

**IMPACT OF CLIMATE CHANGE AND SOCIO-ECONOMIC  
DEVELOPMENT ON WATER ALLOCATION FOR  
ECOSYSTEM-WATER-ENERGY-FOOD SERVICES: A CASE  
STUDY ON MAHAWELI RIVER BASIN, SRI LANKA**

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Degree of Master of Science

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Sri Lanka

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Supervised by  
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Thesis submitted in partial fulfilment of the requirements for the Degree of Master of Science  
in Water Resources Engineering and Management

UNESCO Madanjeet Singh Centre for  
South Asia Water Management (UMCSAWM)

University of Moratuwa  
Sri Lanka

August 2022

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## **ABSTRACT**

### **Impact of Climate Change and Socio-Economic Development on Water Allocation for Ecosystem-Water-Energy-Food Services: A Case Study on Mahaweli River Basin, Sri Lanka**

This study was carried out to assess the impacts of climate change on the dynamics of surface water availability for different present and future users in the Mahaweli river basin.

A multi-tier modeling method was applied in the analysis by combining the Soil and Water Assessment Tool (SWAT) and Water Evaluation and Planning Models (WEAP) to mimic stream flow under climate change and evaluate situations of future water accessibility for diverse socio-economic activities by the year 2050. Three standard global circulation models (GCMs), CSIRO Mk3.6, Had, CM2-ES, and MIROC5, were downscaled, rectifying bias using CMHyd.

The SWAT model was successfully calibrated with  $R^2$  equals 0.65 for calibration period and for validation the  $R^2$  equals 0.57. The calibrated model shows a Nash- Sutcliffe efficiency (NSE) values of 0.68 during the calibration period and 0.73 in validation period. The SWAT model was initially calibrated using available data to forecast future stream flows. Then those stream flows were used as inputs for the WEAP model to assess water availability for various socio-economic activities. Results from GCMs indicate that an increase in annual mean rainfall within a range of 16-18% can be expected by the 2050s, compared to the rainfall during the period between 2006 to 2009. The average temperature is forecasted to increase by about 2°C compared to the temperature baseline period. Further, there will be an increase of about 10% in long-term average stream flow. However, the model predicted a decrease in peak flows in the 2050s compared to the current average flows. The model forecasted that the overall total water demand in the Mahaweli basin will increase to 3,249.69 Mm<sup>3</sup> in the year 2050, compared to the current demand of 1,879.73 Mm<sup>3</sup>. This will create a situation where 51.5% of the total demand amounting to about 1,673.80 Mm<sup>3</sup> will not be met in the 2050s. A severe water shortage is predicted that about 71.12% of future irrigation demand will not be fulfilled in the 2050s. Water for hydropower generation will also be significantly affected as its unmet demand will be around 27.47%. However, the water demand for livestock will be marginally affected by about 1.41% of unmet demand as per the model's forecasts.

The modeling results raise the need for paying attention to future water shortages for various socio-economic activities, which can be caused by climate change, and the need for taking necessary steps to address this situation effectively.

**Key Words:** Irrigation Demand, Multi-Tier Modelling, Unmet Demand, , Water Resource Management

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## LIST OF ABBREVIATIONS

AMDP	Accelerated Mahaweli Development Programme
AOGCM	Atmosphere-Ocean General Circulation Model
CEB	Ceylon Electricity Board
CMIP	The Coupled Model Intercomparison Project
CMIP5	Phase Five of the Coupled Model Intercomparison Project
GCM	General Circulation Model
GHG	Greenhouse Gas
IPCC-TGIC	Intergovernmental Panel on Climate Change – Task Group on Data and Scenario Support for Impact and Climate Assessment
MASL	Mahaweli Authority of Sri Lanka
MCB	Mahaweli Consultancy Bureau
NEM	Northeast Monsoon
NCP	North Central Province
SIM	Second Inter-Monsoon
OFC	Other Field Crops
SRES	Special Report on Emission Scenarios (Stenseth, et al., 2003)
SWM	Southwest Monsoon
R <sup>2</sup> -	R squared
RCP	Representative Concentration Pathways
RMSE	Root Mean Square Error
UNDP/FAO	United Nations Development Program/ Food and Agriculture Organization
WGCM	Working Group on Climate Modelling

# **1 INTRODUCTION**

Many countries situated in South Asia are facing severe challenges in providing adequate water for domestic use, meeting energy demand, and ensuring adequate food supplies for the rapidly increasing population with growing water stress, inadequate energy supply, and limited land resources. Although there are many river basins in Sri Lanka, the Mahaweli river basin is the only river basin used for multiple uses. This study investigates the linkage among water, food, and energy on a basin dimension. Emphasizing the role of the Mahaweli river basin ecosystem in sustaining the security of food, water, and energy.

Many studies carried out in South Asian countries have disclosed that problems and challenges in the sectors of food, energy, and water are highly interrelated, and they can be effectively managed only by intersectoral collaboration. The most significant feature of interrelation in South Asian River basins is the high dependency on upper stream ecosystems for the fulfilling needs of domestic and irrigation water, hydropower, nutrients, and soil fertility in the downstream community. Equal attention must be paid to the management of ecosystems significantly on watersheds, water catchments, and headwaters of river systems and tapping of collaborative gains in water, food, hydropower, and ecosystem services through intensive corporation between stakeholders in addressing the nexus in various ecosystem services.

This study explores the impact on ecosystem services, water, food, and hydropower nexus in the Mahaweli river basin in Sri Lanka amidst impending climate changes and socio-economic development.

## **1.1 Climate Change and Socio-Economic Development**

### **1.1.1 Climate Change in Sri Lanka**

Sri Lanka is an island located south of India, extending about 65,600 km<sup>2</sup>. Central parts of the country are hilly areas and in gradually become flat towards the surrounding coastal area. About 75% of the extent of the country is a flat area. The country is situated in the south of the Indian sub-continent, experiencing two monsoons that bring rains to the island. Sri Lankans experience a warm climate frequently affected by ocean winds and high moisture.

Sri Lanka does not experience considerable annual temperature variance due to the changes in latitude as the country is small. But latitude change creates considerable regional temperature variations. In low land areas, the average yearly temperature falls within the range of 26.5 to 28.5° C, but it falls significantly with increasing altitude. For example, Nuwara Eliya, which is

situated at an altitude of about 1,800 m, falls up to 15.9° C. Therefore, the average climate pattern in each area varies mainly depending on the change of precipitation, as significant seasonal variation of temperature is not happening. The country’s rainfall usually falls within the range of 900 mm-5,000 mm, with an average rainfall of about 1,850 mm. Sri Lanka has three major sources of rainfall monsoonal, convectional, and depressional. The country’s climate is generally divided into four seasons based on variation in precipitation (Table 1-1)

Table 1-1: Climate Seasons in Sri Lanka

<b>Name of the Season</b>	<b>Period</b>	<b>Average rainfall (mm)</b>	<b>As a % of Annual Rainfall</b>
First Inter Monsoon (FIM)	Mar- Apr	2,68	14%
Southwest Monsoon (SWM)	May- Sep	5,56	30%
Second Inter Monsoon (SIM)	Oct – Nov	5,58	30%
Northeast Monsoon (NEM)	Dec - Feb	4,79	26%

During the First Inter Monsoon (FIM), which occurs from March to April, southwestern quarters, and some parts of central highlands experience rainfall of over 250 mm. In this period, few localized slope areas in southwestern parts receive very high rainfall, such as 700 mm, while many other parts receive rainfall within the range of 100 mm -250 mm. During this period, flash floods occur due to high rainfall, and many areas experience frequent hazardous lightning combined with thunderstorms. Southwestern monsoon is experienced throughout the period from May to September, and during this season, over 3,000 mm of rainfall is received for mid-elevation western slopes of central highlands. Southwestern coastal belt gets a rainfall within the range 1,000 mm-1,600 mm during this period, and higher elevation of central highlands gets rainfall of about 800 mm. Floods and landslides, respectively, in low-lying areas and hilly areas, are also possible during this period due to continuous monsoon rains. Further, rains can be expected any time, day, or night during this period.

During the period from October to November, Second Inter Monsoon (SIM) occurs. The influence of common depression is common in this period, and the entire country experiences widespread rainfall of about 400 mm. Rains are combined with strong winds, leading to floods and landslides. It is also the season in Sri Lanka with equally distributed rainfall. Many areas experience rainfall of about 400mm, while high rainfall of about 750-1,200 mm is recorded on

southwestern slopes. From December to February, the Northeast Monsoon season occurs. During this period, northern, northcentral, and eastern parts of Sri Lanka experience rainfall due to the humid wind gusting from the northeast Asian continent. Eastern slopes in Knuckles/Rangala range and eastern slopes in hilly areas record the peak rainfall during this period.

The above general pattern of rainfall in the country delivers annual rainfall between 900 mm – 5,000 mm with a mean annual average rainfall of 1,850 mm. Especially the Western slopes of central highlands in southwestern parts of the country record the highest annual rainfall, with rainfall of more than 5,000 mm in the Yatiyanthota, Ginigathhena, and Watawala areas. The lowest value for rainfall occurs in southeastern (Yala, Palatupana < 1,000 mm) and northwestern (Mannar < 1,000 mm) seaside areas.

There are three climatic zones generally experienced in Sri Lanka. The first zone is the “Southwest zone plus central hill country,” whereas the “dry zone” consists mainly of the northern and eastern sections of Sri Lanka. The third zone is called the “Intermediate zone,” which is the area boarded by the central hills in the north and the east. The factors widely used for differentiating the above three zones include annual rainfall, type of soil, inputs from the southwest monsoon for overall rainfall, vegetation, and land use methods and vegetation (Punyawardhana & Premalal,2013). The wet zone generally receives a comparatively high mean annual rainfall exceeding 2,500 mm, without a noticeable dry period. The Dry Zone experiences a different dry period from May to September, while it gets less than 1,750 mm of annual rainfall. The Intermediate Zone records an annual rainfall within the range of 1,750 mm – 2,500 mm with short and less remarkable dry periods. The country has been further partitioned into 46 agro-ecological regions considering monthly rainfall (taken with 75% probability), distribution of rainfall, and common variables used for classifying climatic zones. The map in Fig.2 shows the agro-ecological regions of the country.

Analysis of historical temperature records shows that the average atmospheric temperature in all parts of Sri Lanka is gradually increasing (Chandrapala, 2007a; De Costa; Eriyagama et al., 2010; Nissanka et al., 2011; Sathischandra et al., 2014). During the last few years, different rates of temperature increases have been reported from various locations, and a faster warning trend has been noted (Basnayake,2007; Chandrapala,2007a; De Costa; Sathischandra et al.,2014). During the last few decades, a considerable increase in anomalies of annual mean air

temperature has been recorded in all stations (Basnayake,2007). ). The mean values of daytime maximum temperature and minimum temperature in the night-time have also been noticed (Basnayake,2007: Zubair et al.,2005). Further, it has been noticed that the contribution of an increase in night-time minimum temperature is more than the input from an increase in daytime maximum temperature to the annual increase in temperature (Basnayake,2007). No definite pattern or trend has been noticed in precipitation, unlike in temperature variations. However, some researchers have suggested that annual rainfall shows a decreasing trend by comparing the present and past mean annual precipitation (Basnayake, 2007: Chandrapala, 2007b: De Costa:Jayatilaka et al.,). But there is no harmony seen in this relationship among researchers as different trends have been observed in different locations (Punyawardhana & Premalal, 2013). Furthermore, the central hills have experienced more frequent events of high rainfall during the last few years. However, many researchers agree that in recent years, many variations in rainfall have been observed, especially during the Yala Season (Chandrapala, 2007b: Eriyagama et al.,2010: Punyawardhana, 2002). Moreover, a trend of increasing successive dry days and decreasing successive wet days have been observed (Premalal, 2009; Ratnayake & Herath, 2005). Studies also indicate that although still a clear pattern cannot be recognized spatial distribution of rainfall seems to be changing (Basnayake, 2007: B.G.Marambe et al.,2013:Nissankaet al., 2011: Sathischandra et al., 2014:). A few studies indicate changes in distribution can even result in the shifting of agro-ecological borders (Eriyagama et al., 2010: Mutuwatta & Liyanage, 2013).

Also, an increase in the strength and frequency of extreme incidents like floods and droughts has been noticed (Imbulana et al., 2006; Premalal & Punyawardena, 2013; Ratnayake & Herath, 2005). There is a strong correlation between the locations of landslides and areas that receive rainfall with high intensities (Ratnayake & Herath, 2005). The Asian region experiences an average sea level rise of about 1-3 mm/year, which is slightly above the average universal value (Cruz et al., 2007). Further, sea level rise has also indicated an increasing trend throughout the period from 1993 to 2001 (3.1 mm per year) in the Asian region. However, no assessment has yet been carried out to determine the extent of sea level rise in surrounding areas of Sri Lanka.

### 1.1.2 Projected Climate Change Impacts for Sri Lanka

There are three modelling approaches adopted for projecting climate change for Sri Lanka as follows (Eriyagama et al.,2010).

1. General circulation models (GCM)
2. Regional climatic models (RCM)
3. Statistically downscaled GCM models

The Inter-Governmental Panel of Climate Change (IPCC), in its fourth and fifth assessment reports (AR4 and AR5) for projections for Asia, has published key global projections in relation to Sri Lanka. These projections have established their general agreement that warmer climates will be increasingly experienced in South Asian countries. (Cruz et al.,2007; Hijiki et al.,2014). They also predict that warming in South Asia will exceed the global average increase. The following predictions have been made with a high probability for South Asia (Hijioka et al.,2014).

1. Increase in mean annual temperature by more than 3<sup>0</sup> C.
2. By mid of twenty-first-century increase in precipitation
3. Extreme high precipitation in monsoons
4. Increase in temperature in the oceans in tropical Asia.

Ahmed and Suphachalasai (2014) forecasted that there might be a temperature rise by 3.6°C, 3.3°C, and 2.3°C under A2, A1B, and B1 scenarios, respectively, by 2080, based on an RCM. Figure 1-1 displays the respective projections.

Climate parameter	2030			2050			2080		
	A2	A1B	B1	A2	A1B	B1	A2	A1B	B1
Precipitation (%)	7.4	11.0	3.6	15.8	25.0	16.5	39.6	35.5	31.3
Temperature (C)	1.0	1.1	1.0	1.8	1.5	1.3	3.6	3.3	2.3

Figure 1-1: Projected Impact of Climate Change in Sri Lanka Source

According to the observed changes, forecasts are also less confident about the changes in the rainfall pattern. Ahmed and Supachalasai (2014) forecast growth in precipitation levels by 39.6%, 35.5%, and 31.3%, consecutively, under A2, A1B, and B1 scenarios by 2080 as displayed in Figure 1-1. However, locally downscaled models indicate different predictions on variations in precipitation where they predict a trend in both directions—increasing and decreasing mean annual rainfall (MAR) (Eriyagama et al., 2010). According to one such

projection, MAR will increase by 14 percent and 5 percent for A2 and B2 respectively by 2050s compared with the period 1960-1991 (C.S.De Silva & Lanka, 2006). This is not a uniform overall increase. It predicts a decrease of 34 percent and 26 percent for A2 and B2, respectively, in NEM, while projecting increases of 38 percent and 16 percent for A2 and B2, respectively, for SWM rainfall. Some studies have projected an increase in rainfall in the wet zone, intermediate zones, and north and south-western dry zones and a decrease in rainfall in the remaining areas of the dry zone by 2050 (Basnayake & Vithanage, 2004). Studies have also predicted for the upper Mahaweli watershed in the central highlands that by 2025 rainfall will be reduced by 17 percent (Shantha & Jayaundara, 1995). According to Marambe et al. (2015) and Punyawardena et al. (2013), a polarization of the climate pattern in Sri Lanka is seen where the dry zone becomes drier, and the wet zone becomes wetter in years to come.

The IPCC research has also predicted an increased occurrence of extreme weather events for the South Asian region, possibly including heat waves and severe precipitation events (Cruz et al., 2007). Coastal disasters have also been predicted, including a rise in the incidence of tropical cyclones by 10-20 percent (Cruz et al., 2007).

### **1.1.3 Socio-Economic Development**

Water is a basic human need. Apart from drinking and other domestic needs, water serves as an important factor in agriculture and hydropower generation and in the environment. It is, therefore, necessary to maintain the ecosystem. People in many developing countries suffer severely due to the non-availability of water sources to fulfil their daily water needs. In many Asian and African countries, people, especially women and children, must travel long distances to collect their daily water needs. This wastes valuable time, which can be used for any revenue-generating activity, thereby increasing their poverty. Water is a major contributory factor to the economy of any country, as, without access to adequate and safe water, the country will lose the efficiency of its workforce. Furthermore, nowadays, it is considered a basic economic commodity. Without good quality water, there may be various health issues that eventually increase health expenditure in any country. Further, it is evident that the lack of adequate water in the vicinity discourages children's schooling, thereby creating a dangerous situation for the country's future. As water is required for many activities such as domestic supply, industries, farming, navigation, recreation, and, more importantly, for balancing the ecosystem, effective sharing of water among all above the sectors is very important. In any country, it is customary

to give priority to domestic water supply whenever there is competition for water resources. As investment in water and sanitation infrastructure brings multiple benefits, it is an important factor for national wellbeing. The ability to generate of direct employment is relatively limited in the water sector, and it varies from region to region.

The water cycle, consisting of evaporation, precipitation, and runoff, continuously renews the global freshwater resources. Further, the water cycle determines the spatial and temporal variation of the distribution and availability of water resources. There are different methods adopted to define and measure water scarcity and/or water stress. The most common global indicator of water scarcity is renewable water available per person per year, where limiting values are used to differentiate among different levels of water stress. (Falkenmark & Widstrand, 1992).

There are several indicators adopted to express the wealth of a nation. The most common and regularly used indicator is the Gross National Product (GNP). The GNP per capita is widely used to indicate the monetary rating of an economy. The Human Development Index (HDI), introduced by the United Nations Development Programme, is also used to express the wealth of a country in broader terms. It is composed of social and environmental factors in addition to economic factors. The role of water in the context of development is well accepted all over the world. Suitable management of water resources is a major contributor to human development. The link between the management of water resources and human development must be well understood and included in policies and programs to achieve a win-win situation. The term “development” means progress. The concept of human development is regularly adapted to focus on the results rather than the process of achieving them. The main objective of the development is the creation of an environment in which people can enjoy a healthy and long life.

Water is considered the basic and most significant component of human development. However, the indicators used to express the development do not clearly concentrate on the relationship between water and water availability with human development.

Water can be a hindrance to the process of human development under many conditions. Some of them are as follows.

- a) When water inputs into the main production process are static in relation to output,

- b) When the supply of water is constant, or there is only a limited possibility for slow and costly expansion

When supplies are precisely allocated among uses over time, When water acts as a regulator of human wealth and productivity.

Water is a unique liquid as it cannot be produced artificially, and nothing can be substituted for water. The total amount of water available on Earth remains constant, and only conversion from one state to another is possible. Water is a predominant factor in human development. This is evidence that people had their initial settlements close to water bodies since the inception of mankind. Lack of adequate water can adversely affect the well-being of people in numerous ways. It may increase health hazards and result in less productivity. On the other hand, the lack of availability of water in proximity may involve spending a lot of energy and time collecting water for day-to-day use.

The key fundamental role of water in human development is its use for domestic needs; use for drinking, sanitation needs, and other domestic uses, including cooking, bathing, and washing, constitute a primary component of human welfare in the developing world (Kelso & Martin, 1973). Improved access to water Supply is the dominant individual factor in preventing diseases and improving living status. An increase in health benefits to a large extent can be expected when water supply improvements are carried out in combination with other programs, including public health education designed to modify hygiene practices. (Linsely, 1993).

## **1.2 Mahaweli River basin and EWEF Services**

### **1.2.1 Mahaweli River Basin**

Sri Lanka has faced few impacts of climate change during the last decade. They include an increase in the mean value and variability of temperature as well as that of precipitation. Sri Lanka is in South Asia, which is among the most vulnerable regions to global climate change. Sri Lanka is a country where many people rely on water for a living, so any effects of climate change that have a negative impact on water security will have serious consequences for people's livelihoods. Therefore, it is much more appropriate to study the present rainfall patterns and future projections. The Mahaweli river basin was selected as the study area as it is the country's biggest and socio-economically most important river basin.

The Mahaweli river basin covers an area of about 10,448 km<sup>2</sup>, which accounts for about 16% of the total land area on the island. Mahaweli river flows across seven administrative districts out of 25 districts in Sri Lanka and all three climate zones. The Mahaweli basin receives a long-term average annual rainfall volume of 26.4 billion m<sup>3</sup>. About 11 billion m<sup>3</sup> of this is converted into the surface runoff, and this equals Sri Lanka's shallow water resources. It has a length of 335 km (Manchanayake & Madduma Bandara, 1969). Therefore, in relation to the length, the extent of the watershed, and surface water resources, Mahaweli is the most important river in Sri Lanka.

Mahaweli river has number of tributaries, and major tributaries are given below.

1. Kotmale Oya
2. Badulu Oya
3. Loggal Oya
4. Uma Oya
5. Ulhitiya Oya
6. Hulu Ganga
7. Heppola Oya
8. Amban Ganga
9. Kalu Gnaga
10. Hasalaka Oya
11. Kaudulla Oya
12. Heen Ganaga

Among the tributaries, the biggest is Amban Ganga, which extends over a watershed extent of 1,486 km<sup>2</sup> and the Amban Ganga basin consists of several minor streams (Arumugam, 1969). The map further shows three climatic zones in Sri Lanka.

### **1.2.2 Energy, Water, Ecosystems, and Food Nexus**

As in many other countries, in Sri Lanka too, there is a strong correlation between water, energy, and food, which becomes more complex with the decentralized conveyance system and storage facilities.

Hydropower substantially contributed to total energy production for many years. In drought periods, results in trade-offs between hydropower generation and irrigation water. By today, the study area on the Mahaweli river consists of hydropower plants which account for about 70% of the total hydropower generation in Sri Lanka. The thermal plants principally generate base demand but cannot react swiftly to meet peak demands. Therefore, the hydropower generated is mainly used to fulfill increasing domestic and industrial demand during the morning and evening.

While substantial amounts of water are still flowing from the Mahaweli to the ocean near Trincomalee on the east coast, management of demand is, while challenging, not as complex as it will be in the future. Because a significant amount of water is still flowing to the sea, the scarcity of water in parts of the country presents the potential for increases in livelihood and improved food security through higher cropping intensities, relief of municipal and industrial water shortages, and better health by substitution with surface water of polluted groundwater, which is thought to be responsible for chronic kidney disease (CKD) that afflicts most of the people in the north and north-west of the country.

In order to add water demand caused by the above requirements, additional reservoirs, conveyance systems comprising canal systems and tunnels, and flow control systems, pumping stations with additional storage facilities are required. Mahaweli Development Programme (MDP) was commenced in 1970 to address the above issues. The first task implemented under the MDP was the construction of a tunnel at Polgolla, which diverts water from a location close to Kandy town to agricultural areas dependent on irrigated water. The MDP has the final goal of transferring excess water to the north and north-western provinces of the island, by constructing large-scale infrastructure, for fair distribution among basins where water is supplied through the MDP. Since the commencement of MDP in 1970, it has completed major irrigation reservoirs, hydropower stations, large irrigation systems, and social infrastructure for new and existing settlements. The first phase of MDP is generally called the Mahaweli Water Security Investment Programme (MWSIP).

Construction of infrastructure or any other single methodology is not adequate to effectively solve multiple issues created in relation to the nexus of water, hydropower, and food. It is necessary to adopt a wide set of approaches that are recognized as flexible and adaptable. Heavy water transfers are frequently faced with various conflicts that erupt through various

sources such as differences in ethnicity, possible environmental damage, and a decrease or loss of economic gains. Some commentators have forecasted that there may be “water wars” unless water transfers are implemented carefully and methodically. They may be either internal wars due to the unequal distribution of water or conflicts with neighboring countries that shares water from the same rivers. Further, concerns are raised over the country’s potential to fulfill the highest energy demand, strongly related to discharges from the existing and future hydropower stations. Additionally, the redistribution of water resources needs responsive plans based on reliable data, correct assumptions, and well-planned and careful management. When the distribution of water is mode-wide, careful attention to all matters is vital, as, with wide distribution, the excess water available for any buffer storage will be limited. Such development will require more precisely planned interventions in social, technical, and institutional reforms, as such developments have already faced many challenges and increasing controversy from various sectors of society.

Therefore, infrastructure planning must be done with rigorous communication programs, increasing awareness and concurrence-seeking, rigorous institutional capacity building, and tactical environmental assessment, together with the establishment of an advanced decision support system (DSS) for the allocation of water resources, as well as taking necessary new steps for improved water efficiency and more intense establishment of IWRM.

Simultaneously, because the study area is affected by climate change, it is necessary to improve water allocation management techniques that focus on climate change as well.

### **1.3 Research Problem**

Studies reveal that trends in precipitation together with extremes could be identified with strong variability, with both up and down trends experienced in diverse regions and seasons in Asia. (IPCC AR%,2014).

This situation leads to substantial variation in a river basin’s runoff, and, subsequently, it may affect numerous lives in the basin. Mahaweli river basin is powerfully related to the Sri Lankan economy, as its influence on many sectors, including hydropower, agriculture, and major water supply for domestic and industrial use, is high.

Mahaweli river basin is the major contributor to the generation of hydropower in Sri Lanka. It generates 815 MW (51%) of total power generation in the country, which has a total installed capacity of about 1,584 MW. During the year 2012, Mahaweli hydropower stations generated 1,343 GWh, which accounted for 11% of total power generation on the island and about 59% of combined hydropower generation. Hydro reservoir storage mainly depends on rainfall, and any decrease in rainfall may lead to a situation where water sharing conflicts have emerged between power generation and irrigation water. The availability of an uninterrupted electricity supply is a mandatory requirement for the smooth running of industries and, in general, for the economic development of the country.

Due to the high impact of water resources of the Mahaweli river basin on irrigation and agriculture, power generation, and industrial and domestic water supply, it is very appropriate to study the influence of climate change on the allocation of water in the basin, as it is still not properly understood. Considering the most likely impacts of climate change on rainfall, this study will address the problem of filling the knowledge gap in relation to projections of climate change anticipated in the Mahaweli river basin. A study on possible impacts will be helpful in estimating the vulnerability and risks associated with impending climate change and identifying appropriate mitigation measures as well as adaptation options.

#### **1.4 Objectives and Specific Objectives**

The main objective of the research is to calculate the unmet demand in the Mahaweli river basin by the year 2050 amidst climatic and socio-economic changes. There are several specific objectives to be followed in achieving this main objective.

First, it is mandatory to figure out how much the basin is concerned by climate and socio-economic changes. The selected study area, the Mahaweli River Basin of Sri Lanka, is the most sensitive basin for energy, food, and water services. Therefore, to find out the changes, it is mandatory to determine the responses for each service.

As a result, the first hydrological model is required to set up for the current scenario, which includes artificial influencers. Finding the possible effects on the basin due to Climate Change.

After finding out the response to climate change, the hydrological model should be performed again to find out the response to hydrological flow. Then the flow, which is subjected to climate change, is allocated for the energy, food, water supply, and environmental demands of the Mahaweli Basin. Further, for a set of selected scenarios, the demand is evaluated.

## **1.5 Scope and Limitations of the Study**

### **1.5.1 Selection of Time Period**

For reasons of data availability, from 1989 to 2016, that period was selected as the baseline period for this study. Daily precipitation and temperature data for the above selected period were obtained through the respective agencies. The rainfall patterns and data on the temperature of the basin at each station were projected for the period from 2016 to 2050 by adopting selected GCMs.

The analysis of future temperature patterns and rainfall in the basin will be found for three upcoming periods of time.

### **1.5.2 Selected Metrological and Hydrological Models**

Nine rainfall stations were selected for this study. They were selected based on their spatial distribution so that the data would be more representative. Another factor considered for selection is the availability of continuous data for the base period of 30 years.

Selected stations based on the above criteria are as follows.

- Dunsaine
- Dyrabba
- Helbodde North
- Holm
- Hope
- Katugastota
- Kobenella
- Liddesdale
- Narangala
- Nawalapitiya

Katugastota and Badulla were selected as metrological stations.

### **1.5.3 Hydrological Modelling**

For hydrological modelling, the Soil and Water Assessment Tool (SWAT) was adopted as the researcher is familiar with the models from her previous undergraduate studies.

WEAP (Water Evaluation and Planning Software) is considered a user-friendly software that adopts an integrated approach to water resources. WEAP is widely used for water resource allocation and management. For this research, a model coupling with SWAT and WEAP is used to get the advantage of SWAT's capability in representing hydrological processes and the strength of WEAP for water allocation scenarios. SWAT model can understand the responses of a catchment to hydrological events, while WEAP can be customized for water resources allocation of water resources within a framework of water management.

Accordingly, a combination of SWAT and WEAP models offers a strong tool to evaluate the effects on water resources due to climate change.

### **1.5.4 Climate Change Scenarios and Downscaling**

CSIROMK 3.6, HadGEM2-ES, and NIROC5 with RCP 8.5 emissions were selected as they are the most compatible with ones with an Asian context and suitable resolutions.

Preparation data for hydrological modeling developed by the SWAT (CMhydr) model was utilized for the preparation of data on climate change for the hydrological modeling.

### **1.5.5 Water Allocation and Scenario Analysis**

The study was carried out for three scenario analyses in the future context. They are the impact of population growth, the impact on livestock population growth, and maximizing energy production.

## **1.6 Limitations of the study**

The major factors limiting the scope of the study were budgetary and time constraints. Due to the limited time available, only three GCMs were adopted for the study. If more CGMs could have been used for the study, models with high variations could have been eliminated, and models that are compatible with historical climate data could have been used. Although more than 200 rainfall recording stations are available, many of them do not have continuous data.

Therefore, it limited the selection of rainfall stations as continuous daily precipitation data was required for the study. Because of the limitations on continuous data and the high cost of acquiring them, the study must be limited only to nine rainfall gauging stations. For this reason, the representative distribution must be restricted.

Research has pointed out that some CGM models consist of some errors that may lead to providing outputs with less accuracy. As these global models have been developed mainly for widely spread river basins, when they are used for a river basin like Mahaweli, which is comparatively small, the resolution and accuracy of the model results may limit the outcome of the study.

According to the assessment of UDA, presently, 20%, 40%, and 50% of the population live respectively in 5%, 8%, and 12% of the land, and the annual rate of urbanization stands as low as 0.72%, while this figure may be higher along Colombo – Trincomalee development corridor. However, for the study, this factor was not accommodated, and hence it might also have limited the output.

## **2 LITERATURE REVIEW**

### **2.1 Ecosystems Water, Energy, and Food Services**

The benefits that can be obtained from an ecosystem are generally known as ecosystem services. They are usually categorized under assisting, supplying, regulating, and cultural (Millennium Ecosystem Assessment (MRA) Report, 2005). Benefits obtainable from ecosystems may be drastically reduced if they are not adequately maintained, such as river basins and land. Further, many external factors may reduce the extent of ecosystem benefits. One of such significant external factors is climate change. Generally, ecosystem services are obtained by deterioration or exploitation of the ecosystem. When the linkages between benefits and the ecosystem are broken, investments need to be provided to restore the ecosystem if the benefits are to be continued.

When economic policies of development and sharing of financial resources such as water are prepared, ecosystem services are usually not considered or receive little attention. But in many developing countries, ecosystems are the leading supplier of food, timber, firewood, medical plants, fiber, and fuel; their existence is essential for the livelihood of poor people. Further, ecosystems ensure the public welfare by controlling microclimate and flood prevention during the rainy season by receiving water and releasing them as return flows during the dry season. The nexus of food-energy-water (FEW) can be defined as the correlation and trades between the production of food, generation of hydropower, and supply of water (Hellegers et al.,2008). There are several varying links among the above components of FEW nexuses. Only some links are related to physical flows. Water is an essential input for the generation of hydropower and food production, where in both cases, water is subjected to degradation of its quality (Khan et al.,2009). Some links are casual and generally create trade-offs among three components of the FEW nexus. Limitations in the availability of land always make competition between food and energy production. When water is used for one such production, it will reduce its availability for others and inevitably reduce the use of water for other non-nexus services. Sometimes these trade-offs are not entirely avoidable. Food production through agricultural activities needs many lands and favorable climatic conditions. However, the generation of energy through renewable methods, such as wind power, needs a smaller number of land except for the case of biofuels generated from food or energy crops.

Irrespective of methods adopted to produce food and energy, both require a high amount of water, which generally becomes a burden to the ecosystem. However, reducing water supply for them is impossible because food production must be continued in any case. As this will create a situation where water must be provided in significant quantities by overloading the ecosystem, ecological degradation of the ecosystem may happen and eventually lead to an unavoidable reduction of food and energy.

To ensure the long-term sustainability of ecosystems, it is necessary to limit the demand for ecosystem services, including food and energy production, to the extent that the ecosystem can provide them without overloading the system. This creates a need for a co-production system between food and energy production while maintaining sustainability in the ecological system. The techno-ecological synergy (TES) concept has been developed to apply on such occasions by balancing ecosystem service demand and supply (X Liu et al.,2018). The co-production system increases the available supply of ecosystem services by using lands for cultivation, energy-producing activities, and engineered eco-system services. However, experience gained through such exercises shows that balancing land use among agriculture, hydropower production, and ecosystem services improvement has delivered positive results in maintaining ecological sustainability and food and power production, but their economic feasibility has gone down. By applying of TES concept to the co-production system of energy and food, it is possible to mitigate the impacts of water sharing and water quality. Further, it uses to maintain productive lands and mitigates adverse environmental effects due to human activities.

The literature shows that ecosystem services are critical in addressing FEW nexus issues successfully. The International Institute on Sustainable Development has suggested that considering ecosystem services as goods and services is the foundation of the FEW nexus (Bizikova et al.,2013). One research performed in California revealed the independencies between food and energy production cycles and the impacts of climate change on them. This study showed that climate changes cause degradation of the eco-services system, which negatively affects food production and energy production (Q Liu,2016). This research has established that reducing ecosystems' degradation and increasing productivity can be achieved by making necessary changes in the production methodology. A study in the Hindu Kush Himalayan region in South Asia has revealed that it is essential to focus on providing ecosystems and more human objectives production of food and energy (Rasul,2014). Studies outside the FEW nexus also showed that many environmental benefits could be achieved by

maintaining and increasing ecosystem services. A researcher quantified the possibility of reducing ecosystem services demand created by industrial facilities in the USA by tactical management of surrounding lands in each facility (Gopalakrishnan et al., 2018). Another researcher studied the impacts of variations in land-use patterns on the provision of ecosystem services (Cheng et al.,2018). His studies were centered around Chengdu, China, and he concluded that changes in land-use patterns had resulted in an increase in the total value of services made by the ecosystems with time. However, this analysis has not quantified the shift in the value of each ecosystem service separately, so there is a possibility that the value of some ecosystems may have increased (ex., supply of foods by the ecosystem). In contrast, the value of others (such as control of erosion, climate changes, and many others) has decreased while a net increase was observed. Several research carried out in this area have revealed that change in land use patterns with appropriate management practices is capable of regulating climate change and providing several ecosystem services (Rose,2012) and can help in complete mitigation or resolving trade-offs among various services provided by ecosystem (Ouyang et al.,2016).

Quantifications and studies on FEW components including physical flows, and interdependencies with casual relationships, can be carried out at any spatial scale. Generally, various ecosystems are applicable at multiple scales; Climate regulations may be applicable at the global scale – A tree planted in America may compensate for carbon emission in China-while regulation for water quality and supply of water may be applicable at regional (watershed) scale and some services like pollination are useful only in regional scale (Flefel et al.,2017; Urban & Bakshi 2013). At the smallest scale (community or household), data may be sufficiently available with enough details, and decisions could be arrived at and implemented efficiently. However, smaller systems highly depend on input data from outside systems that are totally out of the control of smaller designs. Quantification of large-scale services of ecosystems such as climate change and supply and demand for small-scale systems may be difficult as small systems are independently not able to offset the ecosystem services. Regional-scale systems are comparatively large and can be used to balance supply and demand among various ecosystem services to a greater extent (Rasul & Sharma, 2016; white et al., 2017). At large scales, such as national and multi-national, modeling and analysis are complicated due to the high interdependencies of sub ecosystems and lack of sufficient data sets (Buzilian et al.,2011). Analysis of large-scale decisions may be comparatively less complicated, but it may not provide a correct assessment of all benefits and disbenefits (Hanes et al.,2018). The

insufficient data make modeling of any ecosystem complicated at a smaller scale. Still, it does not severely affect analyzing very large-scale ecosystem services like global climate regulations and other global services.

## **2.2 Methodologies for Evaluating Climate Change Impacts on River Basins**

The status of adaptation and mitigation can assess impacts on the river basins due to climate change. Variations of stream flow and runoff in river basins may happen due to climatology of precipitation, soil moisture, and evapotranspiration variations. The Canadian Centre for Climate Modelling & Analysis (CCCma) studied the possible effects of warming on the hydrology of 23 major rivers. Under this study, runoff coupled with a climate model for the present climate networked through the river system up to the river mouth compared with the forecasted results of warmer weather simulated to occur by the end of this century. Variations in mean discharge, denoted by amplitude and phase in the annual streamflow cycle, in the yearly highest discharge and its standard deviation and curves for in flow duration are analyzed. Variations of flood magnitudes with different return periods are examined using extreme value analysis. In the warmer climate, there is a general decrease in the runoff, and 15 out of 23 rivers are considered to have a reduction of mean annual discharge (with a median reduction of 32%). The change of runoff was not uniform, and discharges increased in 8 rivers with a median increase of 13%.

Rivers located at high and middle latitudes generally showed significant changes in the amplitude and phase of their annual cycle associated with a decrease in snowfall and earlier melting of spring in the warmer climate. Rivers at low latitude showed variations in mean discharge but moderate variations in their annual cycle. The study further showed that the annual flood magnitude of 17 rivers out of 23 resulted in a reduction in the mean annual flood with a median decrease of 20%.

Variations in flow duration curves are applied to characterize the different types of performance exhibited by various groups of rivers. Variations in the regional distribution of modeled precipitation and runoff for the control simulation presently limit the use of the approach. The suggested hydrological changes are, however, reasonable and reliable reactions to simulated variations for precipitation and evapotranspiration and offer the types of hydrological variations that could happen in a hotter climate.

Much research has been conducted to determine the climatic change in various river basins. One researcher (Jha et al.,2004) examined the consequences of climate change on the stream flow of the upper Mississippi river basin by using Regional Climate Model (RCM) integrated with a hydraulic model, SWAT. Few research has been carried out to study the consequences of climate change on rivers in Western Kenya by simulating the SWAT model. This model was established by adopting readily available spatial and temporal data and was calibrated using stream flow data available daily. (Kibel et al.,2018) studied the probable consequences of climate change on the hydrology and water resources in the Seyhan river basin in Turkey. They adopted the pseudo global warming method (PGWM), which is a dynamic downscaling method. It was used to interconnect the results obtained from general circulation models (GCMs) and river basin hydraulic models.

Hydrological conditions are replicated for examining climate changes in water resources under the forecasted weather conditions in a river basin (Gosain et al.,2006). The SWAT model has been regularly adapted to analyze the hydraulic modeling for river basins (Arnold et al.,2010). Several research have established that long-term forecasts for the Mediterranean region are frightening because the number of extreme weather events is increased over the last decade in the Mediterranean region (Tayanc et al.,2006; Xoplaki E, 2002; Feidas,2001)

### **2.3 Methodologies for studying socio-economic development impacts on river basins.**

As the water resources are finite, climate change undoubtedly aggravates water security (Gertain et al.,2013; Schewe et al.,2014), mainly affecting dry regions. An increase in temperatures, shifting of seasonal precipitation patterns, and frequent and intense extreme events (flash floods, extended droughts, and heatwaves) are forecasted to occur (Giannakopolous et al., 2009).

Various studies have developed participatory approaches to adapt to climate change (Faysse al.,2014; Harrison et al.,2013). They have been designed to manage the water resources amidst climate change (lital et al.,2011; van Vliet & Kok, 2015). Quantitative simulation models are regularly utilized to obtain descriptive and vital impacts on water resources management under climate changes (Haasnoot et al.,2011; Poff et al., 2016).

Applying quantitative and generally compounded models in the participatory process is not simple, as stakeholders may have regarded them as black boxes. When adequate data to use as input data for quantitative models are not available, semi or non- quantitative models for participatory approaches can be used to manage the data gap. Participatory modeling methods have been established and used widely to improve the understanding and know-how of ecosystems (such as river basins) with their dynamics by stakeholders and to evaluate the impacts of the strategies on policies and management (Voinov & Bousquet 2010).

#### **2.4 Previous Studies Combining SWAT and WEAP for Evaluating Climatic Change and Socio-Economic Development in River Basins**

Three researchers carried out the research by combining SWAT and WEAP models to design water efficiency methods for the Pinios river's catchment in Greece in the year 2016 (Psomas et al., 2016). The specialty of this study was the rural upstream sub-catchment of the river basin, which experiences seasonal water shortages due to increased water abstraction during the summer. This was mainly due to the local crop cultivation, and the SWAT model was used for analyzing the change in land use phenomena. In contrast, WEAP was used for diagnosing scenarios for urban and tourism sectors in the most deficient low land area. The significance of the study was that they applied SWAT and WEAP models for the same basin separately, where different scenarios were compared. Annual unfulfilled demand for the baseline and possible water saving for various water-saving methods. This is better in the context of the policy aspects.

Maliehe and Mulungu performed a study by combining SWAT and WEAP models to estimate water availability for competing uses for the South Phuthiatsana catchment in Lesotho in 2017. Swat was used for flow estimation, whereas WEAP was used for resource allocation. The significance of the study was that the adopted scenarios showed that industrial and ecological demands could not be met. The scenario for an increase in irrigation contributed to 65% of the unsatisfied demand (Maliehe & Mulunu, 2017)

The study. Assessment of consequences of climate changes on availability of surface water utilizing combined SWAT and WEAP models; Upper Pangani river basin case in Tanzania, Proc, IAHS, 378, 23-27 in the year 2018 shows six common GCMs were selected from WCPR-CMIP3 with emission scenario A2 were selected. They are HadCM3, HADGEM1, ECHAM5,

MIROC3.2MED, GFDLCM2.1, and CSIROMK3. Above six models were downloaded to station scale using LARS-WG. The calibration of the SWAT model was carried out with observed data, and outputs from LARS-WG were used to forecast future stream flows before utilizing them as inputs to the WEAP model to estimate the accessibility of water for various future socio-economic needs. SWAT was adopted to simulate multiple climate changes, and WEAP was used to predict water availability in 2060 for diverse socio-economic conditions.

In a study carried out in China, Laohahe river basin in a tributary of Xiluohe river, SWAT and WEAP combined model was used to estimate the water resources vulnerability. SWAT model was utilized for analysing hydrology and WEAP model was utilized to stimulate demand and supply of water under forecasted climate changes. Being a predominantly agricultural area, it was problematic due to the many water users in the agricultural sector. Excessive irrigation was a constraint for integrated water resources management. The main problem is not the quantity of water available but the poor management of water resources. The most effective steps that can be taken to address climate change have been identified as increasing the efficiency of water used for agriculture, changing planting structures, and developing animal husbandry. In many scenarios, dry weather aggravates and intensifies the vulnerability of human activities in water resources. If enough reservoirs are available, that will help to reduce the water resources vulnerability (Kishiwa et al.,2018).

The Upper Duhe basin in China was utilized as the study area for the Cost-Benefit analysis on supply-demand modelling by WEAP for the feasibility study on the Upper Duhe basin. The exercise characteristics of the WEAP model were used for the cost-benefit analysis of green water credit interventions practiced in the Upper Duhe basin. SWAT model was used to explore the consequences of changes in green water management on runoff, recharge of groundwater, and erosion. At the same time, the WEAP system connects the interactions upstream and downstream and is capable of evaluating and comparing different scenarios. The importance of the project depends on the input data required for this model, which were the outputs of the SWAT model, the cost associated with interventions, and the price of water. The WEAP model was checked, optimized, and proven for applications in current ongoing Chinese projects (Droogers et al,2013).

The combination of SWAT and WEAP models was used in 2012 to study on forecasted assessment of water availability in the year 2035 for multiple uses in the South Puthiatsana

catchment in Lesotho (Maliehe, 2012). The SWAT model was adopted for the simulation of hydrology in the catchment. Water resources were then allocated in the catchment (and outside water exported through the Metolong dam) for the period of the dam's planned horizon, 2035 – using a water evaluation and allocation system (WEAP). A specialty of the study lies in checking current water demands, availability of water, and how much water is needed for the future.

In another similar study carried out in Ethiopia by four researchers, Behailu Hussien, Ayalkebet Mekonne, Santosh Murlidhar, and Pingale, in the Bilate watershed in Abaya- Chamo sub-basin of Rift Valley Lakes basin, a combination of SWAT and WEAP models were used (Hussien et al., 2018). The specialty of the above study was using the combined model to assess the consequences of climate change on the availability of surface water and its allocation. The SWAT model was calibrated and validated to simulate future stream flows under the scenarios RCP 2.6 and 8.5. Integrated water resource allocations for various climate change scenarios were modelled using the WEAP model. The significance of this study was it used forecasted time series data for rainfall and temperature acquired from regional climate yields of Coordinated Regional Climate Downscaling Experiment (CORDEXE)- Africa for three distinct concentration pathways (RCP) scenarios (RCP 2.6, RCP 4.5, RCP 8.5) for four periods of time of four years commencing from 2015 to 2035. The model showed that the minimum and maximum temperature could increase under all three scenarios.

## **2.5 Water Resources Management in Mahaweli River Basin in Sri Lanka**

Management of water resources in Amban Ganga, the main tributary of Mahaweli River, commenced long ago during the era of Sri Lankan kings. A diversion weir has been constructed at Elahera in the district of Matale, which diverted water to existing reservoirs in the district of Polonnaruwa and eventually to Kantale reservoir, which was in the Peru Aru basin. At Minipe, in the Kandy district, a diversion weir was constructed across the Mahaweli River, and water was transferred through a network of canals. Above developments have been carried out from the 1<sup>st</sup> to 7<sup>th</sup> centuries. A diversion weir was built in Angamadilla in Amban Ganga to store diverted water.” Parakram Samudraya,” the largest reservoir for Sri Lanka for many centuries, was built in the 12<sup>th</sup> century at Polonnaruwa (Arumumam,1969).

Mahaweli Development Programme was commenced in the 1970s. Before this, the total water diverted annually from the Mahaweli river at Minipe and Angamadilla was 600,000 Ac. Ft

(741million m<sup>3</sup>), whereas the estimated total annual runoff was 8,500,000Ac.Ft (10,490 million m<sup>3</sup>) (Arumugam, 1969).

Apart from the abovementioned major developments, several other developments took place up to the beginning of the 13th century. After that, the capital was shifted from the dry zone first to the intermediate zone and after that to the wet zone. With this change of administration, most irrigation structures were neglected and started to deteriorate. During the 19<sup>th</sup> century and early 20<sup>th</sup> century, the Government took the initiative to build new settlements in dry zone with peasants from the wet zone and rehabilitated some of the ancient irrigation structures. However, no significant development took place until the commencement of the Mahaweli program in the 1970s.

Since 1948, several studies have been carried out to plan a suitable system to develop a dry zone using water in the Mahaweli river. UNDP/FAO carried out the most definitive study in the late 1950s. With their findings, it was proposed to construct a set of reservoirs in the Mahaweli basin so that water can be provided for the cultivation of 214,000 ha of existing and new lands and to increase the installed capacity of hydropower by 540MW(Cooke,1982). ). According to this Mahaweli Master Plan, it was expected to implement within 30 years. The area to benefit from additional water from Mahaweli was divided into 13 Zones, named Zone A to L. This development program was commenced in 1976 by constructing a diversion barrage at Pologolla, which diverted water to Malwathu Oya and Kala Oya basins (Arumugam,1969)

There was a paradigm shift in the policies of the government in 1977. The newly elected government favored the country's open, liberal economy and industrialization. Industrialization needs a large amount of energy. Therefore, the Government decided to speed up the Mahaweli Development Programme, known as Accelerated Mahaweli Development Programme (AMDP). Under the program, action was taken to speed up the implementation of selected components in the Mahaweli program and thereby providing water for 244,000 ha of new areas and increase of installed hydropower generation capacity by 665 MW (Cooke, 1982). Most of the above activities were completed by the mid-1980s. It included the construction of large reservoirs such as Victoria, Kotmale, Randenigala, and Madauru Oya Reservoir in the Maduruoya basin (Mahaweli Consultancy Bureau MCB,2012).

Yan Oya basin also benefitted under the AMDP by constructing the Huruwewa feeder canal. After the above implementations, the average annual amount of water diverted from 2004 to 2009 was as follows in Figure. 2.1.

<b>Diversion</b>	<b>Volume in m<sup>3</sup> million/ year</b>
Polgolla to Amban Ganga System	882
Bowathanna(receiving from Polgolla) to Malwathu Oya and Yan Oya	570
Elahera to Minneriya, Hawudulla etc in Amban Ganga sub basin and Kantale in Peru Aru basin	620
Angamadilla to Parakkrama Samuddraya within Amban Ganga sub basin	398
Minipe diversion within to Mahaweli basin irrigation system and Maduru Oya	1,484

Table 2-1: Average Amount of Water Diverted in Mahaweli River Basin per Year

Table 2-1 shows that the AMDP has immensely helped to improve water utilization in Mahaweli River Basin after the colonial era benefitting Kala Oya, Maduru Oya, and Peru Aru basins. However, by the early 2000s necessity for additional expansion of water resources for irrigation and domestic use was felt, especially in the areas which were left out from the original Mahaweli Programme. In addition, there was a severe water shortage in the North-western province, which was not an area included in AMDP. Therefore, necessary steps were taken to construct two new reservoirs in Moragakanda and Kaluganaga were commenced, and by now, both have been completed.

A significant amount of water is spilled at various diversion points in the Mahaweli river, especially at Angamadilla, Minipe, and Elahera. At present, this spilled water is not used for any purpose. Under a new proposal (known as the NCP project), a new canal will be constructed to divert above spilled water to North Central and Northern provinces. While due consideration is given to allowing the environmental flow, this NCP is expected to shift about 1020 mm<sup>3</sup> of water to the above two provinces. The average annual amount of water diverted to various basins under the above project has been estimated as follows (MCB,2015).

- Maduru Oya Basin                      474 mm<sup>3</sup>
- Ma Oya                                      103 mm<sup>3</sup>
- Yan Oya                                      186 mm<sup>3</sup>
- Parangi Aru/Pali Aru                      91 mm<sup>3</sup>

- Kanagarayan Aru 115 mm<sup>3</sup>

Further panning is being carried out to divert more water from Dambulu Oya and Reservoir at Nalanda in Mahaweli basin to Upper Mee Oya and Hakwatuna Oya, a tributary of Deduru Oya basins which are situated in North Western province. As the water demand of Yan Oya and Malwathu basins is partly to be met by the proposed NCP project, this diversion will be possible. It is proposed to divert the water of about 130 MCM per year, and 30 MCM of this amount will be supplied by the Nalanda reservoir situated at the Nalanda sub-basin in the Mahaweli basin (MCB,2012). Per the above plans, Pali Aru, Kanakarayan Aru, Mi Oya, Parangi Aru, and a tributary of Deduru Oya ( Hakwatuna Oya) will benefit by additional water diverted from the Mahaweli basin. Figure 2.2 shows the development area under the Mahaweli basin.

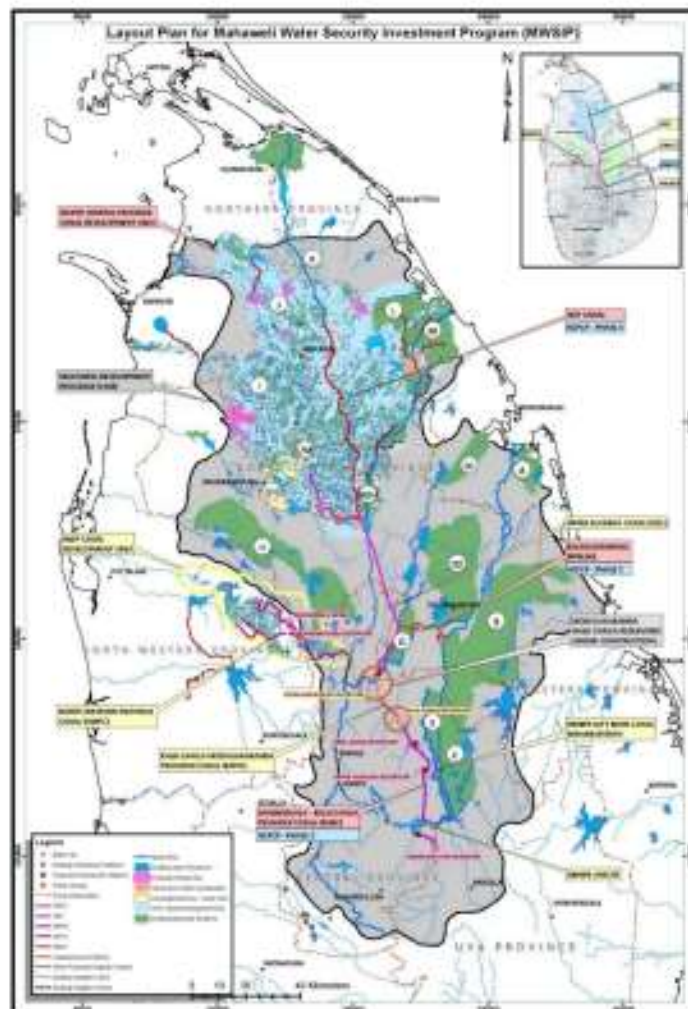


Figure 2-1; Area of Development under the Mahaweli Programme Source: MASL, 2012

## 2.6 Socio-Economic Characteristics of Mahaweli River Basin

Mahaweli river having a length of 315 km, is the longest river in the country and has an average annual runoff of about 11 trillion cubic meters, which is equal to about 21% of total runoffs in all rivers of Sri Lanka. The river's catchment area spreads for about 10,327 square kilometers, about 17% of the total land area on the island (Manchanayake & Madduma Bandara, 1969). It is one of two rivers that divert a high quantity of water from the wet zone to the dry zone. Mahaweli river already provides water to five river basins in the dry zone, and steps are being taken to provide water for another five basins from the same river. Therefore, Mahaweli water is a major contribution to the country's economic development. Water from Mahaweli is vital for the well-being of people as it is the primary source of water for agriculture and domestic needs, industrial needs, and hydropower generation.

Mahaweli basin provides shelter for about 166,269 families, consisting 67,186 farmer families and 58,119 families engaged in other sectors and downstream areas (MASL, 2012).

The total number of people settled in Mahaweli systems, including those living outside river basins, was estimated to be 877,152 in 2011. Figure 2.3 shows the details of settlers from 2007 to 2011.

Table 2-2: Settlements in Mahaweli Basin

Area/Year	2007	2008	2009	2010	2011
Downstream Areas (a)					
Farmer families	93,418	94,106	95,225	96,835	97,024
Non farmer families	50,082	53,143	53,729	55,968	58,119
Other	863	1,056	777	834	834
Sub Total (a)	144,363	148,305	149,732	157,637	155,977
Upper Mahaweli(b)	7,891	9,061	9,269	9,295	10,292
Total Settlers (a+b)	152,254	157,366	158,000	167,932	166,269

The distribution of Social Infrastructure is shown in Table 2-3

Table 2-3: Distribution of Infrastructure in Mahaweli River Basin (MASL, 2012)

	2007	2008	2009	2010	2011
Houses	116,859	124,094	126,320	148,102	168,149
Schools	345	345	367	369	369
Health Centres	228	231	235	243	243
Cooperatives	207	207	205	215	215
Post offices/Post boxes	126	126	130	132	132
Latrines	103,559	122,528	123,975	141,014	170,688
Tube Wells	1,232	1,225	2,330	3,856	4,676
Wells	45,163	49,245	53,098	60,554	60,712

The importance of the Mahaweli basin for the economy of Sri Lanka can be easily understood by its contribution to the overall hydropower generation and agricultural sector. Relevant statistics are summarised in Table 2-4

Table 2-4 Hydro Power Generation in Mahaweli Basin(MASL,2012)

	2007	2008	2009	2010	2011
Mahaweli Power Stations	1,751	1,576	1,238	2,431	1,975
Total in National Grid	9,823	9,002	9,882	10,679	11,518
Mahaweli as a %	18	16	13	23	17
Value of power from Mahaweli (Rs Mn)	18,384	20,488	16,218	31,846	25,675

4.Agriculture - Under Irrigated and Rainfed						
4.1 Crops						
Cultivated Extent,Production & Value						
	Unit	2007	2008	2009	2010	2011
<b>Paddy</b>						
Cultivated Extent	Ha	147,709	158,973	129,393	172,492	175,113
Production	Mt	734,995	790,530	680,028	929,209	789,231
Values	Rs Mn	14,131	26,667	21,761	29,227	22,428
<b>Other Field Crops</b>						
Cultivated Extent	Ha	51,771	42,396	39,734	40,212	40,815
Production	Mt	382,429	326,935	298,516	348,338	340,778
Values	Rs Mn	9,574	12,523	11,873	18,801	21,161
<b>Total</b>						
Cultivated Extent	Ha	199,480	201,369	169,127	212,704	215,927
Production	Mt	1,097,425	1,117,465	976,545	1,275,545	1,130,009
Values	Rs Mn	23,705	39,190	33,634	48,028	43,589
Mahaweli Paddy Cultivated Extent as a % of National Extent	%	18	17	15	18	18
Mahaweli Paddy Production as a % of National Production	%	23	20	19	22	21

Figure 2-2: Productions from Agricultural Sector (Under Irrigated & Rainfed)

Table 2-5:Production of Livestock and Fish in Mahaweli Basin

Year	2006	2007	2008	2009	2010	2011
Production of milk (1000 litres)	17,056	23,425	22,425	19,692	19,465	19,828
Production of eggs ('1000)	20,682	1,996	2,555	3,525	3,129	3,808
Production of chicken (Mt)	561	341	1,055	1,517	2,198	2,997
Production of inland fish (Mt)	4,697	5,004	8,058	6,505	7,168	9,687

<b>Year</b>	<b>2006</b>	<b>2007</b>	<b>2008</b>	<b>2009</b>	<b>2010</b>	<b>2011</b>
Total production of fish & livestock (Rs M)	972	1,857	2,428	2,250	2,761	3,220

## **2.7 Studies on Impacts of Climate Change on Mahaweli Basin**

Literature review indicates that several studies are conducted to evaluate the impacts of climate change on the island; only a few researchers have focused primarily on the Mahaweli basin. One such study carried out by (C.J.De Silva & Sonnadara, 2009) studied variations in temperature in Central parts of Sri Lanka. They have analyzed data collected from five rainfall gauging stations located at Diyathalawa, Rathnapura, Badulla, Nuwara Eliya, and Kandy. Except for Rathnapura, all other stations are situated within the upper reaches of the Mahaweli river. This study showed a considerable temperature reduction only at Nuwara Eliya. At Diyathalawa and Kandy, they have observed a negative trend in rainfall but with less significance during the period of Northeast monsoon.

Rainfall at Diyathalawa and Kandy has shown a negative trend with low significance throughout the Northeast monsoon. Badulla and Nuwara Eliya have indicated a considerable increase in temperature. (Rathnayake & Herath,2005) their research has shown that central mountainous regions have a decrease in rainy days, thereby causing a reduction in annual temperature.

(Withnaachchi et al.,2014) Their study observed high precipitation variations in upstream areas of the Mahaweli river basin caused a reduction in annual rainfall. It is predicted that the decrease in annual rainfall in the upper catchments in the Mahaweli basin by 2025 will be about 16.6%. Therefore, a substantial reduction of the periodic flow regime is predicted by few researchers. Although there is not much research carried out in dry parts of the Mahaweli basin, an increase in temperature has been forecasted. All the above analysis shows that a significant rise in demand for water is expected, although a reducing rainfall in the upper reaches of Mahaweli.

The rainfall in western hill slopes and Mahaweli upper catchment areas shows an increasing trend from October to November (Withanacahci et al.,2014). This may cause floods in downstream areas as the dry zone also gets heavy rains throughout this period due to the Northeast monsoon period. Further, basin stream flow also varies throughout the year. Increased rainfall in the upper catchment, combined with activated inter monsoonal rain in the

dry zone and activated cyclonic conditions in the Bay of Bengal, generates high stream flows. This may lead to flooding affecting agricultural activities downstream.

However, much research has dealt with observed variations in rainfall. Although there is little research based on GCM for forecasting future rainfall, carried out at the country level, such restudies on the basin are rare.

## **2.8 Forecasting of Climate Change using General Circulation Models (GCM)**

The Task Group on Data and Scenario Support for Impacts and Climate Assessment under the Intergovernmental Panel on Climate Change (IPCC-TGICA,2007) has classified climate change scenarios into three groups. The synthetic scenario and analog scenario are the first two, while scenarios that are resulted from outputs of GCS models, which are generally called the climate model-based scenarios, are the third (Santoso et al.,2008).

In its 5th assessment report, the IPCC highlighted that GCM models are the primary tools that can be used to estimate the influence of various factors influencing climate and forecast possible climate changes for different periods varying from years to centuries.

GCM can be effectively used to numerically characterizes the interdependent physical phenomena in the atmosphere, ocean, land, and glacier and can adopt to model the reaction of climate to the growing existence of greenhouse gases in the atmosphere. GCMs, in combination with regional nested models, forecast the effects of climate change on various parts of the globe in a geographically and physically compatible way (IPCC,2013).

GCMs are considered dynamic models as they characterize 3-D climate systems. The system is established at a specified time, and the model arranges to change the system based on the asset of governing equations representing basic physical principles and boundary conditions. Few biological processes are not expressed through formulas, and for such a process, “parameterization,” which uses observations with statistical representation, is adopted (Lupo & Kininmonth).

GCM uses a three-dimensional grid to illustrate the global climate, as shown in Figure 2.8. It adopts horizontal resolution ranging from 250km to 600km,10 to 20 vertical layers in the

atmosphere, and the ocean as high as 30 layers provide to characterize the resolution. This produces rough resolution contrasted to the need for studies of various effects of climate change

Replications of the complicated natural processes correlated with climate by GCMs cause many variables. However, in this study, it is restricted to precipitation and time-based resolution, which may be as high as hourly (for this study, daily). Still, the spatial resolution is rough for effect studies, as discussed earlier. Accordingly, downscaling outputs from coarse models are required (Santoso et al.,2008).

GCM modeling has been developed during the past years and now can be grouped into three categories.

1. A single static layer symbolizes atmospheric GCMs combined with the ocean.
2. Atmospheric GCMs combined with a 3-D model of the oceanic system.
3. Atmospheric GCMs combined with 3-D models represent the ocean and terrestrial environment.

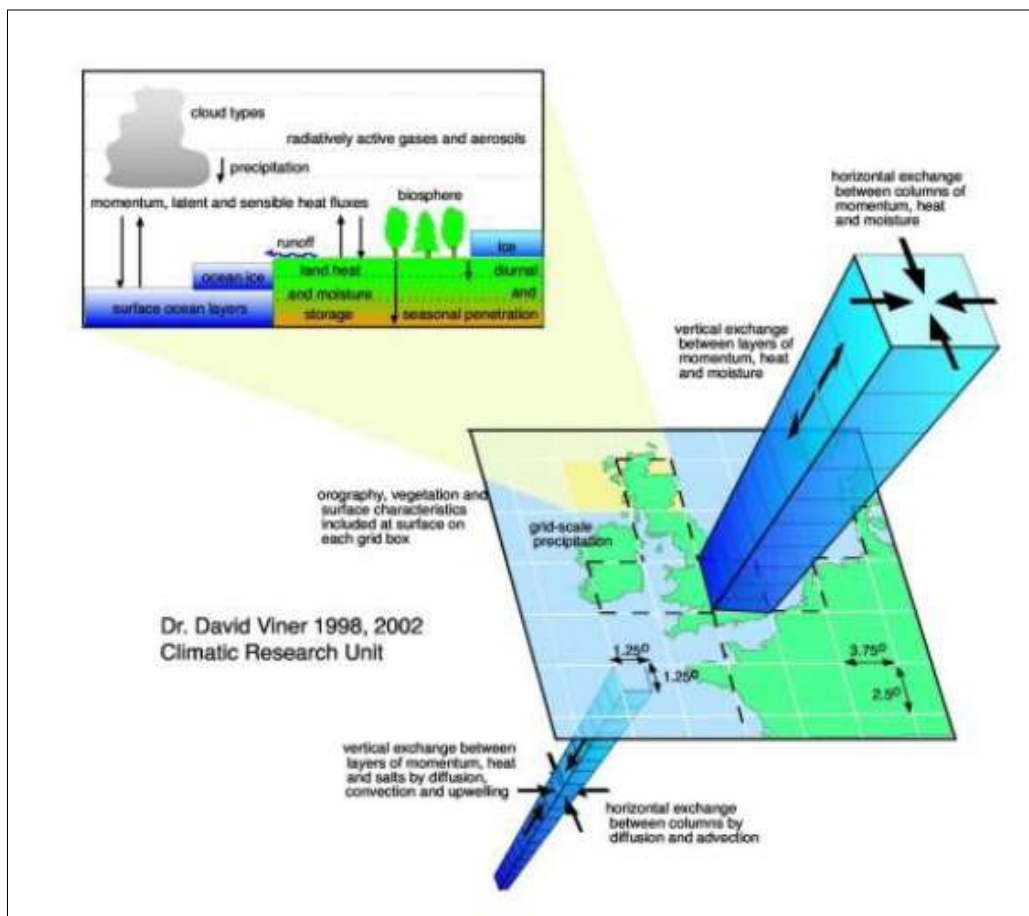


Figure 2-3: Overview of a GCM Source: IPCC Report, 2012

A GCM that simulates the atmosphere and ocean adopts basic scientific equations, using seven fundamental variables. They are called “Atmospheric Ocean General Circulation Models.” It is mainly used for understanding the physical components in a climate system and for the simulation of future status dependent on GHG strengths and aerosols (Lupo & Kinninmonth) and (IPCC AR5,2014).

GCMs are widely utilized for investigating relations among various processes in acclimating systems, simulating the processes and conversion over time, and projecting the status of future climate. With the latest advancements in climate science, there are a few scenarios built to incorporate the factors which affect the progression of the climate system (Lupo & Kinninmonth, Undated).

Few research groups have developed combined ocean-atmosphere GCMs for simulating climate change. Sometimes, it has been noticed that results obtained through such combined models are compatible with each other, although they are based on the same physical principles. The variations are mainly dependent on the assumptions made during modelling. The World Climate Research Programme (WCRP) established a separate working group for combined models in 1995 and initiated a Coupled Model Intercomparison Model (CMIP) project. The project delivered a set of simulation outcomes under standardized boundary situations and compared climate simulations of the combined ocean- atmospheric-cryosphere- land Model. (Meehi et al.,2000). Few phases of the same project have been implemented since then. Phase 5 of CMIP, abbreviated as CMIP5, commenced in 2008 and produced a new bundle of combined climate model studies (Taylor et al.,2009).

CMIP5 used horizontal grid spacing of nearly  $1^0$  to  $2^0$  in the atmosphere and  $1^0$  in the ocean (IPCC,2014). 50% of CMIP GCMs have an average longitudinal resolution higher than 1.30, which is an enhancement over a former model under CMIP3 (Rasheed et al.,2014).

## **2.9 Emission Scenarios and Representative Concentration Pathways**

Due to the dynamics and rapid variations of systems that produce greenhouse gases, the reliable prediction of the number of greenhouse gases (GHG) is quite difficult. A number

of factors affect the amount of greenhouse gases, such as population increases and social, economic, and technological changes in the focus area (Shen et al.2014).

Scientists need to assume the potential behaviour of the above drivers, which is generally complex. The scenarios facilitate accommodating reasonable assumptions regarding such driving forces for the forecast of GHG emissions, analysing the influence of those factors on future scenarios, and assessing the uncertainties built-in into the projections (Van Vuuren Carter, 2014). Climate researchers, planners, and other researchers have used various scenarios to estimate the extent of the human influence on potential climate change due to their involvement in driving forces.

Several scenarios have been adopted for many years, and the most outstanding scenarios are shown in the following table.

Table 2-6: Outstanding Scenarios used in IPCC reports

<b>Year</b>	<b>1990</b>	<b>1992</b>	<b>2000</b>	<b>2009</b>
Name	SA 90	IS 92	SRES- Special Report on Emissions and scenarios	RCP- Representative Concentration Pathways
Used in	IPCC first assessment report	IPCC second assessment report	IPCC third and fourth assessment report	IPCC fifth assessment report

The IPCC released “Special Report on Emission Scenarios (SRES) in the year 2000 and published 40 different scenarios categorized under four “families of Storylines,” indicated as A1, A, B1, and B2.

Using the above families, six scenario groups have been developed. Out of them, three groups are from A1 and one from the other three families. Figure 2-4 shows scenario groups (Van Vuuren & Carter,2014).



Figure 2-4: Scenario Groups (Source: Bjørnæs, Undated)

The SRES scenarios accommodated many drivers evolving due to population dynamics and socio-economic aspects affecting GHG emissions.

In response to this need, the 5<sup>th</sup> assessment report of IPCC established representative Concentration pathways (RCP) in 2009, replacing SRES scenarios (Vuuren et al.,2011). The new RCP scenarios considered,

- A. “Radiative forcing” (which measures the capacity of forcing elements to affect the global energy balance) measured in watts/ square meters by the year 2100.
- B. Emission rates, or the speed with which more greenhouse gases are emitted to the atmosphere.
- C. Concentration of emitted GHGs, measured per parts per million each GRG.

The RCPs examine the policy revisions that have fixed new targets for reducing emissions and the possible effects of new targets on climate change, which were missing in previous SRES scenarios (Battarbee et al.,2008). It contains four routes with high spatial and sectoral resolution leading to “forcing levels” (energy disparities) of 8.5,6,4.5 and 2.6 W/m<sup>2</sup>by 2010, regarding the pre-industrial times. All RCPs cover a long period from 1,850-2,000 and have been further expanded with other assumptions (Vuuren et al.,2011). RCPs have been developed through collaborative efforts made by emission inventory experts, integrated assessment modelers, terrestrial ecosystem modelers, and climate modelers.

RCPs have two specific characteristics.

1. The word “representative” means that any RCP represents a broader set of scenarios in the documentation of climate change, which means the RCP can represent the range covered by scenarios considered.
2. The words “concentration pathways” stress that RCPs are not an ultimate set of new scenarios that fully incorporate socio-economic releases and climate projections but a

set of internally coherent forecasts of the radiative forcing. They can be later used for the computation of emission levels. This is further demonstrated by using the word “concentration” as a replacement for “emission,” which indicate the fact that concentrations are the key output of RCPs, and would make available an input to the climate model (Vuuren et al.,2011).

Four RCPs are briefly explained in Table 2.7 and 2.8. Figure 2.10 shows the variation of all forcing agents' atmospheric CO<sub>2</sub> corresponding concentration with time for all four RCPs.

Table 2-7- Variation of all forcing agents' atmosphere

Name	Pathways	Radioactive forcing	CO <sub>2</sub> equivalent Conce.
RCP 2.6	Peak and decline	3 before 2100 & declining to 2.6 W/S.m by 2100	490
RCP 4.5	Stabilize shortly after 2100 without overshoot	4.5 W/S.m in 2100	650
RCP 6	Stabilise shortly after 2100 without overshoot	6 W/S.m in 2100	850
RCP 8.5	Increasing GHG that leads to high concentration over time	8.5 W/S.m in 2100	1,370

Table 2-8- Overview of RCPs

Name	Radiative Forcing	CO <sub>2</sub> Equivalent XXX	Pathways
RCP 8.5	8.5% Wm <sup>2</sup> in 2010	1,370	Increasing GHG that lead to high concentration over time
RCP 6	6 Wm <sup>2</sup> in 2100	850	Stabilization shortly after 2100 without overshoot
RCP 4.5	4.5 Wm <sup>2</sup> in 2100	650	Stabilization shortly after 2100 without overshoot
RCP 2.6	3 Wm <sup>2</sup> before 2100 declining 2.6 Wm <sup>2</sup> by 2100	490	Peak and decline

Table 2-9: Overview of the Used RCPs

Name	Developed By	Characteristics of Forecast for Future
RCP 8.5 – High emission	International Institute for Applied System Analysis – Austria	<ul style="list-style-type: none"> <li>• CO<sub>2</sub> emissions will be three times by 2100.</li> <li>• Methane emissions will be increased.</li> <li>• Increased population will raise the demand for croplands and grasslands.</li> <li>• Global Population will be 12 b by 2100.</li> <li>• Technology development will be slower.</li> <li>• Depending on fossil fuels increased.</li> <li>• Energy intensity increased.               <ul style="list-style-type: none"> <li>• Poor attention to the implementation of climate policy</li> </ul> </li> </ul>
RCP6 – Intermediate emission	National Institute for Environmental Studies – Japan	<ul style="list-style-type: none"> <li>• Depending on fossil fuels increased.</li> <li>• Medium energy intensity</li> <li>• Growing use of croplands while reducing the use of grasslands.</li> <li>• Methane emissions will be steady.</li> <li>• In 2060, CO<sub>2</sub> emissions will reach a peak of 175% of current levels &amp; then be reduced to 125% of current levels.</li> <li>• Technologies and strategies for reducing GHGs</li> </ul>
RCP4.5 – Intermediate emission	Pacific Northwest National Laboratory - US	<ul style="list-style-type: none"> <li>• Energy intensity will be lower.</li> <li>• Reforestation programs strengthened.</li> <li>• As a result of increased yields and changes in dietary habits, the use of croplands and grasslands was reduced.</li> <li>• Strict policies for climate</li> <li>• Methane emissions will become stable.</li> </ul>

Name	Developed By	Characteristics of Forecast for Future
		<ul style="list-style-type: none"> <li>• CO2 emissions will slightly increase up to 2040 and started reducing.</li> </ul>
RCP2.6 – Low emission	PBL Environmental Assessment Agency – Netherlands	<ul style="list-style-type: none"> <li>• Usage of oil will be decreased.</li> <li>• Energy intensity will be low.</li> <li>• By the year 2100, the global population will be 9 B.</li> <li>• Bioenergy production will increase the use of croplands.</li> <li>• High development in animal husbandry</li> <li>• Reduction of Methane emissions by 40%.</li> <li>• CO2 emissions will be constant up to 2020, then gradually decrease and become negative in 2100.</li> <li>• CO2 concentration will increase to a peak in 2050, gradually reducing to about 400 ppm by 2100.</li> </ul>

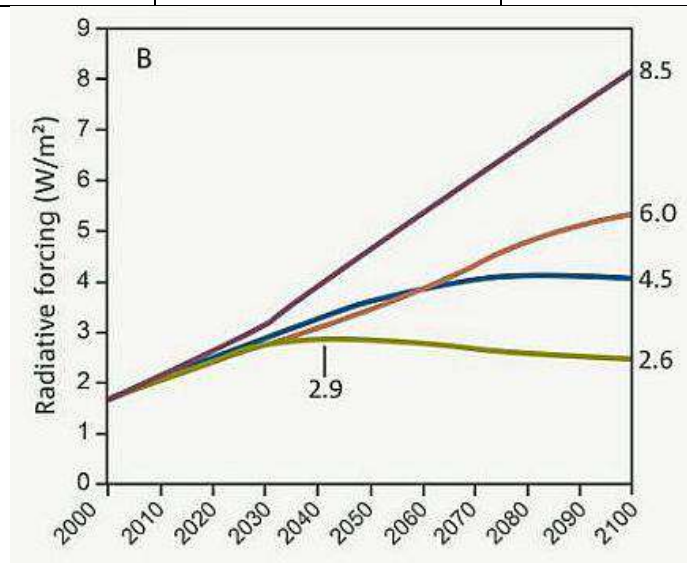


Figure 2-5: Radiative Forcing by four RCPs with time(Source: Bjørnæs, Undated)

## 2.10 CGMs Downscaling and Method of Bias Correction

When simulations are carried out through GCMs, the earth has to be divided into a restricted number of grid cells or spatial components, resulting in horizontal resolutions of hundreds of kilometers. Therefore, the models will deliver rough outputs. However, the above rough

creations need to be downscaled so that results can be obtained in high resolution; without those, studies of climate change will be difficult (Matyasoszky & Bogard 1996).

There are two methods widely used for downscaling: statistical downscaling and dynamic downscaling. Regional climate models with high resolution defined by the boundary conditions for global climatic models are used in dynamic downscaling (Meams,2009). Dynamic downscaling models do not provide substantially better results for precipitation and temperature. Further, their use is restricted by high operational costs. Their advantage is that they do not require local calibration of outputs. Statistical downscaling assumes stationary in predictor-predictand affiliation and needs correspondingly strong affiliation and adequate data to validate the assumptions (Saar et al.,2004). Statistical downscaling is widely used due to the low cost and easy implementation (Rashid et al.,2014)

### **2.11 Bias Correction**

Biases in climatic modelling are the “disagreements “or differences between the output results of the GCM models with the actual observations. As the GCMs are built on many assumptions and approximations, the extent of agreement between the model outputs and observations depends on how far the above assumptions are correct. Biases can further be caused by various other model system errors due to reasons such as defects of the applied system, transfer procedure between continuous and discrete functions (discreditation), and taking average values for the space within a grid cell.

Therefore, biases can be found in any modelling, and it causes those future projections made based on the outputs of such models may be misleading. Accordingly, possible biases should be well considered before using the results from the model (Rashed et al.,2014; Teutschbein & Seibert,2012). Two general biases are the overestimation of wet weather days with low rainfall and inaccurate computation of extreme temperature (Ines & Hansen,2006). Biases may include variations from the real seasonal precipitation and connected inaccuracies (Teutschbein & Seibert,2012).

Researchers have developed several methods for bias corrections to be used for downscaling climate variables from climatic models. They vary within an extensive range from simple scaling methods to advanced methods employing probability mapping or weather generator methods (Teutschbein & Seibert,2012). Biases correction methods evaluate the bias between the observed and derived variables and use such relations to correct the values obtained for

future scenarios. Therefore, in bias correction methods, it is assumed that a “stationary” condition where the correction procedure and its parameterization for present climate conditions are acceptable for future requirements (Teutschbein & Seibert,2012). Above assumptions limit the accuracy of bias correction methods as the condition of bias correction varies on the condition of the observed data set.

Following bias correction methods are extensively used.

1. Linear scaling
2. Delta change method
3. Power transformation method
4. Quantile mapping method
5. Local intensity scaling (LOIC) method
6. Variance Scaling

### **2.11.1 Linear scaling for precipitation and temperature**

This approach is based on monthly scaling (correction factors) values established on the differences between observed and model output values, so that monthly values of bias-corrected data and monthly mean of observations will completely match. This means bias correction can be applied for precipitation and temperature bias but not for the intensity and frequency of wet days. Precipitation is corrected by applying a scaling factor, which equals the ratio of values of the monthly mean of observed and model output. An additive term that is equal to the difference between long-term average monthly observed temperature and output of climate modeling is used for the correction of temperature. As mentioned earlier, the correction factor is assumed to be constant for future conditions (Teutschbein & Seibert,2012).

### **2.11.2 Delta change method for precipitation and temperature**

For many studies, this method has been widely used. In this method, the correction is applied by considering future inconsistencies and agitation of observed data instead of directly applying future climate simulations (Teutschbein & Seibert,2012).

### **2.11.3 Power transformation method for precipitation**

While the LOCI method adjusts only the mean value, the researcher can correct both difference in mean and variance in the observed and model outputs. In this method, the variance of model-generated precipitation data is modified by using a power correction formula in the form of  $a \cdot P_b$ , where  $a$  and  $b$  are parameters obtained using CV (coefficient of variation) and mean observed  $t_a$  (Teutschbein & Seibert,2012).

#### **2.11.4 Quantile mapping method for precipitation and temperature**

This method has also been called Probability mapping or distribution mapping in related literature. Under this method distribution function for model and observed data is adjusted to agree mutually. For this purpose, a transfer function is created that shifts the occurrence distribution of precipitation and temperature data simulated by the model (Teutchbein & Seibert,2012). Literature shows that Gamma distribution is more suitable for precipitation data, and Gaussian distribution is the best for temperature.

#### **2.11.5 Local intensity scaling (LOCI) method for precipitation**

This method can be considered an improved version of the linear scaling method. This method has addressed the weaknesses in linear scaling, such as the lack of ability to change wet dry frequency and intensity. In three separate stages, it adjusts the biases in data for mean, wet day frequency, and intensity (Teutchbein & Seibert,2012)

#### **2.11.6 Variance scaling method for temperature**

This method is similar to the power transmission methods as both adjust the mean and variance. But the power transmission method adjusts the precipitation time series while this method adjusts the temperature time series (Teutchbein,2012)

Literature shows that all the above methods can improve coarse solutions generated from models and can be used to fully remove all biases of mean temperature and precipitation (Teutchbein & Seibert,2012).

### 3 METHODOLOGY

#### 3.1 Study Area

Sri Lanka is blessed with 103 rivers; among them, Mahaweli is the longest and carries the most significant amount of water. This river is fed by both southwest and northeast monsoons. Mahaweli river originates from the Hatten plateau and travels about 335 km before reaching the Bay of Bengal at Koddiyar Bay, south of Trincomalee district. It flows through the Central, North Central, and eastern provinces. The catchment area of Mahaweli extends up to 10,268 square kilometres, which is about 16% of the island's total land area. The Mahaweli basin has an average yield of approximately 11,016 million cubic meters (MCM), which is equal to about 24% of total water resources on the island.

The climate in the Mahaweli basin is mainly affected by monsoons, with the only vital climatic factor being the temperature. The variations in annual temperature are small, though there is significant variation between downstream and upstream areas (Petr,1985).

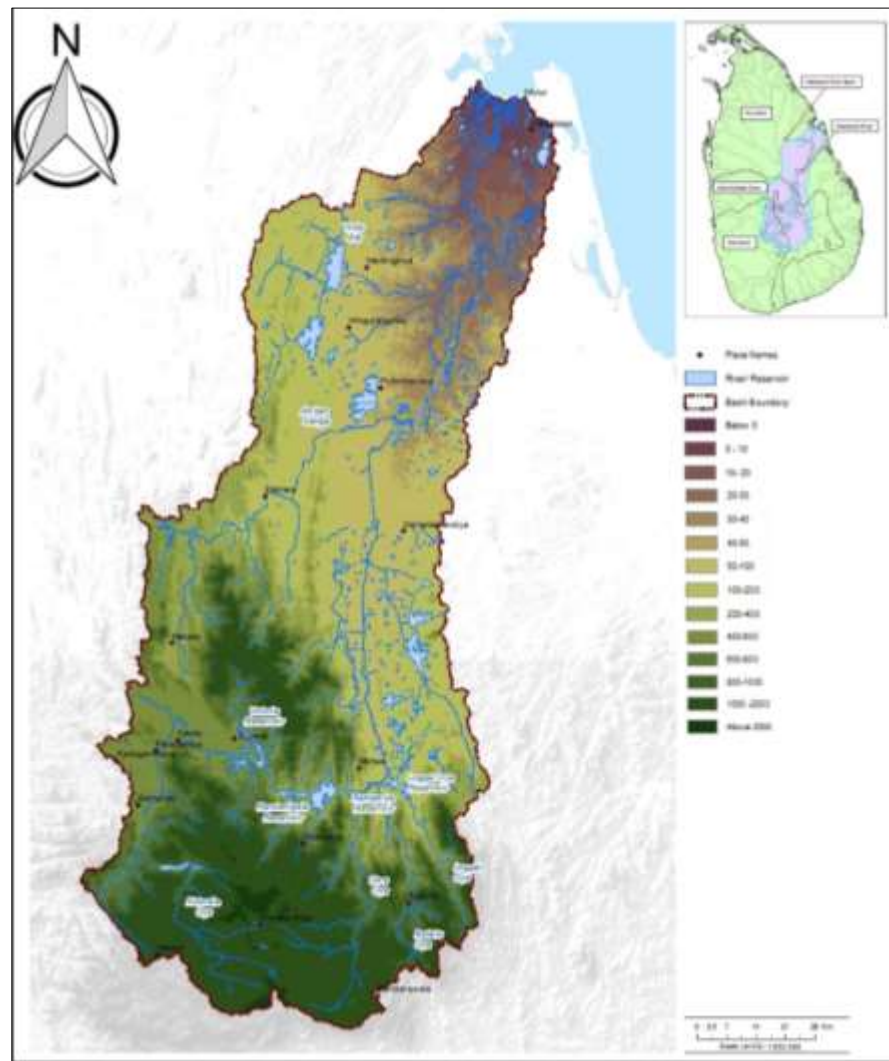


Figure 3-1: DEM in Mahaweli River Basin

### 3.1.1 Basin Hydrology

The main tributaries of Mahaweli are Amban Ganga, Uma Oya, Kothmale Oya, Loggal Oya, Badulu Oya, Hulu Ganga and Hatton Oya. The basins consist of distinctive natural regions having characteristic soil types, climate, land use potential, and topography. Highlands of the wet zones are well developed with tea and rubber (in hill slopes) and paddy (in valleys). The upper catchment area covers 3,200 km<sup>2</sup> and is crucial for power generation and irrigation in the lower Mahaweli basin. Flow rates fluctuate substantially from wet to dry season, and tidal effects can be met nearly six km from the shore (Wharton,1993).

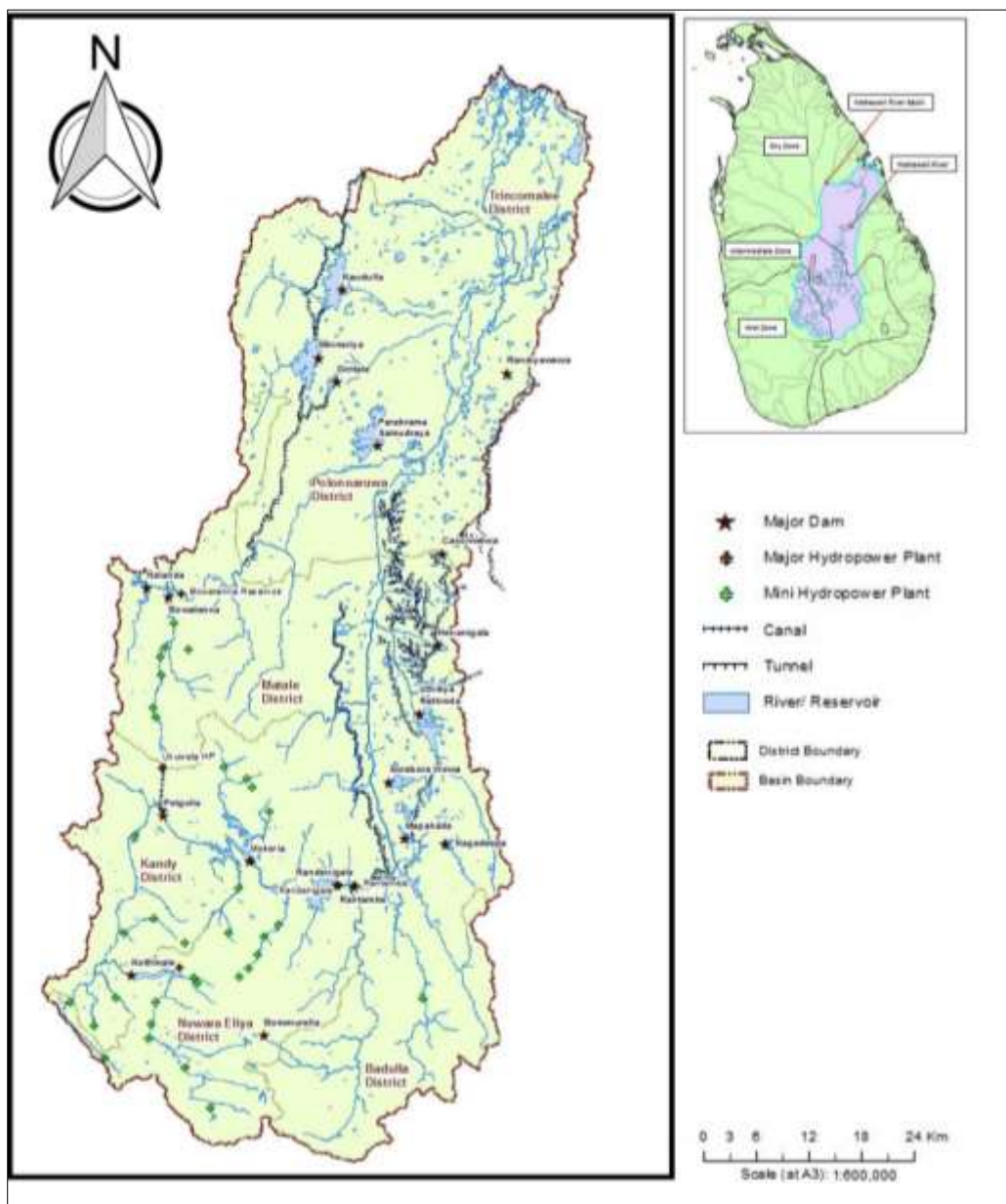


Figure 3-2: Existing Water Infrastructure in Mahaweli River Basin

The upper catchment of the Mahaweli Ganga basin receives rain from the southwest monsoon, while the lower catchment below Peradeniya receives rainfall from the northeast monsoon. The mean annual rainfall varies from 1,650mm to 5,300mm in the downstream area to the upper catchment. The pattern is mainly physio graphically controlled. The hills country parts, which are subjected to the full force of the monsoons, receive the greatest, most significant rainfall, while the low-lying plains and the “rain shadows” areas in hill country receive much lower rainfall.

### **3.1.2 Administration and Population**

Mahaweli river basin lies in the Central, North-Central, and Eastern provinces. As the Mahaweli is the island’s central river basin, it covers numerous Divisional Secretaries and Districts. District coverage is shown in Table3-1. Nuwara Eliya, Kandy, and Trincomalee are a few large cities situated in the Mahaweli basin. Most people live in small neighbourhoods or villages beside the above cities. Mahaweli basin has a population of about 3.3 million and some less populated districts in Sri Lanka. Lower parts in systems A to H in the Mahaweli development area are mainly inhabited by new settlers who have in-migrated from other areas during the last few decades. Colonization systems funded by the government or private sector have provided settlements for people in some newer villages. Many residents’ primary income source is selling and grown crops, with paddy, is grown crops, with paddy being the main leading low land crop potato, fruits, and other vegetables common in the uplands. Many residents have received employment opportunities in tea estates, while there has been a significant development in service industries during the last few decades.

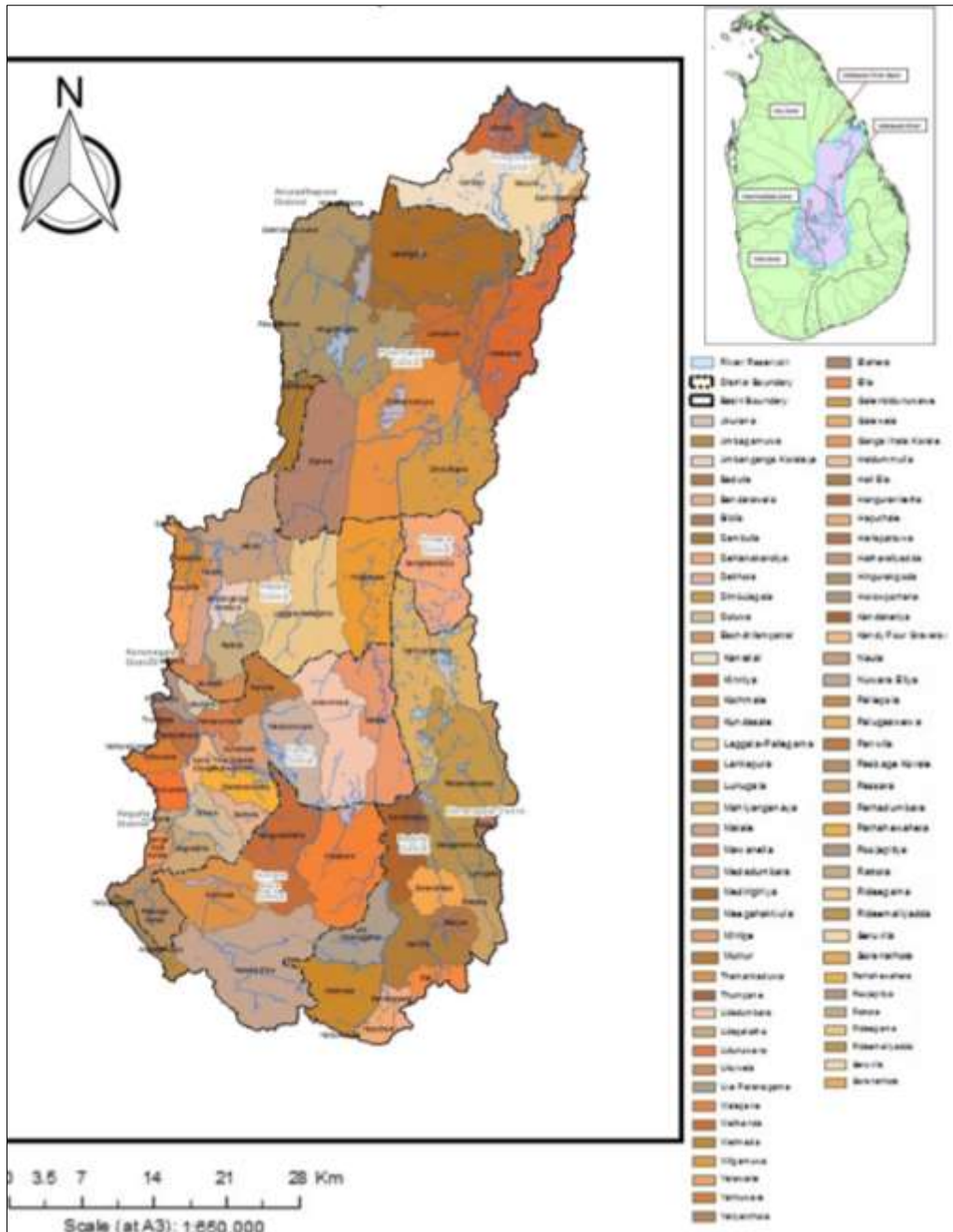


Figure 3-3: Map of Divisional Secretaries in Mahaweli River Basin

Table 3-1: Divisional Secretaries Areas in Mahaweli Basin

District	Total Number of DSs	Divisional Secretaries Areas
Ampara	01	Dehiaththakandiya
Anuradhapura	03	Galenbidunuwewa, Palugaswewa, Horowpathana
Badulla	16	Badulla, Bandarawela, Ella, Haldummulla, Hali Ela, Haputale, Kandaketiya, Lunugala, Meegahakiula, Mahiyangana, kandaketiya, Passara, Rideemaliyadda, Soranathota, Uva Paranagama, welimada

<b>District</b>	<b>Total Number of DSs</b>	<b>Divisional Secretaries Areas</b>
Kandy	20	Harispaththuwa, Akurana, Delthota, Gangawata Korale, Doluwa, Gangaihala Korale Minipe, Panwila, Thumpane, Ududumbara, Yatinuwara, Kundasale, Pasbage Korale, Madadumbara, Pathahewahata, Udunuwara, Pujapitiya, Udapalatha, Pathadumbara, Hatharaliyadda
Kegalla	02	Mawanella, Yatiyanthota
Kurunegala	01	Rieegama
Matale	11	Ambanganga Koralaya, Dambulla, Galewela, Laggala, Mathale, Naula, Pallegama, Pallepola, Raththota, Yatawatta, Wilgamuwa, Ukuwela
Monaragala	1	Bibila
Nuwara Eliya	5	Ambangamuwa, Walapane, Nuwara Eliya, hanguranketha, Walapane
Polonnaruwa	7	Dimbulagala, Welikanda, Lankapura, Elahara, Thabankaduwa, Medirigiriya, Higurakgoda
Trincomalee	5	Eachchilampattai, Kanthalai, Kinniya, Muttur, Seruvila

The National Census conducted in 2012 showed that the basin's population is 3,238,731 and projected that the population would reach 4,237,893 in the year 2040. Table 3-2 shows the district-wise population in 2012 and the projected population in the year 2050.

Table 3-2:Population in year 2012 and 2050

<b>District Name</b>	<b>Total Area (ha)</b>	<b>Area in Mahaweli Ganga Basin (%)</b>	<b>Population (2012)</b>	<b>Population Projected 2050</b>
Ampara	449,551	6.05%	35,594	57,064
Anuradhapura	721,222	0.08%	695	998
Badulla	287,207	65.39%	669,771	855,990
Kandy	192,402	88.13%	1,248,409	1,613,317
Matale	205,782	69.90%	338,140	449,266
Nuwara Eliya	174,535	73.80%	537,530	642,659
Polonnaruwa	344,630	83.18%	344,414	25,443
Trincomalee	264,362	24.82%	62,421	90,615
Kegalle	166,099	0.01%	28	34
Kurunegala	490,447	0.00%	10	16
Monaragala	575,268	0.29%	1,717	2,493
<b>Total</b>	<b>3,871,506</b>		<b>3,238,731</b>	<b>4,237,893</b>

### 3.1.3 Land Use

There is a significant difference in the pattern of land use between the upper catchment and downstream in the Mahaweli river basin. Table 3-3 shows the land use pattern in the downstream Mahaweli Ganga basin.

The upper catchment has four main land use groups (Nanadalal,1998).

1. About 49% of lands in the watershed area are intensively managed, and two-thirds of them are under tea.
2. 14% of land under dry-land agriculture
3. 14% under forest and
4. 22% of underutilized lands are either bush, abandoned tea, chena (small crop agriculture), or grassland.

Table 3.3 exhibits significantly different land use patterns in the downstream area of the Mahaweli Ganga basin (Nandalal,1998).

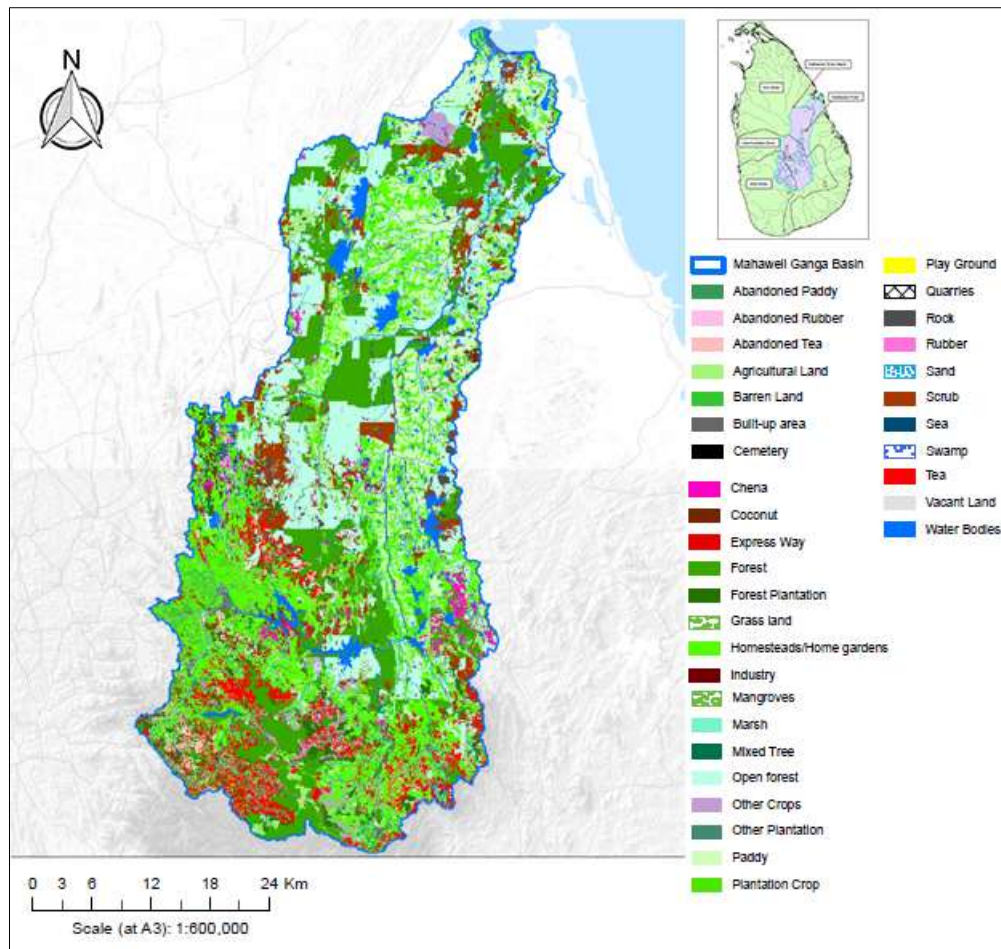


Figure 3-4: Land Use Map of Mahaweli River Basin

Figure: 3-4 describes the land use map of Mahaweli River Basin, and Table 3-3 shows the land use pattern downstream of Mahaweli River Basin

Table 3-3: Land use pattern downstream of Mahaweli Basin

Land Use	Extend(ha)
Rice (Paddy)	75,000
Chena (small crop cultivation)	90,800
Another crop land	48,000
Forest, scrubs, woodlands	140,000
Pastures, grasslands etc	24,000
Surface water	10,000
Other lands	3,000
Total	390,800

### 3.1.4 Water Supply

There are three main players involved in piped water supply in Sri Lanka. National Water Supply and Drainage Board is the main provider of piped water supply, which covers about 40% of the population. Few local authorities also handle piped water supply in their areas of authority, such as Kandy, Kurunegala, Bandarawela, etc. About 10% of the island's population

is served by small-scale water supply schemes located especially in rural areas and maintained by user communities. The domestic and industrial water requirements in many cities such as Anuradhapura, Polonnaruwa, Kandy, Badulla, Trincomalee, Matale, and Nuwara Eliya are met by water from the Mahaweli basin.

In addition to pipe bore water supply, a large percentage of people use dug wells for domestic purposes, which is significant in the lower Mahaweli basin.

District	No of Intakes	Domestic	Commercial	Industrial	Non-Revenue	Total
Nuwara Eliya	9	19708	1872	1872	6180	30900
Kandy	17	258596	22087	22087	75130	377900
Badulla	27	29993	7548	2442	10247	51295
Matale	8	106268	13284	13284	33360	166196
Anuradhapura	22	122802	14977	11978	37439	187195
Polonnaruwa	6	21035	2566	2052	6414	32066
Trincomalee	2	119200	3400	27460	37515	187575
<b>TOTAL</b>		<b>677602</b>	<b>65734</b>	<b>81175</b>	<b>206285</b>	<b>1033127</b>

Figure 3-5: Future Water Demands in Mahaweli River Basin

### 3.1.5 Hydropower

The Mahaweli Development Scheme also covers hydropower schemes. There are six hydropower stations with an installed capacity of 660 MW, and the remaining potential is 194 MW from six more stations.

### 3.1.6 Environment and Biodiversity

Before implementing the Mahaweli development program basically to improve agriculture, most lands were covered with matured tropical wet, sub-wet, or temperate forests. The steep grounds in the upper reaches of the basin were in a diverse closed canopy tropical montane moist forestry cover and cultivated agricultural lands (mostly tea plantations). At the same time, the lower slopes endorsed heavy but drier tropical jungle cover. To a certain extent, all such lands have been trespassed upon, although the habitants were well connected, with an occasional breakup.

The improved cultivated lands in the basin, especially in the lower zones of systems A-H significantly, have dramatically reduced aggregate forest cover.

### 3.1.7 Ongoing Development Activities

Several transboundary diversions have been implemented or are at the planning stage in the Mahaweli basin. Mainly they are for the pursuit of water towards the arid areas in the northern parts of the island, based on the Mahaweli Master Plan Study, 1968.

Mahaweli Development project is an ongoing project which mainly focuses on the development of the Mahaweli Ganga basin. Eight of the total 14 irrigation schemes (A, B, C, D1, D2, E, F & G), which have a total irrigation potential of approximately 120,000 ha, are established in the river basins of Mahaweli and Maduru Oya, out of which only 98,000 ha has been developed. The remaining six systems (H, I, J, K, L & M) are located in north-central parts with an irrigation potential of 125,547 ha, out of which only 50,547 ha (H) has been developed (Ranasinghe et al., 2013). The details are presented below Table 3-4

Table 3-4: Coverage Area of Mahaweli Development Project

Systems	Irrigation area (ha)	
	Developed	To be developed
A	7,050	-
B	18,000	13,500
C	22,801	-
D1&D2	36,621	6,560
E	7,530	-
F	-	3,000
G	5,750	-
H	50,547	-
I, J K, L&M	-	75,000
<b>Total</b>	<b>148,299</b>	<b>98,060</b>

The goals of the Mahaweli Water Security Investment Program (MWSIP) (ADB-funded Mahaweli Water Security Investment Program) focus on two primary areas: Irrigation infrastructure development and improvement to reduce the conveyance and distribution efficiencies and increased stakeholder participation in the crop selection and field input management including water management.

### 3.2 Data Collection and Processing

The following data is shown in Table 3-5 were collected from the following stations for the study.

Table 3-5: Collected Data for the Study

No	Data	Resolution	Availability	Authority
1	Digital Elevation Model	30 m x 30 m		
2	Rainfall	Daily	1987-2009	Meteorological Department
3	Other meteorological data (Temperature, Wind speed, Relative Humidity)	Daily	1987-2009	Meteorological Department
4	Discharge	Daily	1987-2009	Meteorological Department
5	Land Use	Vector		Land Use Department
6	Soil			Food and Agrarian Services Department
7	Existing Reservoir Data			Mahaweli Authority
8	Reservoir Operation Data	Daily/ Monthly		Mahaweli Authority/ Central Electricity Board
9	Population Data	Grama Niladari Division		Census Department
10	Agrarian Data			Agrarian Services Department

### 3.2.1 Rainfall Data

Table 3-6 shows the variation of rainfall data in the period.

Table 3-6: Selected Rainfall Data

No	Name	Start Year	End Year	X (m)	Y (m)	Elevation
1	Dunsaine	1960	2009	7.00	80.70	1,453
2	Dyrabba	1985	2009	6.88	80.93	1,131
3	Helbodde north	1987	2009	7.08	80.68	1,234
4	Holm	1985	2009	6.85	80.72	1,532
5	Hope	1960	2009	7.10	80.75	1,370
6	Katugasthota	1960	2009	7.33	80.63	448
7	Kobonella	1960	2009	7.35	80.85	885
8	Liddesdale	1960	2009	7.03	80.85	1,746
9	Narangala	1985	2009	7.05	81.00	1,091
10	Nawalapitiya	1980	2009	7.07	80.53	715

Considering the availability of the rainfall data for a considerable period and missing data are minimal, the above rainfall stations are selected.

### 3.2.2 Temperature Data

Following meteorological data are collected in respective time series. They are given in Table 3-7.

Table 3-7: Collected Meteorological Data

No	Name	Start Year	End Year	X (m)	Y (m)	Elevation
1	Badulla	1960	2009	7.00	80.70	1,453
2	Katugasthota	1985	2009	6.88	80.93	1,131

Considering data availability for the longest period, temperature data were used for the calculations.

### 3.2.3 Discharge Data at Manampitiya Station

Considering the continuous availability of the discharge data, Manampitiya was selected for the analysis.

### 3.2.4 Reservoir Data

Table 3-8 summarises some critical features of the reservoirs in the Mahaweli Ganga basin. The Mahaweli Authority maintains records for the significant Mahaweli Ganga reservoirs.

Table 3-8: Key Features of Mahaweli Basin

Reservoir	River/tributary	Year commissioned	Type	Capacity (MCM)
Kotamale Reservoir	Kothamala Oya	1985	Hydropower	172.9
Victoria Reservoir	Mahaweli Ganga	1985	Hydropower	721.2
Randenigala Reservoir	Mahaweli Ganga	1986	Hydropower	861.4
Rantambe	Mahaweli Ganga	1990	Hydropower	7.4
Bowatenna Reservoir	Amban Ganga	1981	Hydropower	52.0
Girithale Tank	-	-	Irrigation	23.9
Minneriya Tank	-	-	Irrigation	135.7
Kaudulla Tank	-	-	Irrigation	128.3

<b>Reservoir</b>	<b>River/tributary</b>	<b>Year commissioned</b>	<b>Type</b>	<b>Capacity (MCM)</b>
Parakrama Samudraya	-	-	Irrigation	134.4
Ulhitiya/Rathkinda combined Reservoir	Ulhitiya Oya	-	Irrigation	145.3
Moragahakanda Reservoir	Amban Ganga	2016	Irrigation	570
Kaluganga Reservoir	Kalu Ganga	Under Construction	Irrigation	265

### **3.3 Data Processing**

The available hydrological data needs to be processed and validated for its utilization in consequent hydrological analysis, climate change analysis, rainfall-runoff modelling, and water allocation modelling.

#### **3.3.1 Data Processing – Rainfall**

The Meteorological department provided rainfall data for all rain gauges. Rain gauge data from beyond the catchment was also gathered, primarily to fill in rainfall gaps at research sites. The Double mass curve was used to assess the consistency of the data in the catchment. The double mass curve is a commonly used and highly recognized hydrologic technique. The study period is 1987 to 2009 - this is the period where consistent data are available. It is noted that the data gaps within the catchment are very substantial, varying from 10% to 25%.

#### **Data Gaps – Rainfall**

Gaps in rainfall data are prevalent, and they can be caused by various factors, including instrument malfunction, station vandalism, station relocation, and reader unavailability, to name a few. Because all the data in the study had gaps, a timeline graph was created for all the stations. The timeline shows the pictorial view of the data gaps. Katugasthota and Badulla have minor missing data with 48.3% and 26.6%, respectively. Between 2005 and 2007 the data show gaps in almost all stations.

#### **Filling Data Gaps**

Filling data gaps is widespread, and various strategies have been developed to aid hydrologists in estimating the missing data (Gomez, 2007). Simple average, linear or multi regression, normal-ratio, closest neighbor fuzzy inference system, artificial neural network, and inverse

distance weighting approach are some of the methods available (Gomez, 2007). The optimal strategy to utilize is determined by the data's statistical properties (Xia, 1999).

The estimation of missing data can be done in two ways: the first is to use the historical relationship of the station network to build the relationship between them, and the second is to estimate the unknown using the data of the station in question.

The weighted average rainfall of neighboring stations is used as a function of the distance between the stations in inverse distance weighting (IDW) approaches (Hasan, and Croke, 2013).

A positive spatial autocorrelation is required for this strategy (Campozano et al., 2014). Hydrologists and geographers frequently employ IDW. This isn't just because it's easy to use (Xia, 1999); it has also been shown to be a reliable source of information.

When there is the +bit of spatial dependency between the stations, or the sample density is high, it can be compared to some of the most advanced approaches like Kriging (TWINLATIN, 2009).

In the dry season, it also gives better estimations of the unknown record than Universal Kriging (UK) (Coello Balthasar, 2011). In such cases, Goovarts (2000) suggests that using UK rather than IDW is less advantageous (Coello Balthasar, 2011). The coefficient of the weighted method is another inverse weighted method (CCWM) type. The only difference between CCWM and IDW is that the weighted factor is the Pearson coefficient. CCWM outperforms other methods in terms of ideas and can be utilized in any region (Gomez, 2007). However, Campozano et al. (2014) discovered that the coefficient of correlation, like the multiple linear regression approach, worked well during some seasons but not others. Kizza et al., (2014) discovered that the correlation coefficient is resilient and maintains the dataset's statistical features (Kizza, et al., 2014).

### **Coefficient of Weighted Method (CCWM)**

Teegavarapu and Chandramouli proposed this approach in 2005. (Marteau, 2011). The strength of the spatial correlation is bolstered by coefficient correlation (Marteau et al., 2011). Four stations with the highest correlation coefficient are evaluated by Teegavarapu and

Chandramouli (2005). (Marteau et al., 2011). A minimum of 730 consecutive days must be set as a correlation (TWINLATIN, 2009). A quantifiable geographic autocorrelation can be achieved using the correlation coefficient (Kajornrit, 2012). In processing the respective data, a maximum correlation of 0.74 and a minimum of 0.52.

### **3.3.2 Data Processing - Temperature**

There are many gaps in the temperature data, and the data do not match.

The difficulty with this data was that the highest and minimum values for the same period did not match. This was confirmed by the timeline graph produced for the meteorological stations Katugastota has the maximum temperature, whereas Badulla station noted the minimum temperature data. The analysis method defined in SWAT documentation is used to reconstruct these data.

#### **Gap infilling**

The CCWM was utilized to fill the gaps, and the data was extended to 1985 using reanalysis data. The link between observed data and reanalysis was evaluated, and an  $R^2$  of 0.75 was found. Within a particular period and space, the temperature does not vary significantly.

### **3.3.3 Data Processing - Stream flow**

The continuous data record for the stream flow is recorded only at the Manampitiya Station. Therefore, Manampitiya Stream flow data are used for stream flow data.

#### **Filing missing gaps in stream flow**

Various strategies for filling stream data have been created, and it is always crucial to use the approach that produces the best results. Days with gaps are excluded from time series in SWAT applications.

### **3.4 Hydrological Modelling – Setting up the SWAT Model**

There are significant steps to be followed in setting up the SWAT model and optimizing it for our usage. This model is built up the GIS platform. They can be classified as follows,

A. **Watershed Delineation** – At this point, the schematization of the model is taking place.

1. Digital Elevation Model
2. River Network

3. Inlets, Outlets, and reservoirs
- B. Defining Hydrological Response Unit (HRUs)** – Hydrological Response unit is the smallest determination in the model scale. Each HRU consists of a unique categorization of land use, soil, and slope definition.
1. Land Use classification
  2. Soil Data classification
  3. Slope classification
- C. Weather Generation User (WGEN User)**– At this point, temperature and climate data are added to the model
1. Adding temperature data
  2. Adding rainfall data
- D. Writing SWAT Input files** – Adding data to the artificial influencers at this phase of the model setup
- E. Model Run-**
- F. Optimization of parameters**

#### **3.4.1 Digital Elevation Model (DEM)**

According to the QGIS SWAT documentation, SRTM ((Shuttle Radar Topography Mission) is regarded as a sufficiently good source of Digital Elevation Model data worldwide. SRTM 30m grid size DEM was used for the model.

#### **3.4.2 River Network**

QSWAT tool is used to delineate the river network with the catchment threshold of 60 km<sup>2</sup>. The delineated river networks were confirmed and validated with Google Earth imagery.

#### **3.4.3 Inlets, Outlets, and reservoirs**

The SWAT model is delineated for a whole for whole basin. Therefore, there are no other inlets for the model.

Three separate watercourses are included in the basin's lower reaches: the Mahaweli Ganga, Uppu Aru (to the west of the Mahaweli Ganga), and another watercourse to the east of the Mahaweli Ganga. These watercourses appear to have different outlets, which were placed appropriately based on examination of the derived river network, the DEM, and using google imaginary. Therefore, the SWAT model includes three separate 'outlets.' The model is validated only for one outlet.

There are many existing water bodies in the basin of various sizes. Based on the model cell resolution and the location of the reservoirs in the delineated river network, the following major existing reservoirs have been modeled: Kotmale Oya, Victoriya, Randenigala, Nagadeepa Maha Wewa, Hepolaoya, Sorabora Wewa, Ulhitiya Oya, Minneriya Wewa, Kaudulla Wewa, Bowatenna and Nalanda reservoir.

The following significant waterbodies are located on tributaries that are not represented by the delineated river network; therefore, they can be modeled as ‘ponds’ in SWAT:

Parakrama Samudraya, Girithale Wewa, Ratkinda, Mapakada Wewa. Smaller water bodies can also be modeled as ‘ponds,’ depending on the expected impact they would have on the flow regime to Manampitiya.

The watershed and sub-basin delineation process as described results in the creation of 115 - sub basins of the Mahaweli river basin, shown in the following figure 3.6.

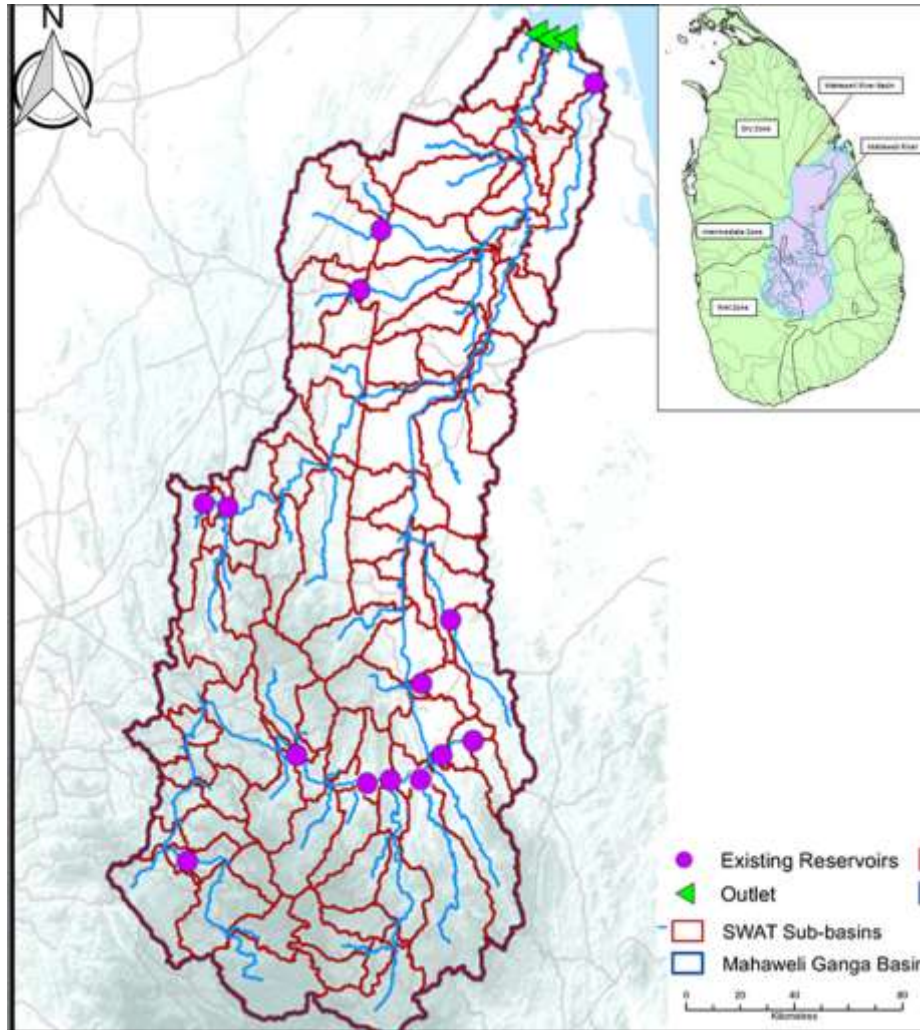


Figure 3-6: SWAT Model Schematation

### 3.4.4 Land Use Classification

Mapping was plotted onto digital 1:10,000 scale base maps provided by the Survey Land Use information has been mapped at a 1:10,000 scale as part of a national land use planning program. The subcategories were developed by Land Use Policy and Planning Department (LUPPD), Ministry of Land.

Table 3-9: Land Use Classification

Major Land Use	Land Use	Area (ha)	%
Built up		200,382	19.5
	Homesteads/home gardens	193,451	
	Build-up area	1,604	
	Built-up area	4,084	
	Cemetery	134	
	Industry	428	
	Playground	681	
Agriculture		294,744	28.7
	Paddy	158,009	

Major Land Use	Land Use	Area (ha)	%
	Tea	80,343	
	Rubber	2,398	
	Agricultural land	14,641	
	Coconut	3,819	
	Chenna	7,700	
	Other crops	20,414	
	Abandoned paddy	2,686	
	Abandoned rubber	274	
	Abandoned tea	4,461	
Bare Land		2,096	0.2
	Vacant land	1,142	
	Barren land	861	
	Bare land	93	
Forest Land		457,984	44.6
	Forest	161,631	
	Open forest	157,777	
	Mixed tree	6,657	
	Forest plantation	19,525	
	Mangrove	649	
	Grassland	13,545	
	Scrub	98,201	
Rock		14,545	1.4
Sand		677	0.1
Wet Land		13,748	1.3
	Swamp	2,879	
	Marsh	10,869	
Water bodies		42,598	4.1
Total		1,026,775	100.00

The above-classified lands, accordingly to the land use map, can be further classified as follows to match the SWAT model.

This classification shows significant changes in the actual scenario to the summarized situation. In the following processing, due to merging and disaggregation, ‘FRSE’ (Forest Land) becomes the dominant land-use class (33.02 %), with ‘RICE’ (Paddy) being second (17.03 %). Along with ‘URLD’ (Urban areas low density; 12.76 %), ‘SHRB’ (Shrub Land; 9.56 %), ‘AGRL’ (Agricultural Land – Generic; 9.20 %), and ‘AGRR’ (Agricultural Land-Tea; 8.27 %), they cover 90 % of the basin.

Table 3-10: Land Use Classification according to SWAT guideline

Land Use Type	Coverage (%)	SWAT code
Agricultural Land-Dense Forest Agricultural	33.02%	FRSE

<b>Land Use Type</b>	<b>Coverage (%)</b>	<b>SWAT code</b>
Land-Forest plantation Agricultural Land-Open Forest Build Up Area-Dense Forest Forest Land-Barren Lands/Distorted Surface Forest Land-Dense Forest Forest Land-Forest Land Forest Land-Forest plantation Forest Land-FP/O Forest Land-FP/OT Forest Land-FP/T Forest Land-Homesteads/Home gardens Forest Land-Open forest Forest Land-RV		
Agricultural Land-Abandoned Paddy Agricultural Land-MAN Agricultural Land-Paddy Agricultural Land-Seasonal Crop Forest Land-Paddy	17.03%	RICE
Build Up Area-GF Build Up Area-Grass land Build Up Area-Homesteads/Home gardens - URLD Build Up Area-PH Build Up Area-RL Build Up Area-ROAD Build Up Area-Security Campus/Security Zones	12.76%	URLD
Forest Land-Scrub Land	9.56%	SHRB

Land Use Type	Coverage (%)	SWAT code
Water Bodies-Scrub Land		
Agricultural Land-Agricultural Farms Agricultural Land-Archaeological Sites Agricultural Land-Barren Lands/Distorted Surface Agricultural Land-Cashew Agricultural Land-Cinnamon Agricultural Land-Foliage/Flowering plants Agricultural Land-Generic Agricultural Land-Mixed tree and other perennials Agricultural Land-OC Agricultural Land-OC/M Agricultural Land-Pepper Agricultural Land-SCUL Agricultural Land-Sparsely used crop land/Chena. Agricultural Land-VEG Build Up Area-Agricultural Farms Build Up Area-Aquatic Farms Build Up Area-Botanical gardens Build Up Area-Homesteads/Home gardens - AGRL Build Up Area-LFS Build Up Area-Livestock Farms Build Up Area-Pineapple	9.20%	AGRL
Agricultural Land-Abandoned Tea Agricultural Land-Banana Agricultural Land-Tea	8.27%	AGRR

<b>Land Use Type</b>	<b>Coverage (%)</b>	<b>SWAT code</b>
Water Bodies-Mango		
Water Bodies-Abandoned Tank		
Water Bodies-Abandoned Tea		
Water Bodies-Canals		
Water Bodies-IRCAN		
Water Bodies-Lagoon		
Water Bodies-Lakes		
Water Bodies-Major reservoirs		
Water Bodies-marsh		
Water Bodies-Minor reservoirs	4.16%	WATB
Water Bodies-Natural Ponds		
Water Bodies-Paddy		
Water Bodies-RIV/STR		
Water Bodies-Rivers/Streams		
Water Bodies-Salters		
Water Bodies-Streams		
Water Bodies-TNK		
Water Bodies-Water Hole		
Water Bodies-WB		
Agricultural Land-Exposed rocks		
Bare Land-Barren Lands/Distorted Surface		
Bare Land-Barren Lands/Distorted Surface		
Bare Land-BL/DS		
Bare Land-Clay pits	1.68%	BARR
Bare Land-Gravel pits		
Bare Land-marsh		
Bare Land-Unutilized Land		
Bare Land-UTV		
Rocky Area-Clay pits		
Rocky Area-Exposed rocks		

<b>Land Use Type</b>	<b>Coverage (%)</b>	<b>SWAT code</b>
Rocky Area-Gravel pits Rocky Area-Homesteads/Home gardens Rocky Area-Mining Rocky Area-Quarries Rocky Area-RA Sandy Area-Exposed rocks Sandy Area-SA Sandy Area-Sand Dunes Water Bodies-WS		
Forest Land-Grass land	1.32%	GRAS
Wet Land-Mangroves Wet Land-marsh Wet Land-VU	1.10%	WETN
Agricultural Land-Sugar cane	0.40%	SUGC
Agricultural Land-Coconut	0.37%	COCO
Build Up Area-Urban Areas	0.36%	URHD
Wet Land-Swamp Wet Land-WL	0.28%	WETF
Agricultural Land-Abandoned rubber Agricultural Land-Rubber	0.26%	RUBR
Build Up Area-BUL Build Up Area-MIR Build Up Area-MR Build Up Area-PTS Build Up Area-SIBA Build Up Area-VP	0.10%	URMD
Build Up Area-Parks/Playgrounds Build Up Area-Parks/Playgrounds	0.07%	RNGE
Build Up Area-Industrial Areas/ Industrial Parks/Estates	0.04%	UIDU

Land Use Type	Coverage (%)	SWAT code
Build Up Area-Industrial Sites		
Build Up Area-Cemetery	0.01%	UINS

### 3.4.5 Soil Data Classification

Soils are categorized accordingly to the Digital Soil Map. Soil classes in the digital soil map are matched with the SWAT soil database. The linkage between the digital soil map and the SWAT soil database is shown below. QSWAT soil database was a beneficial tool in the process of matching the soil classes in

Table 3-11: Key Features of Mahaweli Basin

Soil association / complex	Soil – slope	Coverage (%)	SWAT soil	Soil association / complex	Soil – slope	Coverage (%)	SWAT soil
Akurana Kiribathkumbura Association	Akurana-undulating	1.88%	Rd31-1-2b-3852	Mattekele Series	Mattekele - undulating	2.31%	Ao1-3b-5358
	Kiribathkumbura-flat	0.96%	Ge59-2-3a-4504		Mattekele -steep	0.88%	Ao78-3c-3649
	Akurana-steep	0.27%	Rd31-1-2b-3852		Mattekele -flat	0.49%	Ao13-3ab-5365
Aluthnuwara Series	Aluthnuwara-flat	19.18%	Jd7-2a-3146	Mawanella - Kandy - Kiribathkumbura Association	Kandy-undulating	0.87%	Bd73-2b-6420
	Erosional remnants (Inselberg) -steep	1.44%	ROCK-193		Kiribathkumbura-flat	0.44%	Ge59-2-3a-4504
	Erosional remnants (Inselberg) - undulating	0.50%	ROCK-193		Kandy-steep	0.19%	Bd52-1-2c-6360
Aluthnuwara-Manampitiya Association with undifferentiated soils of alluvial origin	Manampitiya-flat	0.04%	Je72-2a-4393	Medawachhiya-Aluthwewa Association with Lithosols	Hurathgama-flat	9.27%	Ge18-2a-5187
	Manampitiya-undulating	0.02%	Je26-2b-3405	Medawachhiya-undulating	1.13%	Lc38-2bc-1403	

Soil association / complex	Soil – slope	Coverage (%)	SWAT soil	Soil association / complex	Soil – slope	Coverage (%)	SWAT soil
Aluthwewa Hurathgama Association	Aluthwewa-flat	1.92%	Lc3-2b-3768	derived from quartzite	Erosional remnants (Inselberg)-steep	0.45%	I-Bd-T-2c-4355
	Aluthwewa-undulating	0.95%	Lc3-2b-3768	Nuwaraeliya - Horton - Lithosols Complex	Horton-undulating	3.97%	Bd73-2b-6420
	Erosional remnants (Inselberg)-steep	0.34%	ROCK-193		Lithosols Complex-steep	2.35%	I-Bd-T-2c-4355
Badulla Lithosols Complex	Badulla-undulating	0.67%	Lo57-1-2b-5983	Ragala Series	Horton-flat	0.76%	Bd73-2b-6420
	Badulla-steep	0.65%	Lo56-1-2c-5982		Ragala-undulating	2.42%	Lo65-2-3b-4534
	Badulla-flat	0.16%	Lo79-2a-6572		Ragala-steep	1.92%	Lo56-1-2c-5982
	Badulla-undulating	0.07%	Lo57-1-2b-5983		Ragala-flat	0.28%	Lo16-3a-4899
	Badulla-flat	0.04%	Lo79-2a-6572	Rikillagaska Series	Rikillagaskada-steep	1.19%	Lo56-1-2c-5982
	Lithosols Complex-steep	0.04%	I-Bd-T-2c-4355		Rikillagaskada-undulating	0.94%	Lo57-1-2b-5983
	Badulla-undulating	0.04%	Lo57-1-2b-5983		Rikillagaskada-flat	0.06%	Lo79-2a-6572
	Badulla-steep	0.03%	Lo56-1-2c-5982	Rock Knob Plains	Rock Knob Plains-flat	8.51%	ROCK-193
	Erosional remnants (Inselberg)-undulating	0.02%	ROCK-193		Rock Knob Plains-undulating	1.22%	ROCK-193
	Badulla-flat	<0.01%	Lo79-2a-6572		Rock Knob Plains-steep	0.28%	ROCK-193

<b>Soil association / complex</b>	<b>Soil – slope</b>	<b>Coverage (%)</b>	<b>SWAT soil</b>	<b>Soil association / complex</b>	<b>Soil – slope</b>	<b>Coverage (%)</b>	<b>SWAT soil</b>
Badulla Mahawaletenna Complex	Badulla-steep	5.22%	Lo56-1-2c-5982	Siyambala-Puttulam Association	Siyambala-flat	0.94%	Sg2-3a-4038
	Badulla-undulating	4.39%	Lo56-1-2c-5982		Erosional remnants (Inselberg)-steep	0.01%	ROCK-193
	Badulla-flat	0.49%	Lo79-2a-6572		Erosional remnants (Inselberg)-undulating	<0.01%	ROCK-193
Bandarawela Series	Bandarawela-undulating	2.51%	Ah19-3b-6341	Ukuwela - Hunugala - Matale Complex	Hunugala-undulating	1.13%	Lc43-2c-1408
	Bandarawela-steep	1.09%	Ah22-3c-6204		Hunugala-flat	0.62%	Lc43-2c-1408
	Bandarawela-flat	0.52%	Ah1-3a-6340		Hunugala-steep	0.25%	Lc43-2c-1408
Erosional remnants (Inselberg)	Erosional remnants (Inselberg)-undulating	7.62%	ROCK-193	Ukuwela - Matale Association	Ukuwela-undulating	1.73%	Ap21-2b-3656
	Erosional remnants (Inselberg)-steep	6.44%	ROCK-193		Ukuwela-steep	0.82%	Ap21-2b-3656
	Erosional remnants (Inselberg)-flat	3.84%	ROCK-193		Ukuwela-flat	0.53%	Ap21-2b-3656
Gampola Series	Gampola-flat	0.02%	Jd10-2-3a-4515	Ukuwela-Hunugala Matale Association	Ukuwela-flat	0.25%	Ap21-2b-3656
	Erosional remnants (Inselberg)-steep	<0.01%	ROCK-193		Ukuwela-undulating	0.01%	Ap21-2b-3656
Horton-Lithosol Complex	Horton-undulating	0.59%	Bd53-1-2c-6362		Ukuwela-steep	<0.01%	Ap21-2b-3656

Soil association / complex	Soil – slope	Coverage (%)	SWAT soil	Soil association / complex	Soil – slope	Coverage (%)	SWAT soil
	Lithosols Complex-steep	0.32%	I-Bd-T-2c-4355	Ulhitiya - Kuda Oya Association with bed rock exposures	Kuda Oya-flat	10.24%	Lg40-2ab-6553
	Horton-flat	0.09%	Bd53-1-2c-6362		Kuda Oya-undulating	1.79%	Lg40-2ab-6553
Hunnasgiriya Lithosols Complex with erosional remnants	Hunnasgiriya-steep	6.73%	Lo56-1-2c-5982		Ulhitiya-steep	0.69%	Lp13-2a-3813
	Hunnasgiriya-undulating	5.97%	Lo57-1-2b-5983	Ulhitiya (rolling) - Lithosols Complex with bed rock exposures	Ulhitiya (rolling)-undulating	5.70%	I-Bd-T-2c-4355
	Hunnasgiriya-flat	0.88%	Lo79-2a-6572		Ulhitiya (rolling)-steep	4.25%	I-Bd-T-2c-4355
Kaduruwela-Mutugala-Ulhitiya-Kuda Oya-Complex	Mutugala-flat	15.76%	E1-2a-4694		Ulhitiya (rolling)-flat	3.34%	Lp1-2a-5613
	Ulhitiya-steep	0.25%	Lp13-2a-3813	Ulhitiya-Kuda Oya Association	Kuda Oya-flat	12.01%	Lg40-2ab-6553
	Mutugala-undulating	0.03%	E1-2a-4694		Kuda Oya-undulating	0.52%	Lg40-2ab-6553
Kaduruwela-Seruwila-Siyambala Association	Kaduruwela-flat	0.74%	Be64-1-2a-461		Ulhitiya-steep	0.47%	Lp13-2a-3813
	Kaduruwela-steep	0.01%	Be116-2c-4475	Ulhitiya-Welikanda-Mutugal-Galwewa-Alawakumbura Complex with rock knob plains	Alawakumbura-flat	5.50%	Ge18-2a-5187
	Kaduruwela-undulating	<0.01%	Be11-2b-3338		WATER-steep	1.48%	WATER-1972
Kandy Galigamuwa Lithosols Complex	Kandy-undulating	7.19%	Bd73-2b-6420		WATER-flat	1.10%	WATER-1972
	Kandy-steep	4.40%	Bd52-1-2c-6360	WATER-undulating	0.70%	WATER-1972	
	Kandy-flat	0.70%	Bd3-2a-3334	Alawakumbura-steep	0.13%	Ge18-2a-5187	

Soil association / complex	Soil – slope	Coverage (%)	SWAT soil	Soil association / complex	Soil – slope	Coverage (%)	SWAT soil
Kandy - Matale Association	Matale-undulating	2.20%	Nd39-3bc-807	Wegala - Hunugala - Kundasale - Mahaberiyatenna Complex	Alawakumbura-undulating	0.09%	Ge18-2a-5187
	Kandy-steep	1.18%	Bd52-1-2c-6360		Hunugala-steep	0.59%	I-Bd-T-2c-4355
	Matale-flat	0.85%	Nd62-3ac-6297		Hunugala-undulating	0.44%	I-Bd-T-2c-4355
Kiruwana-Melsiripura Association	Melsiripura-undulating	0.50%	Lc3-2b-3768	Welimada Lithosols Complex	Mahaberiyatenna-flat	0.04%	Lc57-2a-717
	Kiruwana-flat	0.40%	Lo79-2a-6572		Lithosols Complex-undulating	1.00%	I-2b-5896
	Melsiripura-steep	0.17%	Lc43-2c-1408		Welimada-steep	0.94%	Bc29-2c-5864
Maskeliya-Mattekele_Lithosols Complex	Mattekele-undulating	1.25%	Ao1-3b-5358	Welimada Lithosols Complex	Welimada-flat	0.14%	Bc20-2a-1884
	Lithosols Complex-steep	0.59%	I-Bd-T-2c-4355				
	Mattekele-flat	0.14%	Ao13-3ab-5365				

### 3.4.6 Slope Classification

The slope was categorized into 5 main classes. With the combination of land use, soil, and slope; Hydrological response units (HRUs) were created to assess the hydrological impact. Each HRU is a unique combination of above-said classes.

### 3.4.7 Addition of the Artificial Influencers

The “with significant artificial influences” model includes the parameterization of major reservoirs. Off-line waterbodies that lay on tributaries not explicitly modeled in SWAT.

Physical characteristics and historical water level or storage data were collected for the parameterization of each major waterbody in the basin. Various sources of information were made available; however, big gaps in data and significant discrepancies between sources were quickly noticed. As there was no standard method of confirming the validity of each source, local knowledge, aerial photography, and professional judgment were utilized to determine the required reservoir parameters. The selected parameter values can be seen in Table 3-12

Table 3-12: Artificial Influencers to Mahaweli River Basin

<b>Reservoir</b>	<b>RES_ESA</b>	<b>RES_EVOL</b>	<b>RES_PSA</b>	<b>RES_PVOL</b>	<b>RES_VOL</b>
Bowatenna	480	2,459	468	2,350	225
Hepolaoya	215	410	215	410	10
Kaudulla Wewa	3,240	17,760	2,560	12,830	2,540
Kotmale Oya	660	18,110	640	17,290	2,220
Loggal Oya	445	850	445	850	10
Minneriya Wewa	2,830	17,890	2,480	13,570	930
Nagadeepa Maha Wewa	390	2,931	390	2,931	10
Nalanda	336	1,998	278	1,530	10
Randenigala	2,430	96,500	2,360	86,140	30,340
Rantambe	225	3,200	182	2,200	440
Sorabora Wewa	512	2,800	430	2,070	172
Ulhitiya Oya	1,400	9,610	1,400	9,610	10
Victoriya	2,480	76,800	2,380	72,120	3,400
<b>Reservoir</b>	<b>Start of operation</b>	<b>IFLOD1R</b>	<b>IFLOD2R</b>	<b>NDTARGR</b>	<b>STARG</b>
Bowatenna	Jan-1981	Jan	Apr	15	1984-2016
<b>Hepolaoya</b>	<b>Jan-1985</b>	<b>Jan</b>	<b>Apr</b>	<b>15</b>	<b>Estimated</b>
Kaudulla Wewa	Jan-1960	Jan	Apr	15	1983-2010
Kotmale Oya	May-1985	Jan	Apr	15	1985-2016*
<b>Loggal Oya</b>	<b>Jan-1985</b>	<b>Jan</b>	<b>Apr</b>	<b>15</b>	<b>Estimated</b>
Minneriya Wewa	Jan-1960	Jan	Apr	15	1983-2010
<b>Nagadeepa Maha Wewa</b>	<b>Jan-1968</b>	<b>Jan</b>	<b>Apr</b>	<b>15</b>	<b>Estimated</b>

<b>Nalanda</b>	<b>Jan-1985</b>	<b>Jan</b>	<b>Apr</b>	<b>15</b>	<b>Estimated</b>
Randenigala	Aug-1986	Jan	Apr	15	1986-2016*
Rantambe	Feb-1990	Jan	Apr	15	1990-2016*
<b>Sorabora Wewa</b>	<b>Jan-1960</b>	<b>Jan</b>	<b>Apr</b>	<b>15</b>	<b>Estimated</b>
Ulhitiya Oya	Jan-1985	Jan	Apr	15	1995-2010
Victoriya	Nov-1984	Jan	Apr	15	1984-2016*

Cells highlighted in bold indicate values that were not identified after cross-checking all available sources for these outstanding values. The available GIS data was utilized, and assumptions were made.

Specifically, the reservoir surface area from the GIS database was selected to represent the reservoir surface area at the principal spillway level (RES\_PVOL). In some cases, the same values were selected for the emergency spillway without further information.

The reservoir storage at the beginning of the simulation was set to the minimum operating reservoir storage where that was available. Otherwise, a minimum value of  $10^5 \text{ m}^3$  was selected.

As reliable daily outflow data was unavailable for most of the reservoirs, the “simulated controlled outflow – target release” option was determined for the reservoir outflow simulation method in SWAT.

As shown, monthly storage data was made available for only eight (8) reservoirs.

The monthly target storage was estimated using the monthly average values of the recorded storage data.

For the remaining reservoirs, based on similarity of physical characteristics, the credibility of available data, and personal judgment, the monthly target storage values for Bowatenna were scaled based on the reservoir PVOL ratio to obtain estimates for Nalanda. In contrast, the monthly target storage values for Rathkinda/Ulhitiya were scaled to get estimates for Loggal Oya, Hepola Oya, and Nagadeepa Maha Wewa.

There is high uncertainty in the existing reservoir parameters due to the reasons mentioned above; however, as shown in the following section, the modeled results are encouraging ahead of the model validation, indicating some confidence in the selected/derived parameters.

With the artificial influence, the SWAT model does not consist of irrigation ponds.

The main limitation of the modeled results presented in this report is that, except for a few stations, “artificial” influences, such as off-line waterbodies, abstractions, and significant/medium irrigation schemes, are expected to affect the flow regime upstream of the majority of monitoring locations, including the key Manampitiya station.

### **3.4.8 Model Sensitivity analysis, calibration, and validation**

Model calibration is the process of modifying model parameters for the model to represent the features of the catchment. Manual, automated, or semi-automatic calibration are all options. When there are a lot of parameters to calibrate, it's time-consuming to do it manually. (Arnold et al., 2012). It can, however, be used to fine-tune calibration.

Auto calibration is based on upper and lower limit parameters, and when used in conjunction with manual calibration, it is very effective in SWAT (Van Liew et al., 2005).

The initial stage in calibrating is to identify the parameters that will be used to simulate the process. The next step is to figure out how these parameters influence the processes that are being represented. Sensitivity analysis is the phrase for this. Local or global sensitivity analysis is possible. (Arnold et al., 2012). It helps to prevent over-parameterization. (Heuvelmans et al., 2004).

In the study, the model warm-up period is 2 years. The calibration period is set to 1989 – 2003, and the validation period is set as 2003 – 2009.

The calibration is limited to a particular data segment, as previously stated. The model was then run with twenty-two flow parameters, and the sensitive parameters were determined afterward. (Attached table below) During calibration and sensitivity analysis, the parameter will be altered. Nash-Sutcliffe Efficiency (NSE), Root Means Square Error (RMSE), Percentage bias (PBias), and coefficient of determination are some of the most often utilized optimization objective functions ( $R^2$ ). Moriasi et al. (2007), on the other hand, recommend three statistical coefficients: NSE, PBias, and RMSE. These statistical tests check the connection between the observed and the simulated stream flows.

Moriasi et al., (2007) propose NSE be above 0.5 for hydrologic and pollutant evaluations on a monthly time step.

Validation is calibrated model to reproduce simulations (Arnold et al., 2012) sufficiently. Validation uses the same statistical functions used in calibration to measure model efficiency. It's done with a data set that wasn't used in the calibration process. Arnold et al (2012), It is

suggested that both the calibration and validation data sets contain rainy and dry years, although this is not practical. Kannan et al., (2007); Van Liew and Garbreteli, (2003), nevertheless, propose having large runoff occurrences during the calibration period. Currently, there are no guidelines for separating data for calibration and validation, but guidelines should consider a minimum length of the period required for calibration and validation (Arnold et al., 2012). The validation was performed from 2003 to 2009 utilizing the same parameters obtained through the calibration step.

The “with significant artificial influences” SWAT model for the Mahaweli Ganga basin is utilized for model performance testing, calibration, and verification.

The model was run for an extended simulation period from 1989 to 2016.

The modeled results were compared with the observed or/ and re-rated flow data at the monitoring locations at, Manampitiya.

- mass balance checks (only at Manampitiya);
- daily flow data: flow duration curves and selected “wet” year, “average” year, and “dry” year daily flow hydrographs.

### 3.4.9 Optimization of parameters

There are three sources of uncertainties associated with hydrologic modeling (Arnold et al., 2012); uncertainties in the measured data, uncertainties in the measured data used in calibration, and uncertainties in the conceptual model and model parameters.

After several runs of the model, it was identified that the model needs to fit, and parameters should be optimized. The following parameters were optimized.

Table 3-13 – Optimization of parameters in SWAT Modeling

<b>Parameter</b>	<b>Description</b>	<b>Lower</b>	<b>Upper</b>
ALPHA_BF	Baseflow alpha factor (days)	0	1
CANMX	Maximum canopy storage (mm)	0	100
CH_K2	Channel erodibility factor	-0.01	500
CH_L2	Length of main channel	-0.05	500
CH_N2	Manning's "n" value for the main channel.	0	0.3
CH_S2	Average slope of main channel	-0.001	10
CN2	Initial SCS CN II value	35	98

<b>Parameter</b>	<b>Description</b>	<b>Lower</b>	<b>Upper</b>
EPCO	Plant uptake compensation factor	0	1
ESCO	Soil evaporation compensation factor	0	1
GW_DELAY	Groundwater delay (days)	1	450
GW_REVAP	Groundwater "revap" coefficient	-0.02	0.2
GWQMN	Threshold water depth in the shallow aquifer for flow (mm)	0	2
HRU_SLP	Average slope steepness	-0.4	0.4
LAT_TTIME	Lateral flow travel time	0	180
OV_N	Manning's "n" value for overland flow.	0	12
RCHRG_DP	Deep aquifer percolation fraction	0	1
REVAPMN	Threshold depth of water in the shallow aquifer for "revap" to occur (mm).	0	500
SLSUBBSN.hru	Average slope length.	0	400
SOL_AWC	Available water capacity (mm H2O/mm soil)	0	1
SOL_K	Saturated hydraulic conductivity (mm/hr)	0	100
SOL_Z	Depth from soil surface to bottom of layer.	-0.8	0.8
SURLAG	Surface runoff lag time (days)	0	24

### **3.5 Climate Change Analysis**

In this section, future rainfall patterns and temperature rise in the Mahaweli river basin are analysed utilizing three GCMs based on RCP 8.5 scenarios. Depending on the extent of the study area, the large amount of data required for the study and analysis, and the limited time available for completion, the study will be conducted only for 9 stations, where continuous data are available.

#### **3.5.1 GCMs Selection**

Various research centres in the world use different GCMs for analysis and some differences exist. These analyses result in climate sensitivities within a range of about 2<sup>0</sup>-4.5<sup>0</sup> C (Solomon,2007). Therefore, obtaining data from some models in scenario construction is always better. Consequently, it is always safer to get data from several models for scenario construction. The criteria proposed by Smith and Hulme (1998) can be used for selecting of most applicable GCM or GCMs for a particular climate scenario construction. They have

offered that the factors to be considered when deciding on a proper GCM for particular research are validity, vintage, resolution, and representativeness of the results.

**Vintage** – Latest models are always better compared with old models, as the latest models have been constructed based on the latest knowledge.

**Resolution** – Models with higher resolutions contain sharper spatial details such as complicated topography, better-defined water/land boundaries, etc. Over time, models have increased their spatial resolution resulting in the latest one having more satisfactory resolutions. But the higher resolution does not guarantee better model performances.

**Validity** – The choice of the model varies on how well it can replicate the present-day climate. This can be reviewed by comparing the observed and model data. Up-scaling of observed data to the GCM grid size is usually applied, followed by verifying a few statistical factors such as mean standard deviation etc, between the observed and model data sets.

**Representativeness of Results** – Selecting a few GCMs for an impact study is commonly preferred. Therefore, choosing a few representative GCMs is beneficial in showing a range of variations in a particular climate variable within the study area. For example, if some GCM simulate less, high, and similar results for annual precipitation, one from each group can be selected for the study.

Accordingly, the three GCMs below were chosen for this research after considering the abovementioned criteria.

1. CSIRO-Mk3.6 (Beijing Climate Center Climate System Model)
2. HadGEM2-ES (Hadley Global Environment Model 2 - Earth System) and
3. MIROC5 (Model for Interdisciplinary Research on Climate)

Table 3-14 - Selected GCMs

<b>Model Name</b>	<b>CSIRO-Mk3.6</b>	<b>HadGEM2-ES</b>	<b>MIROC5</b>
Vintage	2011	2015	2010
Institute		Met Office Hadley Center	University of Tokyo, National Institute for Environmental Studies, and Japan Agency for Marine- Earth Science and Technology

<b>Model Name</b>	<b>CSIRO-Mk3.6</b>	<b>HadGEM2-ES</b>	<b>MIROC5</b>
Atmosphere (1) Component Name (2) Horizontal Grid (3) Number of Vert Levels (4) Grid Top	(1) BCC_AGCM2.1 (2) T42 T42L26 (3) 26 (4) 2.917 hPa	(1) CAM4 (2) 0.9° × 1.25° (3) 27 (4) 2.194067 hPa	(1) CCSR/NIES/ FRCGC AGCM6 (2) 1.40625 × 1.40625° T85 (3) 40 (4) about 2.9 hPa
Aerosol (1) Component Name or type	Prescribed	Interactive	(1) SPRINTARS
Atmos Chemistry (1) Component Name	Not implemented	Not implemented	Not implemented
Land Surface (1) Component Name	Not implemented	(1) Community Land Model 4 (CLM4)	(1) MATSIRO
Ocean (1) Component Name (2) Horizontal Resolution (3) Number of Vertical Levels (4) Top Level (5) z Co-ord (6) Top BC	(1) MOM4-L40 (2) 1° with enhanced resolution in the meridional direction in the tropics (1/3° meridional resolution at the equator) tripolar (3) 40 (4) 25 m (5) z (6) linear split-explicit	(1) Nominal 1° (1.125° in longitude, 0.27– 0.64° variable in latitude) (3) 60 (4) 10 m thick with surface variables at 5 m (5) depth (level) (6) linearized, implicit free surface with constant-volume ocean	(1) COCO4.5 (2) 1.4° (zonally) × 0.5–1.4° (meridionally) (3) 50 (4) 1.25 m (5) hybrid z-s (6) linear split- explicit
Ocean Biogeochemistry (1) Component Name	Included	Not implemented	Not implemented
Sea Ice (1) Component Name	(1) GFDL Sea Ice Simulator (SIS)	(1) CICE4 with modifications	Included

### 3.5.2 Selection of RCPs

RCP 8.5 was selected for this study.

RCP 8.5's socio-economic advancement route is characterized by gentle economic development with limited merging across regions, a rapidly increasing population to relatively high levels, and a comparatively slow pace of scientific change. In this scenario, GHG

emissions grow about three to four times during the century. This has the maximum radiative forcing out of the four RCPs discussed (Riahi et al,2010).

RCP 2.6 is not much applicable for modeling climate changes in Sri Lanka, as it is a developing nation in the third world. As it is always justifiable to consider the worst case, scenario 8.5 was selected for this study.

GCM data necessary for the study can be obtained from the CPIM5 website. The CPIM5 data can be downloaded from the data portal, the Earth System-Grid Centre for Enabling Technologies (ESG-CET). To obtain the above data, an account must be created. All GCMs include a chronological run data set for RCP2.6, RCP 4, RCP 6,5, and RCP 8.5. The future data can be modelled for the period from 2006 to 2100. Data will be available for a few climate variables containing precipitation, maximum, minimum, and average temperature, relative humidity (RH), speed of wind and evaporation etc. The time-frequency can be carefully chosen from scales such as 3h,6h, daily or monthly.

Downloaded data will be in CDF format and extracted using Arc GIS. GCMs can be verified by R squared ( $R^2$ ) and root-mean-square-error (RMSE), between observed and simulated data sets for the baseline period.

### **3.5.3 Selection of Bias Correction Method**

Few bias correction methods are available, varying from simple linear scale approach to sophisticated distribution mapping approaches. Chen et al showed that distribution-based methods are reliable better than methods based on the mean. In previous research, it has been observed that, of all bias correction methods they utilized, the quantile mapping method delivered the best results (Chen et al.,2013, Teutschbein & seibert,2012).

As the quantile mapping method offers a good blend of precision and robustness, this method was utilized for this study

Quantile mapping has been accepted in the literature as one of the most effective methods of bias correction. In applying this method, the distribution function of modelled data is transferred using a transfer function to match it with the observed data.

VMhyd software provides an opportunity for performing quantile bias correction for the data modeled from GCMs by inserting net CDF files as they are.

### **3.6 Water Evaluation and Analysis Program (WEAP) Analysis**

Water Evaluation and Analysis Program (WEAP) is used for the water demand and the water allocation process.

The WEAP model has taken as primary input monthly naturalized flow for the extended reference period 1989 to 2016 for sub-basins formed from SWAT analysis. There is a strong relationship between the schematization and results of the SWAT rainfall-runoff modeling process.

Current accounts, essential assumptions, and scenarios must be defined during the model setup. Current accounts serve as a calibration step, revealing current demands, pollution loads, resources, and supply in the catchment. In current accounts, key assumptions may be established to represent policies, costs, and factors affecting demand, pollution, supply, and hydrology. Scenarios based on current accounts allow you to investigate the effects of various assumptions (Van Loo, and Doorgers, 2006). The reference scenario is where the data is accessible (Van Loo, and Doorgers, 2006). Calibration is essentially accomplished by assessing previous water demand trends and modeling the resulting flow (McCartney et al, 2005, as cited in Arranz and McCartney, 2007).

To improve the accuracy of WEAP, Arranz and McCartney (2007) assessed previous demand patterns, changed demand priorities, modified reservoir operation regulations, and included environmental flow needs. Between actual and modeled flows, PEST can be used to calibrate WEAP (Parameter Estimation Tool). It comes in handy when calibrating the hydrology catchment using the soil moisture approach (Rodrigues et al., 2005). On the SWAT River, a river was subsequently drawn. On top of the SWAT River, the river sign is clicked, dragged, and dropped. Each tributary has its name and was developed in the same way. When the tributary's name was unknown, the main river's name was given to it. The demand site nodes were placed in relative places in the schematic view.

Water demands have been specified for four main demand categories: hydropower, irrigation, domestic and non-domestic water supply, and environmental demand.

The demands were then given names, and a priority was assigned to them (as per Water Act 2008). Transmission links were used to connect the supply sources to the demand sites, while return flow links were used to return trash from the demand sites. The environmental flow requirement (EFR) site and stream gauges were then added. The stream gauges supply the measured flow, while the EFR site is utilized to determine the minimal quantity of water required to preserve the site's environmental status.

Major and medium irrigation schemes within the Mahaweli Ganga basin have been modeled in WEAP. In contrast, minor irrigation schemes have not been considered to avoid the complex model due to data unavailability.

The key monitoring locations at Manampitiya have been included in the WEAP model to enable the comparison of WEAP modeled river flows with observed river flows / SWAT modeled flows.

### **3.6.1 Define and Parameterize Supply**

The Mahaweli Ganga basin's surface water river network has been defined as the principal source of water supply in the WEAP model. No groundwater components of the Mahaweli Ganga basin are included in the WEAP modeling. Other local supply features (e.g., major, medium, and minor tanks, hydropower plants, transmission links, and diversions) are modeled concerning the modeled surface water river network.

### **3.6.2 Rivers**

The river network is shown in blue; model sub-basin extents are shown in black. The -basins defined at the beginning of the SWAT model are used in this analysis. Figure 3.7: Schematization of Mahaweli River in WEAP shows the river schematization of the whole basin and represents 115 sub-basins.

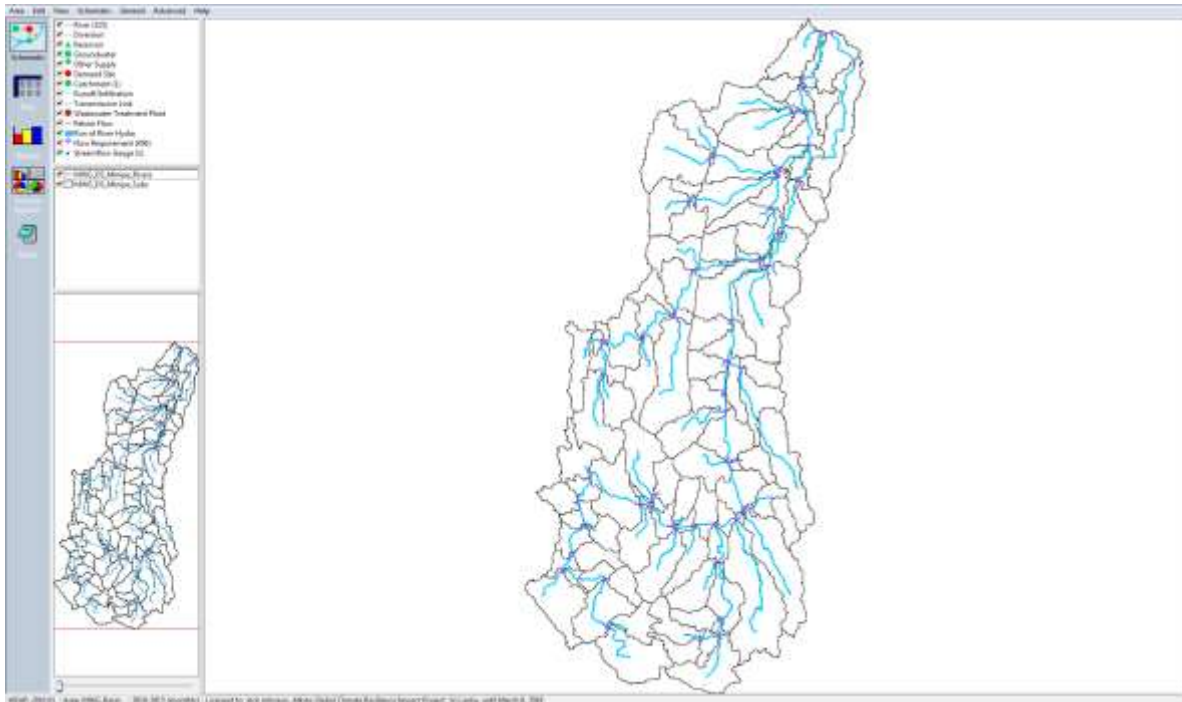


Figure 3-7: Schematization of Mahaweli River in WEAP

The schematization of the WEAP model “river” network is closely linked to the schematization of the SWAT rainfall-runoff model as typically; the SWAT “natural flow” model sub-basin water yield is used to define WEAP river inflows.

SWAT “natural flow” model sub-basin water yield is used to define the head-flow entering each WEAP river.

### 3.6.3 Define and Parameterize Demands

#### Energy Demand

Hydropower plants have been identified. The data used for the input for the hydropower are shown in Table 3-15

Table 3-15: Hydropower plants used for Energy Demand Calculation

Reservoir	River/tributary	Year commissioned	Capacity (MCM)
Kotamale Reservoir	Kothamala Oya	1985	172.9
Victoria Reservoir	Mahaweli Ganga	1985	721.2
Randenigala Reservoir	Mahaweli Ganga	1986	861.4
Rantambe Reservoir	Mahaweli Ganga	1990	7.4
Bowatenna Reservoir	Amban Ganga	1981	52.0

Regarding the reservoirs for hydropower generation, records are kept for levels and turbine flows - called power flows - and spillway flows computed from a spillway rating. Inflows are also estimated monthly from a water balance approach. Digital copies with recorded water levels and discharge data are available from the Mahaweli Authority, including inflow and spillway flow estimates.

Table 3-16: Basic Data about Hydropower Plants

<b>Reservoir</b>	<b>Type</b>	<b>Start Year</b>	<b>End Year</b>	<b>Interval</b>	<b>Source/ Authority</b>
Kothmale	Powerflow (MCM)	1985	2016	Day	Mahaweli Authority
	Spill (MCM)	1985	2016	Day	
	Inflow (MCM)	2001	2015	Month	
	Level (Masl)	1985	2016	Day	
Victoria	Powerflow (MCM)	1984	2016	Day	Mahaweli Authority
	Spill (MCM)	1984	2016	Day	
	Inflow (MCM)	2001	2015	Month	
	Level (Masl)	1984	2016	Day	
Randenigala	Powerflow (MCM)	1986	2016	Day	Mahaweli Authority
	Spill (MCM)	1986	2016	Day	
	Inflow (MCM)	2001	2015	Month	
	Level (Masl)	1986	2016	Day	
Rantembe	Powerflow (MCM)	1990	2016	Day	Mahaweli Authority
	Spill (MCM)	2001	2015	Month	
	Inflow (MCM)	1990	2016	Day	
	Level (Masl)	1990	2016	Day	
Bowathenna	Powerflow (MCM)	1984	2016	Day	Mahaweli Authority
	Spill (MCM)	-	-	-	
	Inflow (MCM)	1984	2016	Day	
	Level (Masl)	1984	2016	Day	

### **Irrigation Demand**

As with other areas of Sri Lanka, agriculture in the Mahaweli Ganga basin may be directly rainfed or irrigated through irrigation systems either based on systems of anicuts and diversion

canals or through major and medium tanks for storage on main rivers or minor tanks situated on smaller tributaries off the main river network. Irrigation water demands are therefore associated with major / medium scale irrigation schemes and minor scheme irrigation in the Mahaweli Ganga basin.

For the following study, only major/medium irrigation schemes are considered.

Rain-fed agriculture is currently not considered.

Table 3-17: Major/Medium Irrigation area

<b>Scheme Name</b>	<b>Sub-basin</b>	<b>Gross Area (Acres)</b>	<b>Average Cropping Intensity</b>	<b>Area for WEAP Modelling (Ha)</b>
Attaragallewa	24	520	94%	197.5
Bebiyawewa	5	220	94%	83.5
Boowewa	88	200	110%	88.8
Bowatenna	73	290	99%	116.2
Eriga oya	11	210	72%	61.4
Hattota Amuna	24	532	91%	195.7
Himbiliyakada	21	384	81%	125.6
Peramadu	4	600	66%	160.6
Radagalpotha	101	212	100%	85.4
Ratne Ela	103	265	89%	95.9
Waduwwala	11	486	71%	139.9
Wewala wewa	14	250	72%	73.0

### **Water Supply Demand**

The general approach for estimating domestic and non-domestic water supply schemes is shown. Table 3-18 Summarizes the water supply intakes and associated GN-based populations served by each intake.

Table 3-18: Water Supply Demand

<b>Intake</b>	<b>Population Served</b>
Neelapola	210,878
Mediriya, Badulla Oya Basin	158,411
CEB penstock, Sudu Ganga	119,819
Nalanda reservoir, Amban Ganga	92,196
Mahiyanganaya	90,567
Ulpathpitiya, Sudu Ganga	74,515
Minneriya Canal, Kaudulla Oya	63,661

<b>Intake</b>	<b>Population Served</b>
Pulathisigama Tank, Kaudulla Oya	62,798
Kivula, Sudu Ganga	61,444
Parakrama samudraya	55,809
Girandurukotte	52,213
KaudullaTank, Kaudulla Oya	51,389
Channel Intake, Seruvila	47,928
Viyadiguna, Badulla Oya	44,019
Dehiattakandiya	41,785
Gammaduwa, Amban Ganga	38,092
Westmoreland, Stream intake	37,550
Bambarakiriella, Amban Ganga	30,411
Hettipola	27,175
Bakamoona	21,787
Aththanakadawala, Amban Ganga	20,300
Hasalaka town	20,195
Manampitiya	19,427
Medakumbura	16,149
Elahara	13,959
Sevanawewa	13,501
Ellewera	13,360
Kaluganga, Tributary of Mahaweli	6,960
Senapura Tank	6,754
Nuwaragala	6,639
Weerana Tank	6,347
Dimbulagala	5,612
Dalukana	4,790
Singhapura	4,710
KobonillaHerepark	4,007
Peletiyawa	2,752

## **Model Validation**

Validation of the WEAP, water allocation model, is monthly modeled flow data at Manampitiya to provide an overall validation of the impacts of modeled artificial influences.

### **3.7 Analysis for Future Scenario**

In order to adapt to climate change and socio-economic change, in the year 2050, the following scenarios are checked.

- **Scenario 1** – Impact of population growth

In this scenario, it was assumed that current water supply schemes would meet the increased population's demand.

The population for the year 2050 is calculated using following equation.

$$P_{2050} = P_o(1+r/100)^n$$

$P_o$  shows the population in current year,  $r$  shows the growth rate per year,  $n$  shows the no of years.

- **Scenario 2** – Impact of irrigation expansion

In this, it was assumed that major/medium irrigation tanks would be able to cultivate the full irrigation area.

- **Scenario 3** – Maximizing HEP production

In this, it was assumed that the hydropower plants would enhance their capacities for the developed capacities rather than the active ones.

## 4 RESULTS

### 4.1 Hydrological Modelling

The Mahaweli Ganga basin used the SWAT model to analyse model performance, calibration, and validation. The SWAT model was run for the simulated period from 1989 to 2001.

1989-2001 was used for the model calibration, and 2002-2008 was used for the model validation. Model performances are valid through the following figures (Krause,2005). Comparison of different efficiency criteria for hydrological model assessment

Table 4-1: Model Performances

Indicator	Meaning	Match/Error	Implication
$R^2$	Square root of R	Match Indicator for pattern	Value of $R^2$ is purely driven by the pattern and not the values. Although this behavior is helpful in terms of achieving the "disturbances" in the hydrograph, it will overlook the volume problem
NSE rel	Nash-Sutcliffe coefficient	Match Indicator for base flow	NSE rel is sensitive on low flows only and not reactive on peak flows. Thus, it is an ideal statistic to evaluate base flow and high
		Error Indicator for base flow	Due to normalized expression, NSErel is not reactive on peak flows. Any poor performance in base flow is promptly noticed.

The following table shows the model performances for the SWAT model for the said time period.

Table 4-2: Model Performances

Parameter	Calibration Period	Validation Period
Time Period	(1/10/1989 – 30/9/2001)	(1/10/2001-30/8/2008)
$R^2$	0.65	0.57
NSE rel	0.68	0.73

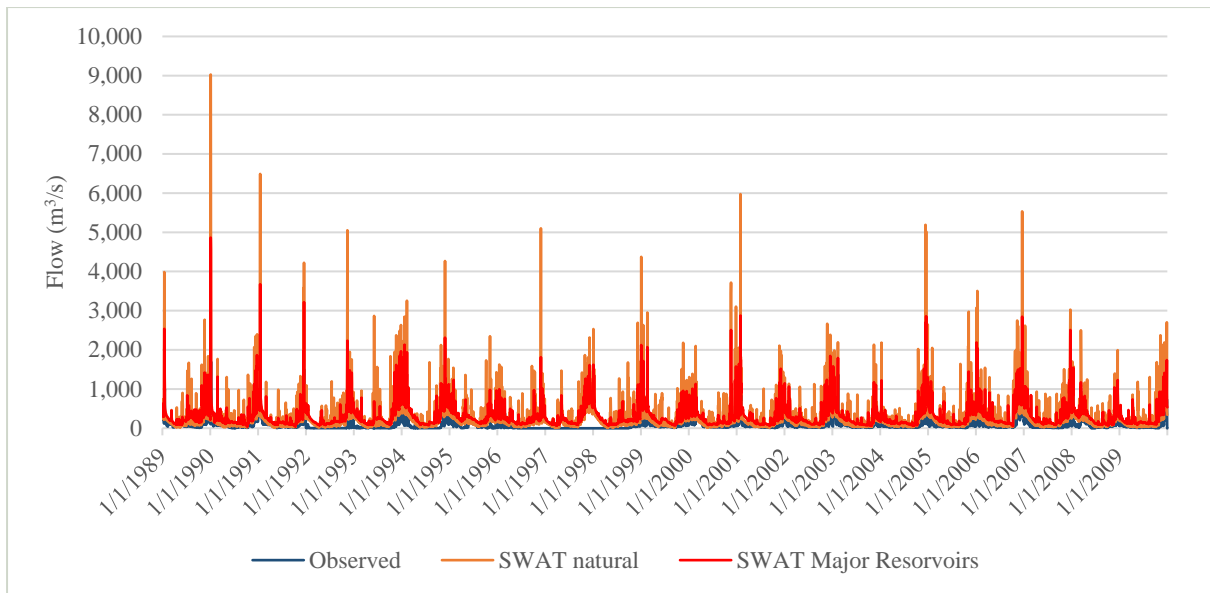


Figure 4-1: Flow series in the time period

This clearly shows the SWAT model is overestimating the observed flows for the entire record that was made available. A declining trend is noticeable in the observed flow hydrograph, which needs to be investigated further during the SWAT model validation, along with the hydro-meteorological data, runoff parameters, and artificial influences in the SWAT model.

Keeping in mind the uncertainties in the observed flow data, the graphs show a mismatch between modeled and observed peak flows. The graphs show that the SWAT model generally produces flows at Manampitiya that respond too quickly to rainfall – modeled peaks are early.

The modeled hydrograph shapes tend to be similar to the observed. However, the SWAT model tends to overestimate runoff volume.

Further model's performance was checked in the following scenarios, as well.

- Daily flow data: flow duration curves and selected “wet” year, “average” year, and “dry” year daily flow hydrographs.

A further comparison at Manampitiya of observed and “with significant artificial influences” modeled data for the “wet”, “average,” and “dry” water years 1983-1984, 2002-2003, and 2003-2004 is shown in Figure 4-1, Figure 4.2, Figure 4.3, and Figure 4.4.

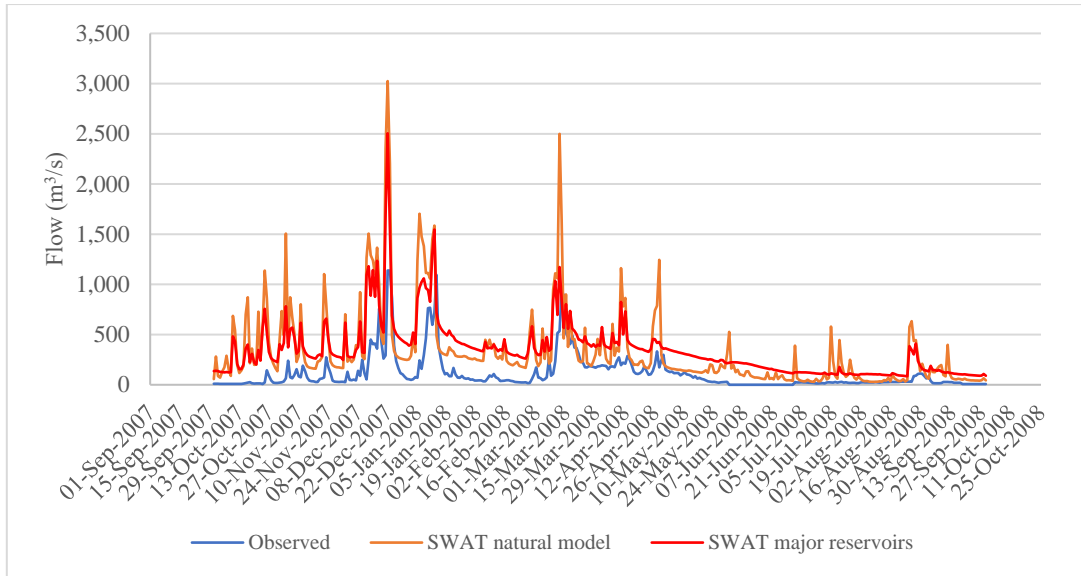


Figure 4-2: Observed and modelled daily flow at Manampitiya for "wet" year

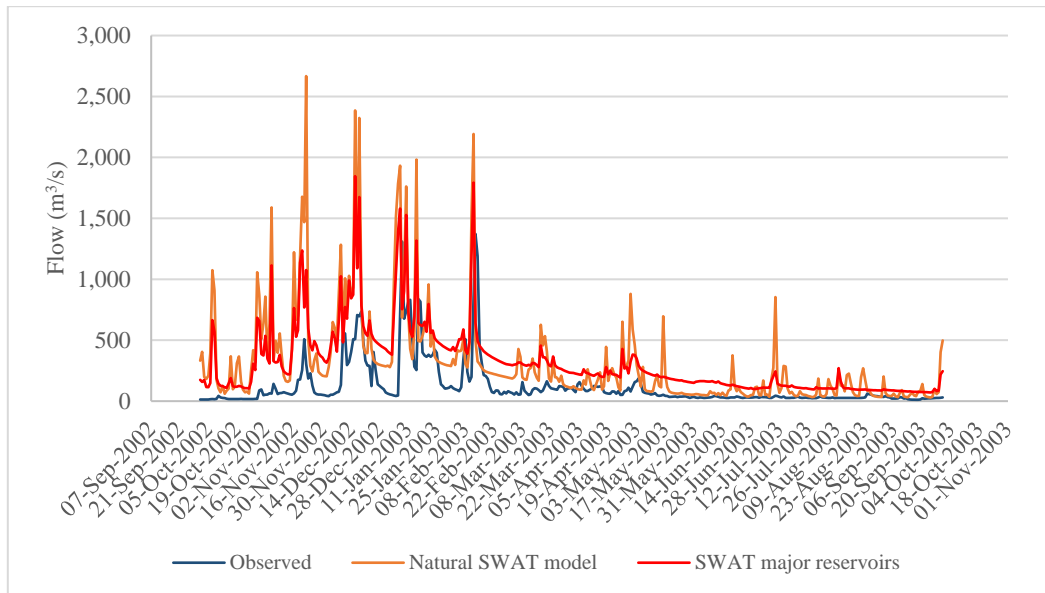


Figure 4-3: Observed and modelled daily flow at Manampitiya for "average year"

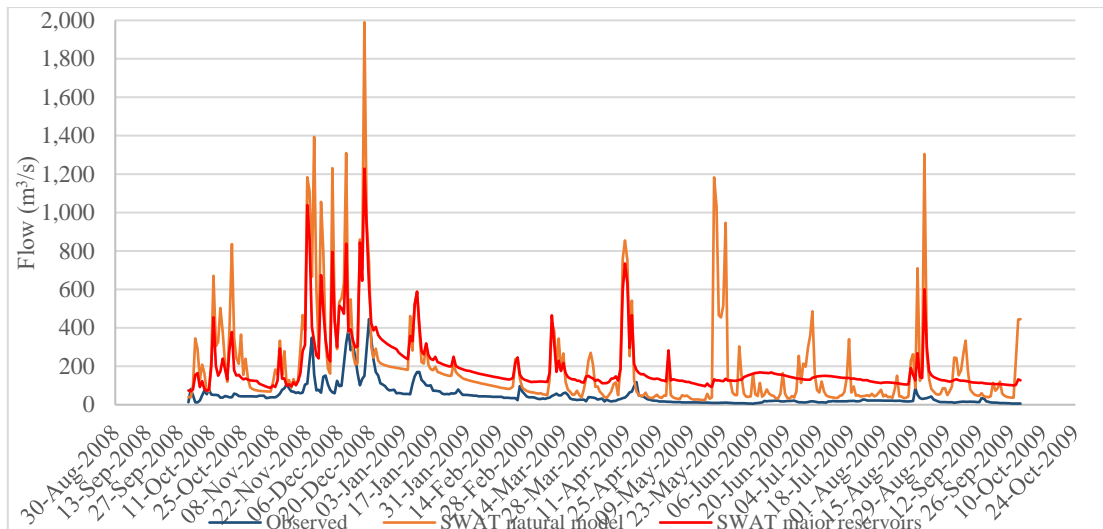


Figure 4-4: Observed and modelled daily flow at Manampitiya for "dry year"

This shows a general overestimation of peak and medium / low flows in extended dry periods. The hydrograph shapes are similar, but the modeled runoff volumes appear higher than the observed.

The model is calibrated to Nawalapitiya Station.

Hydrographs below illustrate the modeled and observed flow data variation along with the observation rainfall. Figure 4-5 and Figure 4-6 illustrates the observed and modeled flow data vs observed rainfall data in calibration period

Figure 4-5: Observed and Modelled Flow Data Vs Observed Rainfall in Calibration Period.

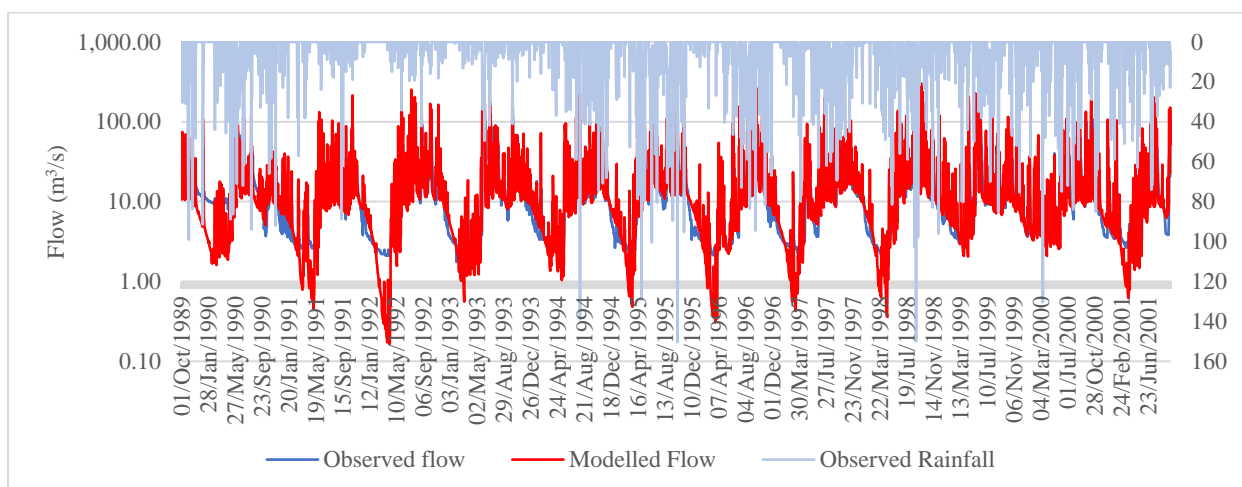


Figure 4-6 Observed and Modelled Flow Data vs Observed Rainfall in Calibration Period (in log scale)

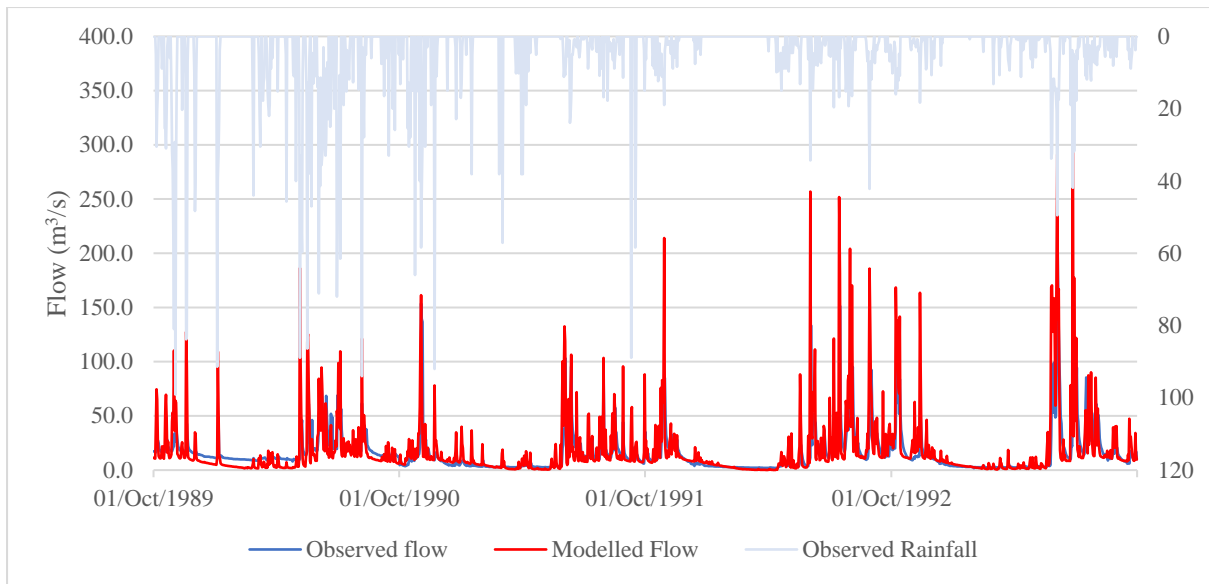


Figure 4-7 Observed and Modelled Flow Data vs Observed Rainfall in first four years (1989 – 1992) Calibration Period

In order to analysis critically, considering the first four years of the data in calibration period and of last four years of data in calibration period, they clearly defines the same pattern has followed. Further the respective data are coincides with the temperature values. Figure 4-8Figure 4-9 shows the hydrograph over the observed rainfall values for the first four years in the normal and in log scale. Following up with in Figure 4-10Figure 4-11, graphs illustrate the last four years in calibration period.

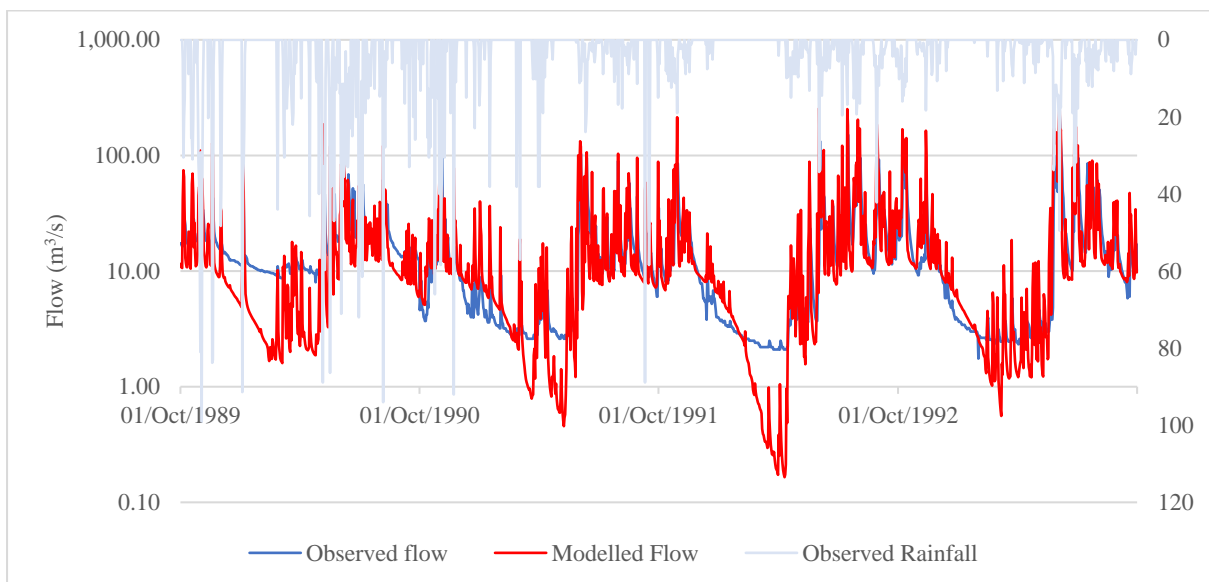


Figure 4-8 Observed and Modelled Flow Data vs Observed Rainfall in in first four years (1989 – 1992) Calibration Period (in log scale)

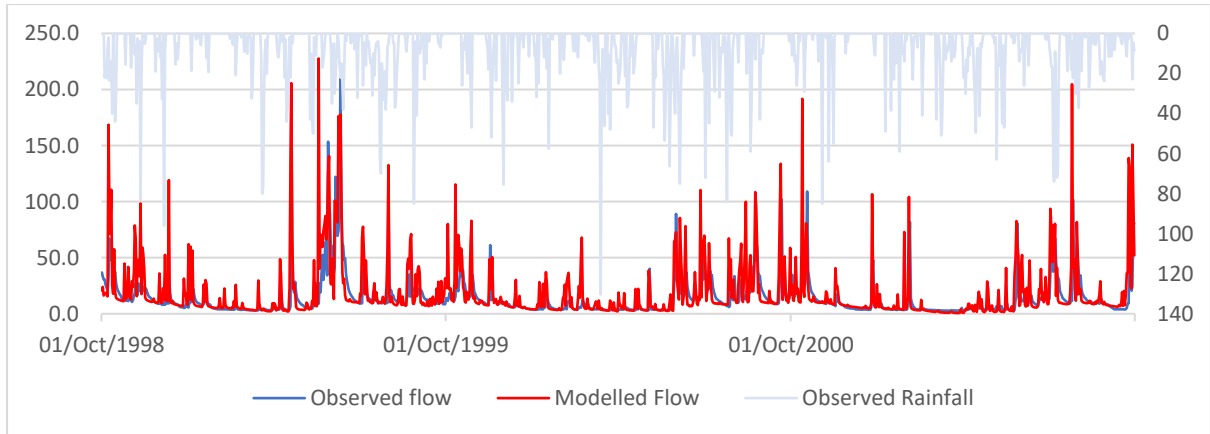


Figure 4-9 Observed and Modelled Flow Data vs Observed Rainfall in in last four years (1998 – 2001) Calibration Period

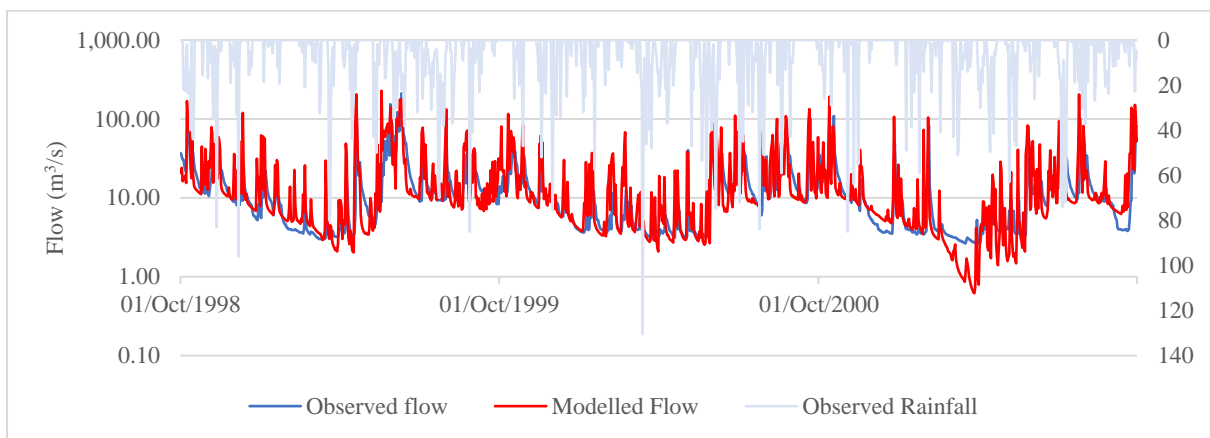


Figure 4-10 Observed and Modelled Flow Data vs Observed Rainfall in in last four years (1998 – 2001) Calibration Period (in log scale)

The data in the validation period are analyzed as follows. The pattern of the flow matches as of the observed and modelled, further highest and lowest values also match with each other.

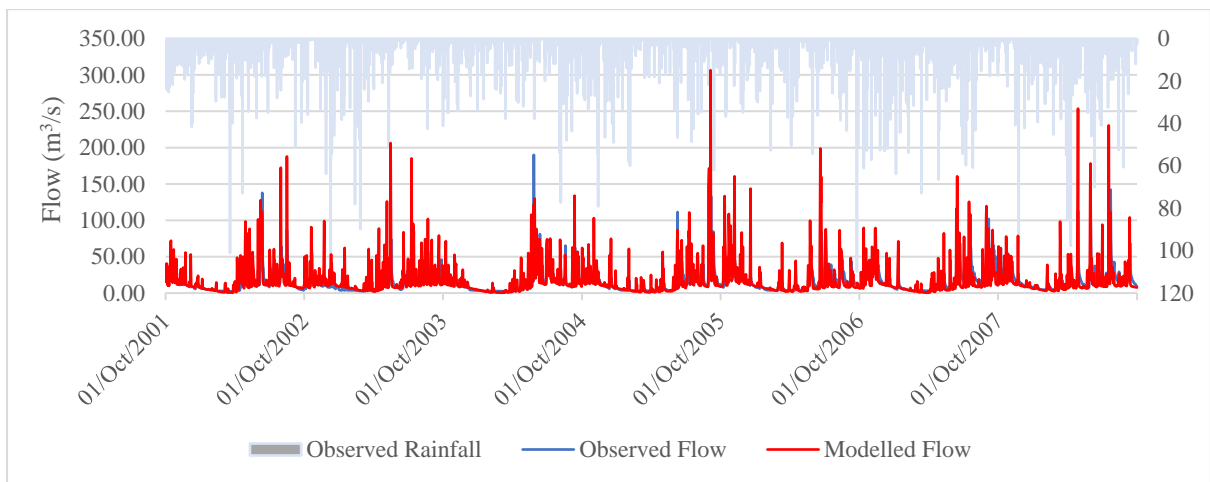


Figure 4-11 Observed and Modelled Flow Data vs Observed Rainfall in Validation Period

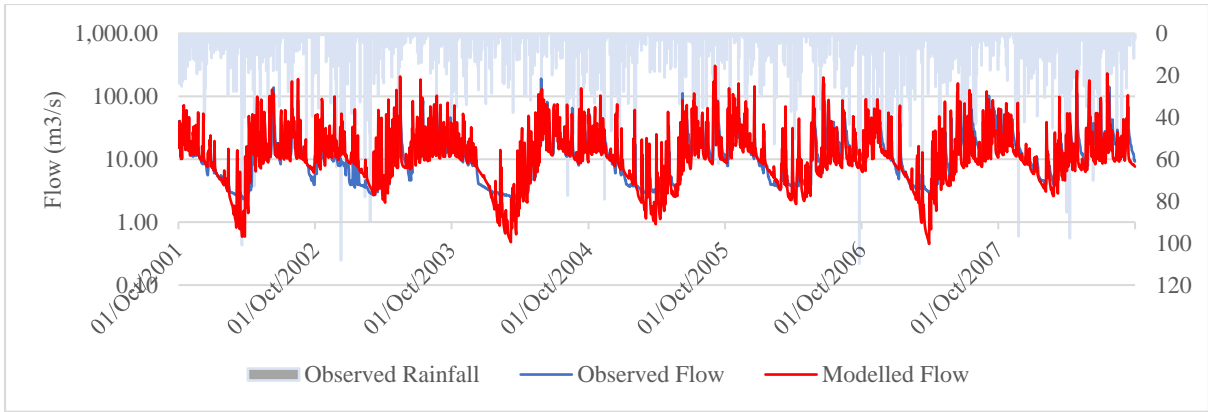


Figure 4-12 Observed and Modelled Flow Data vs Observed Rainfall in Validation Period (in log scale)

In order to analysis critically, considering the first four years of the data in validation period and of last four years of data in validation period, they clearly defines the same pattern has followed. Further the respective data are coincides with the temperature values. The first four years in the validation period are shown in the Figure 4-13 following the same data series are critically analyzed in log scale in Figure 4-14 whereas in Figure 4-15 the flow data are shown with respect to the temperature values in last four years of validation period following up in next figure in Figure 4-16 shown them in log scale.

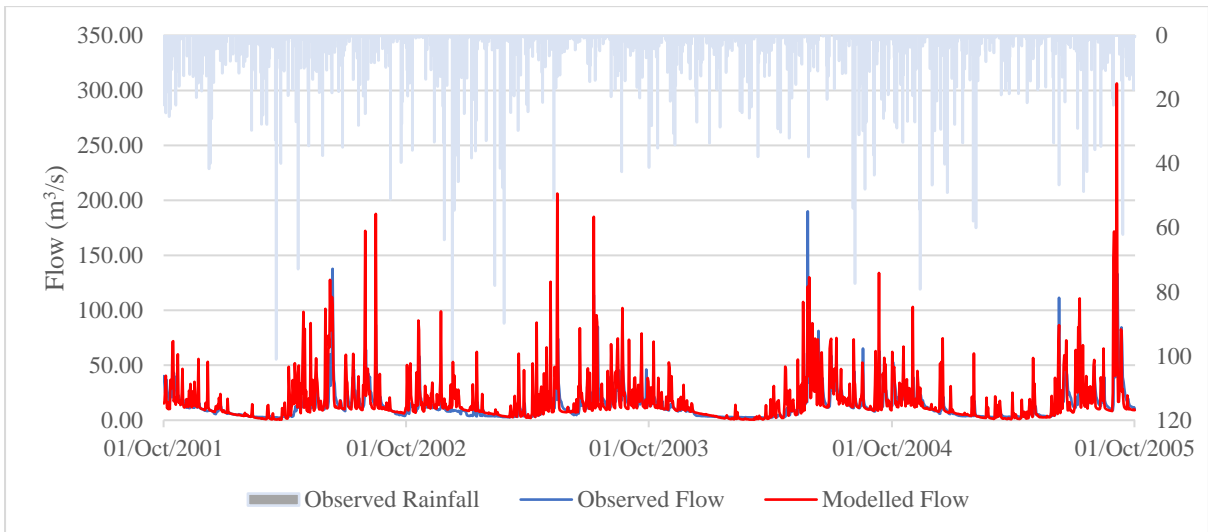


Figure 4-13 Observed and Modelled Flow Data vs Observed Rainfall in first four years (2001 - 2005) in Validation Period

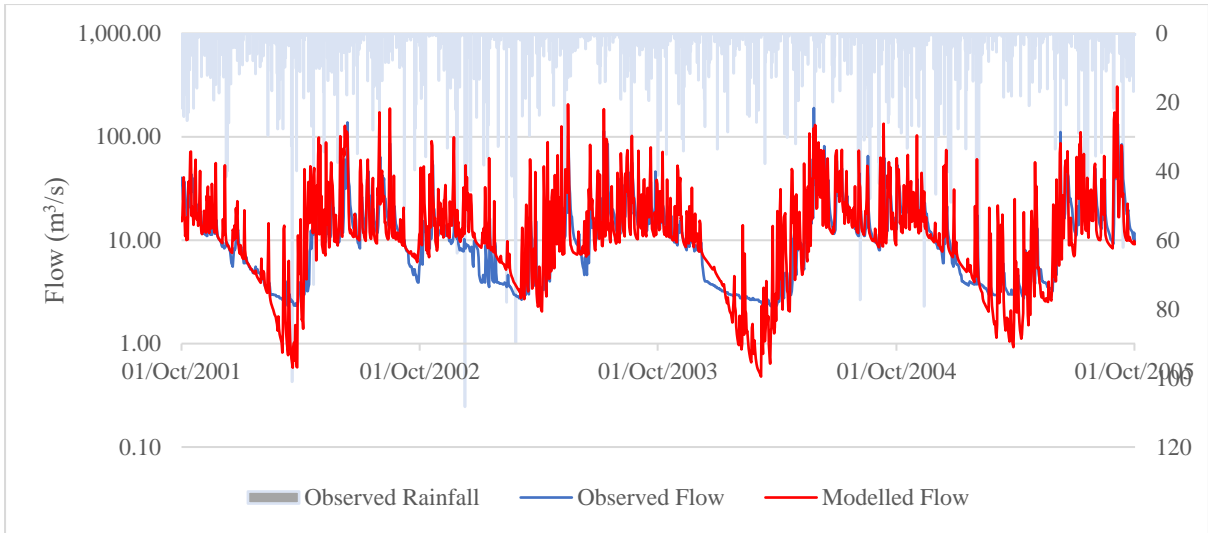


Figure 4-14 Observed and Modelled Flow Data vs Observed Rainfall in first four years (2001 – 2005) in Validation Period (log scale)

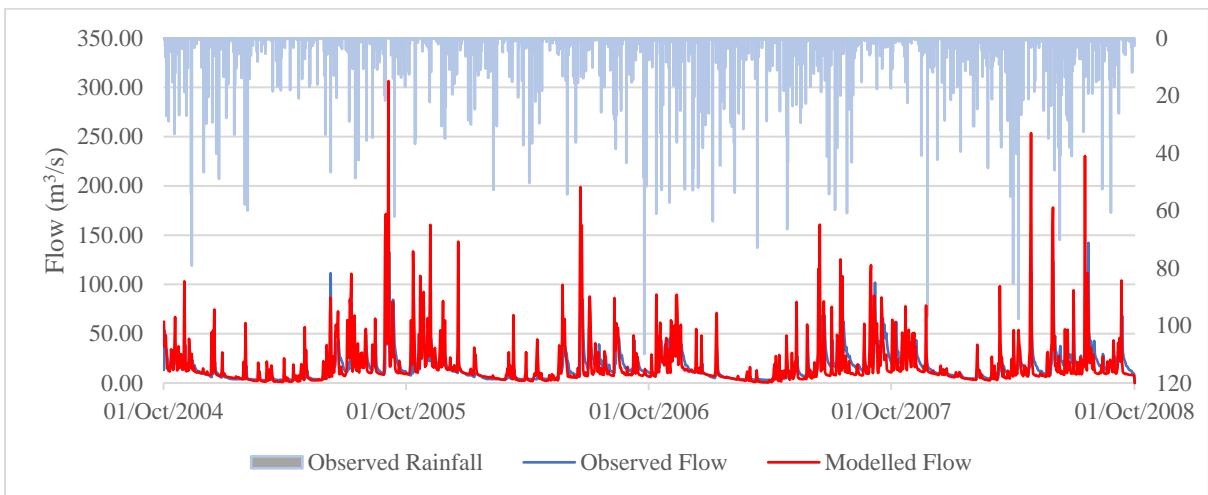


Figure 4-15 Observed and Modelled Flow Data vs Observed Rainfall in last four years (2005 – 2008) in Validation

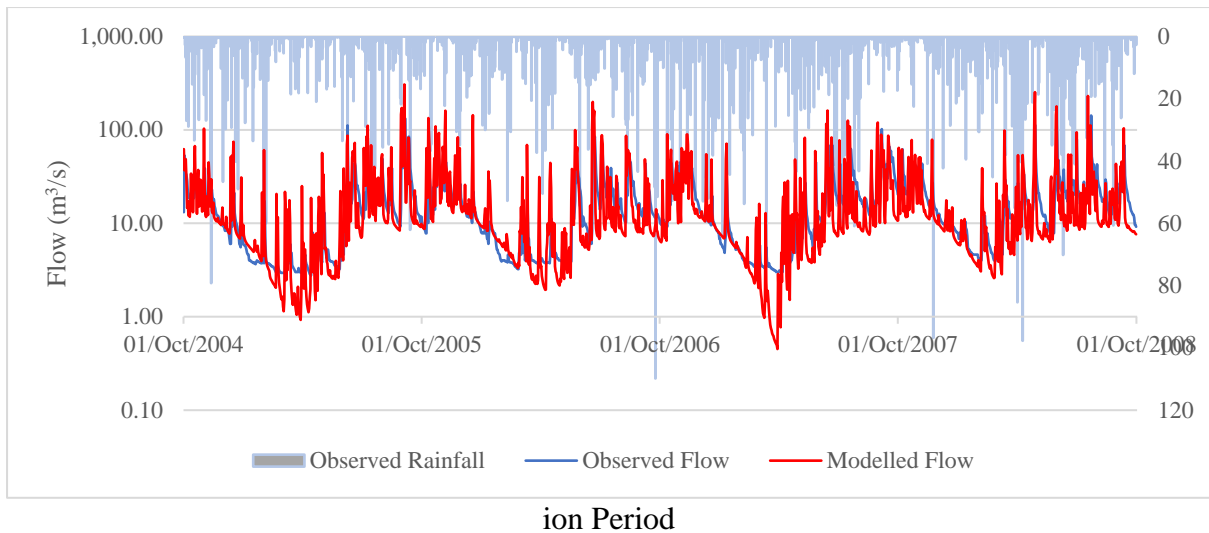


Figure 4-16 Observed and Modelled Flow Data vs Observed Rainfall in last four years (2006 - 2009) in Validation Period (log scale)

Flow Duration curve for the model is shown as in Figure 4-17 as follows.

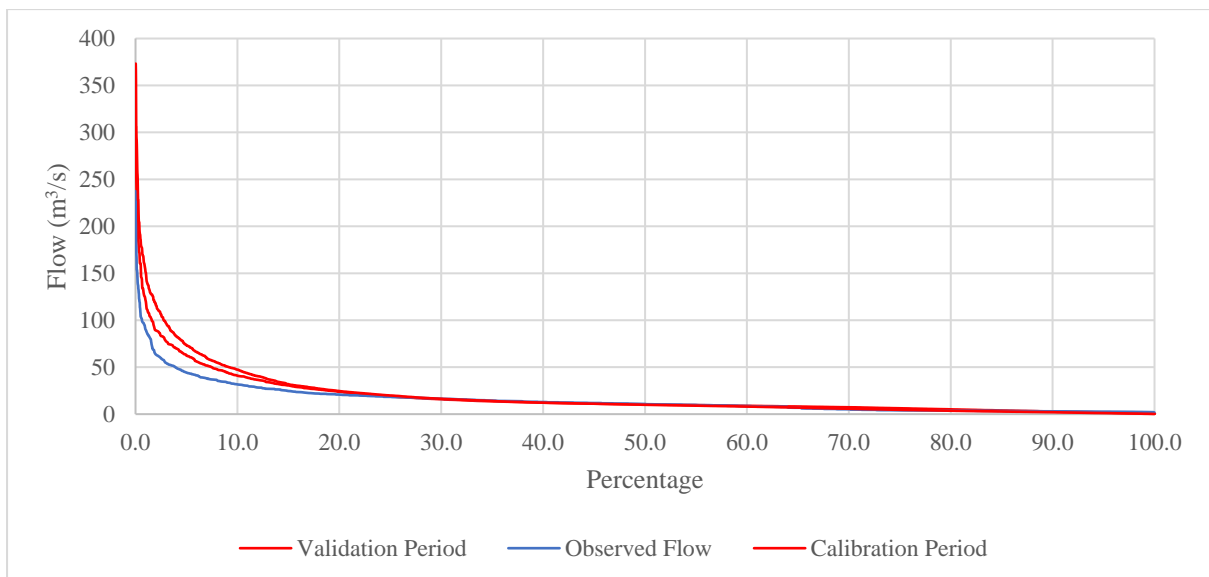


Figure 4-17 Flow Duration Curve (Observed Data vs Modelled Data in Calibration and Validation)

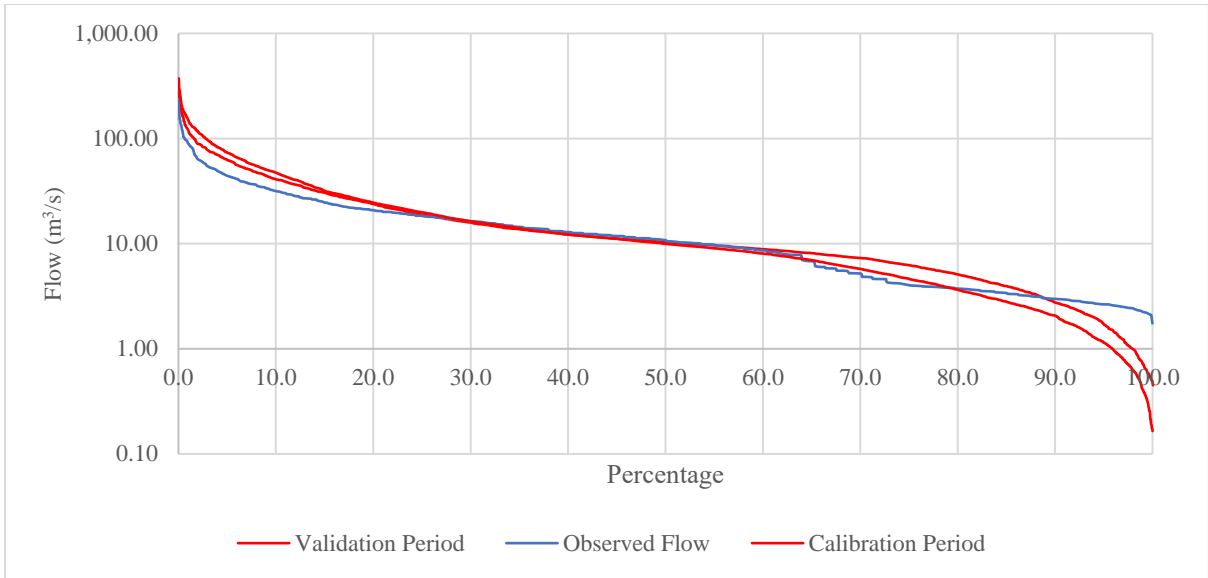


Figure 4-18: Flow Duration Curve (Observed Data vs Modelled Data in Calibration and Validation) in log scale

Considering an year's period of data in calibration period, in order to critically analyse the following graphs were produced. The same pattern is followed all through the calibration period. Figure 4-19 and Figure 4-20 illustrates the observed and modelled flow data over the observed rainfall for year 1999 during calibration period in normal and in log scale. Figure 4-21 and Figure 4-22 shows out the flow duration curve in normal and log scale.

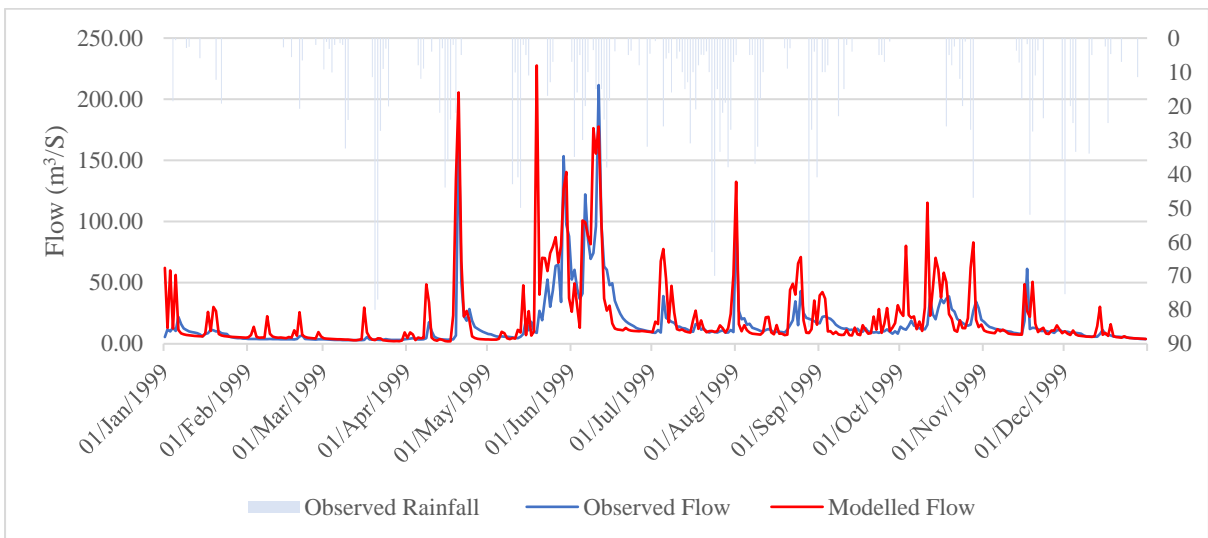


Figure 4-19 Observed and Modelled Flow Data vs Observed Rainfall during year 1999 (In calibration period)

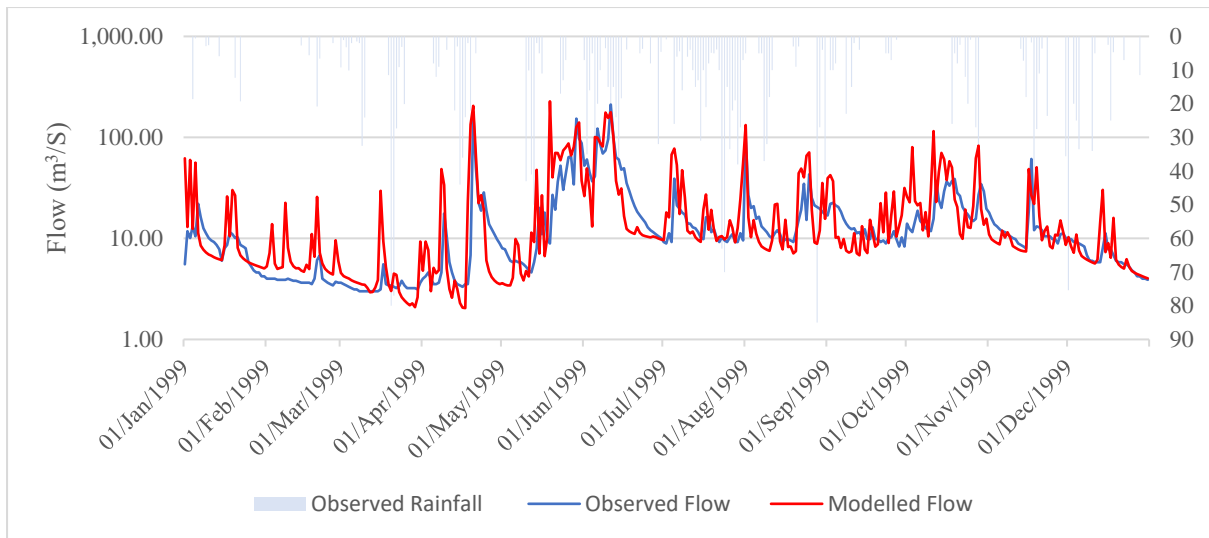


Figure 4-20 Observed and Modelled Flow Data vs Observed Rainfall during year 1999 in calibration period (log scale)

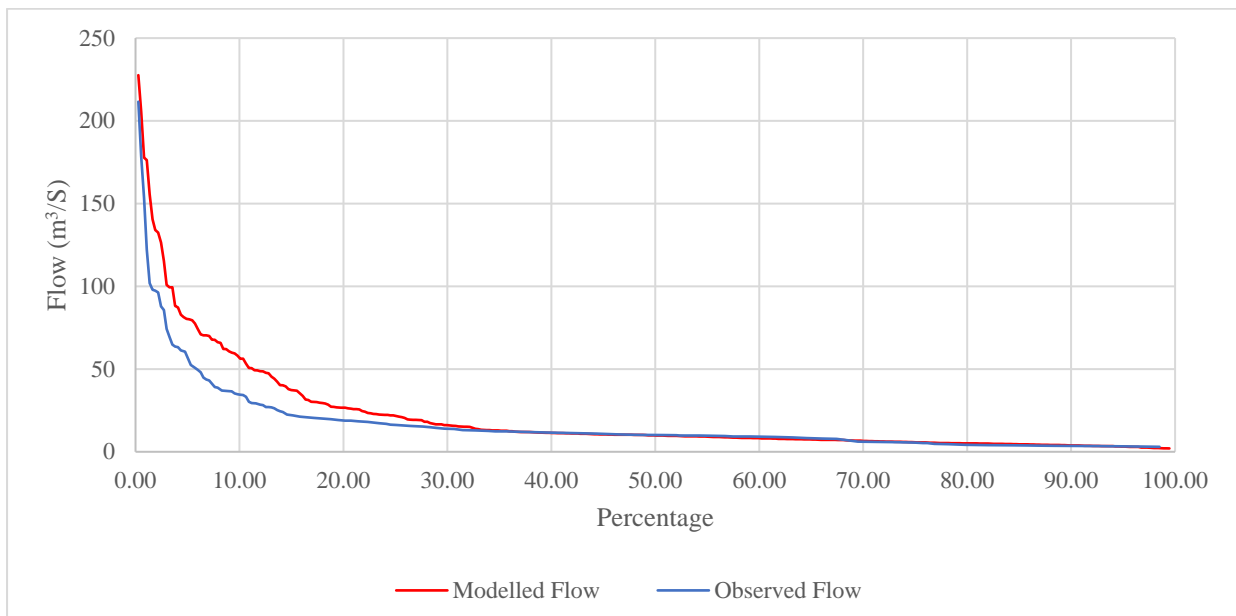


Figure 4-21 Flow Duration Curve during year 1999 in calibration period

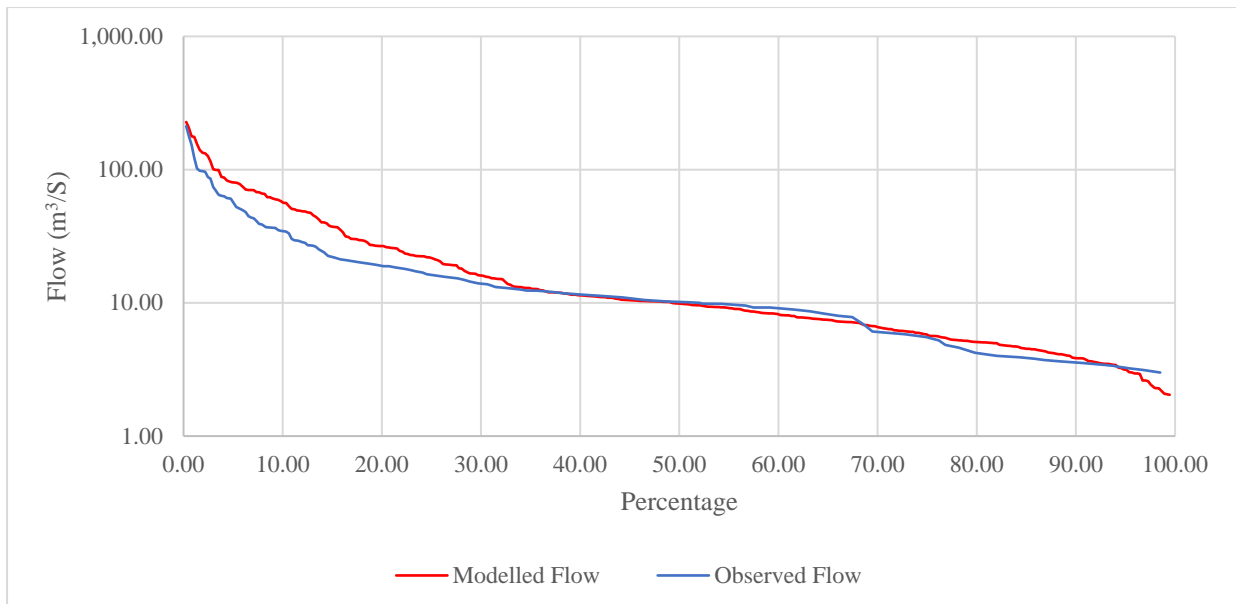


Figure 4-22 Flow Duration Curve during year 1999 in calibration period (In log scale)

Considering an year's period of data in validation period, in order to critically analyse the following graphs were produced. Figure 4-23 shows the hydrograph over the received rainfall during year 2008 where Figure 4-24 followed by the same graph in log scale. Figure 4-25 shows the flow duration curve for the respective year and Figure 4-26 followed the same in log scale.

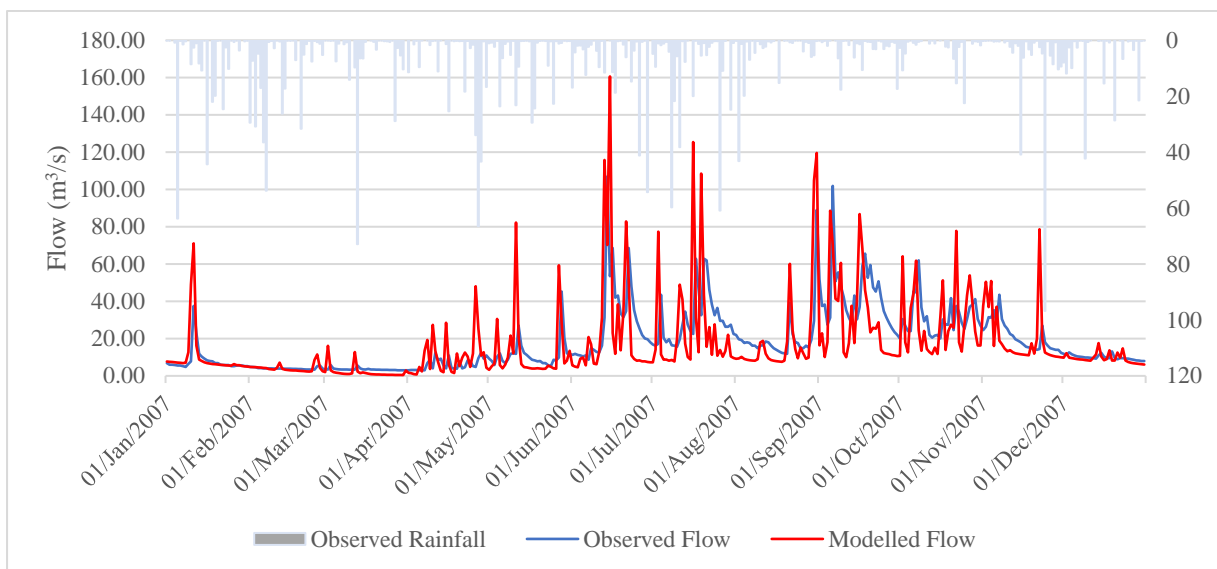


Figure 4-23 Observed and Modelled Flow Data vs Observed Rainfall during year 2007 in validation period

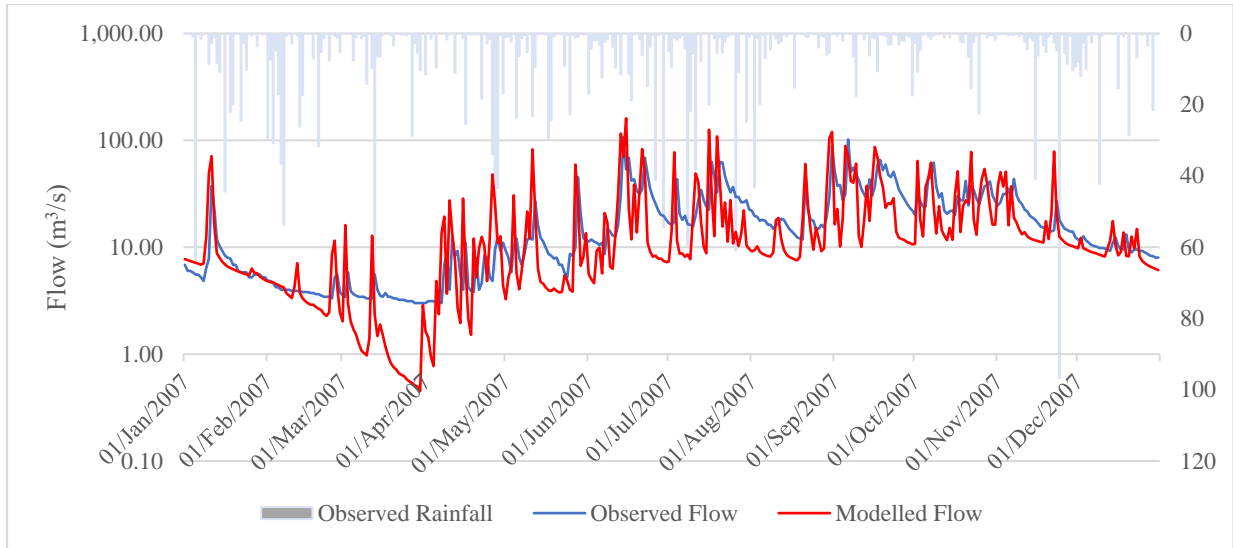


Figure 4-24 Observed and Modelled Flow Data vs Observed Rainfall during year 2007 in validation period (In log scale)

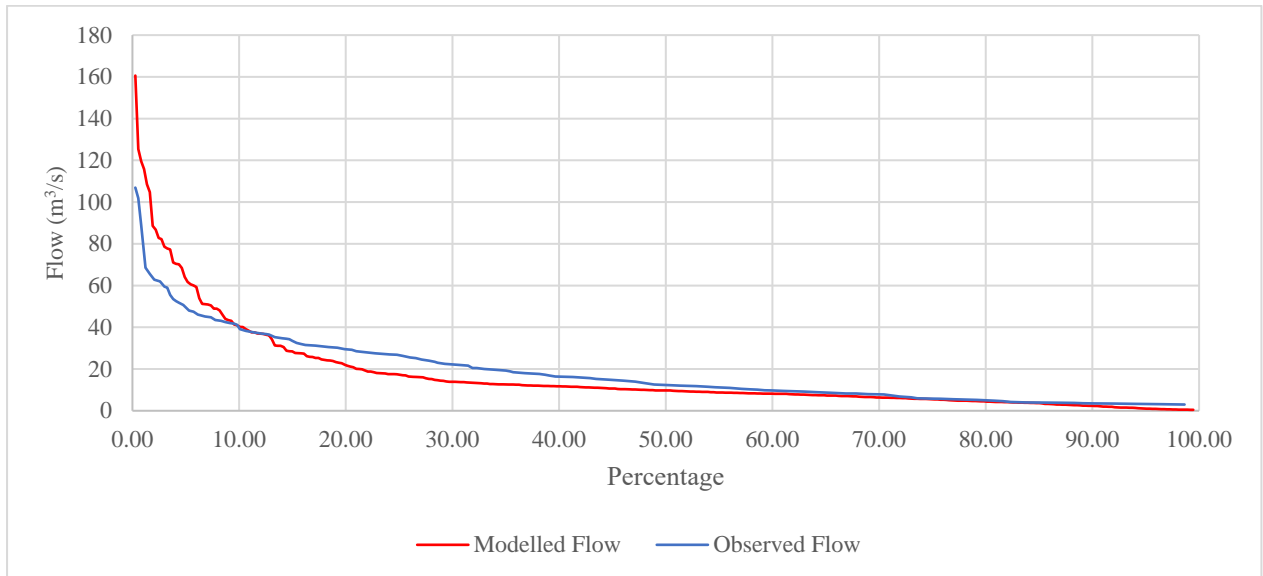


Figure 4-25 Flow Duration Curve during year 2007 in validation period

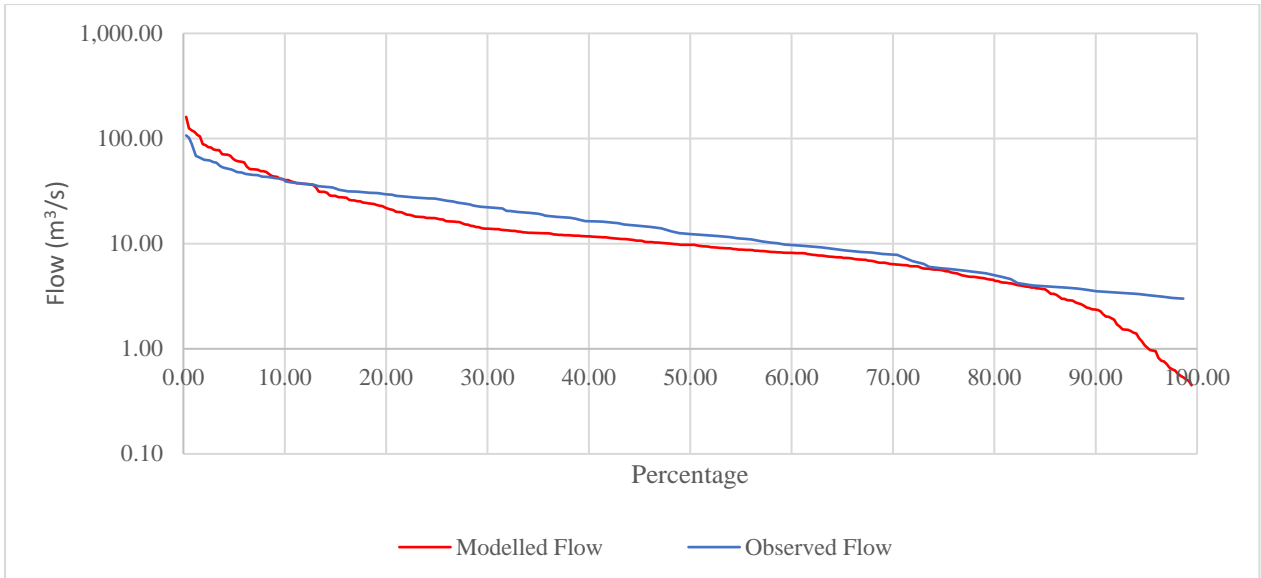


Figure 4-26 Flow Duration Curve during year 2007 in validation period (log scale)

#### 4.2 Climate Change Analysis

The observed data were classified concerning monthly average values. The maximum temperature, minimum temperature, and rainfall projections are shown below.

Analysis of temperature in the study area shows an increase of around 2°C of temperature by the year the 2050s.

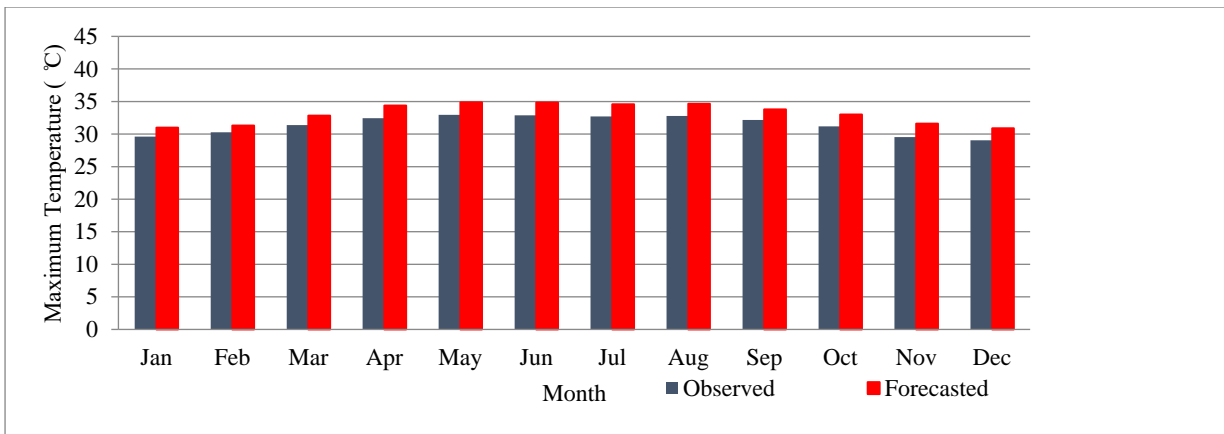


Figure 4-27 Maximum Temperature in 2050s

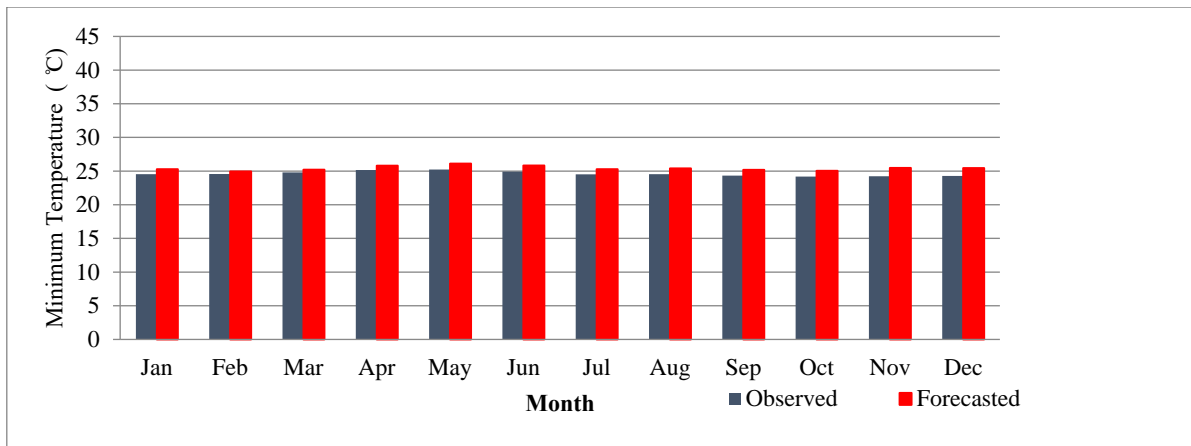


Figure 4-28: Minimum Temperatures in the 2050s

Modelled Flow for year 2050 is shown below, these values are used for flow allocation.

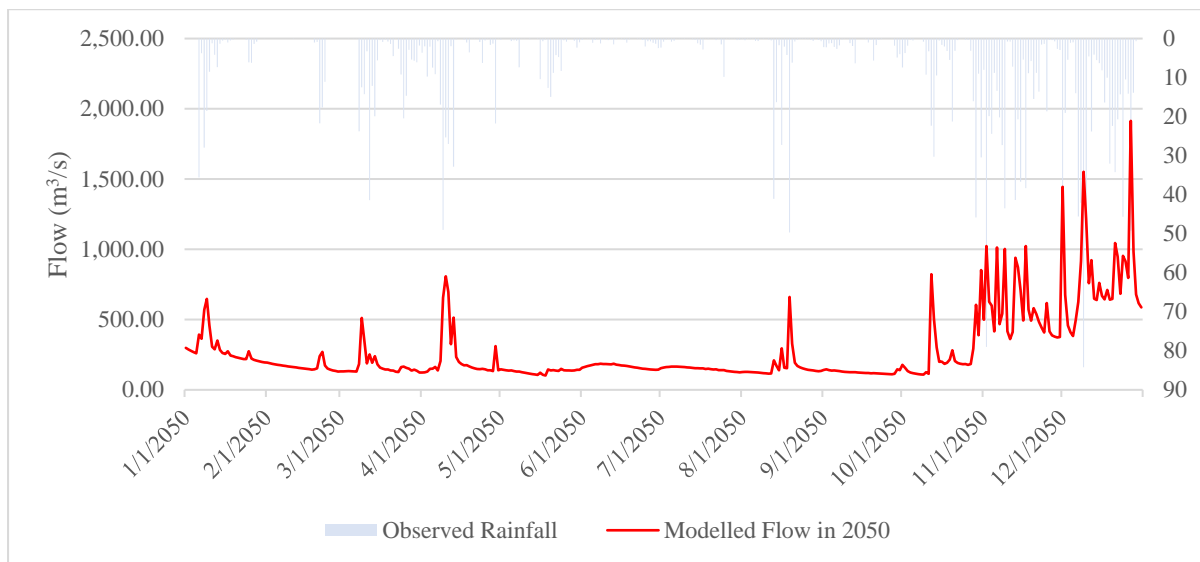


Figure 4-29: Modelled Flow in year 2050

Analysis of the rainfall shows an increase of 20% of rain by the year 2050s.

Then, the WEAP model was performed with the future analyzed rainfall and temperature data.

### 4.3 Water Allocation Analysis

The results from the WEAP modeling presented to show how the climate change induced flow would be assessed in socio-economic impacts on a basin scale, concerning ‘raw unmet demand’; these results would be evaluated for the future demands, this would be useful to provide a greater understanding of drought hazard in the basin.

The results are shown to the scenario identified for the basin.

At the basin scale, demand deficits in Mahaweli Ganga according to different scenarios in the year the 2050s under the impact of Climate Change. Magnitudes are for water supply, energy, agricultural and environmental demands.

For example:

There is a 0% high municipal demand deficit for 10% of the time and a 13% high municipal demand deficit for 1% of the time.

There is an 0% high industrial demand deficit for 10% of the time, a 22% high industrial demand deficit for 1% of the time; and

There is a 0% major/medium scheme and 42% minor scheme agricultural demand deficit for 10% of the time, and a 26% major/medium scheme and 80% minor scheme agricultural demand deficit for 1% of the time.

Analysis shows that the high municipal demand (119.2 thousand CM) and agricultural land preparation (in April and October), and minor irrigation scheme crop irrigation demands (from January to February and May to August) are major demands in the Mahaweli Ganga basin.

These demand deficits/risks can then be assessed concerning acceptable levels of risk statements to assess risk across different demand categories/water users.

An assessment of demand deficit by frequency can be used to both help express. Further, it would help develop an acceptable level of risk statements and an associated Water Use Plan.

### Scenario 1 – Impact of population growth

Table 4-3: Scenario 1 Impact of population growth

Demand Basin & Type	Unmet Demand (%) relative to event frequency						Demand Priority
	50%	20%	10%	5%	2%	1%	
<b>Water Supply</b>							
High Municipal	0	0	0	2	9	13	10
High Industrial	0	0	0	8	18	22	15

Low Municipal	0	8	9	9	9	9	40
Low Industrial	0	22	33	41	50	56	50
<b>Irrigation</b>							
Major/Medium Agri	0	0	0	2	16	26	30
Major/Medium Agri in Low	0	0	0	0	1	3	30
<b>Environmental Flow (EF)</b>							
High Priority EF	0	3	4	5	7	8	20
Medium Priority EF	1	5	8	10	14	19	30
Low Priority EF	6	16	23	26	29	34	60
Negligible EF	23	44	51	56	59	61	70

### Scenario 2 – Impact of irrigation expansion

Table 4-4: Scenario 2 - Impact of irrigation expansion

Demand Basin & Type	Average Monthly Demand (Thousand CM)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Major/ Medium Tanks	24.4	39.2	1.1	1.72	37.5	40.0	20.8	3.7	0.5	0.8	0.2	1.2
Major/Mediums Tanks in maximum	-	-	-	126.7	-	-	-	-	-	126.7	-	-

### Scenario 3 – Maximizing Hydropower production

Table 4-5:: Scenario 3 - Maximizing Hydropower Production

Demand Basin & Type	Average Monthly Demand (Thousand CM)	Number of Demand sites
MWG High Industrial	27.0	36
MWG High Municipal	119.2	36
MWG Low Industrial	17.4	36
MWG Low Municipal	2.4	36

Critically, the percentage of unmet demand increases in both magnitude and frequency as the relative demand priority of the Environmental Flow Risk Boundaries reduces

It is further noted that an overall assessment of socio-economic impacts and risk requires that acceptable levels of risk statements be defined for each demand category for future Water Use plans.

The further following would be used to develop as part of the socio-economic drought risk plans to help illustrate socio-economic drought hazard and risk from the perspective of economic benefits, social (equity) benefits, and environmental benefits

## 5 DISCUSSION

The SWAT model was used for this study, while discharge data from the Manampitiya gauging station were utilized for modelling from 1989 to 2001 was used for calibration of the model while data applicable from 2002 to 2009 was used for verification of the model.

The study conducted by Psomas et al., 2016 in Pinios river's catchment in Greece in the year 2016 shows out  $R^2$  equals 0.88 and 0.87, shows that the data have very good fitting, given the complexity of the study area, but calibration period tends to perform better in simulating the observed streamflow. Following up the study performed by Maliehe & Mulunu, 2017 shows out  $R^2$  0.59 for calibration and  $R^2$  was 0.66 during validation period, Further in the study conducted by (Hussen et al., 2018) for Bilate watershed in Abaya- Chamo sub-basin of Rift Valley Lakes basin, shows out a satisfactory correlation coefficient  $R^2$  equals 0.77, Nash–Sutcliffe efficiency (NSE) equals 0.755, during calibration and  $R^2$  equals 0.798, NSE equals 0.778, in the validation period. The model was successfully calibrated with  $R^2$  equals 0.65 for calibration period and for validation the with  $R^2$  equals 0.57. The calibrated model shows a Nash- Sutcliff efficiency (NSE) values of 0.68 during calibration period and - 0.73 in validation period.

Even though values of these variables cannot be easily specified by literature, due to their high uncertainty and sensitivity. Further SWAT model behaved perfectly during the calibration and the verification by delivering results in a calibrated model with  $R^2$  equals 0.71 and 0.60. The model did not perform very well in both low and high flows, as shown in the line graph and scattered plots. As an inbuilt character, a number of springs in the basin generate significantly increased base flows all over the year. Due to this reason, the model was not capable of capturing baseflows.

The study conducted by Droogers et al,2013 also predicted temperature increase  $2^\circ\text{C}$  by 2050 together with a 10% reduction in precipitation has a disproportionately greater impact on the vulnerability of water resources in the Asian region. The study conducted at Upper Pangani river basin case in Tanzania; GCMs results show future rainfall increase in upper Pangani River Basin between 16–18 % in 2050s relative to 1980–1999 periods. Temperature is projected to increase by an average of  $2^\circ\text{C}$  in 2050s, relative to baseline period. Long-term mean

streamflows is expected to increase by approximately 10 %. Further in the study conducted by Hussien et al., 2018 the models were analysed in to RCP2.6, RCP4.5, and RCP8.5 both three scenarios for the future time period up to 2035. The result revealed that the future maximum and minimum temperature can be increased during all three scenarios. However, precipitation showed an increase or decreasing trend in future scenarios at different time scales. Catchment will receive higher rainfall in the future.

Concerning the base figures in 2009, the forecasted temperature increase will be about 2<sup>0</sup> C, while a rise in rainfall within the range of 16-18% will be anticipated. As per the model's output, an increase of about 10% in mean streamflow in the long term is forecasted.

### **Scenario 1- Impacts due to the growth of population.**

Under this scenario, a varying growth rate within the range of 1.8% to 3.2% was assumed from region to region. The growth in all other sectors was assumed to be negligibly low, therefore, their demand in 2050 will be the same as the current demand. The sectors that will be most affected due to increased population are HEP and irrigation. The contribution of HEP unmet demand for the total future unmet demand will be about 60.6%, whereas that from irrigation demand will be 38.75% of unmet demand. However, the total demand for domestic water supply will be fulfilled under the above scenario.

### **Scenario 2- Impacts due to expansion in irrigation.**

Under this scenario, it was assumed that irrigated area would be increased by 45%, as that is the additional land available for cultivation under irrigation. The forecast from the model shows that irrigation will be the most affected sector due to climate change as it will contribute to about 75% of the total future unmet demand.

The HEP sector is also expected to be experienced a significant water shortage, as the model shows that unmet demand due to HEP will be about 23.72%. As in scenario 2, here in scenario 3 also, domestic water supply will not be affected, while the livestock sector will be marginally affected by contributing to unmet demand by 0.38%.

### **Scenario 3- Impacts due to maximizing the production of HEP.**

Under this scenario, the impacts of hydropower generation are prioritized and allowed to be operated at maximum capacity; the impacts of hydropower generation are prioritized and allowed to be operated at maximum capacity were studied. The model output shows that HEP

will contribute 35 % of unmet demand while the irrigation sector will experience a water shortage of about 20% of unmet demand.

In summary, the forecasts from the model studies show with e that the rainfall will be increased substantially within a range of about 16% to 18%, while during an average temperature increase by 2°C concerning the 2011 base year.

Mid-term average stream flow is forecasted to rise roughly by 10%. The model results further show that future peak flows will be less than current average peak flows. In contrast, dry period base flows during the period from November to February are predicted to be increased. The average annual water demand for the Mahaweli river basin is expected to increase from 1,879.73 Mm<sup>3</sup> (2020) to 3,249.69 Mm<sup>3</sup>(2050).

Therefore, the worst impact of climate change combined with growth in annual water demand will cause an unmet demand of 1,673.80 Mm<sup>3</sup>(51.51% of total unmet demand) and mainly influence the irrigation sector (72.09% of total unmet demand). This will increase the tension on water due to enhanced unmet demands, particularly for irrigation.

## **6 CONCLUSIONS AND RECOMMENDATIONS**

### **6.1 Conclusions**

This is one of the initial attempts of using SWAT and WEAP models in the Mahaweli River Basin. WEAP and SWAT follow two different modelling approaches. They are varied in concept, structure, methodology and operational orientation. SWAT follows a more sophisticated approach in modelling hydrology and crop growth. Its scope is focused on agricultural catchments, processes and practices WEAP follows a balanced approach between being an integrated water resources planning and management tool and a hydrological model. Regardless of data unavailability, the two models proved to be applicable in the catchment. Considering the complexity of the model, with the limited usage of data following results were produced. It can be concluded that, the Mahaweli River Basin SWAT model depends on soil, runoff and channel parameters. The model was successfully calibrated with with  $R^2$  equals 0.65 for calibration period and for validation the with  $R^2$  equals

Results from GCMs indicate that an increase in annual mean rainfall within a range of 16-18% can be expected by the 2050s, compared to the rainfall during the period between 2006 to 2009. The average temperature is forecasted to increase by about 20°C compared to the temperature baseline period. Further, there will be an increase of about 10% in long-term average stream flow. However, the model predicted a decrease in peak flows in the 2050s compared to the current average flows. The model forecasted that the overall total water demand in the Mahaweli basin will increase to 3,249.69  $Mm^3$  in the year 2050, compared to the current demand of 1,879.73  $Mm^3$ . This will create a situation where 51.5% of the total demand amounting to about 1673.8,  $Mm^3$  will not be met in the 2050s. A severe water shortage is predicted that about 71.12% of future irrigation demand will not be fulfilled in the 2050s. Water for hydropower generation will also be significantly affected as its unmet demand will be around 27.47%. However, the water demand for livestock will be marginally affected by about 1.41% of unmet demand as per the model's forecasts.

### **6.2 Recommendations**

Accordingly, following areas necessary to be researched in future to acquire enhanced knowledge on possible effects, so that mitigation measures could be planned and implemented timely.

Mahaweli is the major river in the island which provides water for three main sectors, namely hydropower generation, irrigation and domestic water supply and contributes substantially for the Gross Domestic Production of Sri Lanka. Therefore, paying high attention on possible effects due to climate change on Mahaweli water is a very appropriate activity.. Further, some of the measures already taken/are being taken to address them are discussed below.

1. A study on variations of rainfall and temperature on the whole basin and assess the impacts of possible variations. Data from 1989 to 2009 were used for this study. As significant changes in climate and land use patterns have been observed during the past few years, if it is possible to use data at least up to the year 2020, results will be more accurate. Further, if data can be collected from a greater number of gauging stations, study will be more successful. It is understood that an ongoing World Bank project under the Ministry of Irrigation (Integrated Watershed and water Resources Management Project – IWWRMP) has taken to increase the rainfall gauging stations substantially in near future.
2. An operational study on the storage reservoirs. As there are multiple users of water with varying demand throughout the year, effective water management is vital for the sustainable use of water. Having understood the above need, a more sophisticated reservoir management system is to be established under the above IWWRMP Project. This will facilitate capturing and transferring of real time data to a central location, so that effective management could be carried out.
3. The output of the model studies showed that an increase of annual rainfall is expected throughout long period. Therefore, it is advisable to assess the capacity of existing reservoirs in Mahaweli area about the adequacy of capacity to store additional quantity of water expected due to increased rainfall. A recent Project implemented under the Ministry of Irrigation (Dam Safety and Water Resources Planning Project - DSWRMP- funded by World Bank) has already established taken necessary steps in this regard. Further, it is a known fact, even the effective capacities of existing reservoirs are restricted by silting. The above includes desilting of few reservoirs as well. However, it is necessary to pay attention for controlling siltation by adequate and effective catchment protection efforts to avoid similar problems in future. Need for above activities will have to be seriously considered as construction of new reservoirs in the Mahaweli basin is very difficult due to

possible adverse environmental effects and resettlement issues. The upcoming IWRMP project has a component to address this issue and it intends to establish basin wise water management committees for strengthening water management.

4. It is well known that although mitigation measures are effectively implemented, that will not be adequate to completely avoid the consequences of climate change. Therefore, it is mandatory to adopt some measures to reduce the water demand. As the major user of water resources, irrigation sector must play a key role in this area by adopting introducing water conservation initiatives such as change of crops, use of drip irrigation etc. Further, more focussing on other renewable energy such as wind, biogas etc water demand for hydro power generation could be reduced. Domestic water sector also can contribute for water saving by reducing non-revenue water and use of water saving apparatus although reduction may be small compared with irrigation and hydro power sectors.
5. This study is recommended to extend for inclusion of a vulnerability assessment, involving several more indicators of vulnerability including the effects on rain water fed agriculture, fishing in internal reservoirs etc.

It is further recommended that adaptation measures for the Mahaweli basin and other river basins benefitted by Mahaweli are to be formulated and implemented based on above results.

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