease in monsoonal flows. These changes are critical as they directly impact water availability for agriculture and domestic use, crucial for sustaining livelihoods in the region. The calibration and validation of the WEAP model against observed data from 2000-2012 showed satisfactory performance metrics (NSE and R^2), validating the model's ability to simulate current and future hydrological conditions accurately. This enhances the reliability of the projected scenarios and underscores the urgency of proactive water management strategies.

Adaptive management approaches are essential to mitigate the adverse effects of reduced water availability, ensuring resilience against climate variability. Integrated water resource management practices, focusing on sustainable use and allocation, are imperative for addressing the challenges posed by climate change in the Katha basin and beyond.

This study contributes to a deeper understanding of climate-water interactions and provides a foundation for informed decision-making and policy formulation aimed at enhancing water security and promoting sustainable development in water-stressed regions.

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