EVALUATION OF BASIN LEVEL CLIMATE CHANGE IMPACTS ON STREAMFLOW AND RESERVOIR OPERATIONS - A CASE STUDY ON DEDURU OYA RESERVOIR

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Degree of Master of Science

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Thesis submitted in partial fulfilment of the requirements for the degree
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DECLARATION

I declare that this is my own work and this thesis does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

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Evaluation of Basin Level Climate Change Impacts on Streamflow and Reservoir Operations - A Case Study on Deduru Oya Reservoir

Abstract

Global climate change is known to trigger local and regional hydrologic variations like changes in precipitation patterns, surface temperatures and streamflows. Apt and efficient water management is extremely important as climate change can considerably affect the water supply-demand balance. Focusing on reservoirs and their management, it is very important to study climate change impacts on streamflow input and reservoir operations with a proper analysis. Targeting on that, this study was conducted as a case study on the Deduru Oya reservoir, Sri Lanka.

The impacts of climate change on the Deduru Oya basin were reviewed and two main parameters of climate indices, rainfall and temperature were identified using the findings from the previous literature. The prediction of the future streamflow data was carried out using a rainfall-runoff based hydrological model developed in Hydrologic Engineering Centre's Hydrologic Modeling System, version 4.3 (HEC-HMS) software, with the aid of the identified climatic parameters. Furthermore, prediction of the reservoir operation data was accomplished using a water balance based hydrological model developed in Hydrologic Engineering Centre's Reservoir System Simulation, version 3.1 (HEC-ResSim) software, with further emphasis on reservoir hydrology and adaptation methods.

It has been observed that there is an increase in the total annual rainfall by 21% - 24% for the 20s (2011-2040) and 42% - 75% for the 50s (2041-2070) while the average annual temperature indicates 0.08% - 0.14% increase for the 20s and 0.28% - 0.43% increase for the 50s under IPCC emission scenarios A2 and B2. Annual streamflow has shown a 62% -77% increase for the 20s and it has increased further in the 50s while the reservoir releases also indicate increased amounts on an annual basis. On a monthly basis, the rainfall, streamflow and reservoir releases in wetter months will get increased further, but in drier months those amounts will get reduced slightly.

Because of the increased release rates from the reservoir, it is needed to exert more attention to the increased downstream basin vulnerability to floods. While increased release rates add pressure to reassure the safety of existing structures, the ability to produce energy, cope with the agricultural and drinking water demand and maintain the ecological flow can be ensured by better water management practices in the future.

Keywords: Climate prediction; hydrologic variations; vulnerability to floods; water supply-demand balance

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LIST OF ABBREVIATIONS

Abbreviation	Description
AGHP	Annual Gross Hydropower Potential
DEM	Digital Elevation Model
ETP	Potential Evapotranspiration
GCM	General Circulation Model
GW	Ground Water
HEC-HMS	Hydrologic Engineering Centre - Hydrologic Modeling System
HEC-ResSim	Hydrologic Engineering Centre - Reservoir Simulation
IDW	Inverse Distance Weighting
IPCC	Intergovernmental Panel on Climate Change
MAR	Mean Annual Rainfall
MCM	Million Cubic Meters
MSL	Mean Sea Level
NSE	Nash-Sutcliffe Efficiency
RCM	Regional Climate Model
RVA	Range of Variability Approach
SDSM	Statistical DownScaling Model
SMA	Soil Moisture Accounting
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change

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1.0 INTRODUCTION

1.1 Background

Climate can be defined as the average weather condition of a particular location over a long period of time (World Meteorological Organization, 2019). There is a large number of research investigations conducted to study climate change and its impacts all over the world. Climate change is a change of climate which was attributed directly or indirectly to human activity that may alter the composition in the global atmosphere which happens in addition to the natural variations in the climate for a considerably long period of time (United Nations, 1992). It can also be defined as changes in the mean and/or variability of the properties of the state of the climate that lasts for a long time period, typically decades or longer (IPCC, 2012).

United Nations (UN) has identified the significance of paying more attention to climate change and they have introduced a set of specific "Sustainable Development Goals" to highlight and emphasize the importance of being alert for the changes in the climate. "Sustainable Development Goal 13: Take urgent action to combat climate change and its impacts" emphasizes, without action, the world's average surface temperature will be increased by 3 °C in this century and it is needed to control this by implementing appropriate actions immediately (See Figure 1-1). Under the Paris Agreement at the COP21 in Paris, in November of 2016, it was agreed for a limitation in the temperature rise to well below 2 °C, understanding the importance of taking immediate actions for the rising global temperature (United Nations, Climate change, 2020).

13.1 Strengthen resilience to climate-related hazards and natural disasters

13.2 Integrate climate change measures in policy

13.3 Improve capacity on climate change

13 CLIMATE ACTION

13.a Implement United Nations Framework Convention on Climate Change (UNFCCC) commitment

13.b Promote mechanisms in least developed countries for climate change management

Figure 1-1: United Nations Sustainable Development Goal 13 targets

Source: United Nations, Climate Change (2020)

There are external (astronomical and orbital), internal (Earth - geophysical, geological and geographical) and anthropogenic factors that can affect the changes in climate. Variations in solar radiation and differences in the orbital parameters can be identified as some of the external factors that affect climate change (Nikolov & Petrov, 2014). Plate tectonics and volcanic eruptions also affect the changes in the climate. Circulation of air can be influenced by mountain ranges and it will make changes in the climate. Human-induced climate change is very significant and it is needed to be minimized as much as possible. Burning fossil fuel releases greenhouse gases like Carbon Dioxide to the atmosphere and it makes the earth warmer. Vegetation coverage on the land is very important to reduce the impact of greenhouse gases as the plants can absorb Carbon Dioxide and reduce its concentration in the atmosphere. But with the current situation, the vegetation coverage is decreasing while causing the effect of greenhouse gases more severe. Because of that reason, it is very important to put more attention on climate change and take necessary actions to reduce the impacts of climate change.

Climate change causes variations in climate parameters like temperature, rainfall, evaporation, humidity and evapotranspiration (Adnan, Ullah, & Ahmed, 2019; Ehsani, Vörösmarty, Fekete, & Stakhiv, 2017). With the changes in the climate parameters, there can be several impacts on factors like runoff, crop water requirements and evaporation rates (Ashofteh, Haddad, & Mariño, 2013; Sharannya, Mudbhatkal, & Mahesha, 2018). Water resources get affected by climate change and there can be many adverse effects occurring with the changes (Shamir, et al., 2015). Climate change impacts on reservoir hydrology are very significant to consider as the impacts on reservoir water balance can make problematic situations in the processes associated with the reservoirs such as flood and drought management, drinking and irrigation water supply and hydropower generation (Ashofteh, Haddad, & Mariño, 2013; Kopytkovskiy, Geza, & McCrayb, 2015; McMartin, et al., 2018). Studies are needed to analyse the climate change impacts in detail to apply the most appropriate solutions for future issues occurring with the changing climate.

There is a large number of researches conducted to analyse the climate change impacts on reservoir hydrology around the world while emphasizing the importance of the detailed studies on that area. The higher emission of greenhouse gases has been identified as one of the main reasons for climate change which may lead to an increase in atmospheric temperature considerably (Adefisan, 2018). Furthermore, the precipitation pattern changes were predicted in many studies and they have mentioned both increased and decreased amounts in the future while highlighting the fact that those variations depend on the region analyzing (Ferreira, Nissenbaum, & Rickenbach, 2018; Sharannya, Mudbhatkal, & Mahesha, 2018; Sipayung, Nurlatifah, Siswanto, & S, 2018; Tal, 2019). Following the changes in the climate parameters, streamflow input, vulnerability to floods and droughts, ability to generate hydropower electricity, ability to maintain the ecological flow, ability to cover the future demands have been analysed by different researches and the findings from them help to mitigate the issues which can arise in the future. The severity of floods and droughts will be increased in the future with the changing streamflow and consideration of climate change information for designing of reservoirs and other hydraulic structures will become very significant (Didovets, et al., 2019; Duan, et al., 2019; Soto-Montes-de-Oca & Alfie-Cohen, 2019). The ability to produce energy, cope with the agricultural and drinking water demand and maintain the ecological flow can be ensured by better water management practices in the future.

There can be both positive and negative impacts of climate change, but the most important fact about these changes is, the impacts are varied from one region to another considerably (Falchetta, Gernaat, Hunt, & Sterl, 2019). Because of this variation, it is very significant to conduct the studies on a regional basis to access the exact impacts of a selected region.

In the Sri Lankan context, climate change studies were conducted since from the past for different regions and very interesting outcomes were obtained (Dissanayaka & Rajapakse, 2019; Marambe, et al., 2014; Rajendran, Gunawardena, & Dayawansa, 2017). Recent research conducted for the Kelani river basin, Sri Lanka has identified that the precipitation extremes and temperature will rise in the future but the annual average precipitation will get reduced (Dissanayaka & Rajapakse, 2019). Another research conducted for the Kalu Ganga basin, Sri Lanka has highlighted the uncertainty in the river flow with climate change and significance of conducting more research works to identify the climate change impacts on water resources in the basin.

As Deduru Oya reservoir is a very recently constructed reservoir (construction was started on 2006 and the dam was opened on 2014), there is only a limited number of researches conducted aiming the reservoir and that tends to demand the requirement of researching on climate change aspects since climate change can affect reservoir hydrology very significantly as discussed before. There are some climate predictions that were obtained for the Deduru Oya basin in previous studies and they can be used as a guide to identify the impacts on the reservoir in a comprehensive manner (Dharmarathna, Herath, & Weerakoon, 2014; Rajendran, Gunawardena, & Dayawansa, 2017). Under this study, it will focus on two major factors that can get affected by climate change; streamflow and reservoir operations. A detailed study on the Deduru Oya reservoir will be used to analyse the impacts and the results can be generalized to the basins with similar characteristics. This study will cover how the changes in the climate can affect the streamflow input and the reservoir operations while following a well-structured methodology and proper analyzing methods.

1.2 Problem Statement

Climate change affects the water supply-demand balance of a reservoir. There is a need for a reconsideration of the aspects like effects on the streamflow and impacts on the reservoir operations in detail. Inattention to the effect of impacts due to climate change will cause unexpected problematic situations in the future. Without a proper analysis regarding climate change and the identification of the effects, it is not feasible to properly estimate the future conditions. It is needed to analyse the climate change impacts on the regional basis and at the basin level scale to recognize and find solutions to more specific issues.

1.3 Scope of the Study

This research has been conducted to analyse the climate change impacts on streamflow and reservoir operations and it was conducted as a case study on the Deduru Oya reservoir. The future climate data were projected using previous literature and a rainfall-runoff based hydrologic model and a water balance based hydrologic model were developed to obtain future variations in the streamflow and reservoir operations. Finally, the impacts were analysed in detail and appropriate water management strategies were discussed for the future situations occurring due to the climate change impacts.

1.4 Research Objectives

The main objective of this study is to evaluate basin level climate change impacts on streamflow and reservoir operations in Deduru Oya Basin. Specific objectives are,

- To identify the climate change impact on rainfall and temperature based on past studies and previous literature
- To develop a rainfall - runoff based hydrological model to simulate and verify the streamflow data
- To develop a water balance based hydrological model to analyse the impacts of climate change
- To study the future water management options and make recommendations on mitigatory measures to resist the impact of climate change

1.5 Outcomes of the Research

There is an increase in both total annual rainfall and average annual temperature in the future. It has been observed that there is an increase in the total annual rainfall by 21% - 24% for the 20s (2011-2040) and 42% - 75% for the 50s (2041-2070) while the average annual temperature indicates 0.08% - 0.14% increase for the 20s and 0.28% - 0.43% increase for the 50s under IPCC emission scenarios A2 and B2. Further, on the annual basis, under both scenarios, the streamflow showed an increase (a 62% -77% increase for the 20s and it has increased further in the 50s) while the total release rates from the reservoir have also revealed an increased amount. On a monthly basis, the rainfall, streamflow and reservoir releases in wetter months will get increased further, but in drier months those amounts will get reduced slightly. Because of the increased release rates from the reservoir, it is needed to exert more attention to the increased downstream basin vulnerability to floods. The ability to produce energy, cope with the agricultural and drinking water demand and maintain the ecological flow can be ensured by better water management practices in the future.

1.6 Arrangement of the Thesis

This thesis includes eight chapters, having an introduction and the structure of the thesis as Chapter One. Chapter Two includes a literature review for the study and it explains the findings from the literature in a comprehensive manner. Chapter Three elaborates details about the materials and methods related to the study and Chapter Four discusses the results and analysis details. Chapter Five contains an extended discussion regarding the results obtained and the analysis carried out. Chapter Six presents the conclusion of the study and additional recommendations are provided there. The reference list and the appendices are attached next.

2.0 LITERATURE REVIEW

2.1 Introduction

World Meteorological Organization (WMO) defines “Climate” as the average weather condition for a particular location over a long period of time (World Meteorological Organization, 2019). A change of climate which is attributed directly or indirectly to a human activity that alters the composition in the global atmosphere and which is in addition to the natural climate variability observed over comparable time periods is identified as the “Climate Change” by the United Nations Framework Convention on Climate Change (UNFCCC) report which was published in 1992 (United Nations, 1992). It is debatable to define climate change only as an occurrence due to human activities as according to Intergovernmental Panel on Climate Change (IPCC), while the changes in the mean and/or variability of the properties of the state of the climate that lasts for a long time period, typically decades or longer has been defined as the climate change (IPCC, 2012).

Climate change is responsible for several variations like changes in the precipitation patterns, increase in the surface temperature, increase in the intensity and the frequency of floods and droughts, and increase in the rate of ice melting (Ehsani, Vörösmarty, Fekete, & Stakhiv, 2017). Several literature reviews have been carried out to document the impacts of climate change with the use of the existing estimates of the global and regional impacts from the studies conducted using different climate models and different climate prediction scenarios (Warren, et al., 2015; Jamet & Corfee-Morlot, 2009). A review conducted very recently has highlighted that the main causes of climate change are human activities and the industrial revolution (Mamuye & Kebebewu, 2018).

Water resource management is very important to adapt to climate change impacts. However, climate change-related information is vast and scattered, and its application to specific analyses is yet a challenge (Fluixá-Sanmartín, Altarejos-García, Morales-Torres, & Escuder-Bueno, 2018).

For instance, reservoir hydrology or reservoir water balance consists of several components; rainfall-runoff, rainfall on the water surface of the reservoir, consumption (demand), evaporation, infiltration in the bottom of the reservoir and discharge. Change in the water storage can be expressed with these components by using the relationship between the total inflow, total outflow and the reservoir storage (UNESCO & WMO, 2012). Because of that, when there is an impact on any of those components due to climate change, it directly or indirectly affects the reservoir water balance.

This study focused on both climate change impacts on reservoir hydrology and long-term basin-wide water resource management, and the case study was conducted for Deduru Oya basin considering two major impacts; impacts on streamflow and impacts on reservoir operations using a rainfall-runoff based hydrological model and a water balance based hydrological model.

2.2 Climate Impacts on Reservoir Hydrology

The overall climate impact on reservoir hydrology can be explained using the climate change impacts on the individual components of reservoir water balance. Streamflow is the inflow to a reservoir and it gets affected when there are changes in the precipitation patterns and increase in the temperature and evaporation rates (Sharannya, Mudbhatkal, & Mahesha, 2018).

A review which was conducted in 2009 to identify the climate change impacts has mentioned that climate change can increase or decrease energy consumption, water resources like reservoir storages and demand. Similarly, it describes that the impact is strongly dependent on the regions while warm areas being more adversely affected than cooler areas (Jamet & Corfee-Morlot, 2009) which is a concern for all tropical countries.

One of the purposes of a reservoir is to store water for the future water usages when it is required especially in dry seasons. There can be differences in the acceptability of some factors like sizes, designs and number of dams available with the changing climate. Operations of the reservoirs can be affected by changed climatic conditions as inflow as well as the regulated flows can get affected as a result of it (Lee, Hamlet, & Grossman, 2016). Further, most importantly, assessing the vulnerability of those kind of structures is very important with the effects due to climate change particularly like floods and droughts (McMartin, et al., 2018). It has been highlighted in a review conducted focusing on dam safety, that the dam risk models are needed to be updated considering the effects of climate change as it will later help to define the adaptation strategies to those impacts (Fluixá-Sanmartín, Altarejos-García, Morales-Torres, & Escuder-Bueno, 2018).

One of the main purposes of the regulated flow is to use for drinking and other daily purposes by human beings. Further, reservoirs are water resources which are constructed to regulate water for the agricultural and other water use purposes. With the changing climate, this demand can also get affected considerably since the amount of the outflow from the reservoir depends on the prevailing climate patterns in the future (Ashofteh, Haddad, & Mariño, 2013).

Hydropower generation is also associated with water resources like reservoirs. When the inflow gets affected with the changing climate, the amount of water and the rate of flow get changed which has effects on the power generation indirectly (Kopytkovskiy, Geza, & McCrayb, 2015). It has been identified that there can be both positive and negative impacts by climate change and it varies from one region to another (Falchetta, Gernaat, Hunt, & Sterl, 2019).

Ecological flow or the amount of water that is needed to maintain the reservoir ecosystem functions is very important as it affects the existence and sustainability of the reservoir system for a long period of time with the capability of satisfying the needs of the consumers. There is a risk of maintaining the system with climate change as it alters the precipitation patterns and also the evaporation rates (Mikołaj, Laizé, Acreman, Okruszko, & Schneider, 2014).

2.2.1 Impacts on temperature

Most of the studies have proven that climate change impacts lead to significant increases in temperature. A study which has been carried out for Western Ghats of India has shown that the average temperature is supposed to be increased by 0.10 °C per decade for both scenarios analysed as historical (1951–2005) and future (2006–2060) (Sharannya, Mudbhatkal, & Mahesha, 2018). Ten-year mean (decadal) analysis for West Africa showed that there is a gradual and almost constant rise in temperature while emphasizing the key causing factor as higher emission to the environment (Adefisan, 2018). Athabasca River basin which is located in Western Canada was analysed in order to identify the impact on stream temperature regimes and it has concluded that the temperature is expected to be increased and the highest increases will be 2.0 °C to 7.4 °C in summer (Du, Shrestha, & Wang, 2019). All the studies which have been conducted around the world provide the common conclusion that there will be a temperature rise in future which can cause several effects like impacts on the water quality dynamics of water resources by decreasing the level of the dissolved oxygen concentration and increasing the reaction rates of biochemical processes. In addition, it can impose an adverse effect on aquatic life as well (Du, Shrestha, & Wang, 2019). Furthermore, there is a significant impact on the evaporation rates as well with the temperature increase (Helfer, Lemckert, & Zhang, 2012).

2.2.2 Impacts on precipitation patterns

When earth warms as a result of the changing climate, it affects the hydrological cycle considerably while imposing a significant effect on the rainfall patterns. A study which was conducted for south-eastern United States has concluded that the average precipitation is having a possibility to increase by 45% from the future climate simulation conducted (Ferreira, Nissenbaum, & Rickenbach, 2018). It has been shown that the rainfall in Sambas district, West Kalimantan is supposed to be increased by 0.018 mm/month until 2055 (Sipayung, Nurlatifah, Siswanto, & S, 2018).

But, a decreasing trend with a rate of 2.63 mm per year for the baseline scenario (1951–2005) and 8.85 mm per year for the future scenario (2006–2060) have been shown in a study which was conducted for Western Ghats of India (Sharannya, Mudbhatkal, & Mahesha, 2018). This has been proven in a study which was conducted for Kinneret Lake (Sea of Galilee) in Israel also by identifying that there is a reduction in the rainfall which causes a lowering in the water levels of the lake as well (Tal, 2019).

Some studies have put their attention, especially on extreme events. A study which was conducted for Flamingo Tropicana watershed in Las Vegas, Nevada identified that summertime convective storms which considered as an extreme storm for the area will be even more intense in the future (Acharya, Lamb, & Piechota, 2012). From all the studies, it is possible to come to a common conclusion that climate change can cause both an increase and decrease in precipitation and according to the region analysed, the result can be varied. Further, extreme events will become more intense as a result of the changing climate.

2.2.3 Impacts on total runoff and streamflow

It has been projected to experience an increase in the runoff and streamflow by the analysis carried out using some Indian basins in 2018. However, the majority of the increase is supposed to be due to the extreme storm events during monsoon seasons and it is important to note that the water availability in the dry season may not increase substantially as in wet seasons (Shah & Mishra, 2018). Bhakra reservoir in Satluj River basin in India was analysed using generated climate projections by PRECIS for two centuries, mid-century (2021–2050) and end century (2071–2098) and it has concluded that there is 12.8% increase and 19.4% increase respectively for both centuries in the mean annual streamflow (Hamid, Sharif, & Narsimlu, 2017). Increased annual streamflow of 5.8%, 2.8% and 9.5% was obtained in a study conducted for North Iran under three emission scenarios A1F1, A2 and B1, respectively (Azari, Moradi, Saghafian, & Faramarzi, 2016).

Sharannya, et al. (2018) obtained a decreasing trend of streamflow at the rate of 1.2 Mm^3 per year and 2.56 Mm^3 per year, for the past (1951–2005) and future scenarios (2006–2060) under a study conducted in the Western Ghats in India while highlighting the main cause for the reduction of streamflow is the decreasing trend in the precipitation as stated in before. A similar result was obtained in a research carried out for Yellow River basin, China and it has been proven that there is a reduction in the streamflow which agrees with the decreasing precipitation but not with the increasing evaporation rates (Yang & Liu, 2011).

When there is an increase in the precipitation, it was reflected by an increase in the streamflow for many studies. But in the case of temperature, even though the temperature rise increases the evaporation rate, still there can be a less significant effect from that for the streamflow as streamflow increase was found in some studies despite having an increased evaporation rate (Yang & Liu, 2011). This shows that the precipitation is more dominant for the streamflow changes than evaporation.

2.2.4 Climate impacts on reservoir operations

In order to assess the combined effect from varying natural flows and reservoir operations on the regulated flows, a study was conducted for Skagit River basin which extends in parts of Canada and United States using an integrated daily-time-step model for reservoir operations. It has shown that there can be considerable seasonal changes in the natural flow and regulated flow with climate change (Lee, Hamlet, & Grossman, 2016). With the use of Neural Networks based General Reservoir Operation schemes, climate change impacts on dams were identified from research conducted for the Northeast United States in 2017. The findings explained that the significance of dams for providing water security in the area will rise considerably in the future and the effectiveness of regulation by dams is supposed to be increased especially in drier months with the predicted climate change. It also highlighted the need for many and enlarged dams to enhance the security of water resources like reservoirs in future (Ehsani, Vörösmarty, Fekete, & Stakhiv, 2017).

A combined monthly hydrological model and a General Circulation Model (GCM) was used for a study conducted for Norris Reservoir in Northeastern Tennessee, the United States and it emphasised the importance of considering the projected climate changes as a significant tool for reservoir operation and long term water resource management (Rungee & Kim, 2017). A study in New York City water supply watersheds found that there will be an overall increase in the mean streamflow and the intensity and the frequency of extreme hydrological events are estimated to increase with future climatic conditions. Hence, it is very important to ensure water security while following adequate processes to manage the water supply facility for future needs (Mukundan, Acharya, Gelda, Frei, & Owens, 2019). Integrated monitoring is mentioned as a need to resist changing climate and water resource management is mentioned as a very significant requirement under that study (Duan, et al., 2019). In overall, climate change considerably affects the reservoir operations and regular monitoring is essentially needed while ensuring to follow water apt managing strategies.

2.2.5 Vulnerability to floods and droughts

Effect of climate change on floods and droughts are needed to be analysed to identify whether the existing reservoir systems are adequate for future conditions. Particularly, it is crucial to identify the exposure level of reservoirs to floods and droughts. Figure 2-1 displays the flood exposure level of each district in Sri Lanka and most importantly it highlights the fact that most of the reservoirs are located in high indexed areas which have a higher vulnerability to floods. It emphasizes the need of focusing more on the possible impact from floods with impending or ongoing climate change as the vulnerability will only increase with the climate change in future (Eriyagama, Smakhtin, Chandrapala, & Fernando, 2010).

A study which was conducted in Tisza and Prut catchments in the Carpathian region in Europe has shown a considerable increase in the 30-year flood level of the Tisza ranging from 4.5% to 62.0% and in Prut 11% to 22% moderate increases (Didovets, et al., 2019). Mexican peri-urban areas were studied for the risk of droughts with the climate change and it has been identified that there is an increase in the temperature which can enhance the evaporation rates and also there is a possibility of a reduction in rainfall in the area. This highlights the risk of droughts in the area which is caused due to climate change (Soto-Montes-de-Oca & Alfie-Cohen, 2019). A study which was conducted in the northern part of the Extremadura region, Spain showed, under future climatic projections, a consistent increase in the duration and an earlier onset of drought are possible (Rolo & Moreno, 2019). Based on the conclusions of above studies and focusing on further consequences, it can be derived that future floods and droughts can be even more severe than the prevailing conditions and it can impose an adverse impact to the reservoir systems which were designed without considering the climate change aspects.

Data of floods and droughts are specially considered when designing reservoirs as it affects the design scenarios like engineering grade and scale, type of dam, height of the dam, and the downstream hazard after dam-breaking (Ren, et al., 2017). Variations in the patterns of floods and droughts with climate change may cause inadequacy of the designed structures if the climate change effect was not considered when designing. It may cause hazardous situations for the downstream as well as damages to the hydraulic structures associated with the reservoir.

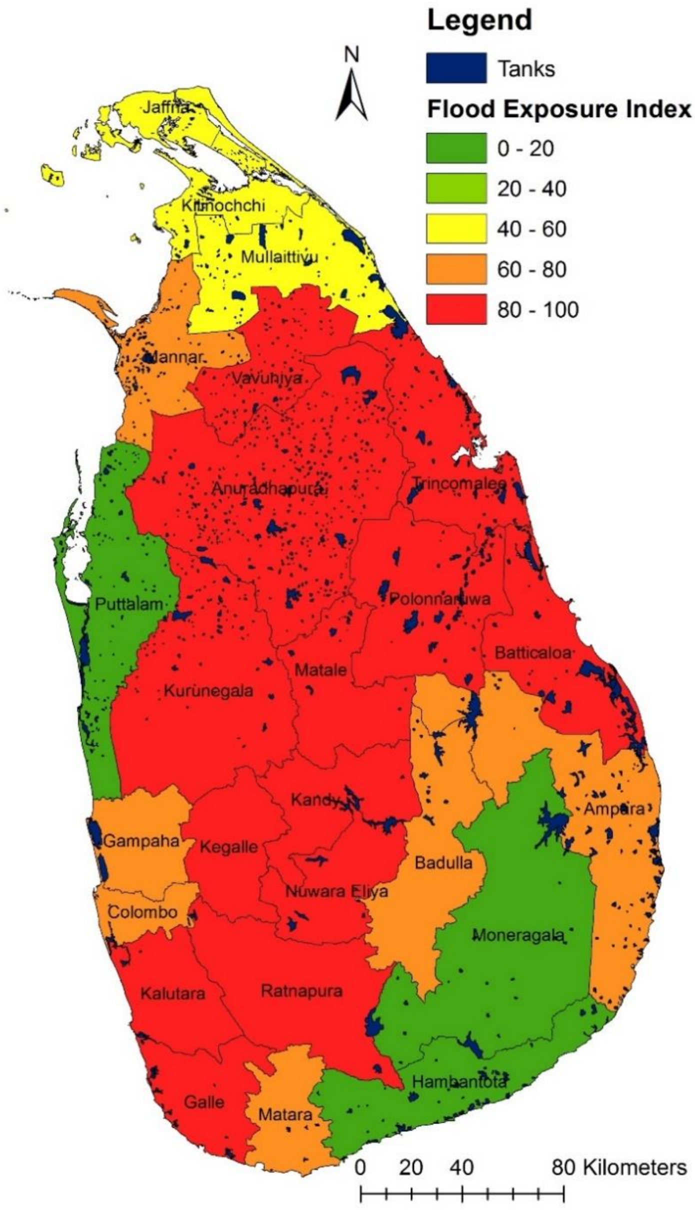

Figure 2-1: Reservoir vulnerability to floods in Sri Lanka

Source: Eriyagama, Smakhtin, Chandrapala, & Fernando (2010)

A study conducted for two reservoirs in central Texas, USA showed an increase in inorganic and organic nitrogen in a period of drought and possibility of amplifying the potential for harmful blooms of Aphanizomenon (Gámez, Benton, & Manning, 2019). Due to that reason, when the droughts become more severe, the above harmful effects can also become even more severe in future with climate change. It is recommended to especially consider climate change impact when designing hydraulic structures and regular monitoring of the reservoirs is needed to eliminate the hazardous situations which can occur due to changing climate (Duan, et al., 2019).

2.2.6 Agricultural and drinking water demand

Climate change affects considerably the water supply-demand balance of a reservoir. A study conducted for Pong Reservoir in northern India has shown that the future climate will become drier and the existing reservoir storage capacity will not be enough when considering the future situation. It has been mentioned that the coefficient of variation for the required water capacity is as higher as 0.3 in here (Soundharajan, Adeloye, & Remesan , 2016). Due to this reason, it will be unable to supply future demand with the existing capacities for both agriculture and drinking purposes while assuming the existing demand will not reduce in the future.

A study on semi-arid Millbrook catchment-reservoir system in Australia has emphasised the importance of the quality of water which is another critical concern for the water supply especially for the drinking purposes and delivered the findings as with the global warming and land-use changes in the future, significant eutrophication effects can be resulted in especially in summer periods (chlorophyll concentrations greater than 40 mg/l in summer if artificial destratification was not performed at the beginning of the season) (Nguyen, Recknagel, Meyer, Frizenschaf, & Shrestha, 2017).

An assessment conducted for sub-region water balance in the United States has mentioned that one of the largest impacts from the climate change is on low-valued consumptive uses like agriculture as when water is reallocated with reduced water amounts due to climate change, the priority will be given to the drinking, domestic uses, commercial uses and industrial uses with higher marginal values before considering the above mentioned secondary uses (Henderson, et al., 2015). Furthermore, many studies highlight the importance of water conservation, risk management and application of mitigation measures for the impacts on the agriculture as well as on the human health that occur due to climate change (Ahmed, Scholz, Al-Faraj, & Niaz, 2016). Regional planning and water management is needed as a must to face all the changes presently ongoing and happening to the climate in the future (Andrew & Sauquet, 2017).

2.2.7 Impacts on hydropower generation

Hydropower can be considered as a clean, an environmentally friendly energy source which is categorized under renewables. Hydropower generation gets affected when there is a reduction in the streamflow to a reservoir which causes as a result of climate change. A review which was conducted on the role of hydropower on climate change mitigation stated that the overall impact of climate change on existing hydropower generation is supposed to be negligible or even slightly positive (Berga, 2016).

A study which was conducted for Dajia River basin located in north-central Taiwan has shown that in the A1B scenario, it is expected to see the percentage change in hydropower generation for the seven General Circulation Models (GCMs) ranges between −14.9% and 4.6% in the wet season (May–October) and between −33.1% and 0.2% in the dry season (November–April). Furthermore, it highlights the requirement of proposing adaptation strategies for the case of the possible reduction in the hydropower generation as a future recommendation (Yu, Yang, Kuo, Chou, & Tseng, 2014).

The modifications inflicted by the climate change in total annual inflow affects the hydropower generation and the possible impact of climate change on varying electricity demand was identified as negligible in a study which was conducted for Mauvoisin installations (7° 35′ E, 46° 00′ N), in Switzerland. It also described that the changes in consumer behaviour will be more significant with respect to the demand and it will affect demand considerably causing increased production in the summer season (Gaudard, Gilli, & Romerio, 2013). A study which was carried out in China has identified that the Annual Gross Hydropower Potential (AGHP) is supposed to be changed by -1.7% to 2.0% in 2020–2050 period and 3% to 6% in 2070–2099 period. It has emphasized the significance of considering climate change aspects in planning hydropower developments in future (Liu, Tang, Voisin, & Cui, 2016).

2.2.8 Climate impacts on ecological flow

A method conceptually based on the Range of Variability Approach (RVA) was used to identify the impact of climate change on the environmental flow in Narew basin in north-eastern Poland and the study has concluded that the environmental flow regime has climate change risk with varying magnitude and spatial variability when modelling (Mikołaj, Laizé, Acreman, Okruszko, & Schneider, 2014). With the use of seven GCMs, 2 °C increase in the global temperature was identified in research conducted for Mekong River, in Southeast Asia and considerable inter-GCM differences in risk of change is identified. It has been mentioned that the uncertainty is larger for low flows while having high and medium risk at most of the locations (Thompson, Laizé, Green, Acreman, & Kingston, 2014).

For the purpose of identifying the impacts in an accurate manner, it is needed to predict the future climate data and analyse that using the developed models. There are several models which are based on different principals that can be used for the purpose of prediction of future climate data. After obtaining the predictions from those models, the future data can be used to quantify the impacts in a logical and a precise way. It is very important to select the most suitable model to predict future climate data as the accuracy of the output may vary from one model to another.

The summary of the discussed climate change impacts can be given in a table for the comparison purpose and the ease of reference. Table 2-1 displays the literature summary of the discussed parameters with factors affected, focal points and regions analysed. It summarizes the points discussed under each factor and the relevant literature sources with the regions where the studies were conducted. Temperature, precipitation pattern, streamflow, reservoir operations, floods and droughts, water demand, hydropower generation and ecological flow are the factors summarized in here.

Table 2-1: Literature summary table of factors, focal points and regions analysed

Factors Affected	Points Discussed	References and Regions Analysed
Temperature	-Is supposed to increase in everywhere -Highest increase will occur in the summer period -Will have impacts on aquatic life, dissolved oxygen concentration of water and reaction rates of biochemical processes	Sharannya, et al., 2018 (Western Ghats of India); Adefisan, 2018 (West Africa); Li & Jin, 2017 (Jing River, China); Du, et al., 2019 (Athabasca River basin, Western Canada); Helfer, et al., 2012 (South-East Queensland, Australia)
Precipitation pattern	-Both increasing and decreasing trends can be observed depending on the area analysed -Extreme events will lead to more intense precipitation in the areas getting increased rainfall	Ferreira, et al., 2018 (South-Eastern United States); Sipayung, et al., 2018 (Sambas district, West Kalimantan); Sharannya, et al., 2018 (Western Ghats of India); Tal, 2019 (Kinneret Lake, Israel); Acharya, et al., 2012 (Las Vegas, Nevada)
Streamflow	-Both increasing and decreasing trends can be observed depending on the area analysed -Even though temperature increase enhances the evaporation, there will be no considerable impact when the precipitation is increasing	Shah & Mishra, 2018 (India); Hamid , et al., 2017 (Satluj River basin, India); Yang & Liu, 2011 (Yellow River basin, China); Ficklin, et al., 2013 (Upper Colorado River basin); Shao, et al., 2018 (Hailiutu River basin, China); Li & Jin, 2017 (Jing River, China); Olsson, et al., 2015 (Finland)
Reservoir operations	-It is needed to increase the efficiency of regulation of water from dams and increase the sizes and number of dams in the future -Regular monitoring and usage of water management strategies are needed -Consideration of climate change information when designing the structures is becoming a significant factor	Lee, et al., 2016 (Skagit River basin, Canada–United States); Ehsani, et al., 2017 (Northeast United States); Rungee & Kim, 2017 (Norris Reservoir); Mukundan, et al., 2019 (New York); Duan, et al., 2019 (United States)
Floods and droughts	-Severity of floods and droughts is increased with climate change -Consideration of climate change information for designing of reservoirs and other hydraulic structures is very significant	Didovets, et al., 2019 (Tisza and Prut catchments, Carpathian region); Soto-Montes-de-Oca & Alfie-Cohen, 2019 (Mexican peri-urban areas); Rolo & Moreno, 2019 (Northern part of the Extremadura region); Li & Jin, 2017 (Jing River, China); Ren, et al., 2017 (China, United States, Russia, Japan, Britain, Germany, Canada, Sweden, Norway, France, India, Brazil and some other countries);

		Gámez, et al., 2019 (Central Texas, USA); Duan, et al., 2019 (United States)
Water demand	-Water scarce situations can occur specially in dry periods -Proper water resource management will be needed to ensure the water security	Soundharajan, et al., 2016 (Pong Reservoir, India); Nguyen, et al., 2017 (Australia); Henderson, et al., 2015 (United States); Ahmed, et al., 2016 (Pakistan); Andrew & Sauquet, 2017 (Durance and Sacramento Rivers)
Hydropower generation	-Depending on the varying streamflow input this can be positively or negatively affected -Consumer behavior will affect the demand considerably	Berga, 2016 (A review); Yu, et al., 2014 (Dajia River basin, Taiwan); Kopytkovskiy, et al., 2015 (Upper Colorado River basin); Gaudard, et al., 2013 (Switzerland); Liu, et al., 2016 (China)
Ecological flow	- Uncertainties in the flow can occur	Thompson, et al., 2014 (Mekong River, Southeast Asia); Mikołaj, et al., 2014 (Narew basin, North-Eastern Poland)

2.3 Study Area

Deduru Oya river basin, which is located in the North-Western region of Sri Lanka is the 6th largest river basin in the country. It is located between the northern latitude 7° 19′ 00″ to 7° 52′ 00″ and eastern longitude 79° 47′ 00″ to 80° 35′ 00″. It has Mee Oya basin as its northern boundary and Maha Oya basin as the southern boundary while the central hills and coast mark the eastern and western ends. The nature of the variation of the land elevation in this basin is like more mountainous features with high slopes towards the eastern boundary, moderate sloping in the middle and coastal and more flatter features towards the western end (See Figure 2-2). The total area of the basin is 2616 km^2 and the area distribution for climatic zones includes all three regions, 94% from the Intermediate Zone, 5% from Wet Zone and 1% from Dry Zone (Wickramaarachchi, 2004).

The rainfall for the basin has a significant variation in both temporal and spatial basis. The average annual rainfall for the basin is 1600 mm where the annual rainfall varies from 2600 mm in the upper basin area to 1100 mm in the lower basin area (Weerakoon, Sampath, & Herath, 2018). Having the major purpose of utilizing the water available in the basin, the Deduru Oya Reservoir Project was initiated in the last decade in Sri

Lanka (construction was started on 2006 and the dam was opened in 2014). The location of the Deduru Oya reservoir is shown below in Figure 2-3 and Figure 2-4 displays the block diagram of Deduru Oya Reservoir Project.

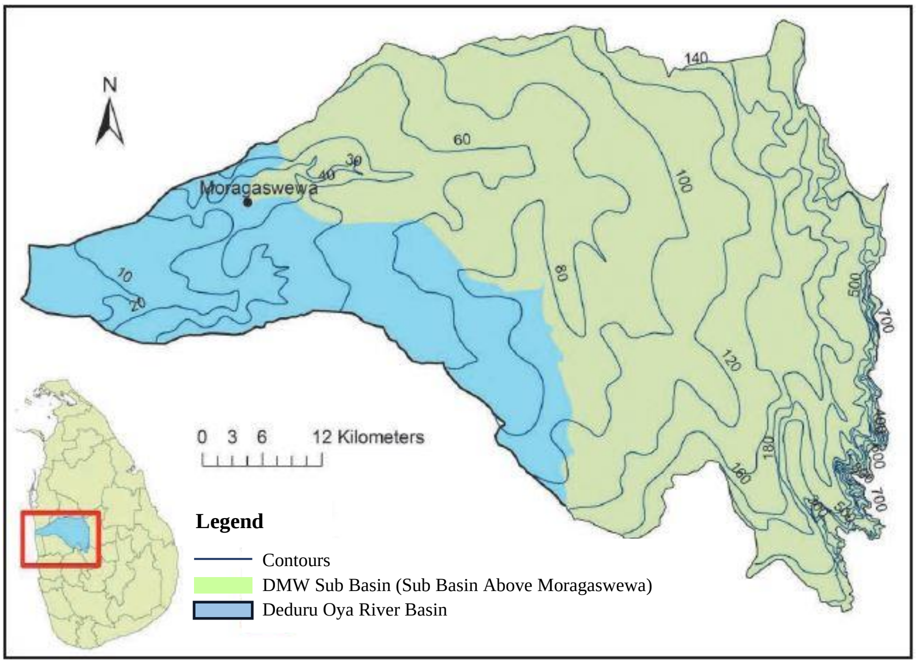

Figure 2-2: Location and topography of Deduru Oya basin
Source: Sampath, Weerakoon, & Herath (2015)

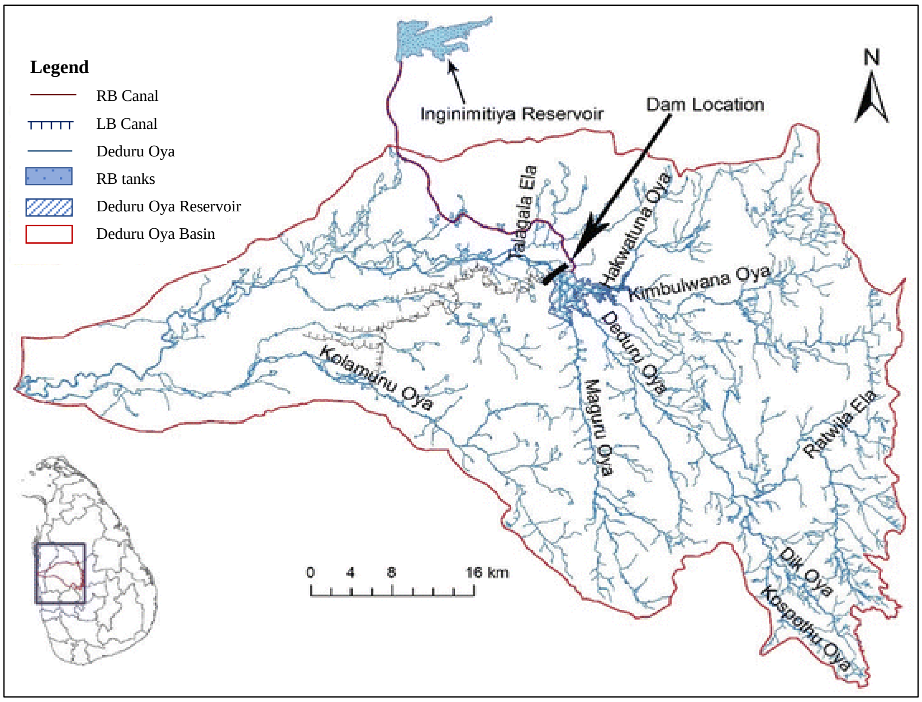

Figure 2-3: Location of the Deduru Oya reservoir in the basin
Source : Weerakoon, Sampath, & Herath (2018)

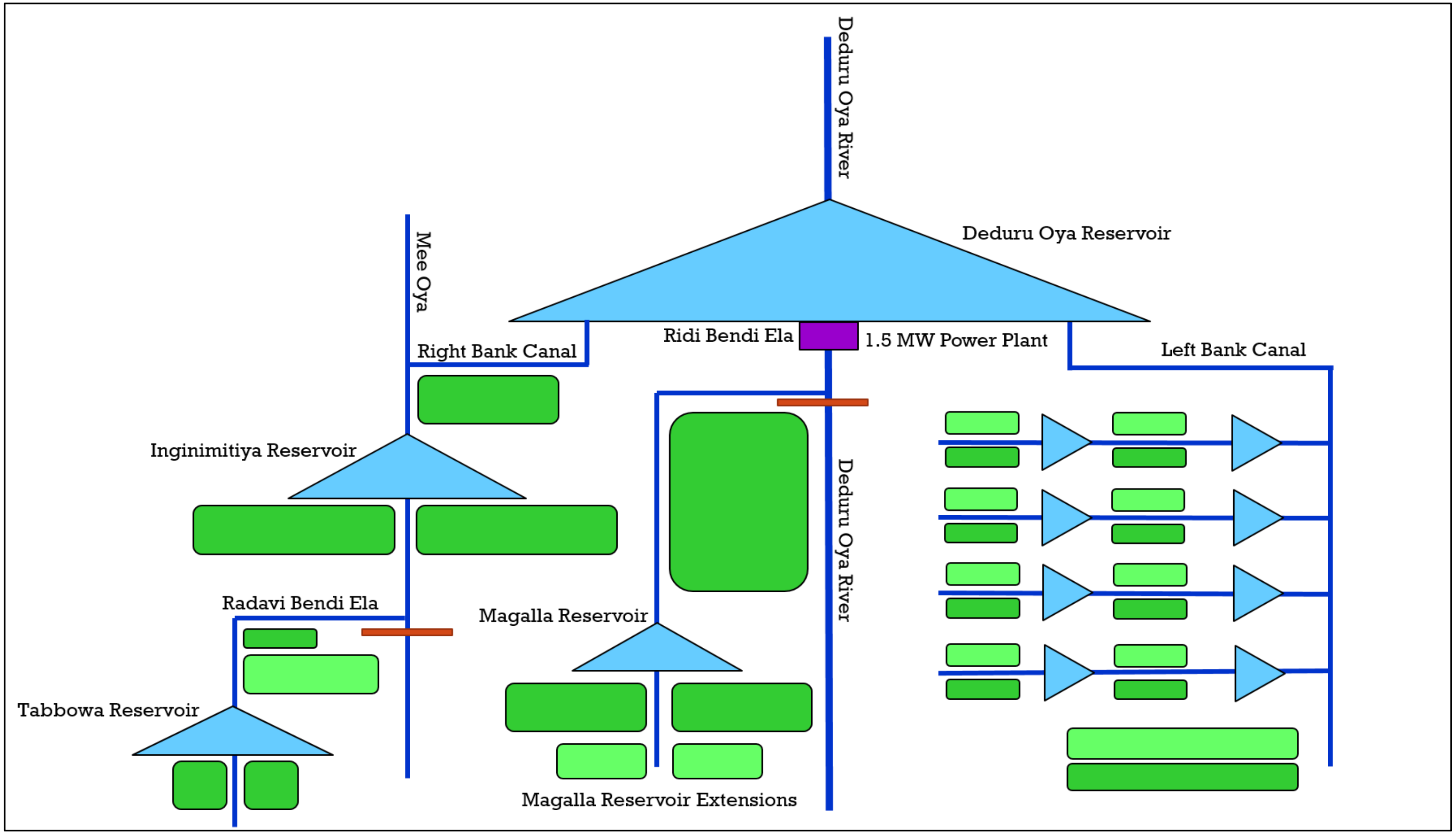

Figure 2-4: Deduru Oya reservoir project block diagram

Source: Weerakoon, Sampath, & Herath (2018)

2.4 Future Climate Data Generation

2.4.1 Methods for future climate data generation

General circulation of a planetary atmosphere or ocean is mathematically represented in the General Circulation Models (GCMs) and they can be used to predict future climate data. These models are widely used for many research works and very credible information can be obtained by using these models (Li, Zhang, Jing, Liu, & Sun, 2017). However, as their spatial resolution is too coarse to be compatible with hydrological models, for regional studies, Regional Climate Models (RCMs) are developed based on the GCMs. A method called downscaling is used to connect these finer and coarser scales (Hidalgo, Amador, Alfaro, & Quesada, 2013). Reliability of climate models are needed to be considered prior to the predictions as the level of accuracy of the predictions should be within an acceptable and a reasonable range. Because of that reason, it is recommended to compare an observable matrix with the predicted data set in a way like the sensitivity of the climate model across model ensembles.

2.4.2 Generated future climate data for the region

There is a fair amount of studies conducted to predict future climate data in Sri Lanka. They have highlighted the changes in both rainfall and temperature depending on different climate change scenarios. Under this study, a special focus was given to the studies conducted in the Deduru Oya basin or basins nearby and the results were analysed of those studies to identify the possible changes in the climate parameters; rainfall and temperature.

A study conducted for the Hakwatuna Oya irrigation scheme which is in the upper Deduru Oya basin has analysed the impact of climate change with respect to rainfall and temperature on the irrigation water requirement. From 1972-2001 was taken as the base period for the study and two IPCC (Intergovernmental Panel on Climate Change) emission scenarios; A2 and B2 were used with a SDSM (Statistical Downscaling Model). As results, they have found that the Mean Annual Rainfall (MAR) is expected to be increased by 12% under the A2 scenario and by 14% in the B2 scenario in the 2020s (2011-2040). MAR increase for the 2050s (2041-2070) will be 32% in the A2 scenario and 27% in the B2 scenario (Rajendran, Gunawardena, & Dayawansa, 2017)

(See Figure 2-5). De Silva (2006) also proves the possibility of having an increase in MAR in the study. However, some studies have found out bit dissimilar results to the findings of the above studies and some have concluded that there is no significant increase or decrease in the annual rainfall under some scenarios. A study conducted for Kurunegala District using an SDSM 4.2 downscaling model for a base period of 1961-2000 has concluded that there is only a marginal increase in the rainfall trend under A2 scenario while it remains as a constant in the B2 scenario up to around 2100 (Dharmarathna, Herath, & Weerakoon, 2014).

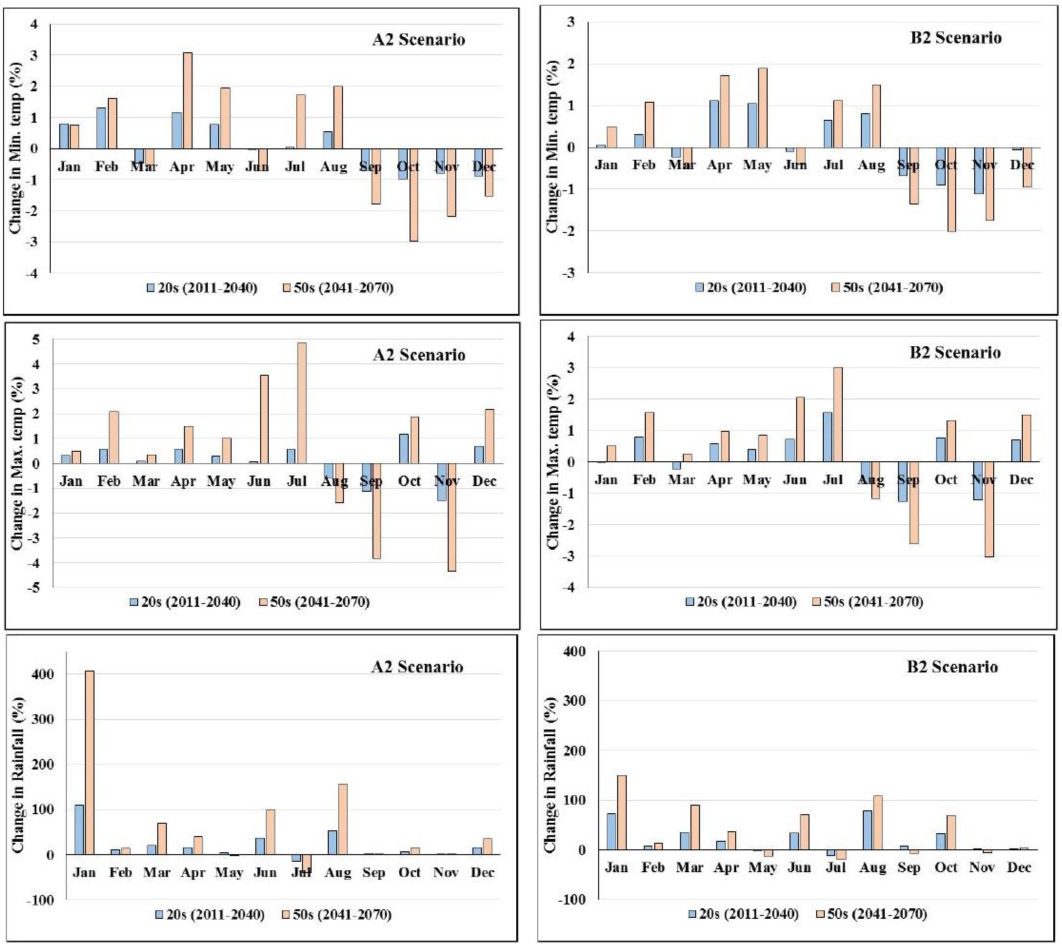

Figure 2-5: Monthly variation (%) of future rainfall and temperature with reference to base scenario (1972-2001)

Source : Rajendran, Gunawardena, & Dayawansa (2017)

According to the data from the Department of Meteorology, Sri Lanka in 2010, it has been mentioned that it is hard to identify a trend in the precipitation but the patterns have changed. It also highlights that a decreasing trend has been observed historically but the decrease is not statistically significant (Ministry of Mahaweli Development and Environment, 2010). Changes in the maximum and minimum temperatures were studied and almost all the studies referred pointed up that there is a trend for an increase in the annual temperature. Some studies have conducted separately for Yala and Maha seasons (Rajendran, Gunawardena, & Dayawansa, 2017) and some have focused in the increase per year or a decade. According to (Dharmarathna, Herath, & Weerakoon, 2014), there can be an increase of 0.05 °C per year under A2 scenario and 0.03 °C per year increase under the B2 scenario for the maximum temperature. Moreover, a similar study has called attention to the minimum temperature increase and it has observed that there is an increase of 0.02 °C per year under scenario A2. Department of Meteorology data describes a 0.2 °C increase per decade in the temperature considering a most recent time band for the year the study was conducted (2010) (Ministry of Mahaweli Development and Environment, 2010).

2.5 Analysing the Impacts of Climate Change using Hydrological Modelling

2.5.1 HEC-HMS modelling to analyse the impacts on streamflow

The Hydrologic Engineering Center–Hydrologic Modelling System (HEC–HMS) software is one of the most widely used open-access software for rainfall-runoff modelling. It can be used to estimate the streamflow output for a specific basin or a specific sub-basin by using the rainfall, temperature and evaporation data. This application has been successfully applied for many basins in Sri Lanka under several research works and reliable and acceptable results were obtained (De Silva, Weerakoon, & Herath, 2014; Halwatura & Najim, 2013; Sampath, Weerakoon, & Herath, 2015). By using the projected rainfall, temperature and evaporation data for the future, future streamflow output is supposed to be obtained by using this software under this research.

A runoff simulation was conducted for the same basin and it has been identified that there is a potential in HEC–HMS to reproduce streamflows ensuring an acceptable accuracy level with averaged Nash Sutcliffe Efficiency (NSE) value of 0.80. Furthermore, the methods they have used can be used for this research as well as it has obtained very acceptable results. They have used soil moisture accounting method for the loss model, Clark unit hydrograph method as the direct runoff model and Recession method for the baseflow model (Sampath, Weerakoon, & Herath, 2015). Figure 2-6 displays the development structure of HEC-HMS model.

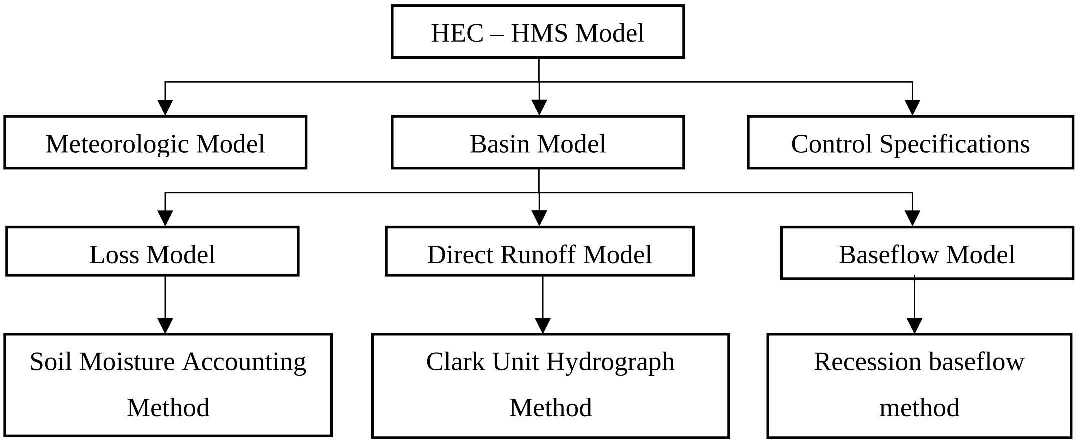

Figure 2-6: Development structure of HEC – HMS model
Source: Sampath, Weerakoon, & Herath (2015)

2.5.2 HEC-ResSim modelling to analyse the impacts on reservoir operations

The suitability to simulate a real reservoir system with the Hydrologic Engineering Center-Reservoir System Simulation (HEC-ResSim) software has been mentioned in previous literature while recommending it for future studies as well. The use of many variables for the simulation comparing with several other simulation methods is highlighted as a major reason for this higher accuracy level in the simulations (Baraa, Jebbo, & Awchi, 2016). Furthermore, the ability of multi-reservoir simulation is also emphasized in some of the literature under simulation of water resource systems (Lara, Lopes, Luz, & Bonumá, 2014). Hence, it will be suitable to use this software for the reservoir system simulation to assure acceptable results under this study as well.

2.6 Long-Term Basin-Wide Water Resources Management

Consideration of climate change as an important fact in all planning strategies and development of mitigatory and adaptation measures will be very important for a country to face climate change in the long-term basis. A review conducted for Arab countries underwater resource management with climate change describes the importance of basin-wide agreements with neighbouring countries in order to ensure the facilities even in worse climatic situations (Gayar & Hamed, 2018). Most importantly, there can be a shift in the climate zones and the instability occurring in the rainfall patterns can cause some adverse impacts like a drawdown in the water table and degradation in the land cover (Gordon, et al., 2013). It highlights the significance of having agreements with neighbouring countries as it may be able to provide some assurance to ensure safe access to water.

Construction of required water infrastructure to manage the water resources will act as a better solution for the climate vulnerability of water resources. Further, improvements in the water regulations can become an assistance to assure proper water management by guiding the society. Further, making a trend towards the rational water allocation will also become a massive initiative to manage water resources. Information based technology applications can be used to ensure the protection of the water resources in advance. All of these policy-level decisions can be implemented and controlled by water resource commissions in basin-scale (Chen, Niu, & Sun, 2013).

It is very crucial to acquire and gather sufficient climate change information required for formulating these policies by the organizations which are supposed to involve in long-term water resource management. Water security is considered as a sound early adaptation strategy for water management. Where the water security is not ensured, climate change may compound the difficulty of achieving that (Andrew & Sauquet, 2017).

It has been identified that water stress can be increased more in the developing regions and decreasing in the industrialized regions. Thus, water resource management can be planned and conducted accordingly (Alcamo, Flörke, & Maerker, 2007). Proper management of water resources may help to face the adverse effects, but also it is needed to identify the methods of minimizing the negative impacts of climate change in advance.

Research conducted for Dongjiang River basin in South China also emphasized the possibility of having seasonal or water quality-related shortages and as a solution, it has been highlighted the need of focusing more on alternative ways of water management (Yang, Chan, & Scheffran, 2018).

It is recommended to use a policy of ‘no regret and flexibility’ to adhere to proper planning and management in the water resources with the uncertainties associated with climate change while considering the cost as well (Middelkoop, et al., 2001). Conducting more and more systematic research on reducing climate change impacts is very significant in addressing the impacts identified under different scenarios in diverse regions across the globe. As a summary, it is very important to conduct more research to identify the possible impacts of climate change and to identify the possible approaches to implement long term water resource planning and management strategies in an acceptable and adequate manner.

2.7 Summary Discussion

Climate change affects reservoir hydrology by increasing temperature, altering patterns of precipitation and streamflow and increasing evaporation rates in most of the areas. It also has an effect on the reservoir operations since the regulated flows get varied with the streamflow input into the reservoir. Both increases and decreases in the streamflow have been identified in several research works and that directly depends on the region analysed. According to the region concerned, the impact varies in a way that warmer regions have more adverse effects than cooler regions. Hence, there is a risk of water scarcity to meet agricultural and drinking water demand with dry areas becoming even dryer. For a sustained generation of hydropower, it is needed to put forth further attention on the water preservation strategies and proper mitigatory measures for the adverse impacts of climate change by implementing necessary actions. Table 2-1 discussed the literature summary of the discussed parameters with factors affected, focal points and regions analysed.

Long-term basin-wide water resources management may help to adapt to the changing climate and to minimize the negative effects on water resources. The increased risk of the occurrence of frequent floods and droughts can also be reduced accordingly. As the climate change information can be varied from one region to another, it is essential to conduct further research on a regional basis and acquire adequate information for a better insight when carrying out designing and other planning works to have effective water resource management in both short- and long-term basis.

3.0 MATERIALS AND METHODS

3.1 Methodology Flow Chart

The methodology followed for the current study is illustrated using Figure 3-1 below.

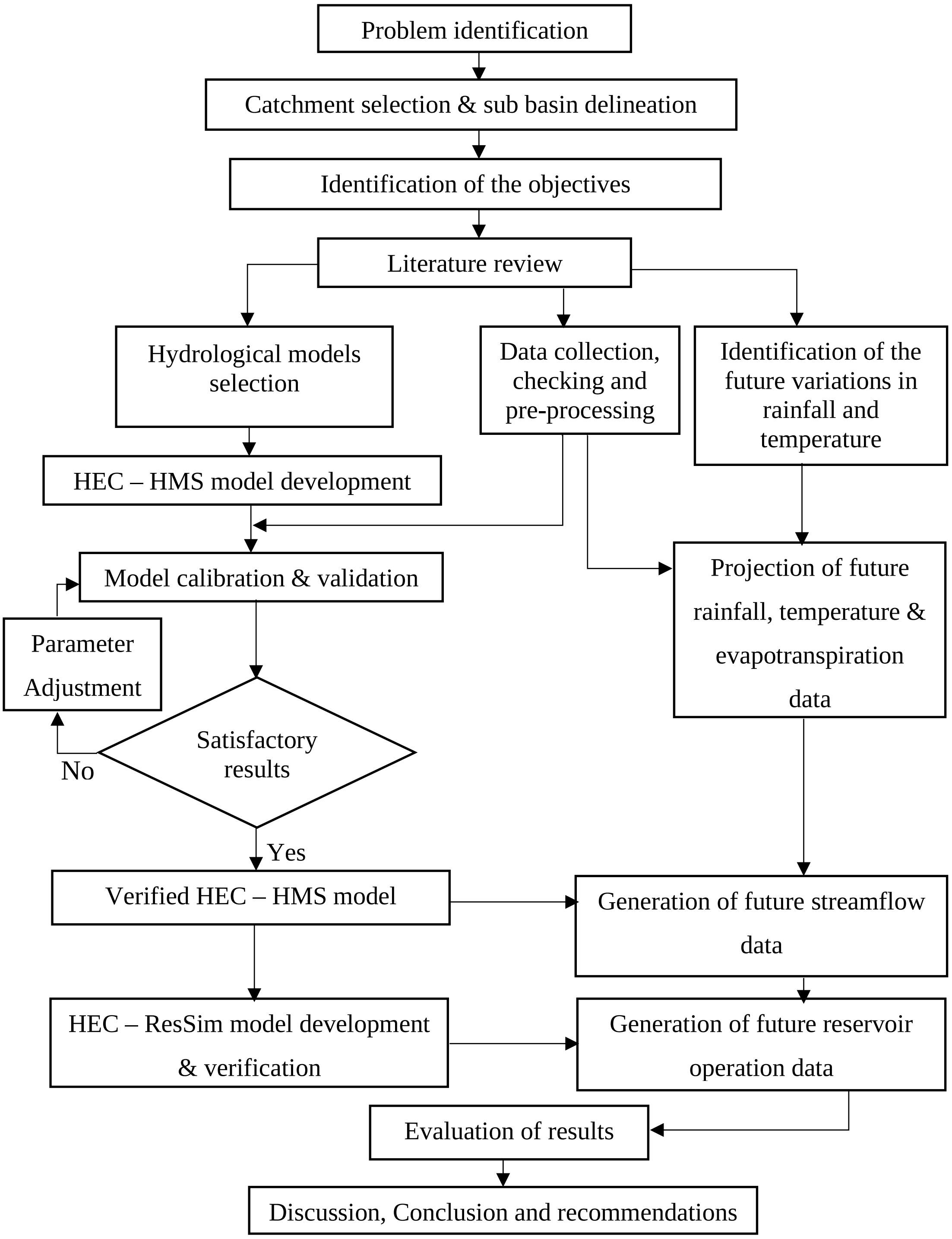

Figure 3-1: Methodology flow chart

According to the problem identified, a suitable catchment was selected and the main and the specific objectives were listed. After that, a comprehensive literature review was conducted to study about climate change, future climate data generation, impacts due to climate changes, hydrological modelling and some other relevant details.

A well-structured methodology that can assist to conduct a comprehensive literature review on analysing the impacts of climate change was followed in the study. The key steps of the methodology are i) Identification of the research problem, ii) Identification of the subcategories which are needed to be studied, iii) Identification of the relevant studies for each subcategory, iv) Studying and screening the studies, and v) Summarising and reporting the results with recommendations. As the first step, the research problem was identified as, "What are the impacts of climate change on reservoir hydrology and how can we identify and implement an adequate water resource management plan in basin-scale in long term basis with those impacts?". Then, the targeted scope was divided into subcategories. Studying about the climate change impacts, generation of future climate data, usage of hydrological models for the climate change impact analysis and long-term basin-wide water resource management was identified as the main areas to be focused on in this study. Under the climate change impacts, impacts on eight different subcategories of reservoir hydrology were identified in the literature review. Identified eight subcategories are, i) temperature, ii) precipitation patterns, iii) total runoff and streamflow, iv) reservoir operations, v) vulnerability to floods and droughts, vi) agricultural and drinking water demand, vii) hydropower generation, and viii) ecological flow.

Selected literature was downloaded and categorized under each subcategory. Several electronic databases were used to get access to the literature and ScienceDirect, SCOPUS databases, as well as Google search engine and Google Scholar, were also used to identify peer-reviewed and indexed publications. This review was limited only to the publications published in the English language. At the original state of studying the literature, recent past review studies were identified under the subcategories and they were screened. Subsequently, more attention was given to the literature that was published after the publication dates of the selected review articles under each category. By using that methodology, many recent articles of literature were studied and proper and adequate review was conducted.

Further, since this is a study discussing about climate change impacts on reservoir hydrology, it was very important to select studies representing all the regions around the world. With that reason, special attention was paid to the studied areas when selecting and screening the literature. The reviewing of the literature was conducted for the other identified major areas like the generation of future climate data, usage of hydrological models for the climate change impact analysis and long-term basin-wide water resource management as well. Subsequently, as the final step, the selected pieces of literature by the screening process were specially analysed and the summarising and concluding works were carried out.

Following the findings from the literature review, the hydrological models were selected for the streamflow generation as well as for the generation of reservoir operation data. HEC-HMS and HEC-ResSim software were selected for the modelling at that stage. Also, with the help of the previous literature, the data requirement was identified for the study and suitable stations were selected considering the data availability and accessibility. All the data were collected from different institutions and they were checked and pre-processed for the analysis. Furthermore, the literature containing details about future predictions relevant to the selected basin; Deduru Oya were well referred and predictions for this study were selected based on the availability of the required details for the projections, acceptability of the results and many other factors. Data checking was conducted using several methods such as visual checking, single mass curve method and double mass curve method. The gaps were filled in the data sets and the interpolation of data was done using the Thiessen Polygon method.

The HEC-HMS model was developed for the basin and the prepared data sets were used to calibrate and validate the model to come to an acceptable accuracy level. Subsequently, the HEC-ResSim model was developed for the Deduru Oya reservoir using the data gathered from the literature as well as form the visits to the institutions. Then the developed model was verified using the observed data and preparation of the models for the study was finished. With the help of the future predictions from the literature on rainfall, minimum and maximum temperature, future data was projected for the basin for two future periods 20s (from 2011 to 2040) and 50s (from 2041 to 2070) and using the temperature data evapotranspiration data were projected. Then the projected data were used to generate the streamflow output from the verified HEC-HMS model and then the model output was used to obtain the reservoir operation data from the HEC-ResSim model. The outputs from both models were used as the results of the study and discussion, conclusion and recommendations were made depending on the results obtained.

3.2 Study Area

3.2.1 Sub basin delineation

Ridi Bendi Ela sub-basin was delineated using the ArcMap 10.3 (ESRI, USA) software and a Digital Elevation Model (SRTM 90 m DEM). The “Hydrology” tool in the “Spatial Analyst” tools in ArcMap software was used for the delineation process. Finding and filling the sinks were done using the “Fill” option and a depressionless DEM was created. Then the “Flow Direction” tool was used for the flow direction analysis. After identifying the flow directions, the number of cells that flow into a particular cell was obtained using the “Flow Accumulation” tool to identify how the flow paths behave. After that, by using the Ridi Bendi Ela pour point, the sub-basin was delineated using some other tools and the stream network was created. The delineated sub basin with the stream network and its location in the Sri Lankan map are shown in Figure 3-2. The sub-basin area is 1394.02 km^2. The delineated sub-basin is helpful to determine the interpolated rainfall, temperature and evaporation values for the basin in further analysis. Using the point values of the above parameters, the interpolated value can be determined together with the delineated sub basin. Apart from that, when developing the hydrological models it is very useful to obtain a better understanding about the features of the drainage basin in detail.

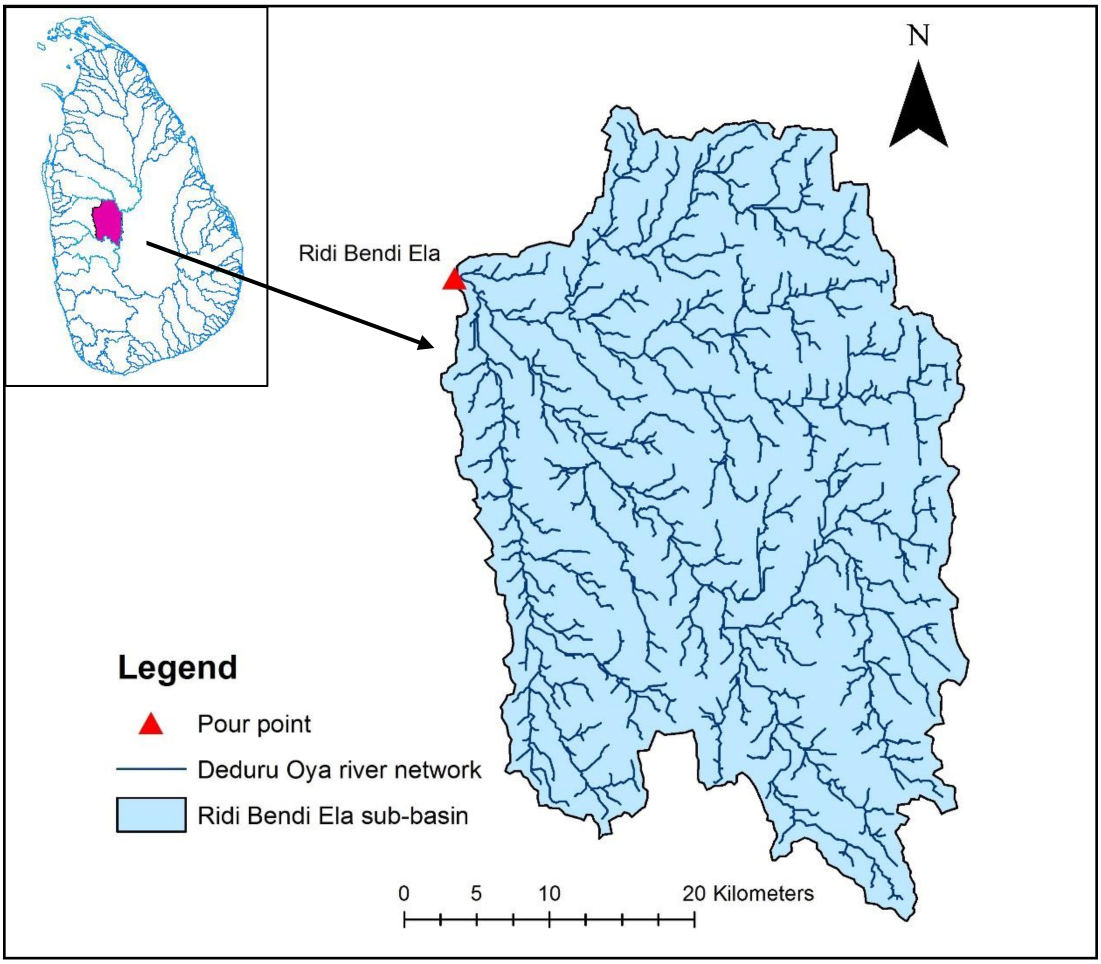

Figure 3-2: Ridi Bendi Ela sub basin

3.2.1 Data collection of the Deduru Oya reservoir

Having the major purpose of utilizing the water available in the basin, the Deduru Oya Reservoir Project was initiated in the last decade in Sri Lanka. The construction of the Deduru Oya reservoir was started in 2006 and after several years of construction, the dam was opened in 2014. The reservoir dam was constructed about 300 m upstream of the existing Ridi Bendi Ella anicut and the reservoir built has a capacity of 75 MCM and a 1394.02 km^2 catchment area. There are numerous benefits of the project such as maximizing paddy cultivation, increasing the Gross Domestic Production (GDP), enhancing the living standards, generating electricity using 1.5 MW power plant and some other additional benefits such as developed road network to ensure both accessibility and mobility. According to the data gathered from the Department of Irrigation, Sri Lanka the reservoir details, spill details and other project details are as follows. There, Figure 3-3 displays the elevation-capacity curve of the Deduru Oya reservoir and Table 3-1 displays the sluice details.

Reservoir Details:

Average Bund Height = 17 m

Capacity = 75 MCM

Full Supply Level = 70.79 MSL

Area at full supply level = 2,100 ha

High flood level = 71.32 MSL

Catchment Area = 1,394.02 km^2

Command Area = 12,000 ha

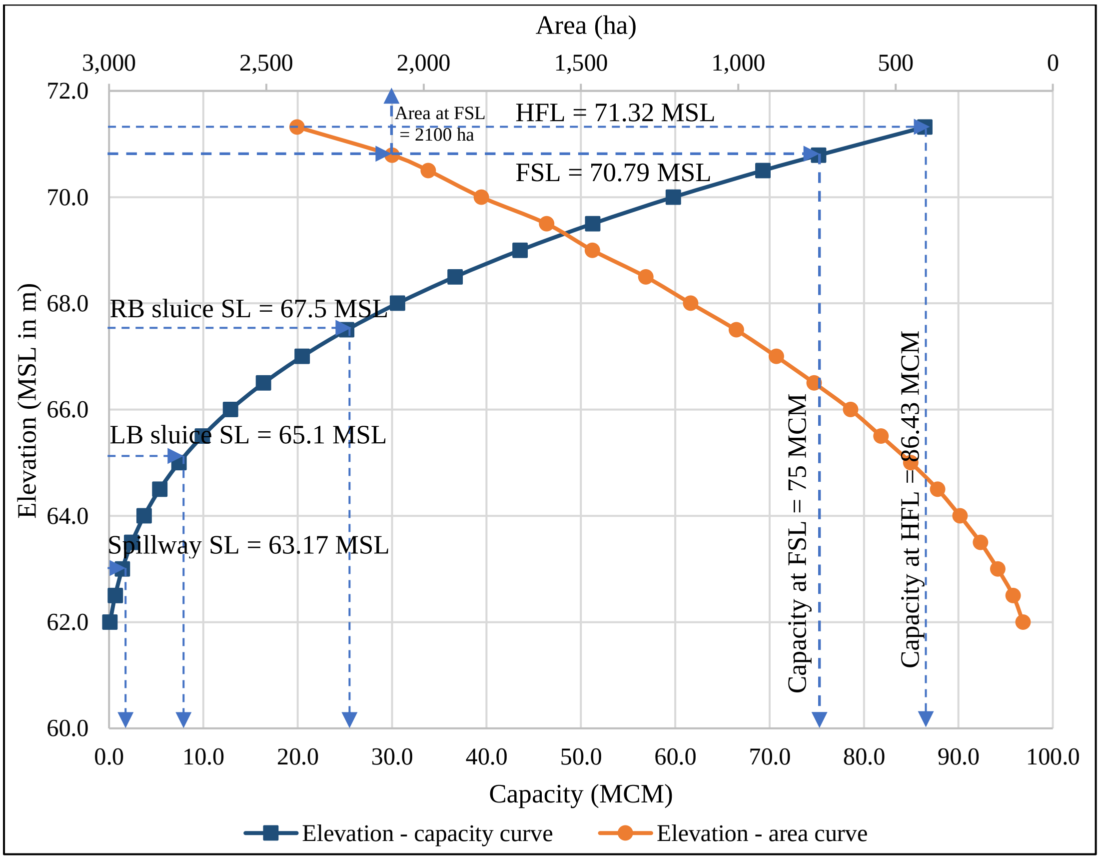

Figure 3-3: Elevation - area - capacity curve of Deduru Oya reservoir

- Sluice Details:

Table 3-1 Sluice details

	Left bank sluice	**Right bank sluice**	**Scour sluice**
Sill level (SL)	65.1 MSL	67.5 MSL	56.5 MSL
Length of channel	44 km	36.7 km	-
Discharge	7 m^3/s	8.5 m^3/s	-
Size of gate	1.5 m * 2.0 m (2)	1.7 m * 2.2 m (2)	1.6 m * 1.8 m (2)

- Spill Details:

Length = 68 m

Type = Radial Gated

Sill level = 63.17 MSL

Size of a gate = 8.5 m * 8.1 m

Number of gates = 8

3.3 Data Collection, Checking and Pre-processing

3.3.1 Data collection

After reviewing several climate studies under the literature review, it has been identified the parameters: rainfall, streamflow, minimum temperature and maximum temperature as the required data for the study. Apart from that, for the reservoir modelling, Deduru Oya reservoir operation data were needed as an additional requirement for the verification of the developing HEC-ResSim model. Daily data resolution was identified as the appropriate resolution for the study as weather extremes can make impacts even within short timescales and as generally the future climate data prediction is done on a daily basis when using the climate models (Dietrich, et al., 2019; Rajendran, Gunawardena, & Dayawansa, 2017). Possible most recent data periods were selected to ensure the accuracy and validity of the results of the study. Data availability for the selected stations was highly considered and it has been ensured to have an acceptable spatial distribution of the stations in the basin to obtain more representative interpolated values for the analysis. When deciding the appropriate number of stations for the selected sub-basin, World Meteorological Organization (WMO) guidelines (WMO, 2008) were followed and the number of stations was selected as showed Table 3-2. Details of the collected data sets are in Table 3-3.

Table 3-2: Selection of the number of gauging stations

Gauging Station Type	**Minimum No of Stations**	**Station Density (km^2/station)**	**WMO Standards (km^2/station)**
Rainfall	3	473	575
Streamflow	1	1500	1875
Temperature	1	1500	5000

Table 3-3: Data sources and availability

Data Type	**Stations**	**Data Resolution**	**Period**	**Obtained from**
Rainfall	Ridi Bendi Ela, Wariyapola, Bathalegoda, Kurunegala, Millawana Estate	Daily	1980 - 2018	Department of Meteorology
Streamflow	Ridi Bendi Ela	Daily	1990 - 2011	Department of Irrigation
Temperature (Minimum and Maximum)	Mahailuppallama, Bandirippuwa, Kurunegala	Daily	1980 - 2018	Department of Meteorology
Reservoir Operation Data	-	Daily	2014 -2018	Department of Irrigation (Kurunegala)

Following figure, Figure 3-4 displays the locations of the rainfall, temperature and streamflow stations in relation to the basin.

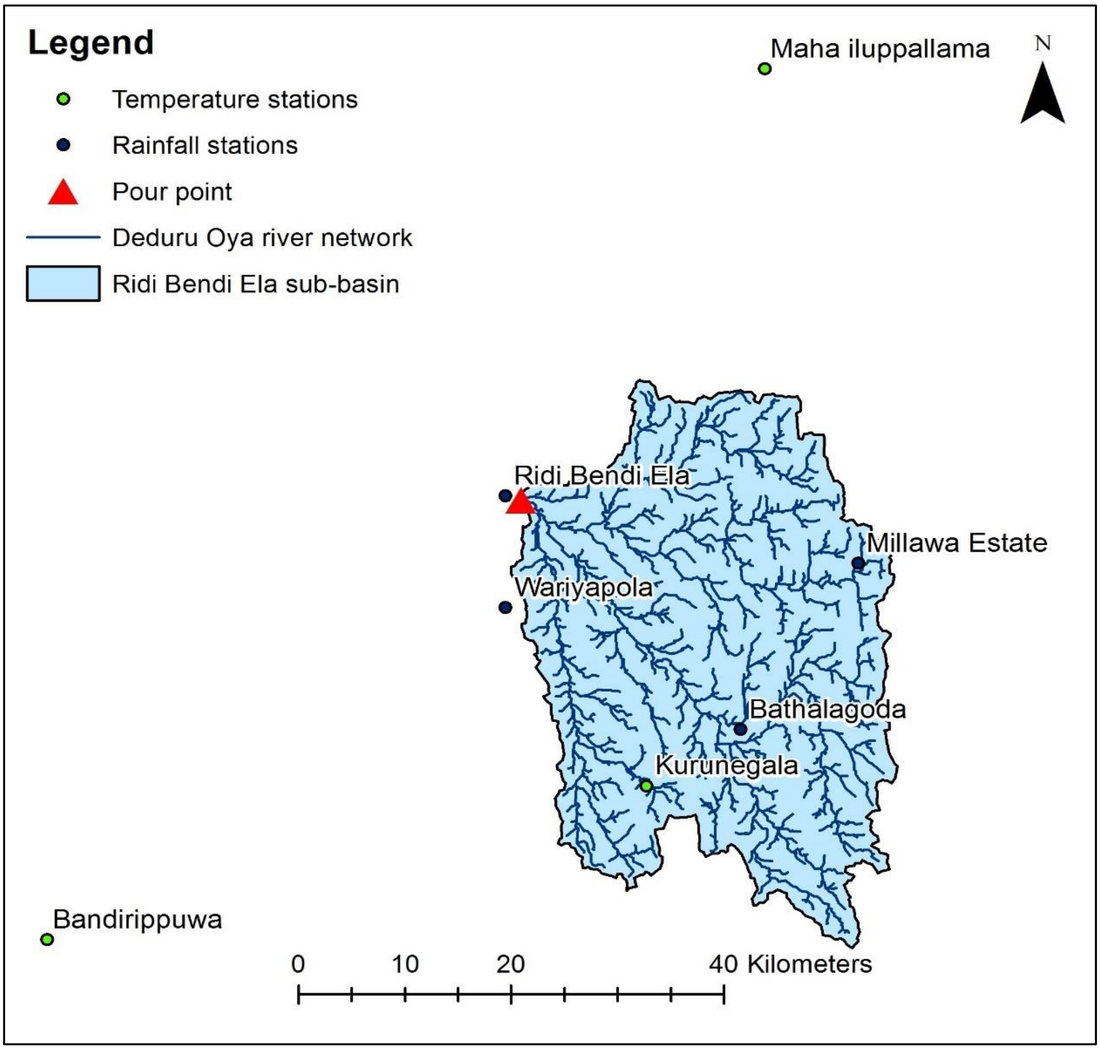

Figure 3-4: Locations of selected stations

3.3.2. Data checking

Visual data checking, single mass curve and double mass curve methods were used for the initial data checking process and to fill missing data. As the first step, all the data were tabulated in the same format for the ease of conducting the data checking. Then the visual data checking was carried out by plotting both streamflow and rainfall in the same plot to identify the inconsistencies in the data. The obtained plot for Ridi Bendi Ela rainfall station is as in Figure 3-5. The identified inconsistencies are highlighted with red rectangles. The graphs for other rainfall stations are attached as Appendix I. Before selecting the methods for filling the missing data, the missing data percentages for each station were identified and those values are as displayed in Table 3-4. As those values were not more than 10%, the single mass curve method was accepted for gap filling.

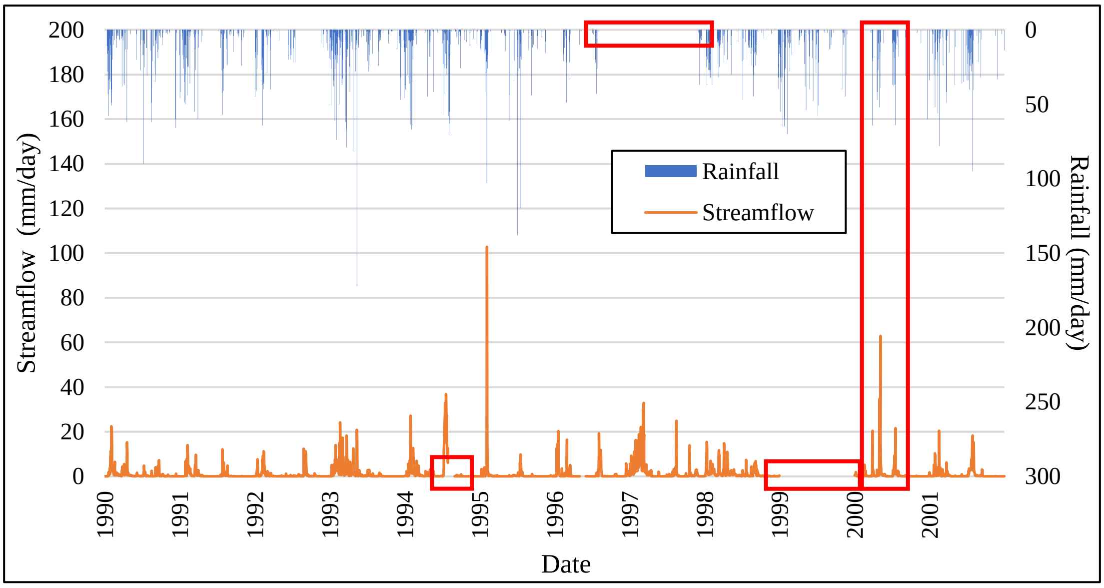

Figure 3-5: Visual checking - Ridi Bendi Ela rainfall station

Table 3-4: Details of missing data

Data Type	Station Name	Missing Percentage
Rainfall	Ridi Bendi Ela	10.00%
	Wariyapola	1.71%
	Bathalegoda	0.06%
	Kurunegala	0.88%
	Millawana Estate	9.91%
Maximum Temperature	Mahailuppallama	2.27%
	Bandirippuwa	3.59%
	Kurunegala	0.59%
Minimum Temperature	Mahailuppallama	1.43%
	Bandirippuwa	2.11%
	Kurunegala	0.28%

The correlations between each station were observed for the purpose of identifying the most correlated station for each station to continue with the missing data filling process. The correlations between the rainfall stations are as in the Figure 3-6.

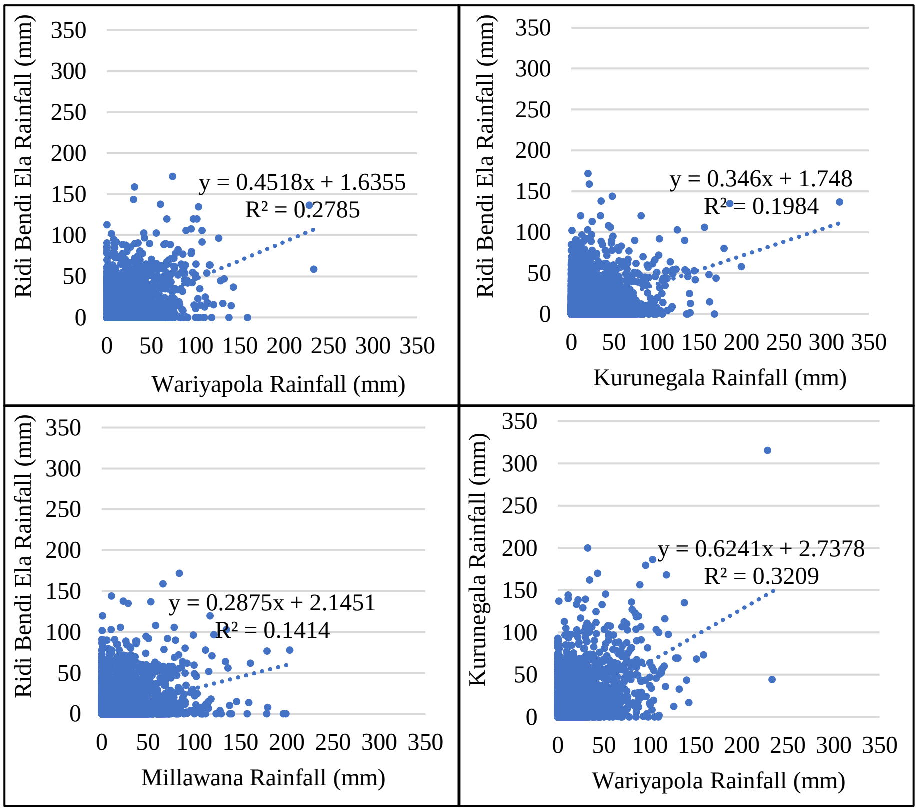

Figure 3-6: Correlations between the rainfall stations

As the missing percentages were not more than 10%, the single mass curve method is acceptable to fill the missing data in the data sets. Basically, single mass curve method is used to check the homogeneity of the data for all stations (Wakachala, Shilenje, Nguyo, Shaka, & Apondo, 2015). With the use of the gradients having the most similar data variation patterns, the missing data can be predicted under this method. After plotting the single mass curve, the stations having the most similar data variation patterns were identified and it was considerably different from the identified relationships from the correlation analysis method. Because of this reason, it was decided to use the station with the nearest gradient in the single mass curve to fill the missing data gaps.

The single mass curves with gaps for rainfall, minimum and maximum temperature are as displayed below in Figure 3-7 to Figure 3-9. The gaps were filled in the single mass curves as in the following figures, Figure 3-10 to Figure 3-12.

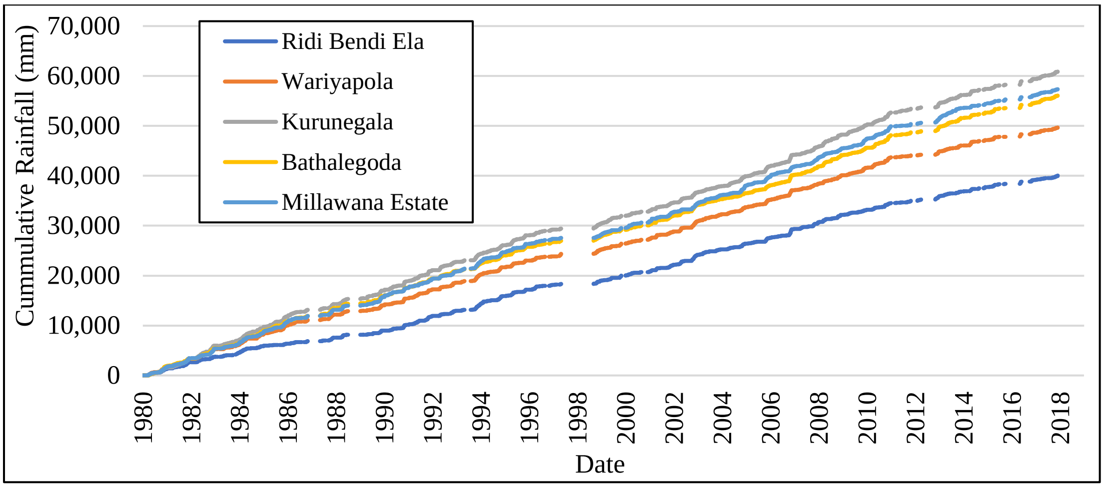

Figure 3-7: Single mass curve for rainfall stations with gaps

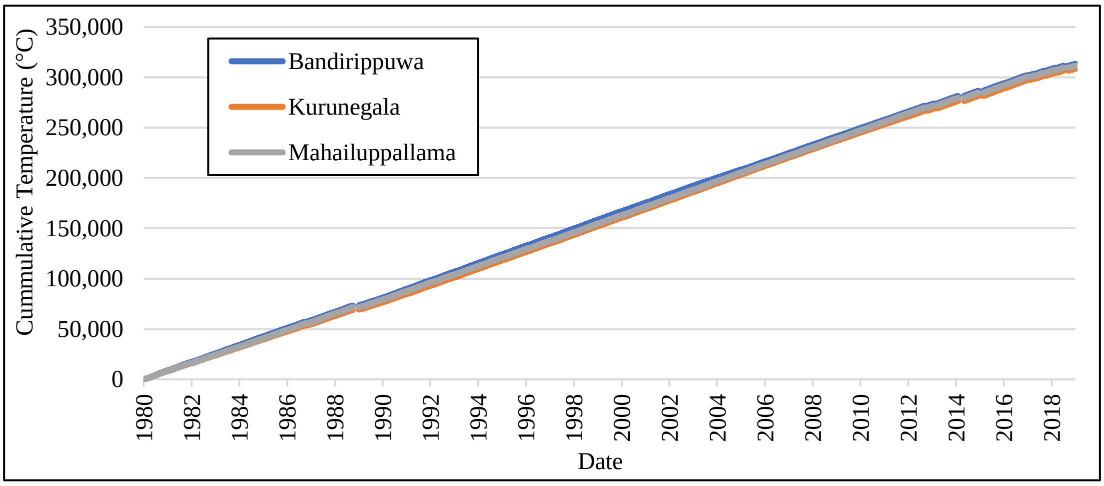

Figure 3-8: Single mass curve for minimum temperature stations with gaps

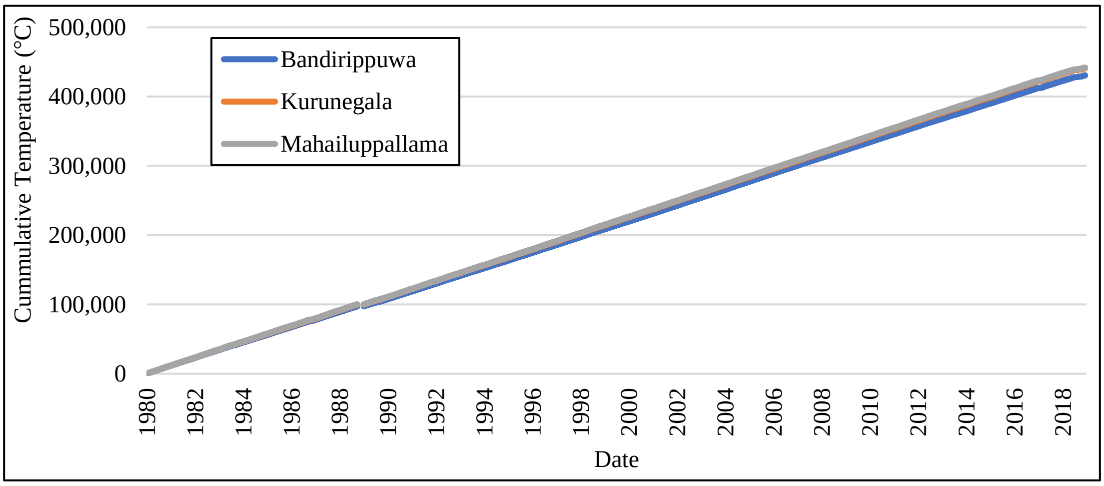

Figure 3-9: Single mass curve for maximum temperature stations with gaps

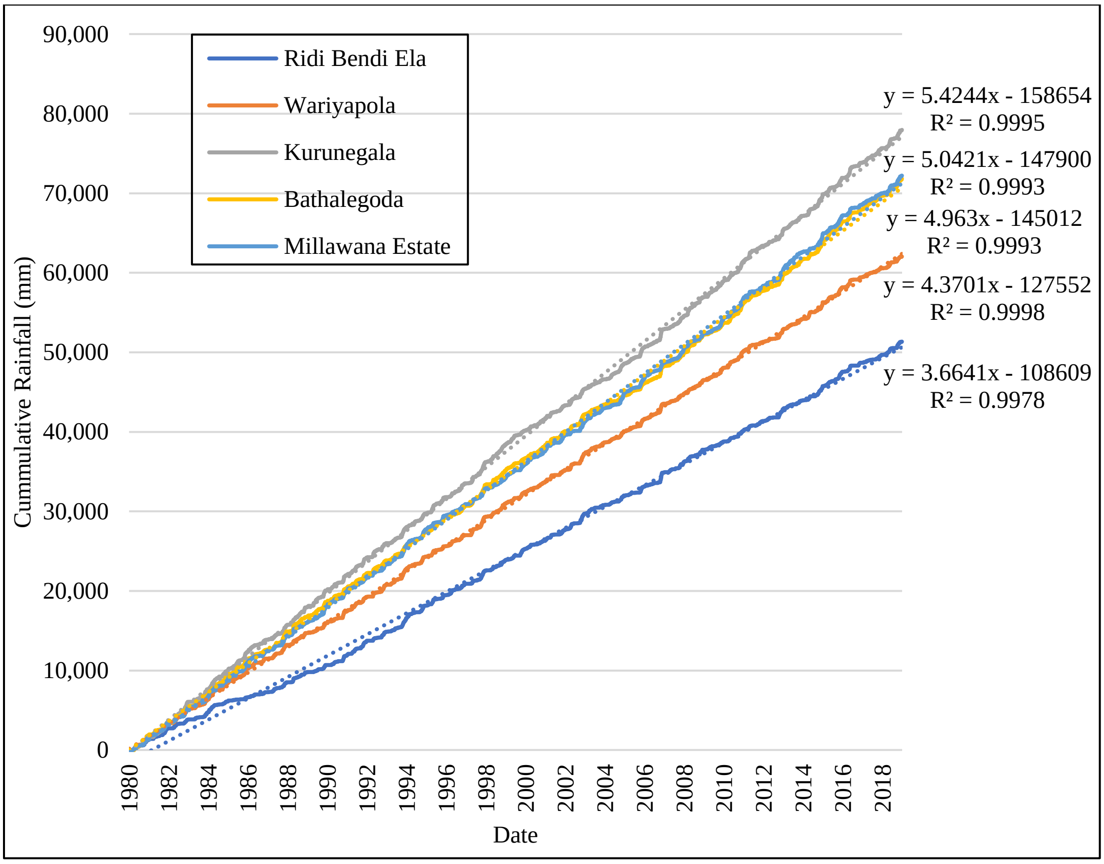

Figure 3-10: Filled single mass curve for rainfall stations

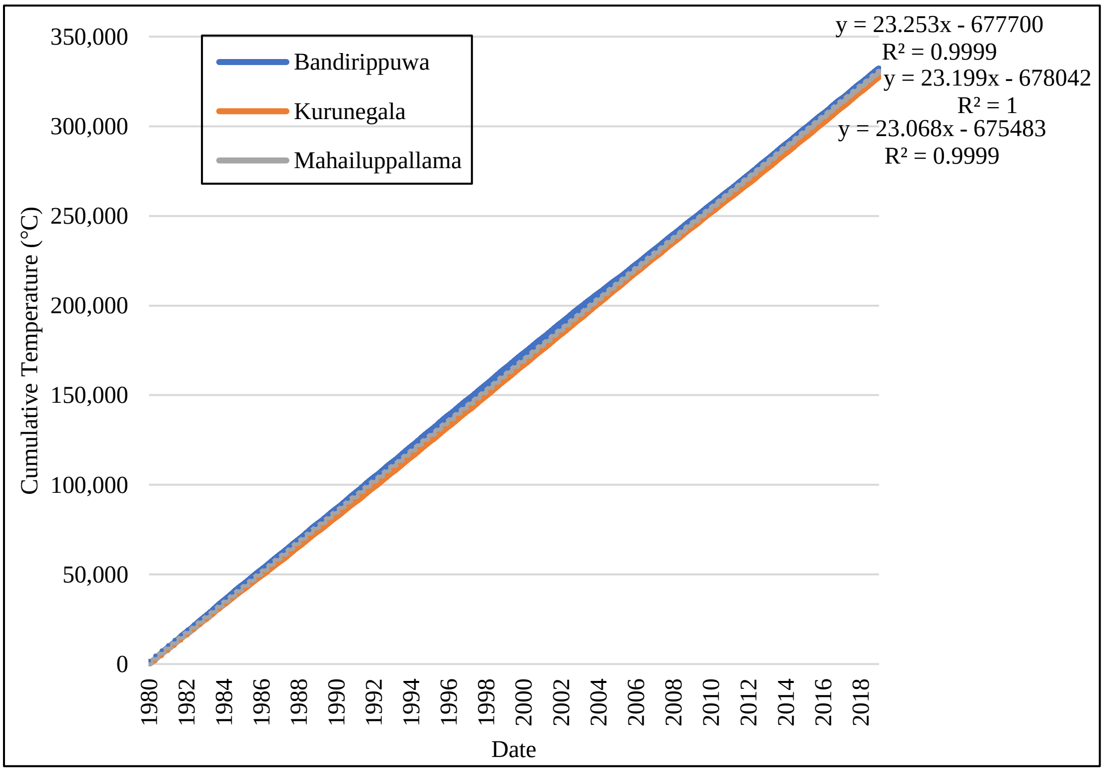

Figure 3-11: Filled single mass curve for minimum temperature stations

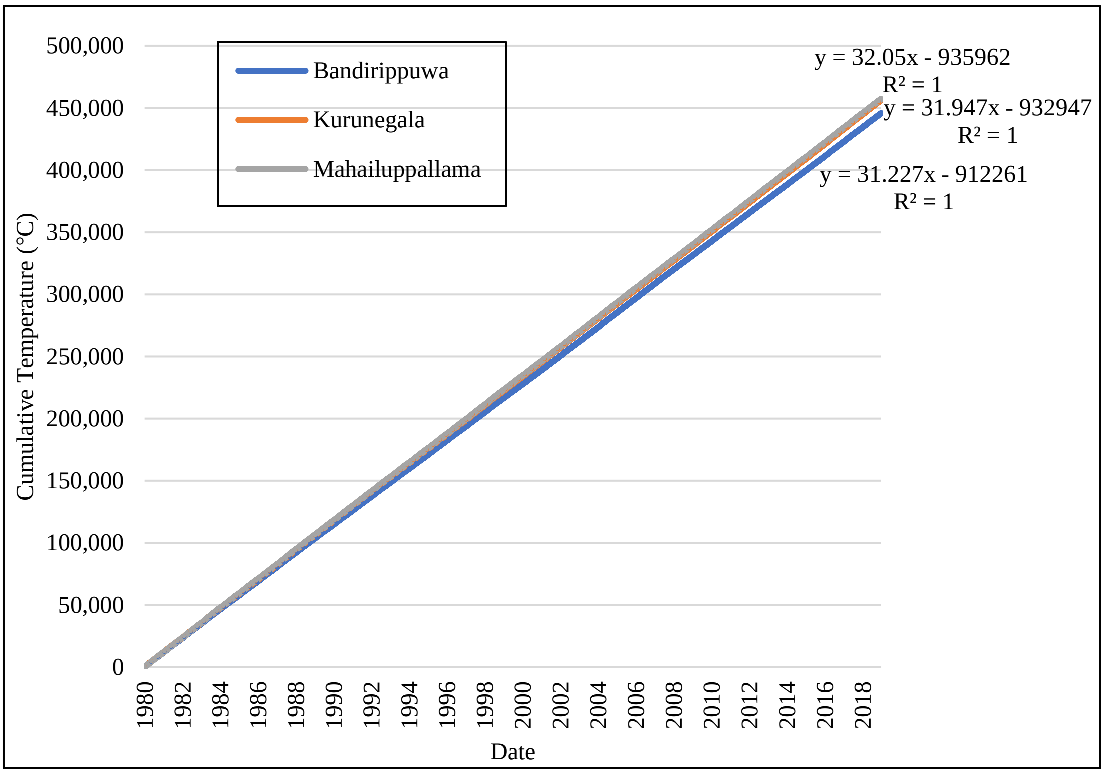

Figure 3-12: Filled single mass curve for maximum temperature

Consistency and the long-term trend of a hydro-meteorological time series can be identified using the double mass curves (Mu, Zhang, Gao, & Wang, 2010) . Obtaining a straight line for the double mass curve displays the consistency of the data sets. The double mass curve is generated of cumulative values of two parameters plotted against one another over a certain time (Searcy & Hardison, 1960). The obtained linear double mass curves showed that there is the consistency feature in the data sets which shows the accuracy and the acceptability of them.

Figure 3-13 to Figure 3-17 show the plotted double mass curves for rainfall stations Ridi Bendi Ela, Wariyapola, Kurunegala, Bathalegoda and Millawana Estate. Double mass curves for minimum and maximum temperature stations are displayed in Appendix II. Considering the temperature data sets, the same behaviour could be observed; all the stations obtained straight lines as the double mass curves and it displayed the consistency of the data sets. It has proved that those data sets also suitable to continue the study and obtain acceptable and valid results.

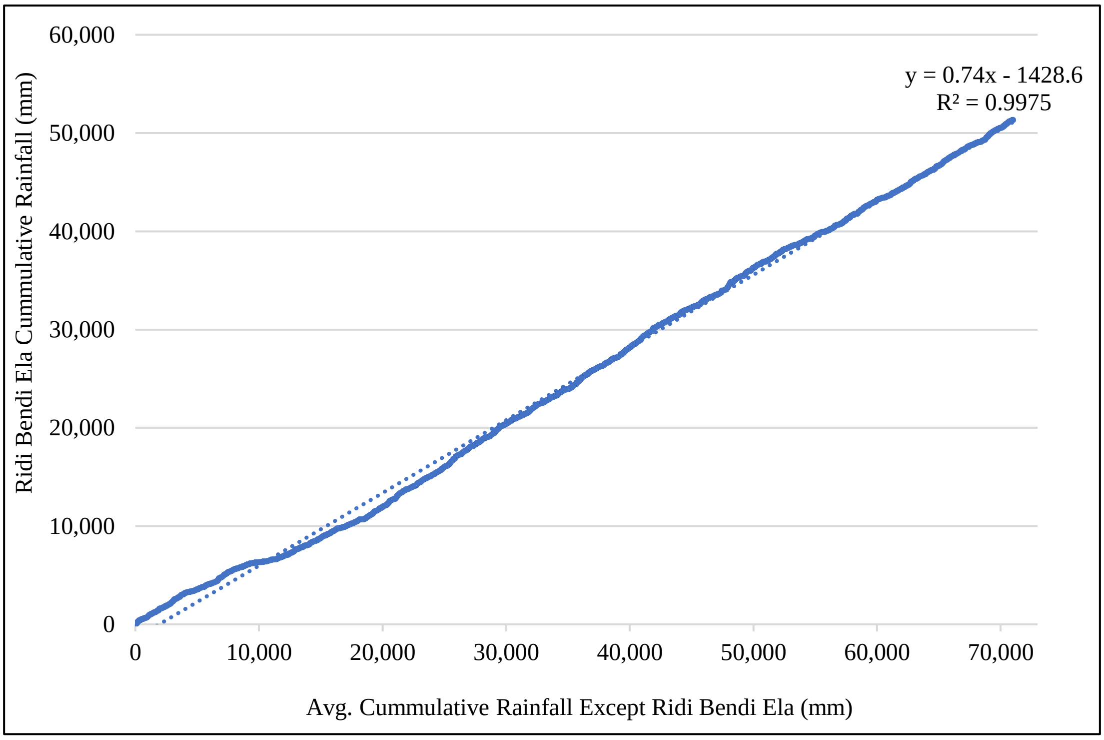

Figure 3-13: Double mass curve for Ridi Bendi Ela rainfall station

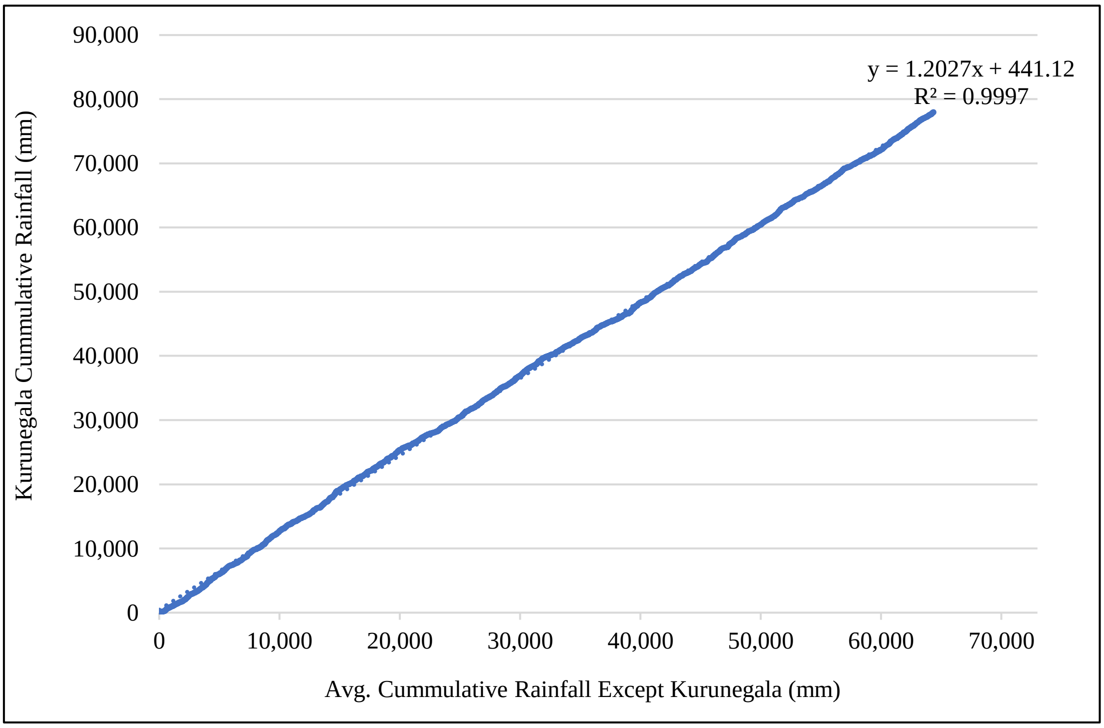

Figure 3-14 Double mass curve for Kurunegala rainfall station

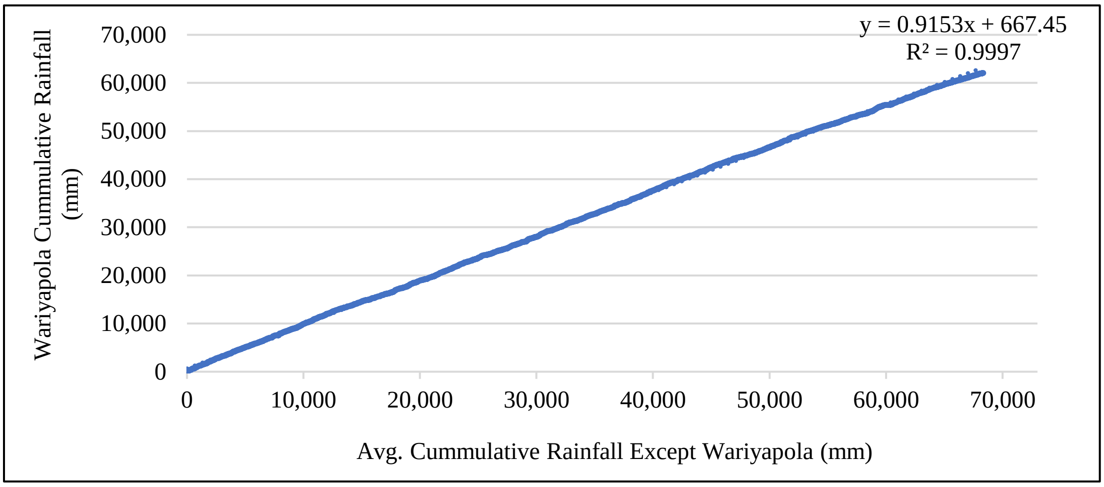

Figure 3-15: Double mass curve for Wariyapola rainfall station

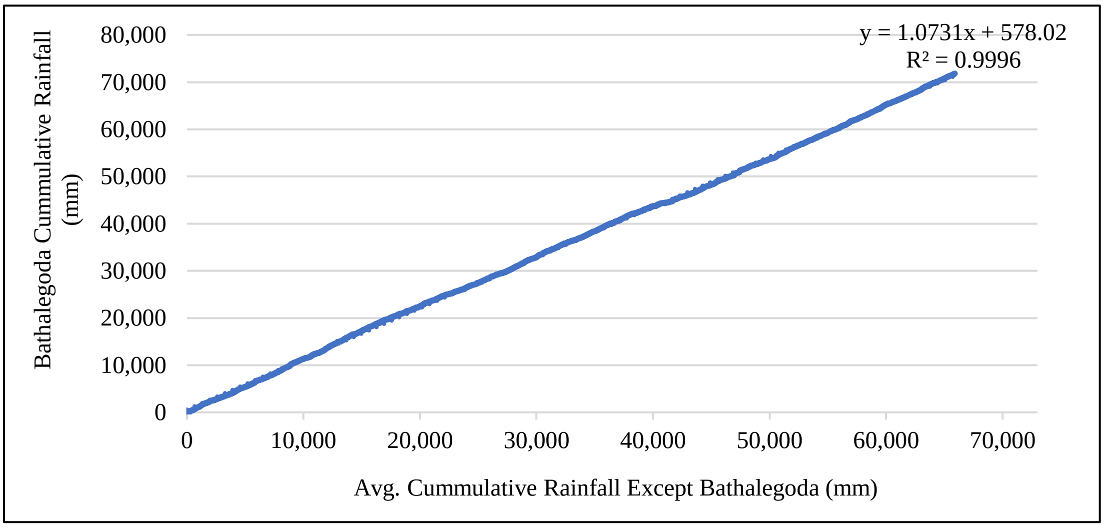

Figure 3-16: Double mass curve for Bathalegoda rainfall station

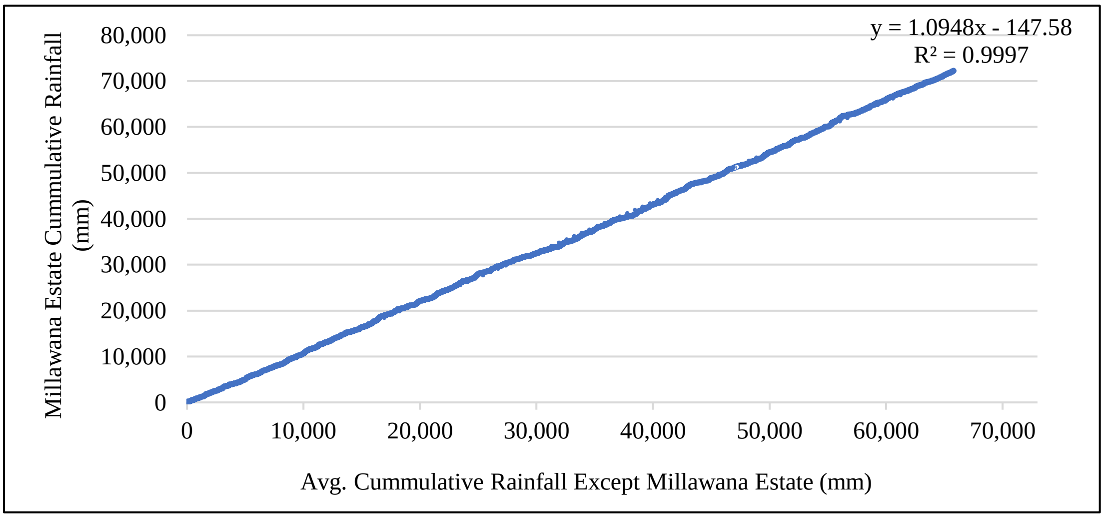

Figure 3-17: Double mass curve for Millawana Estate rainfall station

3.3.3 Data pre-processing

For the modelling process, it is needed to input rainfall, temperature and evaporation or evapotranspiration data as one set for each parameter which should be the representative data set for the entire sub-basin. In order to compile a representative data set, the point data should be interpolated using a suitable interpolation method. There are several spatial interpolation methods which can be listed under two main categories named as Deterministic and Geostatistical (Mendez & Calvo-Valverde, 2016). The simple average method, Thiessen polygon method and Inverse Distance Weighting (IDW) method are some of the methods which come under the deterministic category and Kriging is a very popular method listed under geostatistical category (Chen, et al., 2017; Lyra, Correia, de Oliveira, & Zeri, 2018; Zhang, Lu, & Wang, 2016). As the most popular deterministic interpolation method, the Thiessen polygon method provides a very easy calculation procedure and also acceptable results for the regions without significant mountainous topographies (Ly, Charles, & Degre, 2013; Thiessen, 1911). As Figure 2-2 displayed in Chapter 2, the Deduru Oya basin has a gradual and mild slop throughout the basin and only significant mountainous features contain near to the upper boundary of the basin which contains steep slops only at the edge of the boundary. This proves that using the Thiessen polygon method is totally acceptable and it may deliver accurate and acceptable results with a minimum effort for this study (Kahaduwa & Rajapakse, 2019). Hence, the Thiessen polygon method (Chow, 1964) was used to calculate the average values for the Ridi Bendi Ela sub-basin. As the first step, Thiessen polygon networks were developed using ArcMap 10.3 (ESRI, USA) software. The developed Thiessen polygons for rainfall stations are displayed in Figure 3-18 and Table 3-5 shows the Thiessen weights for each polygon developed.

Table 3-5: Thiessen weights for each rainfall station

Station Name	**Thiessen Area (km^2)**	**Thiessen Weight**
Ridi Bendi Ela	168.47	0.12
Wariyapola	158.64	0.11
Kurunegala	234.70	0.17
Bathalegoda	465.82	0.33
Millawana Estate	366.38	0.26
Total	**1394.02**	**1.00**

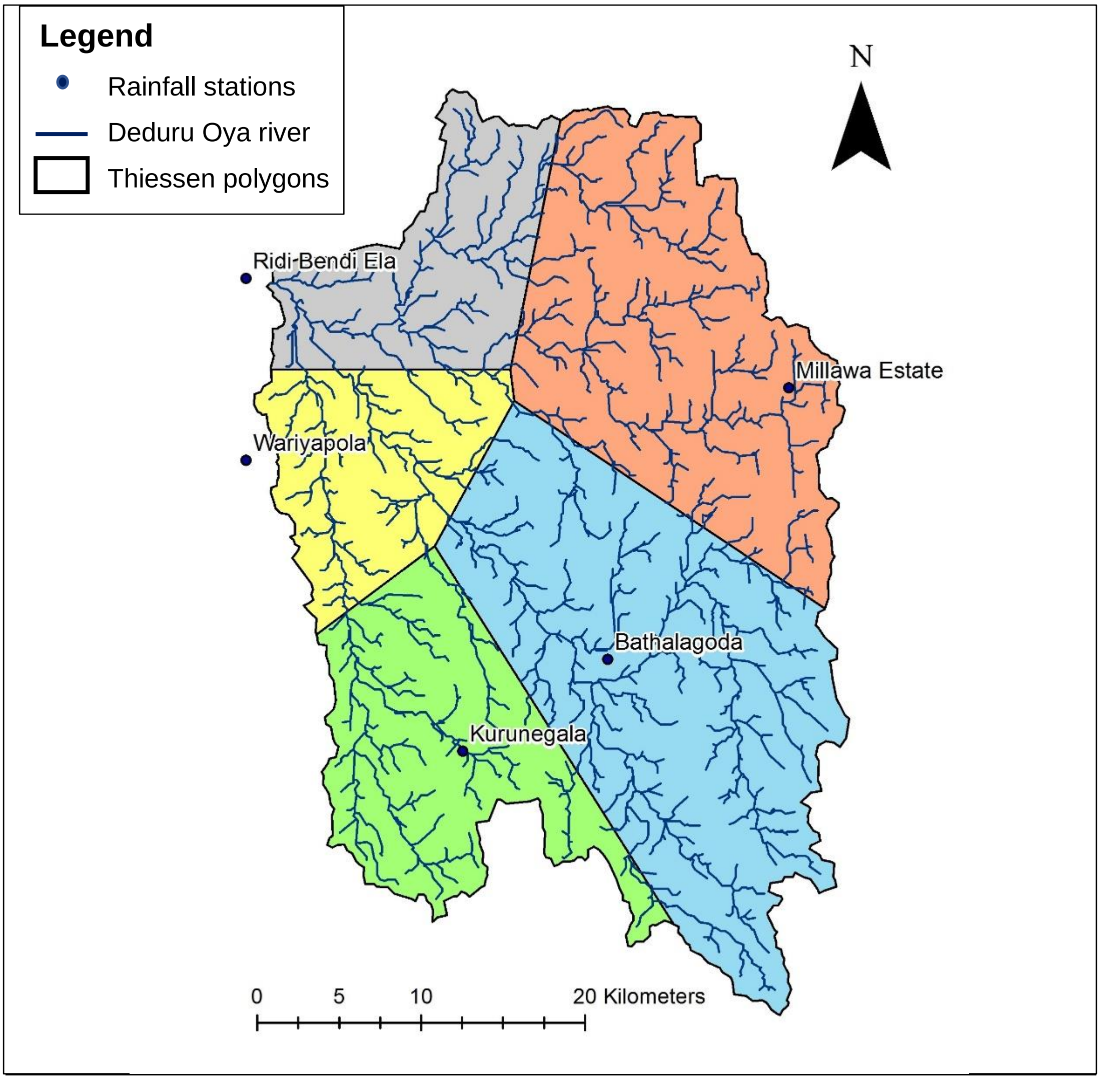

Figure 3-18: Thiessen polygon network for the rainfall stations

Furthermore, Potential Evapotranspiration (ETP) values also calculated prior to the modelling process using minimum and maximum temperature values and equations including the Hargreaves-Samani equation (See Equation 1) as discussed below (Hargreaves & Samani, 1985).

$$ETP = 0.0023 * R_a * (T_{max} - T_{min})^{0.5} * (T_{avg} + 17.8) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..\ldots(1)$$

Here, R_a is the extraterrestrial solar radiation (mm/day), T_{avg} is the daily average temperature (°C), T_{max} is the daily maximum temperature (°C) and T_{min} is the daily minimum temperature(°C). The extraterrestrial solar radiation, R_a was calculated using Equation 2 (Duffie & Beckman, 2013).

$$R_a = \left(\frac{24*3600*G_{sc}}{\pi}\right) * \left(1 + 0.033\cos\frac{360n}{365}\right) * \left(\frac{\pi \mathrm{W}s}{180} sin\phi\, sin\delta + cos\phi cos\delta sin\mathrm{W}s\right) \ldots\ldots(2)$$

Here, G_{sc} is the solar constant, n is the day of the year, ϕ is the latitude , δ is the solar declination and $\mathrm{W}s$ is the sunset hour angle. The angles are in degrees. For the solar constant (G_{sc}), 1.95 calories/cm^2/min amount was used in here. The sunset hour angle, $\mathrm{W}s$ was calculated using Equation 3 (Duffie & Beckman, 2013).

$$\cos(\mathrm{W}s) = -tan\phi\, tan\delta \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(3)$$

There, ϕ is the latitude, δ is the solar declination. The solar declination (δ) was calculated using the following equation, Equation 4 (Cooper, 1969).

$$\delta = 23.45 * \sin\left(360 * \frac{284+n}{365}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(4)$$

Here, n is the day of the year. Using the above equations, the Potential Evapotranspiration (EPT) was calculated and the obtained evapotranspiration series is as displayed in Figure 3-19.

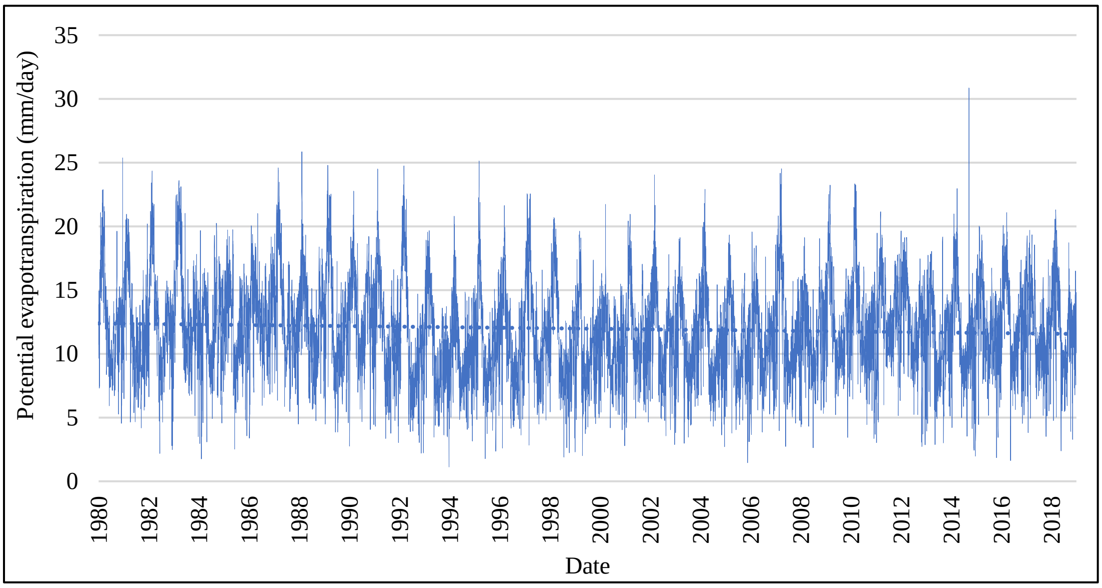

Figure 3-19: Potential evapotranspiration series

3.4 HEC-HMS Modelling

Understanding the natural hydrologic system is very important to take a better idea about how the HEC-HMS application developed. The water that comes from precipitation returns again to the atmosphere by evaporation and transpiration processes. Some of the water get infiltrated to the soil and further they may percolate to the groundwater aquifer. In the meantime, overland flow, interflow and baseflow contribute to increase the water levels in the stream channels which flow from a waterbody. The water in the stream channels can be returned to the land surface as flood and to the groundwater aquifer as a recharge. Because of the capillary rise, the water comes upwards from the underneath soil layers. That is how the natural hydrologic system behaves (Ward, 1975). This concept is used in the development of the HEC-HMS application. In there, the program includes different models to compute runoff volume, direct runoff, base flow and channel flow (Feldman, 2000).

Soil Moisture Accounting (SMA) loss model is one of the loss models used under the HEC-HMS model simulations. It was developed using the findings from Leavesley, Lichty, Troutman and Saindon (1983) literature source. Bennett (1998) describes the continuous soil moisture accounting algorithm as in Figure 3-20.

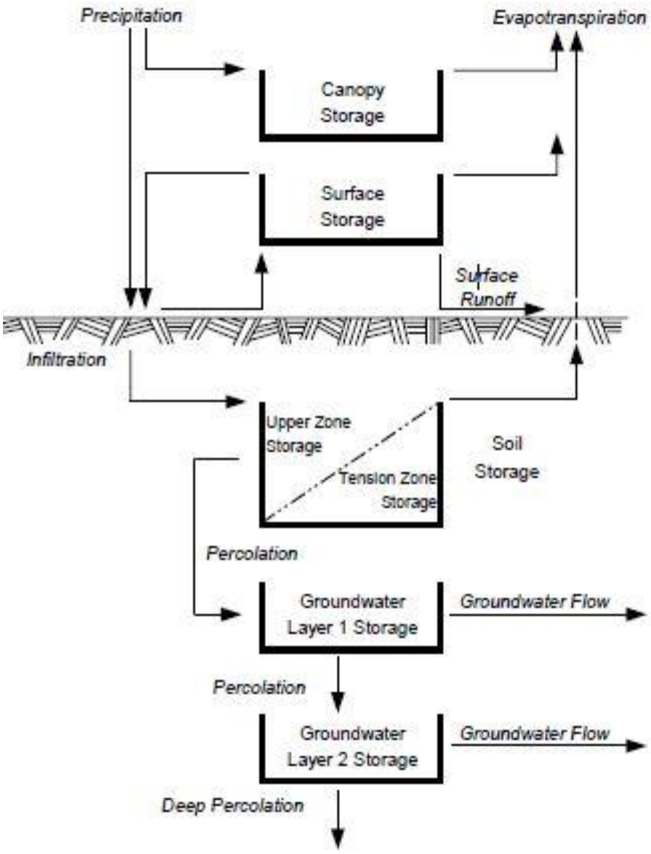

Figure 3-20: Conceptual schematic of the continuous soil moisture accounting algorithm

Source: Bennett (1998)

Under the SMA method, the potential infiltration volume is calculated using the following equation, Equation 5 (Bennett T. H., 1998; Bennett & Peters, 2000).

$$PotSoilInfil = MaxSoilInfil - \frac{CurSoilStore}{MaxSoilStore} MaxSoilInfil \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Here, the $PotSoilInfil$ is the potential infiltration volume, $MaxSoilInfil$ is the maximum rate of infiltration, $CurSoilStore$ is the current storage in the soil profile and $MaxSoilStore$ is the maximum volume of storage. After calculating the potential storage, the actual infiltration rate can be calculated using Equation 6.

$$ActInfil = \text{Minimum of } AvailWater \text{ and } PotSoilInfil \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Here, $ActInfil$ is the actual infiltration rate, $AvailWater$ is the available water for the infiltration, $PotSoilInfil$ is the potential infiltration. In the same manner, other parameters like percolation, surface runoff and groundwater flow are calculated using several equations.

Clark Unit Hydrograph model is a widely used method for modelling the direct runoff. As the first step, it basically uses the continuity equation which can be displayed as the following equation, Equation 7 (Feldman, 2000).

$$\frac{d_s}{d_t} = I_t - O_t \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

Here, d_s/d_t is the storage water changing rate at time *t*, I_t is the average inflow to the storage at time *t* and O_t is the outflow from storage at time *t*. There is a linear relationship between storage and outflow as in Equation 8.

$$S_t = RO_t \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

In here, R is a constant linear reservoir parameter. With the use of the above two equations, the average outflow during the considered period *t* can be calculated.

The Exponential Recession model is one of the models used as a baseflow model. The concepts behind this method are described in many literature (Chow, Maidment, & Mays, Applied hydrology, 1988; Linsley, Kohler, & Paulhus, 1982). The relationship between the initial baseflow value and the baseflow at time t can be explained from Equation 9 as follows.

$$Q_t = Q_0 k^t \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(9)$$

Here, Q_t is the baseflow at time t, Q_0 is the baseflow at the beginning and k is an exponential decay constant.

3.4.1 Development of the HEC-HMS model

As the first step, the Basin Model was created by adding a sub-basin element, a reach and a junction element as in Figure 3-21. Sampath, Weerakoon, & Herath (2015), has conducted a study in the Deduru Oya basin using a HEC-HMS model and they could obtain a very accurate model having the Nash-Sutcliff Efficiency (NSE) values of 0.96 for the calibration period and 0.76 and 0.70 for two validation periods. Because of the high accuracy level in that model, it was decided to use the same methods that they have used when developing the model.

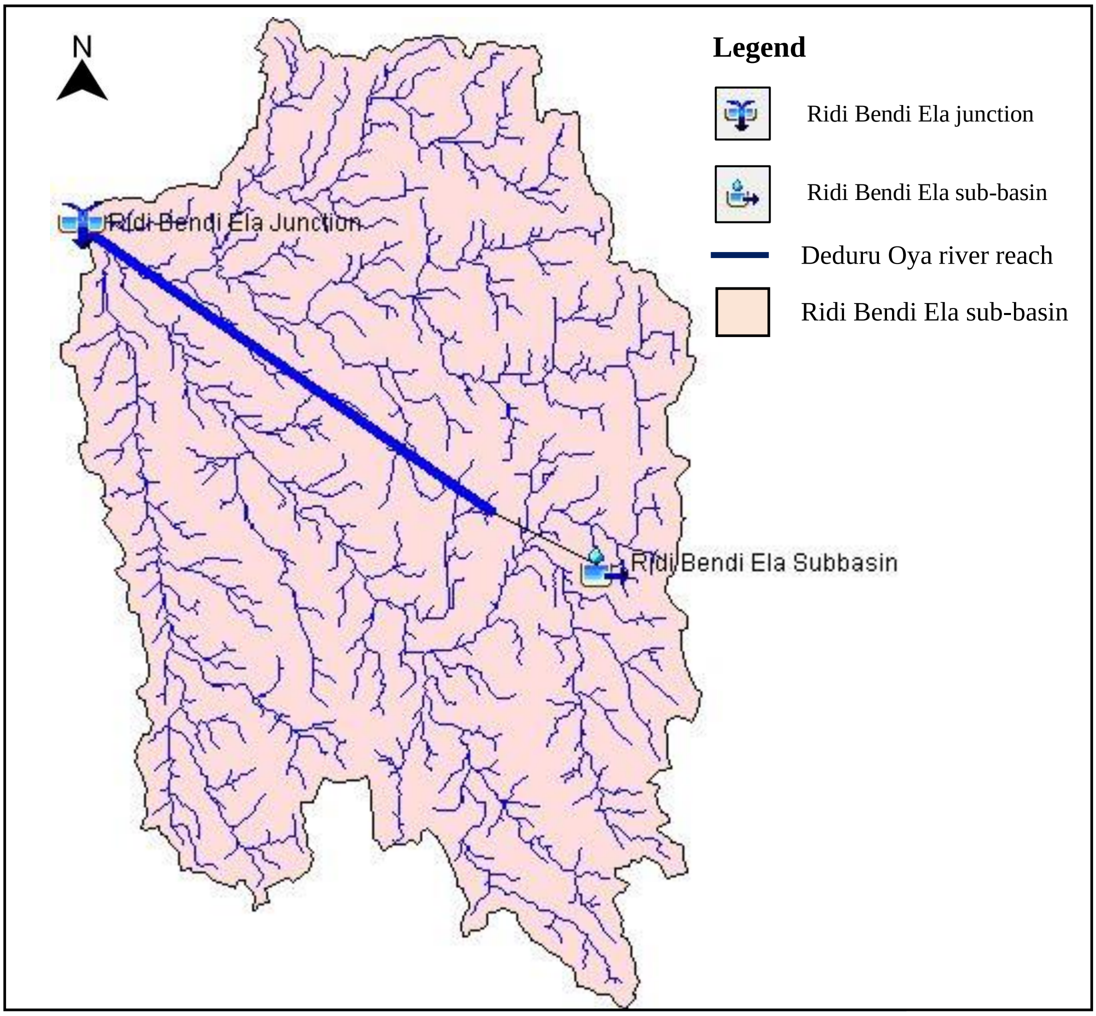

Figure 3-21: Developed HEC-HMS model

The selected canopy method was the Simple Canopy method and the selected surface method was the Simple Surface method. Soil Moisture Accounting method was selected as the loss method which considers underneath soil strata as a combination of the number of different soil layers throughout the analysis. Clark Unit Hydrograph method was selected as the transform method for the analysis and Recession was the selected base flow method. Under the Meteorologic Model, a specified hyetograph and a specified evapotranspiration series were given as the input was supposed to give using the available data sets. Control specifications were given according to the data period analysing. The calibration of the model was carried out from the 1st of October 1990 to the 30th of September 1993 (3 years) and the validation was conducted from the 1st of October 1996 to the 30th of September 1999 (3 years). A precipitation gauge, a temperature gauge, a discharge gauge and an evapotranspiration gauge were created under the time series data and the available data was fed to the created gauges. Here the rainfall, temperature and evapotranspiration values were the averaged data values obtained from the Thiessen polygon method.

Initially, the model parameters were given according to some previous literature findings, but it was unable to obtain acceptable results with those parameters. The reason for this could be, the previous analysis was carried out only for a very shorter period like one year or one and half year in both calibration and validation and those parameters may not perform better when using a longer period for the analysis. Because of that situation, the developed HEC-HMS model was manually calibrated and validated until obtaining an acceptable result. Nash-Sutcliffe Efficiency (*NSE*) was used as the objective function for the analysis which is calculated as in the following equation, Equation 10 (Nash & Sutcliffe, 1970).

$$NSE = 1 - \left(\sum(Q_{obs} - Q_{sim})^2 / \sum(Q_{obs} - \overline{Q}_{obs})^2\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (10)$$

Here, Q_{obs}, Q_{sim} and $\overline{Q}_{obs}$ are observed, simulated and mean observed flows. Theoretically, more the *NSE* value near to 1 the model is more accurate and under this study, the model was calibrated and validated to get the maximum *NSE* possible with the available data. Finally, the calibrated and validated model parameters were used with the future projected rainfall, temperature and evapotranspiration to obtain the future streamflow data set to observe the variations in it compared with the current streamflow series of the sub-basin.

3.5 HEC-ResSim Modelling

Hydrologic Engineering Center-Reservoir Simulation software (HEC-ResSim 3.1) was used for this study to analyse the reservoir operation details of the Deduru Oya reservoir. There are three main functions in a HEC-ResSim model which are called as “Modules”. They are Watershed Setup, Reservoir Network and Simulation (Klipsch & Hurst, 2013). The modules are displayed in the following diagram in a detailed manner (See Figure 3-22).

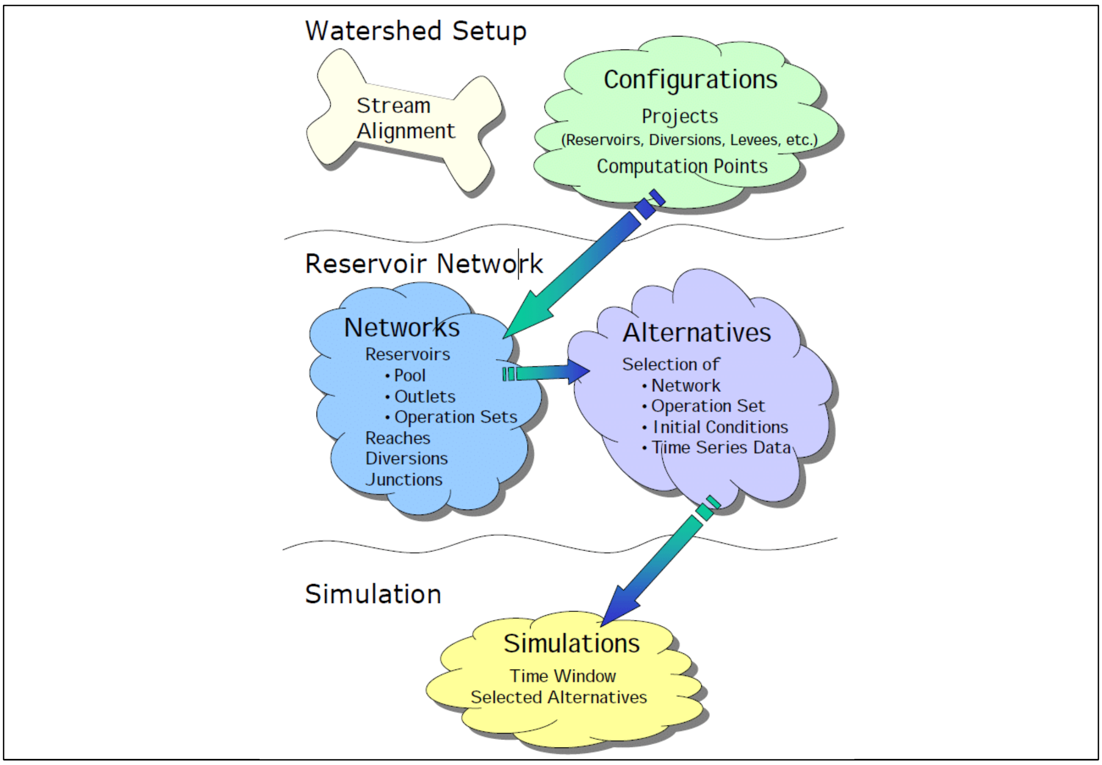

Figure 3-22: HEC-ResSim module concepts
Source: Klipsch & Hurst (2013)

The HEC-ResSim application generates models depending on the concept of reservoir water balance. The main components in the reservoir water balance are precipitation on the water surface, runoff, evaporation, water consumption, infiltration in the bottom and the discharge from the reservoir. Following equation, Equation 11 describes the relationship between those components (Jong Posthumus, 2017).

$$dRS/dt = (PCP - EVAP - INF)A + RR - DISCH - CONS \ldots\ldots\ldots\ldots\ldots\ldots\ldots..(11)$$

Here, dRS/dt is the change occurred in the storage until time t, PCP is the rainfall, $EVAP$ is the evaporation from the reservoir water surface, INF is the infiltration, RR is the rainfall-runoff amount, A is the water surface area, $DISCH$ is the discharge and $CONS$ is the water consumption amount.

3.5.1 Developing the HEC-ResSim model

As the first step, the watershed setup and the reservoir network were developed using the tools available in the application. The developed reservoir network is displayed in Figure 3-23. The reservoir tool, junction tool and the reach tool were used for the development of the structure of the reservoir network.

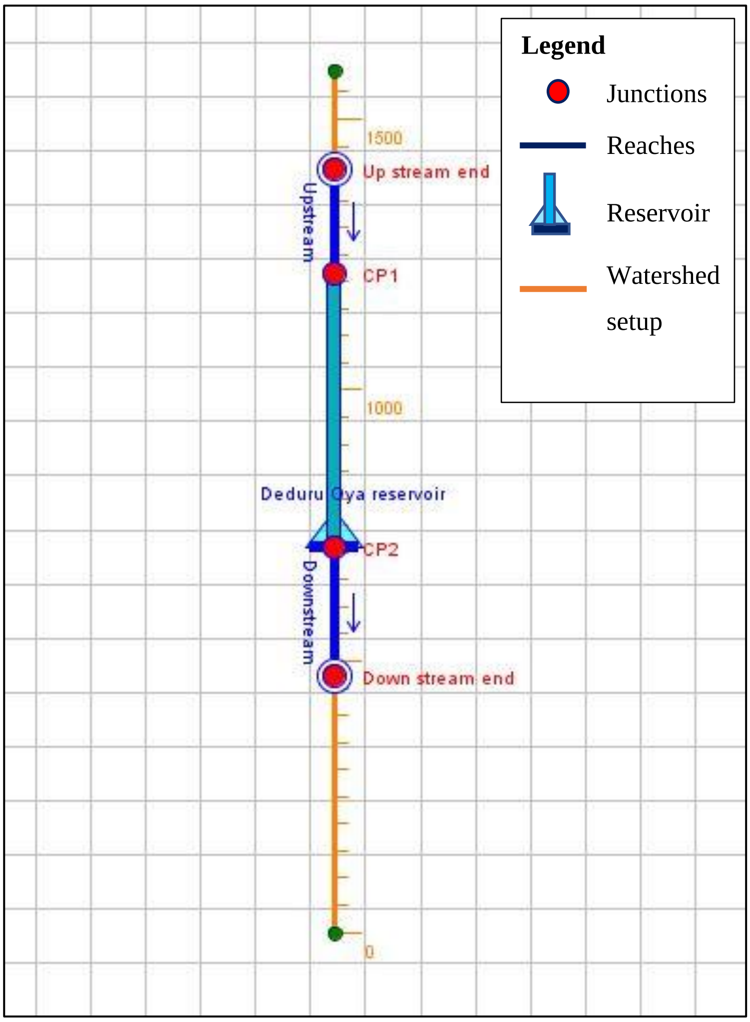

Figure 3-23: Developed HEC-ResSim reservoir network

Reservoir properties were given using the actual measurements of the substructures in the Deduru Oya reservoir. There are two major categories under the physical properties tab and they are the Pool and the Dam. Under the Pool, the evaporation and the seepage details were given in a tabular form. The monthly seepage was calculated according to the literature guidelines as 0.5% of the volume stored in the reservoir (Ponrajah, 1984). Further, the reservoir elevation-capacity details were provided under the same category. Table 3-6 includes the given elevation-area-capacity details of the reservoir using the conical interpolation method (as it is more practical and realistic to use this method other than using the linear interpolation method). Figure 3-24 displays the evaporation variation in the model for the base period (2015-2018). Figure 3-25 shows the seepage data as a function of the reservoir elevation. These include all the details about the reservoir pool, the capacity details and losses. When using the model for future data generation, the evaporation rates were changed according to the projections and those data were used in the model to generate future reservoir operation data.

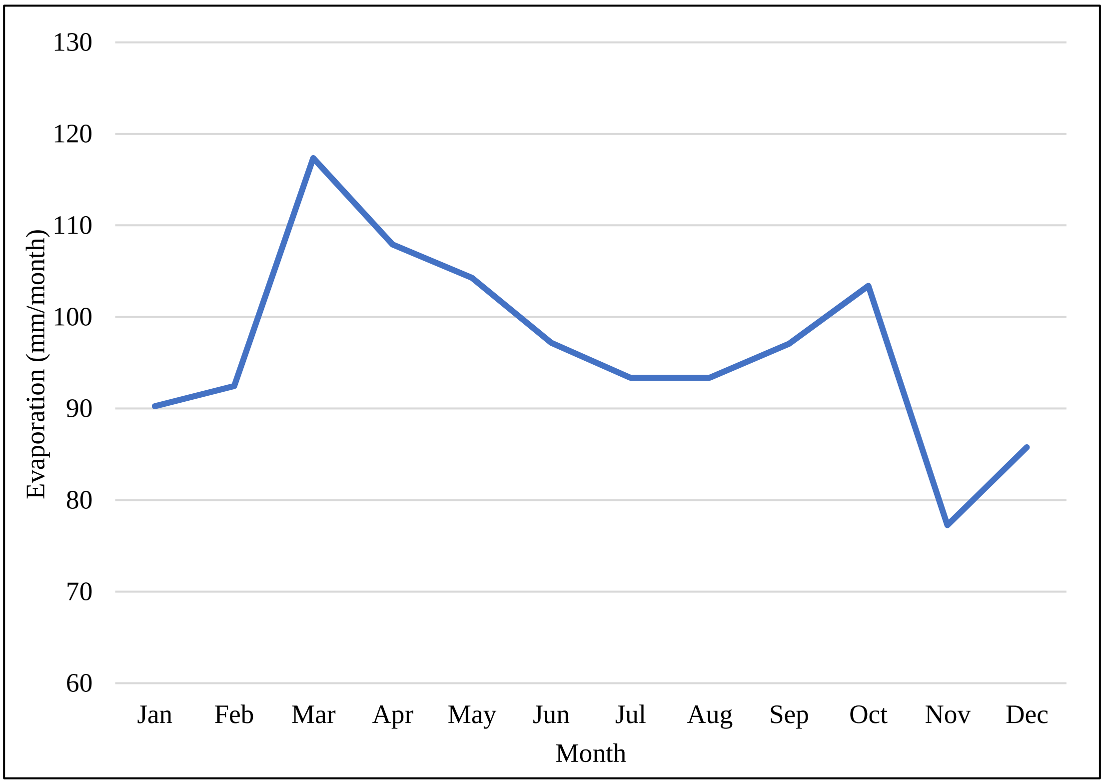

Figure 3-24: Total monthly evaporation rate variation

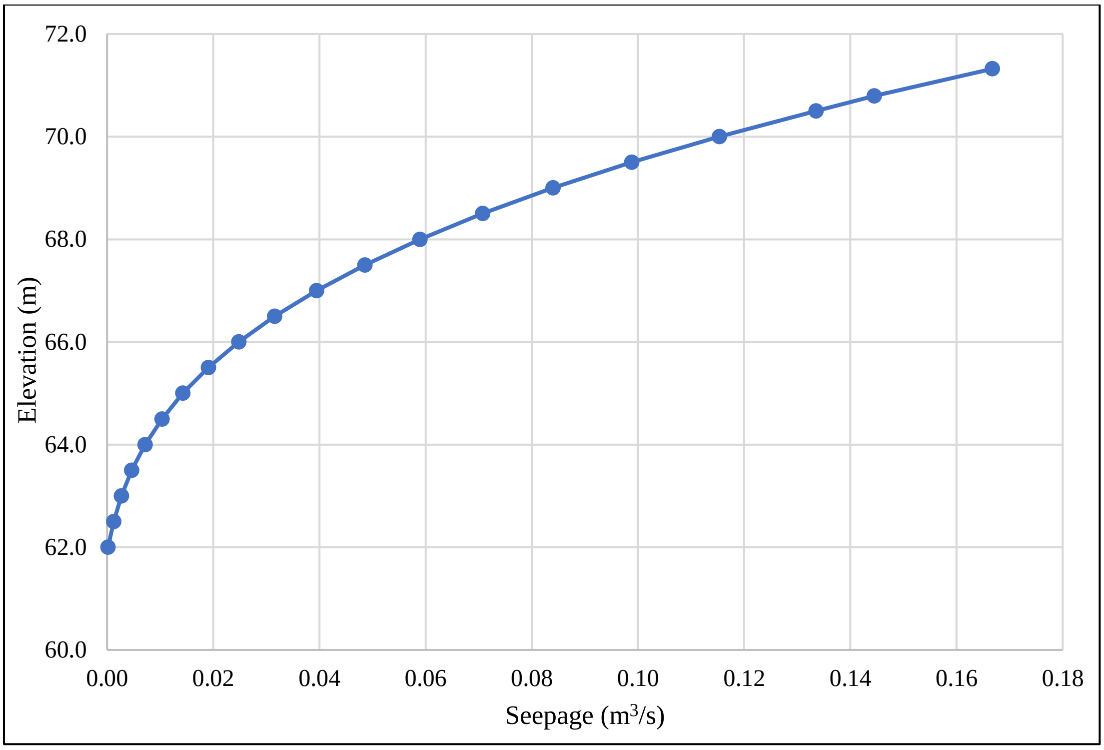

Figure 3-25: Seepage values for each elevation of the reservoir pool

The second category under the physical properties includes the details of the dam at Deduru Oya reservoir. Basically, all the outflow details, diversion and special functions like hydropower generation details are listed here. As discussed before, there are three major ways to release the outflow from the reservoir. Left bank canal, right bank canal and releases from the structures at the dam like spillways, outflow for power generation and scour sluice are those major outflow paths from the reservoir. The release details were provided for all of those outflow paths in detail using the measurements listed before and the model for the Deduru Oya reservoir was developed as accurately as possible. Figure 3-26 and Figure 3-27 are the graphs which display the properties of release from left bank canal and the right bank canal. Depending on the availability of data, the outflows of the canals were considered as constant values as 7 m^3/s for the left bank canal and 8.5 m^3/s for the right bank canal considering the design discharge values of the structures.

There is a radial gated spillway at the dam location which has similar-sized eight gates to release water to the Deduru Oya downstream. The following equation, Equation 12 which is used to calculate the releases from radial gated type spillways was used to calculate the release from the spill gates for each elevation of the reservoir.

$$Q = cBh\sqrt{2gH} \ldots\ldots\ldots\ldots \quad (12)$$

Here, Q is the discharge from the spillway, c is the coefficient of discharge having the value of 0.6, B is the width of a radial gate which is 8.5 m, h is the opening height of the radial gate, g is the acceleration of gravity which is 9.81 m/s^2 . H can be defined using the following equation, Equation 13.

$$H = Mean\ water\ level - Crest\ level - (Opening\ heght\ /2) \ldots\ldots \quad (13)$$

Using the mean water level, crest level and the opening height, the H value can be calculated. Table 3-6 displays the calculated releases from the radial gated spillway and Figure 3-28 displays the corresponding graph for that data set.

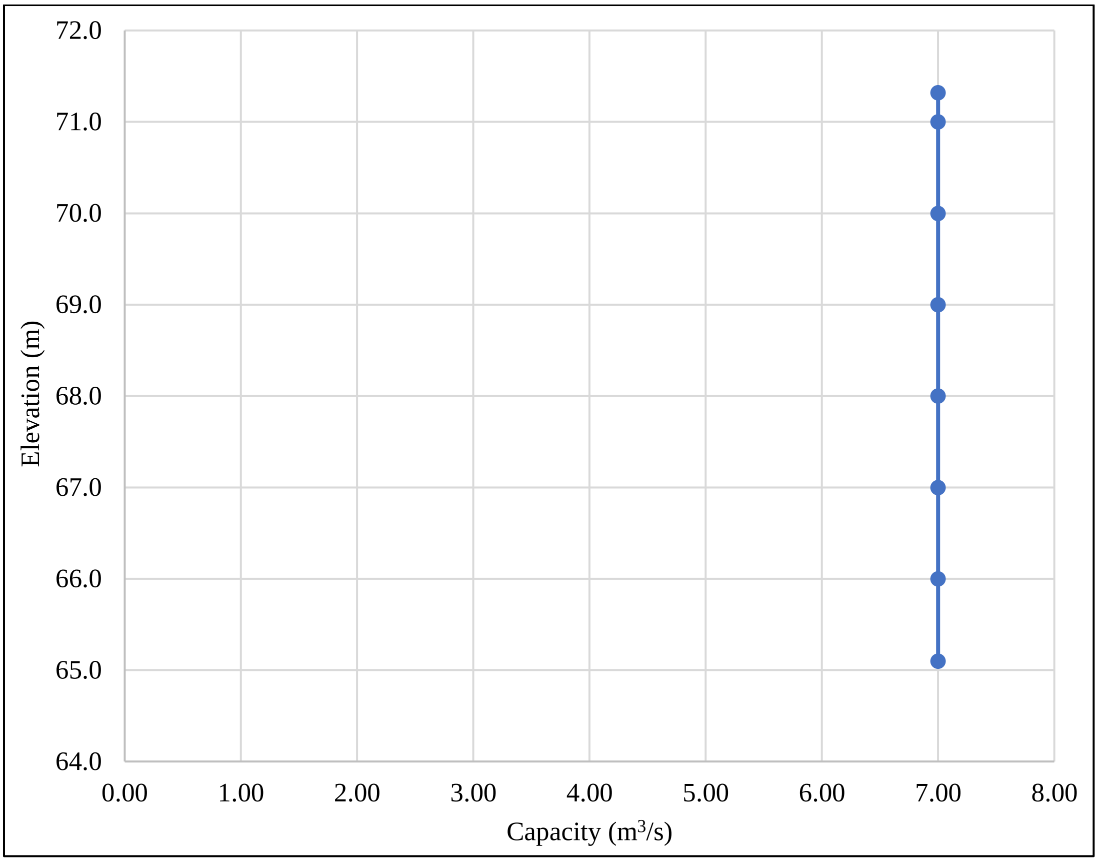

Figure 3-26: Release from the left bank canal sluice gates

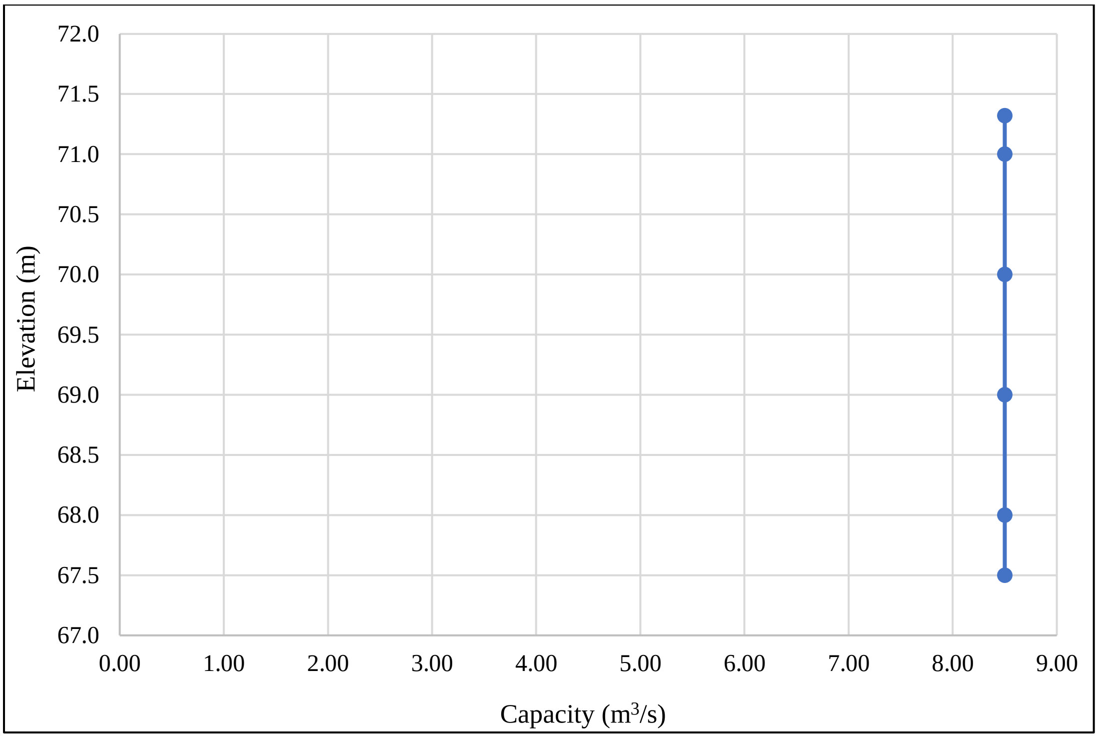

Figure 3-27: Release from the right bank canal sluice gates

Table 3-6: Releases of radial gated spillway

Elevation (MSL)	**Capacity (m^3/s) for different gate openings (m)**								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**8.1**
63.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
64.00	12.98	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
65.00	26.05	41.16	38.93	0.00	0.00	0.00	0.00	0.00	0.00
66.00	34.48	61.12	78.16	82.32	64.89	0.00	0.00	0.00	0.00
67.00	41.22	76.01	103.45	122.24	130.26	123.48	90.84	0.00	0.00
68.00	47.01	88.42	123.67	152.01	172.41	183.36	182.37	164.65	161.60
69.00	52.15	99.29	141.02	176.84	206.12	228.02	241.38	244.48	244.13
70.00	56.84	109.09	156.46	198.59	235.04	265.26	288.56	304.02	305.09
71.00	61.16	118.08	170.51	218.18	260.77	297.88	329.05	353.68	355.75
71.32	62.48	120.81	174.76	224.09	268.48	307.59	340.99	368.16	370.51

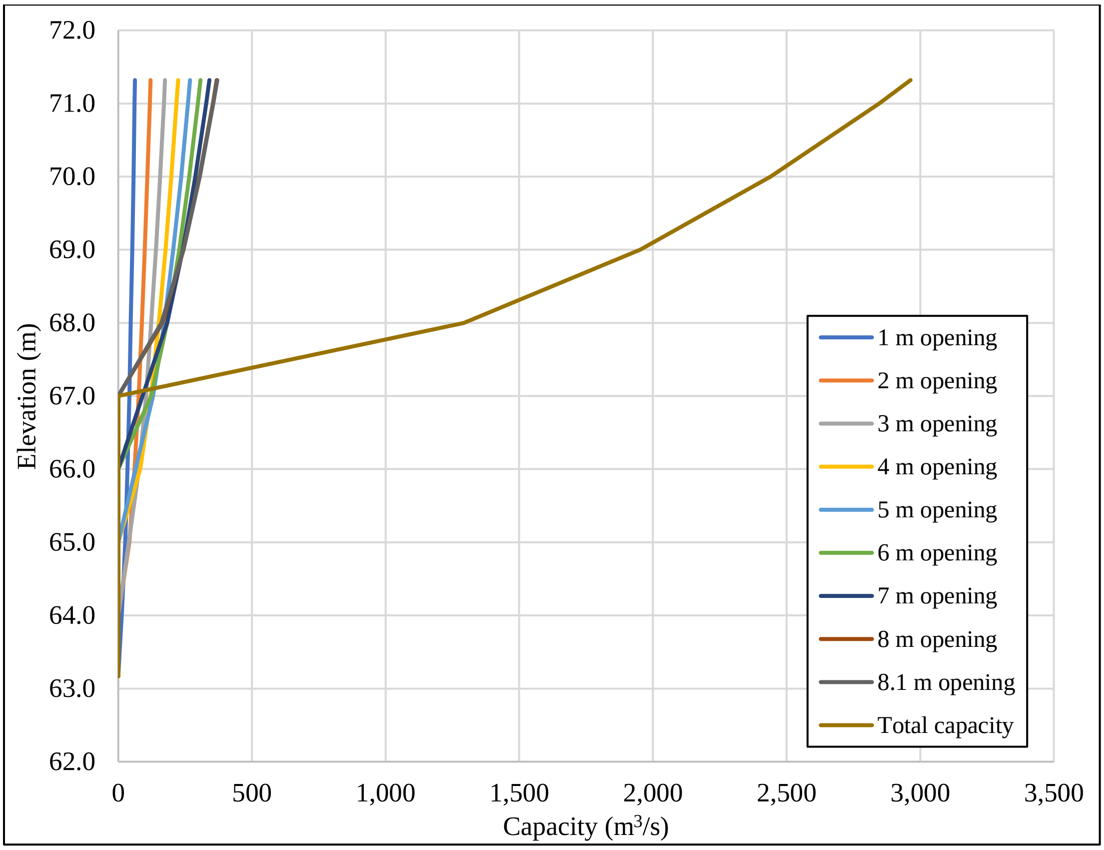

Figure 3-28: Releases from radial gated spillway

There is a power plant that has a capacity of 1.5 MW at the dam location. Furthermore, the scour sluice outflow was also considered in this study and those details are in Table 3-7 and Figure 3-29. The following equation, Equation 14 was used to calculate the release from the sluice gates (Swamee, 1992).

$$Q = 0.864ab\sqrt{gh_0}\left(\frac{h_0-a}{h_0+15a}\right)^{0.072} \quad \text{……………………………………………………...} \quad (14)$$

The parameters in the equation are, *a* is the sluice gate opening height, *b* is the sluice gate length, g is gravitational acceleration, h_0 is the upstream depth and Q is the discharge.

Table 3-7: Releases from the scour sluice

h_0 (m)	**Elevation (m)**	**Capacity (m^3/s)**					
		0.3	**0.6**	**0.9**	**1.2**	**1.5**	**1.8**
0.0	56.5	0.000	0.000	0.000	0.000	0.000	0.000
0.5	57.0	0.911	0.000	0.000	0.000	0.000	0.000
1.5	58.0	1.771	3.332	4.732	5.889	0.000	0.000
2.5	59.0	2.362	4.510	6.525	8.420	10.181	11.766
3.5	60.0	2.844	5.469	7.961	10.344	12.627	14.805
4.5	61.0	3.260	6.300	9.202	11.999	14.702	17.316
5.5	62.0	3.633	7.043	10.315	13.478	16.550	19.538
6.5	63.0	3.972	7.723	11.331	14.830	18.237	21.562
7.5	64.0	4.286	8.352	12.273	16.083	19.800	23.436
8.5	65.0	4.579	8.941	13.155	17.257	21.264	25.190
9.5	66.0	4.855	9.495	13.987	18.364	22.646	26.844
10.5	67.0	5.117	10.021	14.776	19.415	23.957	28.416
11.5	68.0	5.367	10.523	15.529	20.418	25.209	29.915
12.5	69.0	5.605	11.002	16.249	21.378	26.408	31.352
13.5	70.0	5.834	11.463	16.942	22.301	27.560	32.733
14.5	71.0	6.054	11.907	17.609	23.190	28.671	34.065
14.82	71.32	6.123	12.045	17.817	23.468	29.019	34.482

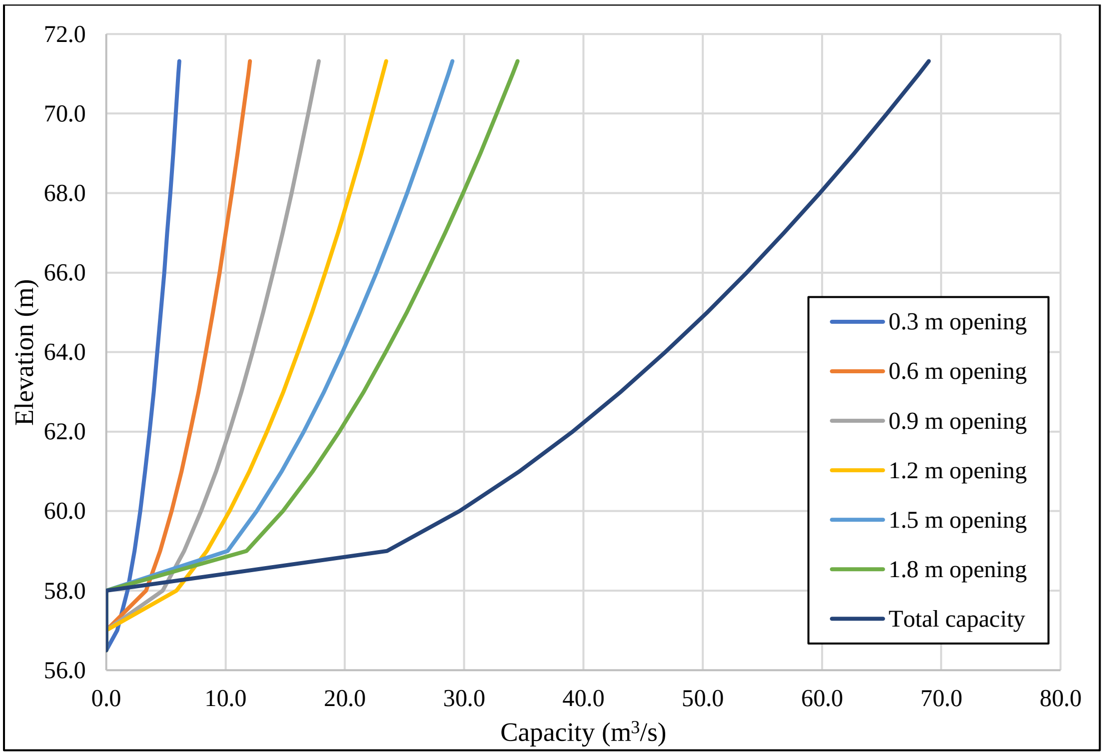

Figure 3-29: Releases from the scour sluice

4.0 RESULTS AND ANALYSIS

4.1 HEC-HMS Model Verification

The developed HEC-HMS model was calibrated and validated for two different data sets to verify the model validity for the study in the selected basin. Here, the calibration was conducted from 1st October 1990 to 30th September 1993 (3 years). Then after conducting manual calibration until obtaining a satisfactory result for the NSE, an acceptable parameter set was obtained. After that, the validation was carried out from 1st October 1996 to 30th Sep 1999 (3 years) and some finer adjustments were carried out for the obtained parameter set to own acceptable NSE values for both calibration and validation series.

4.1.1 Calibration of the HEC-HMS model

After many executions, an acceptable result for the NSE was obtained for the calibration series by manually adjusting the parameters in the model. There were 22 parameters in the model to be adjusted and each and every parameter was adjusted to obtain the most acceptable result. There were three parameters in the baseflow method as initial discharge, ratio to peak and recession constant. The storage coefficient and time of concentration were adjusted under the Clark Unit Hydrograph method which was used as the method for the direct runoff model. Initial storage and maximum storage parameters were adjusted under the Simple Canopy method and the Simple Surface method. Parameters like percolation, storages, storage coefficients, initial contents and infiltration were adjusted under Soil Moisture Accounting method. It has been observed that variations in some parameters like storage coefficients make a huge variation in the NSE value even for small changes of them while some other parameters do not give considerable variations in the results. An NSE value of 0.70 was obtained for the calibration series which is an acceptable result to continue the analysis. The details of the calibration process are summarised in Table 4-1.

Table 4-1: Summary of the calibration process

Process	Data Period	NSE value
Calibration	01 Oct 1990 - 30 Sep 1993	0.70

Figure 4-1 displays the plot containing the observed series, simulated series and the rainfall variation for the calibration period.

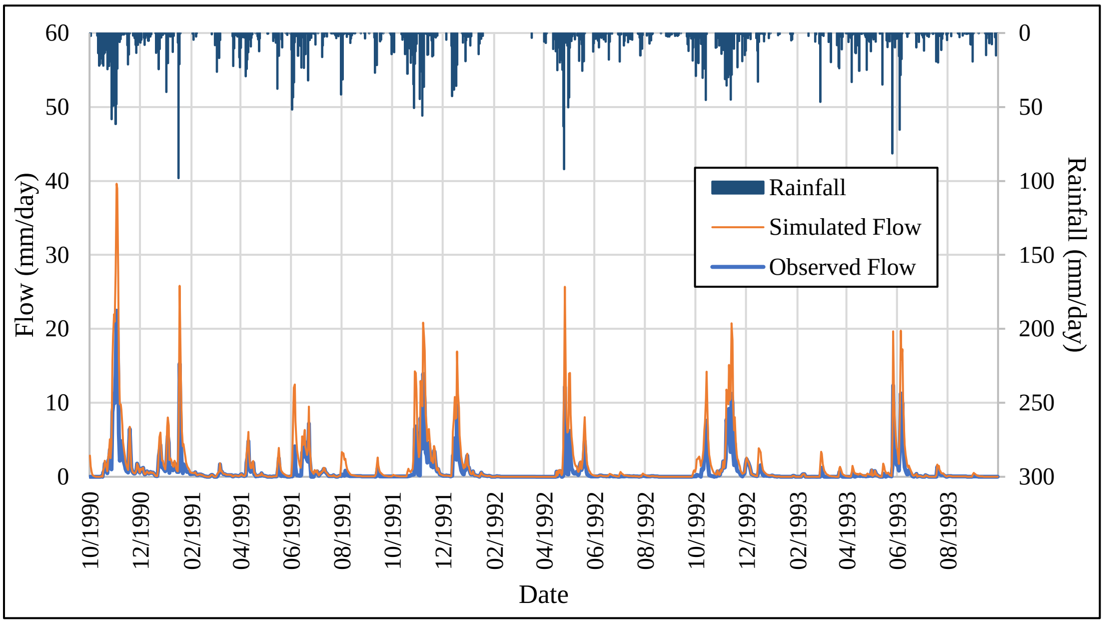

Figure 4-1: Calibration plot for the developed HEC-HMS model

4.1.2 Validation of the HEC-HMS model

After the calibration, the developed model was validated for another data set having the data period from 1st October 1996 to 30th September 1999 (3 years). The optimized parameters of the calibration were used as the initial parameters of the validation process and then finer adjustments were carried out to obtain NSE values 0.70 and 0.62 for calibration and validation. The summary of the process is displayed in the Table 4-2 and the final optimized parameters are displayed in the Table 4-3.

Table 4-2: Summary of validation process

Process	Data Period	NSE value
Validation	01 Oct 1996 - 30 Sep 1999	0.62

The plot generated using observed flow, simulated flow and rainfall is displayed as Figure 4-2 in here. As the model is acceptable with the final optimized parameters, it was supposed to use with the future data to predict the future streamflow of the basin.

Table 4-3: Optimized parameters

Parameter	**Units**	**Initial Value**	**Optimized Value**
Recession - Initial Discharge	m^3/s	40.00	49.189
Recession - Ratio to Peak	-	0.17	0.305
Recession - Recession Constant	-	0.60	0.485
Clark Unit Hydrograph - Storage Coefficient	h	100.00	85.384
Clark Unit Hydrograph - Time of Concentration	h	10.00	8.036
Simple Canopy - Initial Storage	%	100.00	76.565
Simple Canopy - Max Storage	mm	12.00	10.204
Simple Surface - Initial Storage	%	100.00	82.842
Simple Surface - Max Storage	mm	0.00	0.0580
Soil Moisture Accounting - GW1 Percolation	mm/h	1.40	1.517
Soil Moisture Accounting - GW1 Storage	mm	200.00	218.290
Soil Moisture Accounting - GW1 Storage Coefficient	h	80.00	81.366
Soil Moisture Accounting - GW2 Percolation	mm/h	1.30	1.311
Soil Moisture Accounting - GW2 Storage	mm	200.00	197.000
Soil Moisture Accounting - GW2 Storage Coefficient	h	1.50	1.299
Soil Moisture Accounting - Initial GW1 Content	%	100.00	82.880
Soil Moisture Accounting - Initial GW2 Content	%	86.00	76.126
Soil Moisture Accounting - Initial Soil Content	%	10.00	9.460
Soil Moisture Accounting - Max Infiltration	mm/h	5.00	6.046
Soil Moisture Accounting - Soil Percolation	mm/h	0.80	1.0362
Soil Moisture Accounting - Soil Storage	mm	200.00	231.09
Soil Moisture Accounting - Tension Storage	mm	10.00	10.658

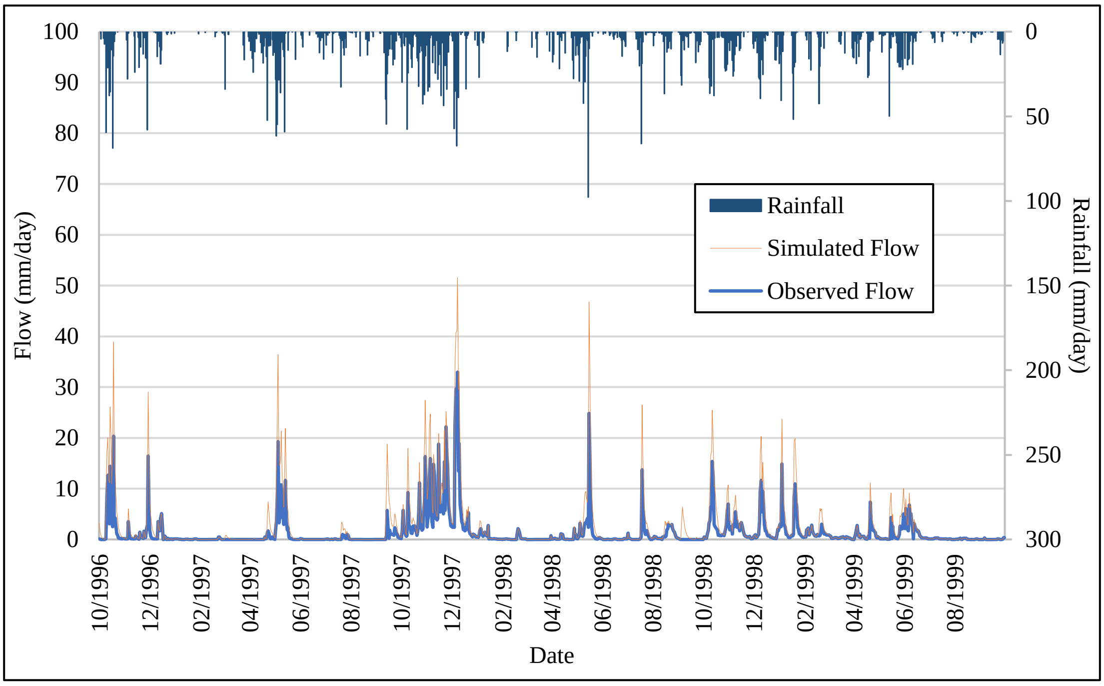

Figure 4-2: Validation plot for the developed HEC-HMS model

The flow-duration curves for the calibration and validation series were obtained as follows. Figure 4-3, Figure 4-4, Figure 4-5 and Figure 4-6 display the sorted observed flow data series and the corresponding values in the simulated series in normal scale and log scale.

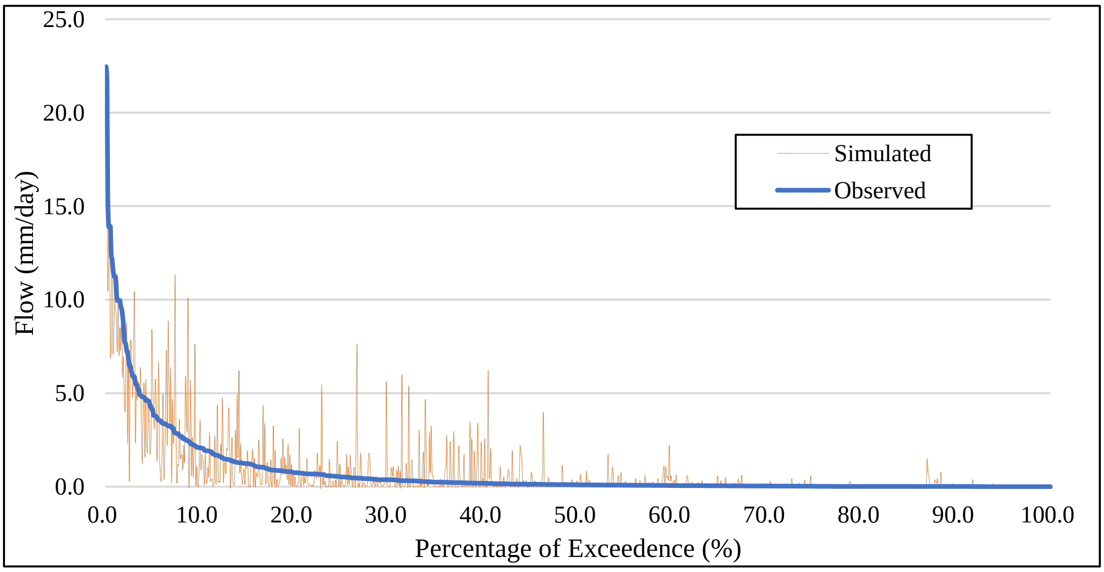

Figure 4-3: Flow-duration curves for the calibration series

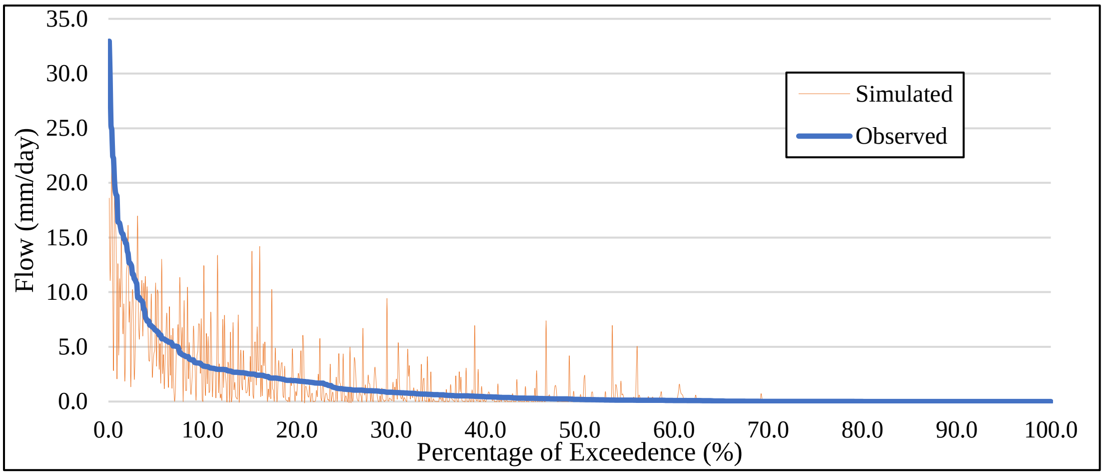

Figure 4-4: Flow-duration curves for the validation series

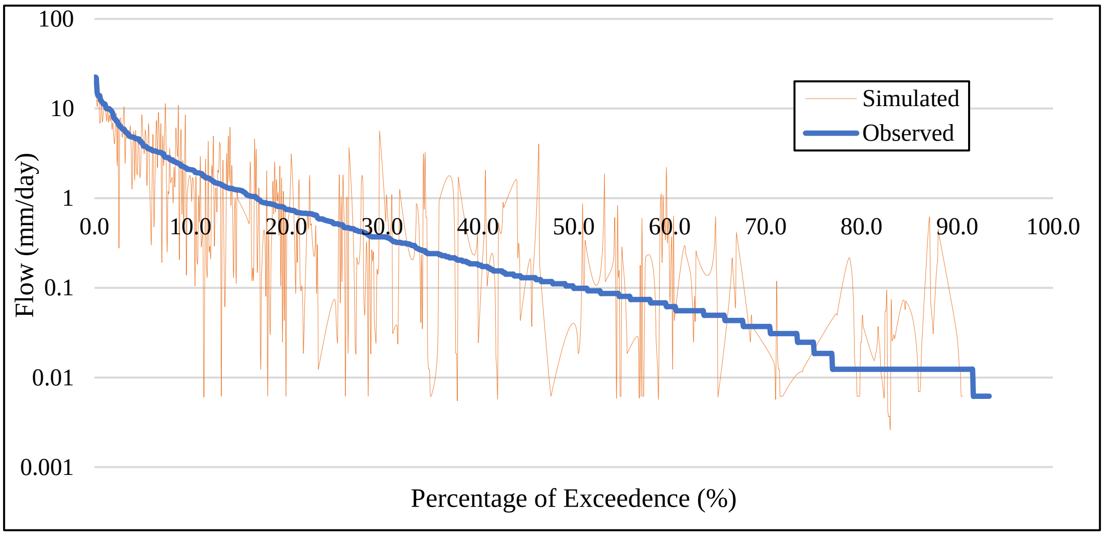

Figure 4-5: Flow-duration curves for the calibration series

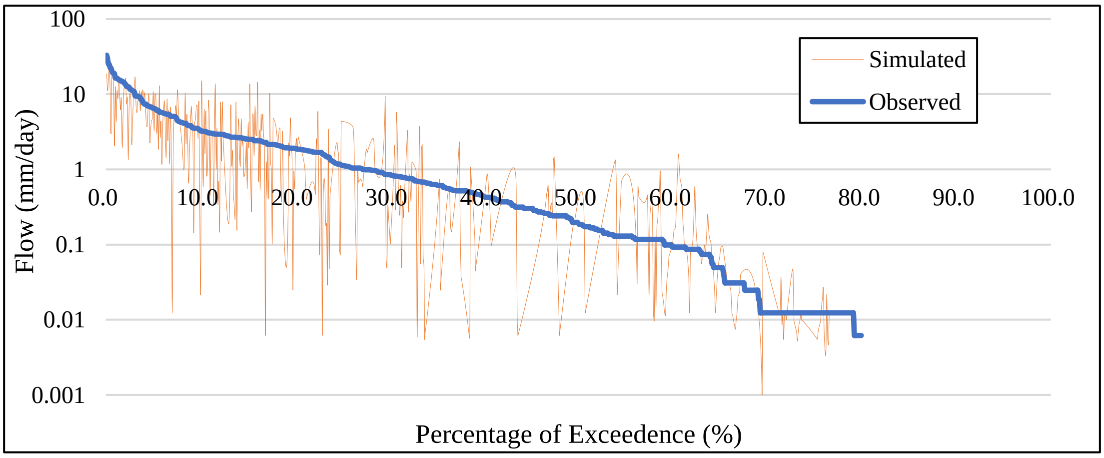

Figure 4-6: Flow-duration curves for the validation series

4.2 HEC-ResSim Model Verification

The developed HEC-ResSim model was verified using the observed elevation data of the reservoir. It was checked for two different data sets; one is from 01st of October 2015 to the 30th of September 2017 and the other is from 01st of October 2017 to the 31st of December 2018. The obtained NSE values for the data sets are 0.95 and 0.71 for the above-mentioned data sets. Figure 4-7 and Figure 4-8 are the plots obtained for the two different data sets.

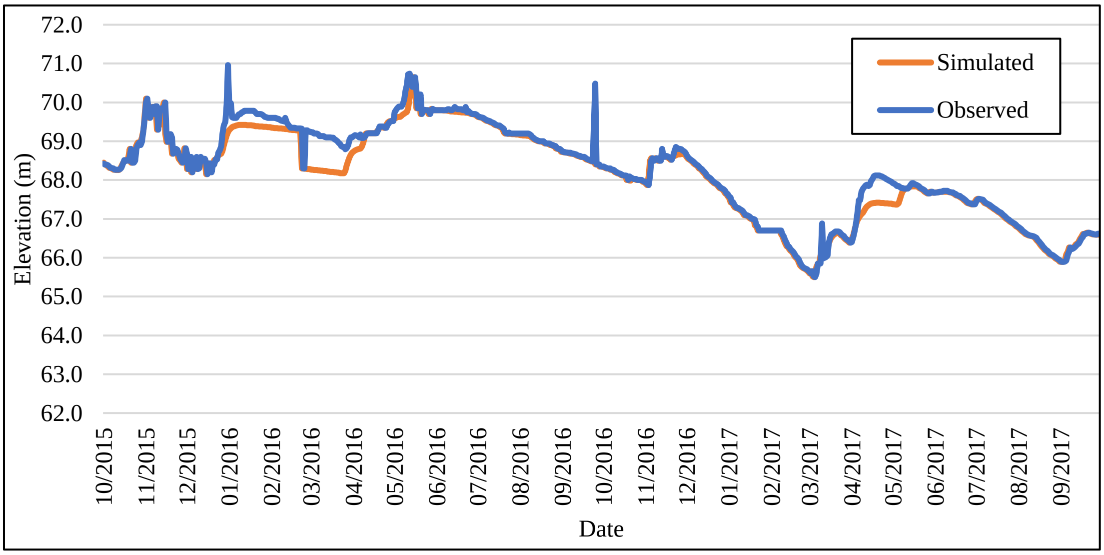

Figure 4-7: Elevation plot for data set 1

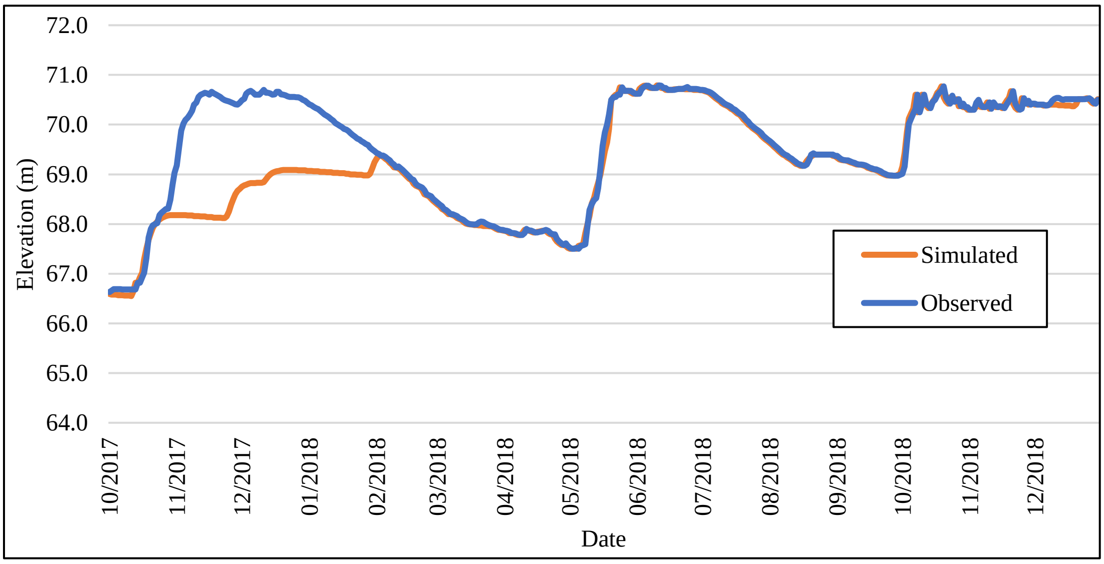

Figure 4-8: Elevation plot for data set 2

4.3 Future Data Generation

Considering the availability of adequate information, acceptability of the predictions, publication details and a few more facts, suitable literature sources were selected as a guidance source to gather information to project future data. According to Rajendran, Gunawardena, & Dayawansa (2017), two periods were selected as 20s (2011-2040) and 50s (2041-2070) to conduct the analysis and future data were projected for those two periods under two IPCC scenarios A2 and B2. Here, the A2 and B2 scenarios were selected as they have the closest population projections to the Sri Lankan context which is recommended in the previous literature sources as well (Arnell, et al., 2004; De Silva, Weatherhead, Knox, & Rodriguez-Diaz, 2007). As this research was conducted considering the base period 1972-2001, 2001 year data were projected considering the future predictions and representative data sets were generated for the 20s and 50s under the two scenarios. Rainfall, minimum temperature and maximum temperature were generated in that process and then by using the generated minimum and maximum temperatures, the potential evapotranspiration and the evaporation rates were calculated. Figure 4-9, Figure 4-10, Figure 4-11 and Figure 4-12 display the projected rainfall, minimum temperature, maximum temperature and evapotranspiration distributions under the scenario A2. Figure 4-13, Figure 4-14, Figure 4-15 and Figure 4-16 display the projected rainfall, minimum temperature, maximum temperature and evapotranspiration distributions under the scenario B2. Cumulative rainfall distributions are shown in Figure 4-17 and Figure 4-18.

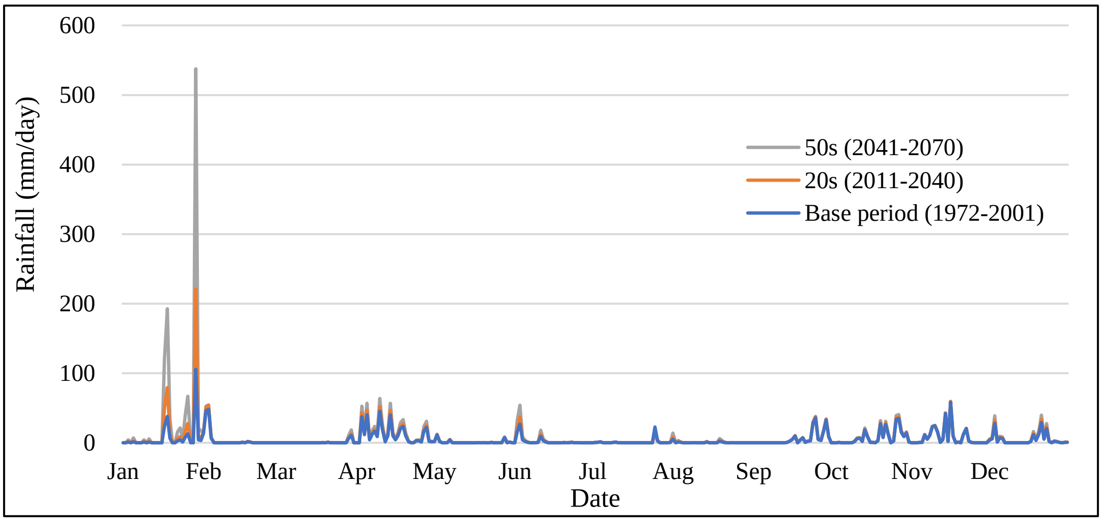

Figure 4-9: Rainfall projections under A2 scenario

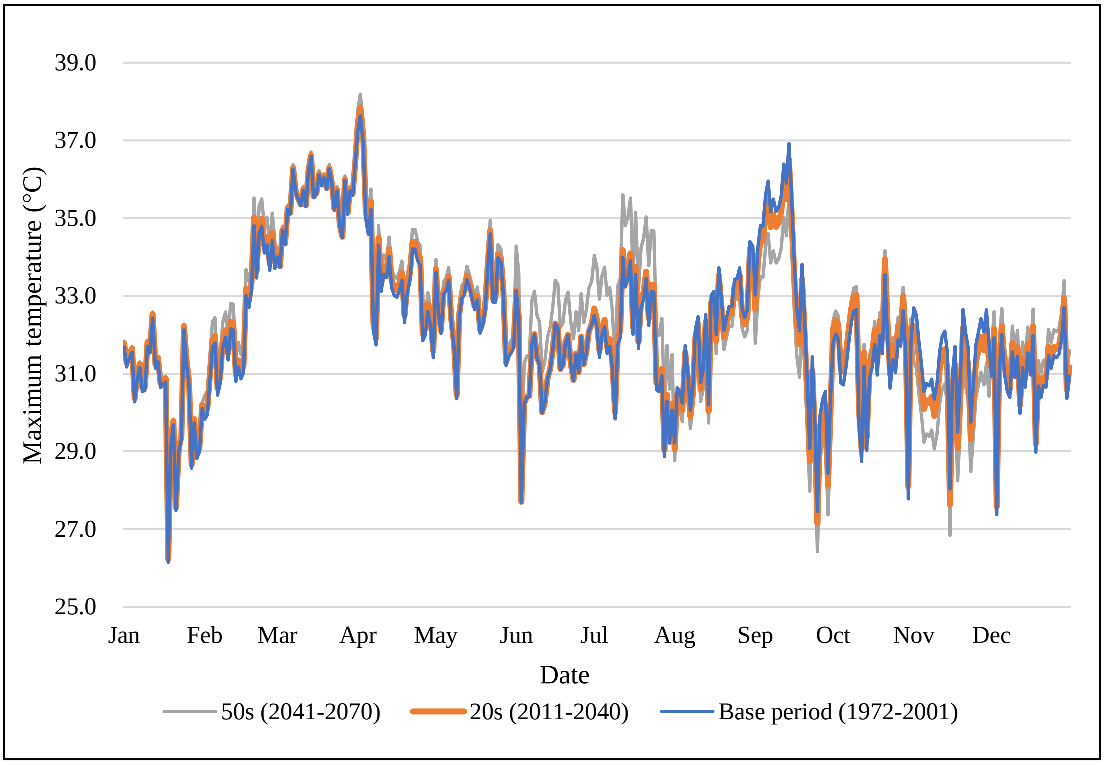

Figure 4-10: Maximum temperature projections under A2 scenario

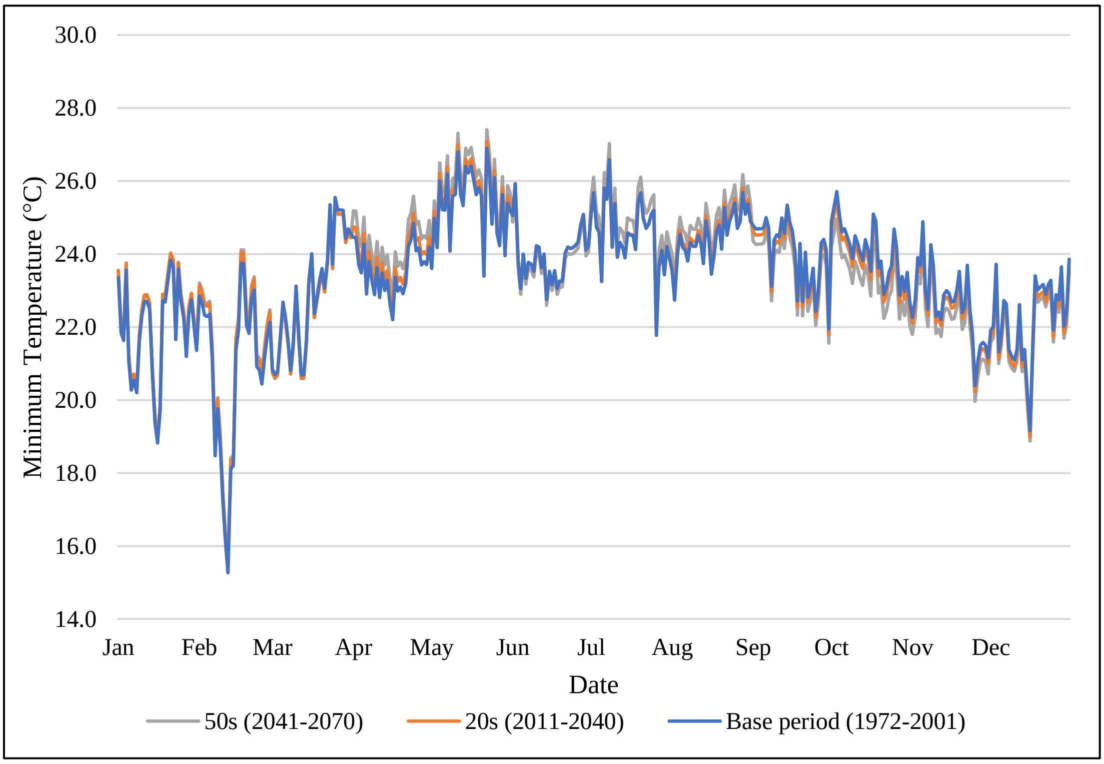

Figure 4-11: Minimum temperature projections under A2 scenario

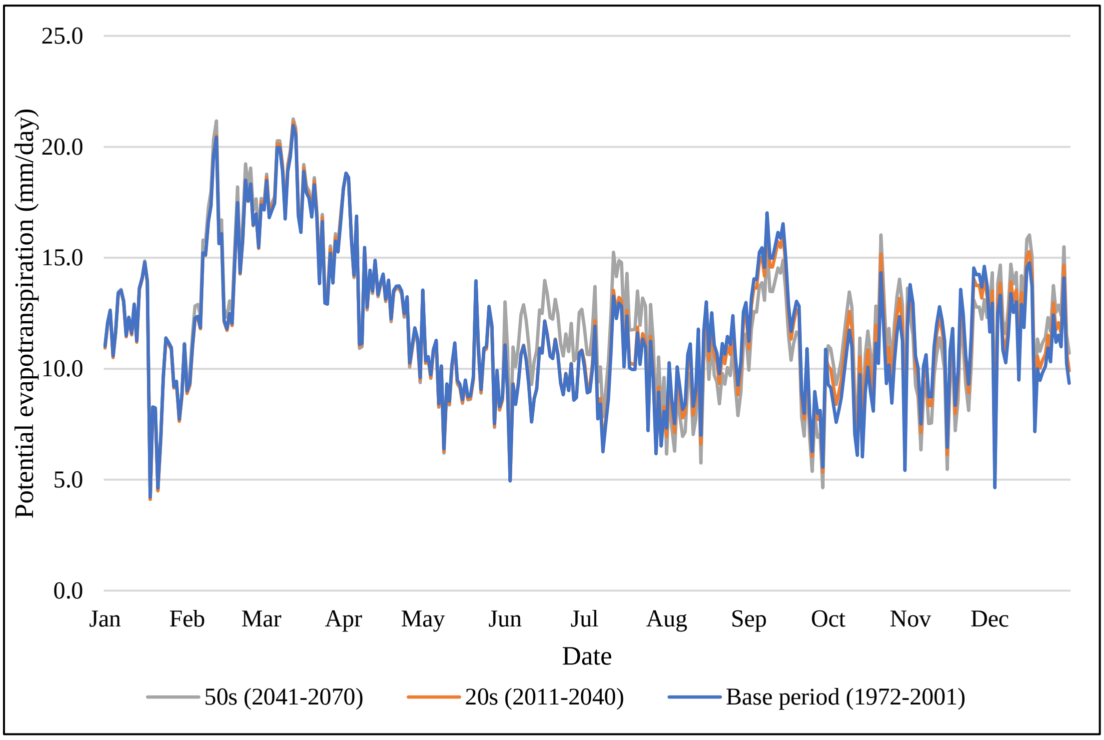

Figure 4-12: Potential evapotranspiration projections under A2 scenario

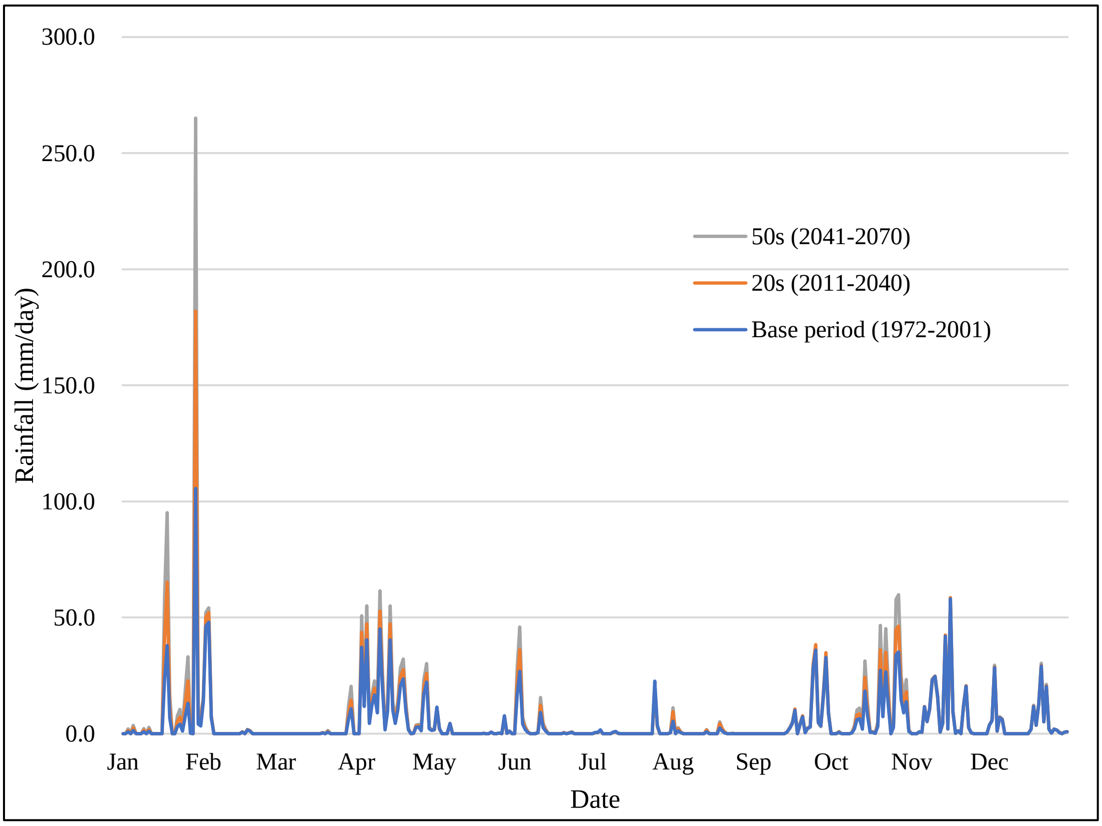

Figure 4-13: Rainfall projections under B2 scenario

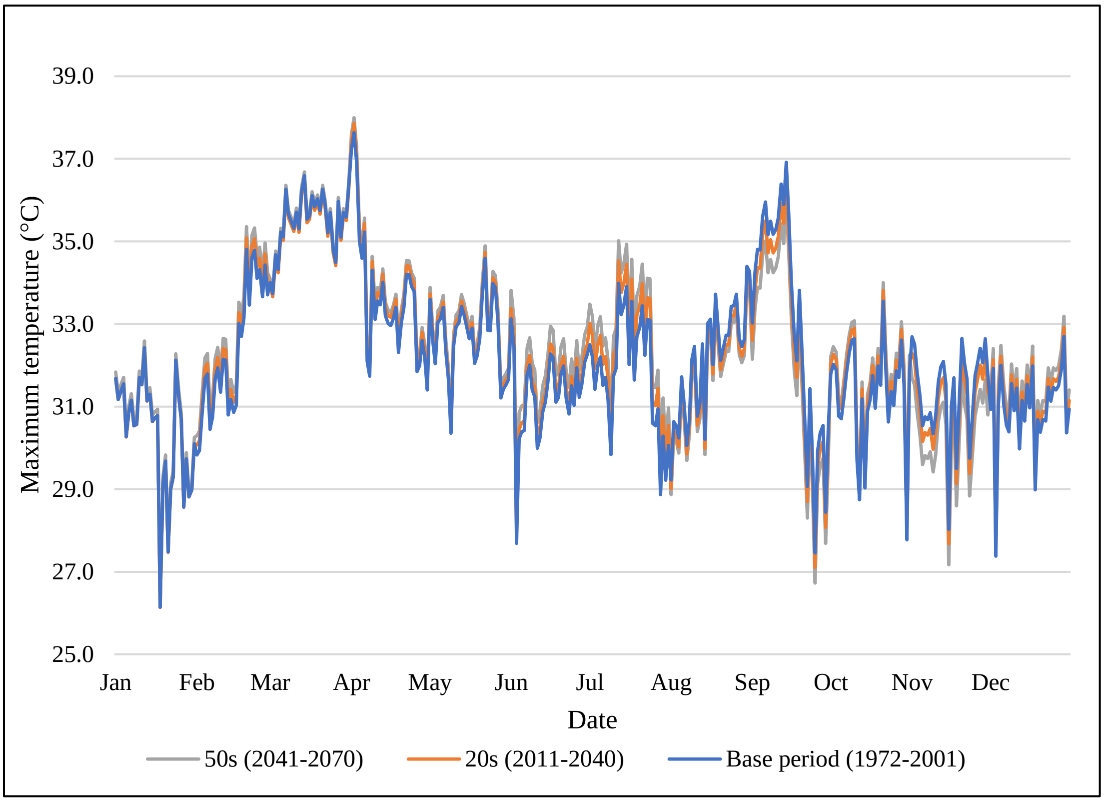

Figure 4-14: Maximum temperature projections under B2 scenario

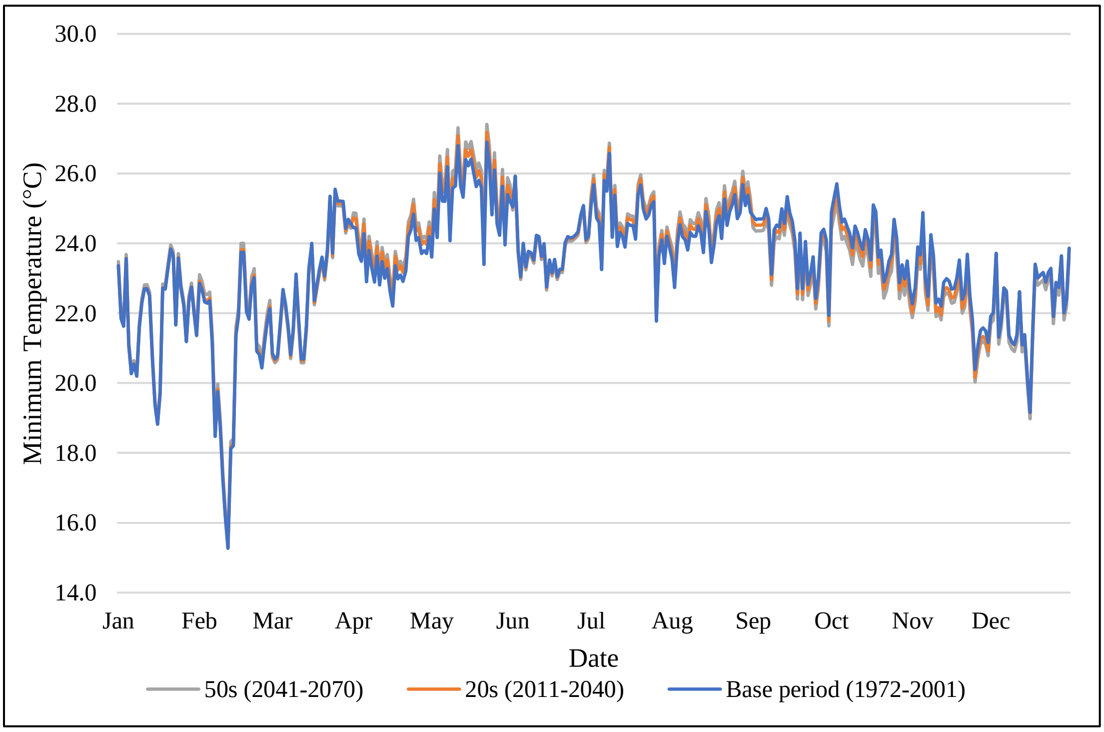

Figure 4-15: Minimum temperature projections under B2 scenario

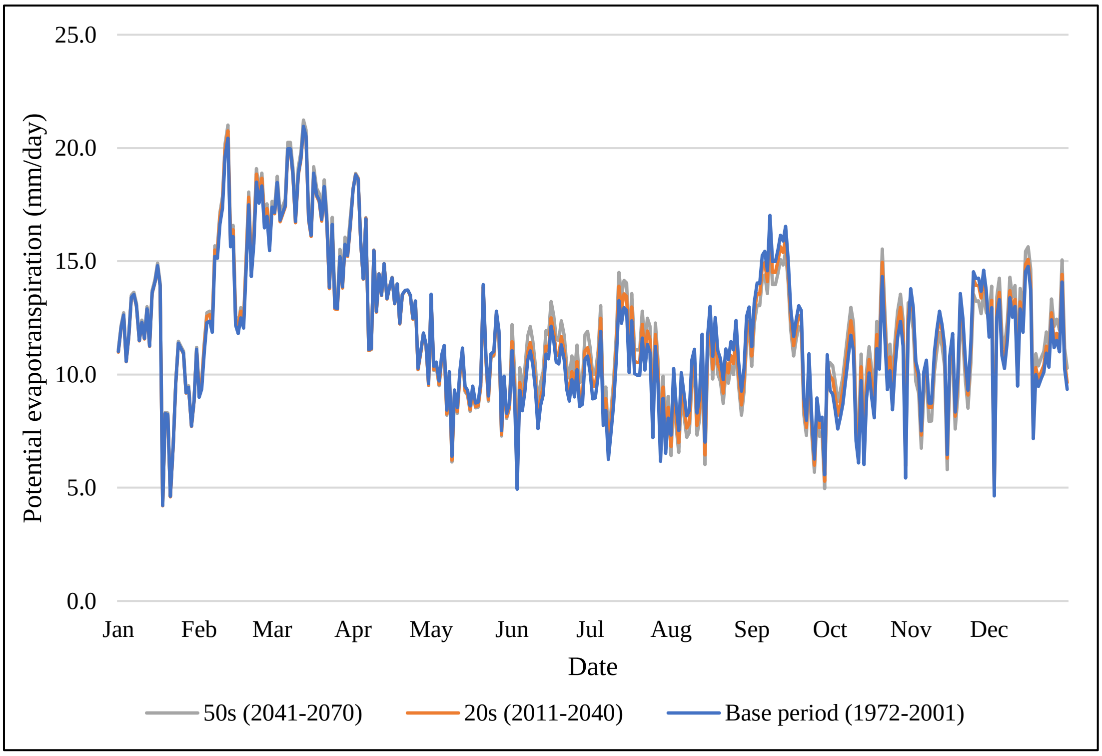

Figure 4-16: Potential evapotranspiration projections under B2 scenario

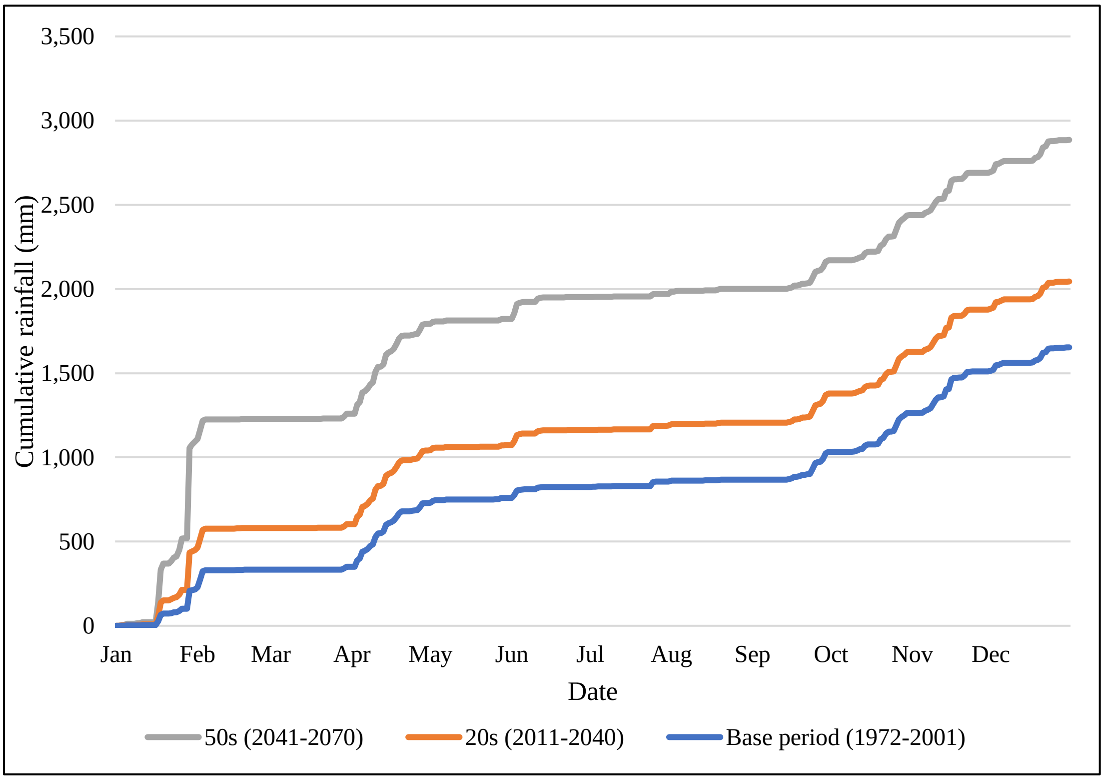

Figure 4-17: Cumulative rainfall distribution for A2 scenario

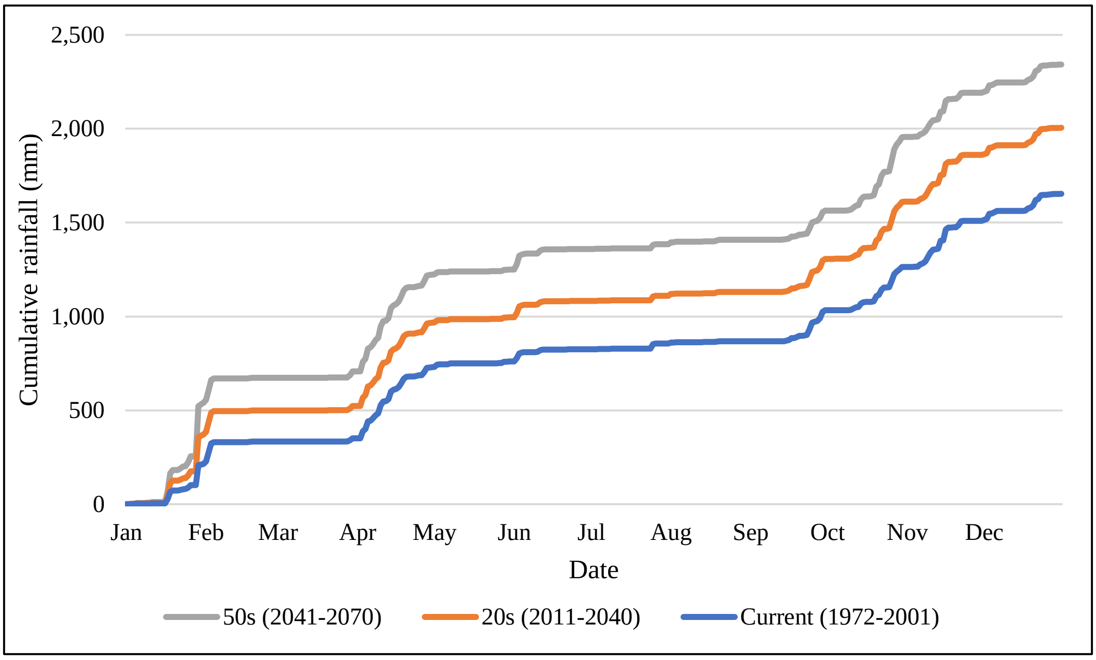

Figure 4-18: Cumulative rainfall distribution for B2 scenario

4.3.1 Generation of future streamflow

Using the generated future rainfall, temperature and evapotranspiration data, the future streamflow data were generated by the verified HEC-HMS model developed before. Figure 4-19 and Figure 4-20 display the generated future streamflow variation for the two scenarios A2 and B2.

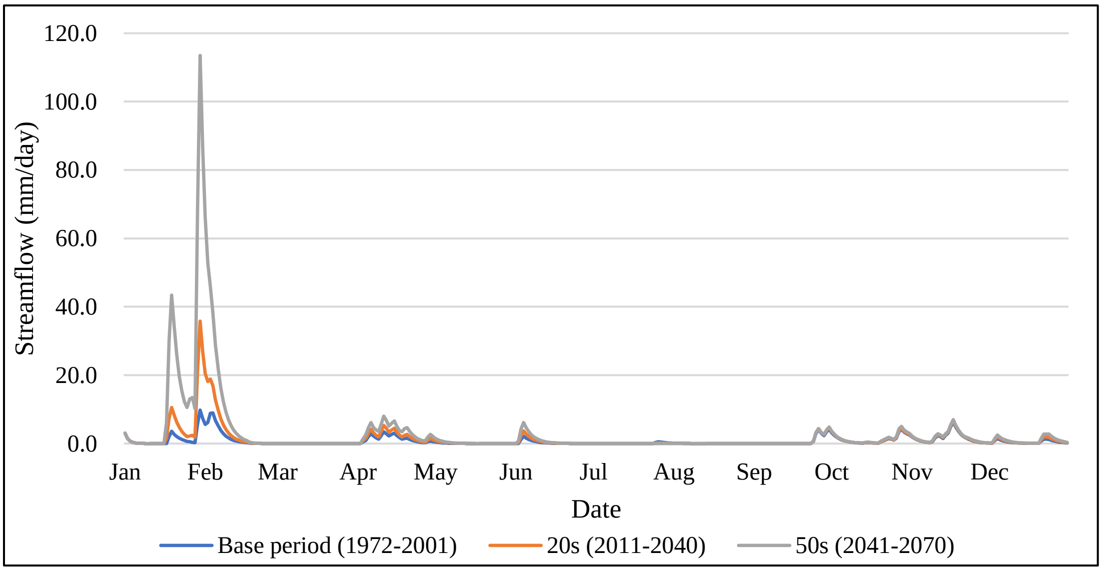

Figure 4-19: Streamflow predictions under A2 scenario

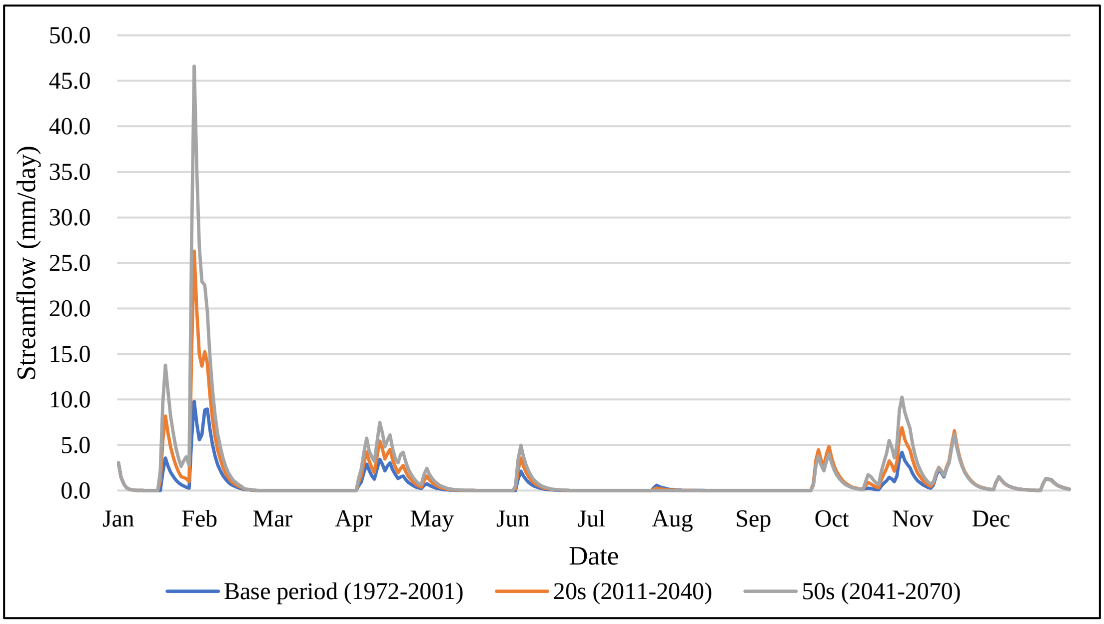

Figure 4-20: Streamflow predictions under B2 scenario

The variations in the cumulative flows are as shown in the Figure 4-21 and Figure 4-22. Under A2 scenario, relative to the base period, the total streamflow has been increased by 76.57% in the 20s and it has been increased by 300.12% in 50s for the considered representative year in each period. In the B2 scenario the same percentages are 61.78% and 131.37%.

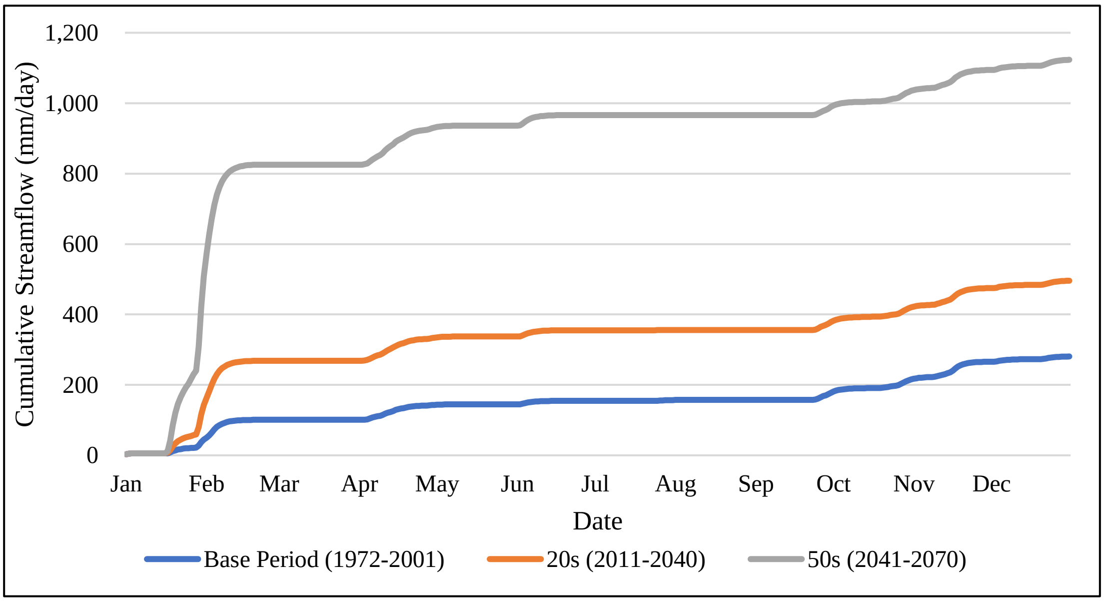

Figure 4-21: Cumulative streamflow variations under A2 scenario

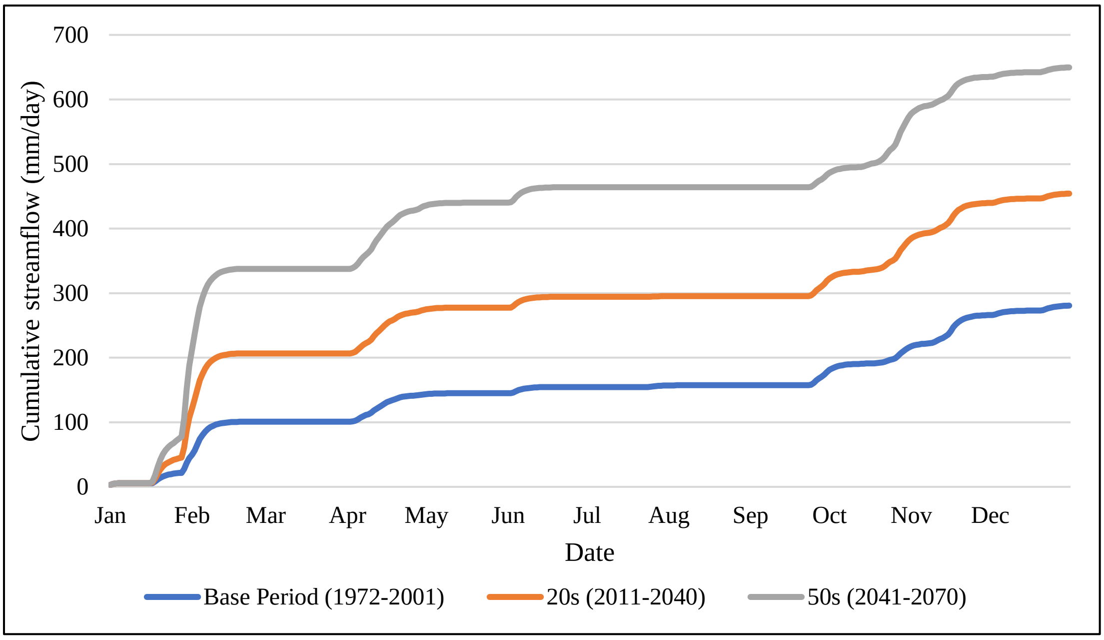

Figure 4-22: Cumulative streamflow variations under B2 scenario

The scenario A2 (very heterogeneous world) and B2 (world in which emphasis is on local solutions to economic, social, and environmental sustainability) contain different predictions and it is very important to compare both scenarios and understand those differences (IPCC Working Group III, 2000). In the 20s (2011-2040), the total streamflow is 38.10% lesser in the B2 scenario compared with the A2 scenario. In the 50s (2041-2070), there is a 59.68% reduction in the total streamflow in the B2 scenario when compared with the A2 scenario. Figure 4-23 and Figure 4-24 display the different predictions obtained for the 20s and 50s under the two scenarios.

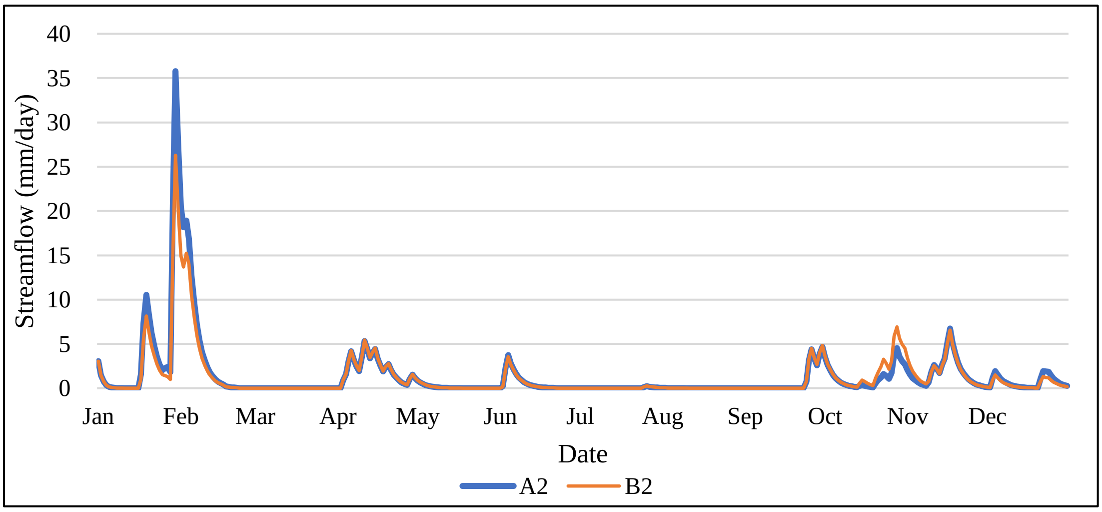

Figure 4-23: 20s streamflow variations under two scenarios

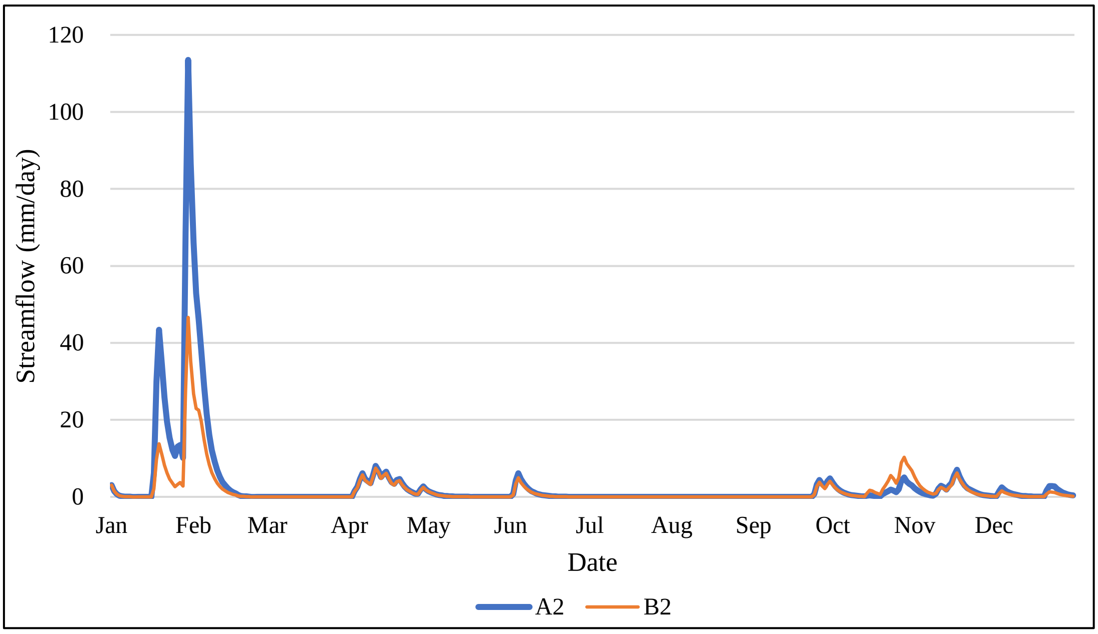

Figure 4-24: 50s streamflow variations under two scenarios

4.3.2 Generation of future reservoir operation data

Generated streamflow data from the HEC-HMS model and the projected evaporation data were used to generate the Deduru Oya reservoir operation data for the two periods the 20s (2011-2040) and 50s (2041-2070) using the developed HEC-ResSim model. For the same water elevation variation, the results were obtained, analysed and compared.

Total release rates from the reservoir were compared under 4 different categories named using the period analysed and the scenario as 20s-A2, 20s-B2, 50s-A2 and 50s-B2. Comparing with 20s-A2, a 7.88% reduction in the average release rate was observed in the 20s-B2. Comparing with 20s-A2, there was a significant increase in the average release rate as by 114.42% in the 50s-A2 scenario while a 27.77% increase in the 50s-B2. Figure 4-25 displays the overall maximum release rates of the reservoir for the considered four categories. As in here, the maximum discharges (design discharges) were considered for the left bank canal and the right bank canal (which are supposed to supply water for the irrigation purposes and other human consumptions), it covers the future addition for water demand and hence the results are valid for the future changes in the water demand as well.

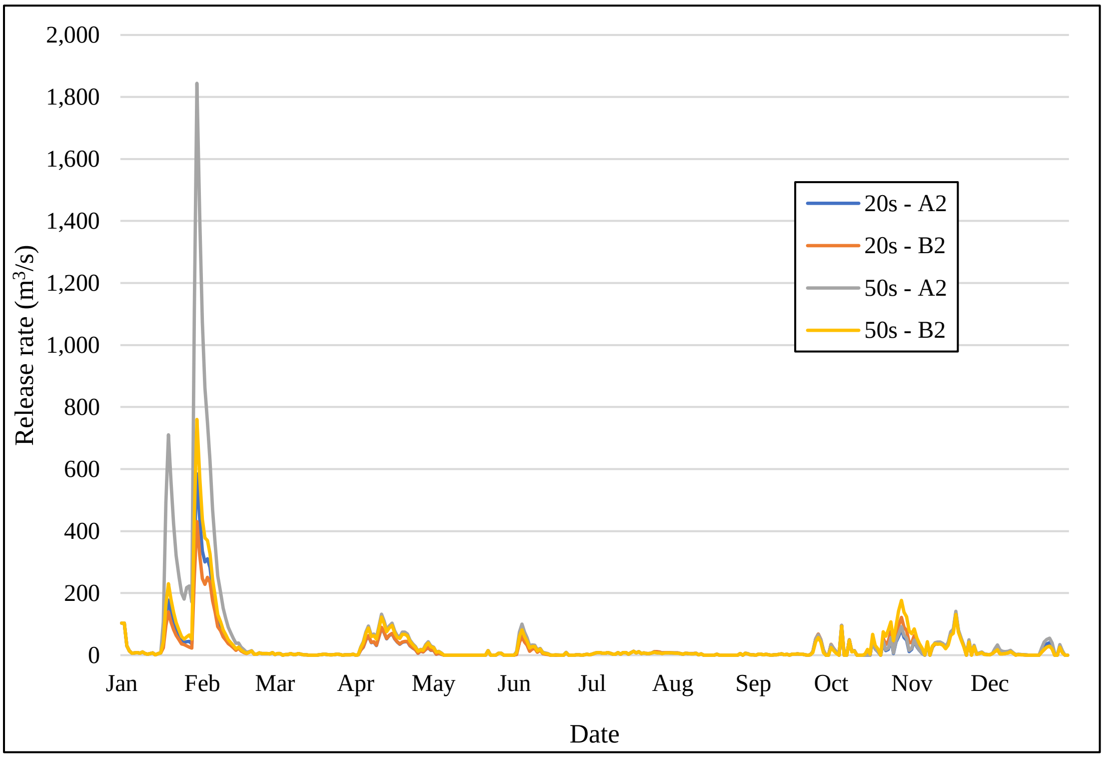

Figure 4-25: Overall maximum release rate of the reservoir

5.0 DISCUSSION

5.1 Introduction

The main objective of this study is to evaluate the climate change impacts on streamflow and reservoir operations using a case study on the Deduru Oya basin. As discussed in previous chapters, a well-organized methodology was followed for that and the results were obtained. Based on the obtained results, this chapter will discuss those outputs in a detailed manner and will make conclusions while stating some recommendations for future studies as well.

5.2 Discussion of Results and Findings

Here, the discussion will be divided into the specific objectives prepared at the beginning of the study and it will discuss the findings under each specific objective in a comprehensive manner.

5.2.1 Identification of the climate change impacts on rainfall and temperature from previous literature

As mentioned under the literature review, several literature sources were referred to identify the most suitable findings for this study to project future rainfall and temperature data and Rajendran, Gunawardena, & Dayawansa (2017) was selected for the current study as the main source because of the acceptability of the predictions, availability of details for the projection process of the current study and some other additional details like publication information. The final year of the base period; 2001 was selected as the representative year to continue projections and using the monthly variations in the rainfall and temperature the values were projected for the selected two periods the 20s (2011-2040) and 50s (2041-2070) under two IPCC emission scenarios A2 and B2.

Basically, an emission scenario describes the way, how greenhouse gases affect between 2000 to 2100 period. The reason for the focus on greenhouse gases is, they affect the variations in the climate parameters considerably. It is very important to have different scenarios to evaluate the future climate as it is not possible to specify an exact future with exact conditions. The scenario A2 discusses about a very heterogeneous world. Some of the main features of such an environment are a continuous increase in the global population, slower per capita economic growth, slower technological change and most importantly lower emissions. B2 describes a condition also having a continuous increase in the population growth but lesser than A2. This scenario is specially focused on the environmental protection on local and also in regional levels (IPCC Working Group III, 2000).

It has been observed that there is an increase in the total annual rainfall by 21% - 24% for the 20s (2011-2040) and 42% - 75% for the 50s (2041-2070) while the average annual temperature indicates 0.08% - 0.14% increase for the 20s and 0.28% - 0.43% increase for the 50s under IPCC emission scenarios A2 and B2. Increase in the rainfall was proved in some other studies as well, as showed in Figure 5-1. Most importantly, the increase in rainfall can be caused under two categories of reasons either due to higher southwest monsoon precipitation and higher northeast monsoon precipitation or due to higher southwest monsoon precipitation and lower northeast monsoon precipitation (Eriyagama, Smakhtin, Chandrapala, & Fernando, 2010). Here, according to the obtained results, this study falls under the first category; higher southwest monsoon precipitation and higher northeast monsoon precipitation under both scenarios. Heavy rainfall is expected in those monsoonal periods and specially extreme rainfalls were projected in January and August.

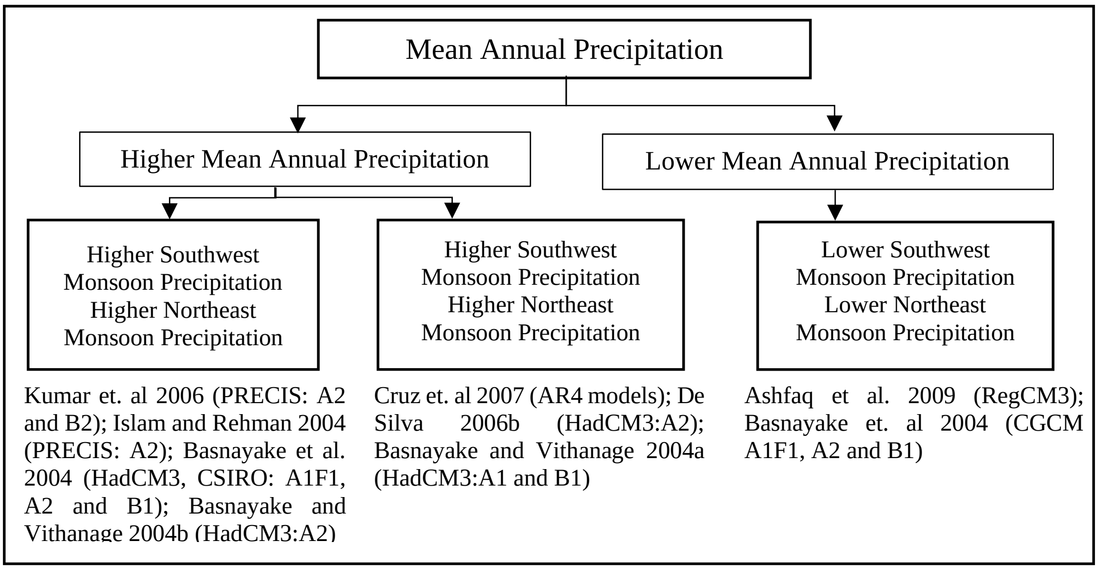

Figure 5-1: Summary of annual and seasonal rainfall projections for the twenty-first century.

Source: Eriyagama, Smakhtin, Chandrapala, & Fernando (2010)

Temperature projections were carried out separately for minimum and maximum temperature and finally, the average temperature was calculated. Annual minimum and maximum temperature were also projected to be increased and hence the annual average temperature will also be increased in the future. That finding was also proved in the previous literature (Dharmarathna, Herath, & Weerakoon, 2014; Eriyagama, Smakhtin, Chandrapala, & Fernando, 2010). Considering the seasonal variations, in Maha season (September to February) mean minimum temperature is supposed to be decreased and in the Yala season (March to August) it is expected to be increased. But the mean maximum temperature will be increased in both seasons.

As a summary, the mean annual precipitation is expected to be increased in both scenarios and the annual average temperature is also expected to be increased. As both scenarios are dealing with either low emission or environment protection concepts the outputs are somewhat similar when considering the future variations. The increase in the mean annual rainfall in the 20s is nearly equal for both scenarios and in 50s, A2 bears the higher increase in the mean annual rainfall. The considerable increase in the annual average temperature for A2 scenario can be the reason for that increase in the rainfall as higher temperature cause an increase in the evaporation rates and more water will be evaporated from the land and surfaces than in the B2 scenario which can cause more rainfall and more heavy downpours.

In general, an increase in the temperature cause increased rates of evaporation which cause a reduction in the streamflow output of a basin. On the other hand, an increase in the rainfall causes an increased amount in the streamflow output. Hence, under the projections of this study, it is not possible to say prior to the modelling that there can be either increase or decrease in the streamflow output.

5.2.2 Development of a rainfall - runoff based hydrological model to verify the streamflow data

A HEC-HMS model was developed as the rainfall-runoff based hydrological model and it was manually calibrated and validated by changing the parameters of the model. The calibration was carried out from 1st October 1990 to 30th September 1993 (3 years) and 0.70 NSE value was obtained. Validation was conducted from 1st October 1996 to

30th September 1999 (3 years) and the obtained NSE value was 0.62. It took a considerable amount of time for the calibration and validation process as it was accomplished manually by adjusting 22 parameters that come under the different methods used in the model.

There were some literature sources which have developed the same kind of HEC-HMS models for the same basin that obtained very acceptable NSE values (Sampath, Weerakoon, & Herath, 2015; Weerakoon, Sampath, & Herath, 2018). But the parameters they obtained for the models did not give acceptable NSE values for the developed model under this study. The reason for that can be as the calibration and validation were done by using a shorter period of time like one year or one and half years under those studies which do not deliver good results when using extended periods like 3 years. Another reason for the mismatch in the parameters can be the use of different data sets in different time periods as sometimes there is a possibility of having some instant trends in the selected data periods which gives different ideas about the variations in the climate parameters, rainfall and temperature. With all the reasons, it was decided to go for manual calibration and validation as most importantly, obtaining an acceptable model that is verified for the study was the significant factor for the success of the current research. After running a number of trials, finally, a verified model was obtained and it was supposed to use this model with projected rainfall and temperature values to obtain future streamflow for the basin.

After projecting future rainfall, temperature and evapotranspiration data sets, those were used as the inputs to the verified HEC-HMS model to predict the future streamflow data. This prediction was carried out under four different categories, 20s-A2,20s-B2, 50s-A2 and 50s-B2. In the 20s (2011-2040), the total streamflow is 38.10% lesser in the B2 scenario compared with the A2 scenario. In the 50s there is a 59.68% reduction in the total streamflow in the B2 scenario when compared with the A2 scenario. Because of that, in both periods a reduction has been observed for the B2 scenario than the A2 scenario but in both 20s and 50s, there is an increase in the streamflow comparing with the base period. The increase in the streamflow has proved in many other literature sources as well, as discussed in the literature review in this report (Azari, Moradi, Saghafian, & Faramarzi, 2016; Hamid, Sharif, & Narsimlu, 2017). The increase in the streamflow in both periods can be explained by the increase in the rainfall for both periods and that concludes that the effect of the increase in the rainfall was highly affected for the streamflow variation than the increase in the temperature which evaporates water which flows to generate the streamflow output. It has been proved from the results obtained, that the variation in the temperature with future projections has a lesser impact than the variation in the rainfall in the future as highlighted in the literature review (Yang & Liu, 2011). The obtained results for the Deduru Oya basin can be generalized to the basins nearby (eg: Mi Oya basin) which have some similar characteristics.

When considering the monthly variations, it shows some different variation pattern than the total context. Even though the annual streamflow delivers an increase in the future, on a monthly basis, in wet months the streamflow shows a considerable increase in the streamflow but in dry months there is a decrease in the streamflow as observed. Because of that reason, we can conclude that the wet months will become wetter and the dry months become drier in the future.

Increased streamflow can cause flooding situations in the future and with the future developments in the basin, as the land use patterns get changed, there is a higher possibility of increased the severity in floods as in the developed areas the infiltration rates will be reduced considerably (Githui, Mutua, & Bauwens, 2009). Hence, to minimize the effect for the downstream of the basin, it may be needed to improve the Deduru Oya reservoir structure capacities to store an additional amount of water in the future in the wet months. Then that water can be used in the dry months which give lesser streamflow than before and it will help to reduce the risk of droughts. It has been observed a considerable increase in the streamflow at the beginning of the year which may be majorly due to the increase in the northeast monsoon in the December - February period and in the rest of the period, the streamflow is not increased considerably. Hence, the higher risk of having floods will be occurred in this period and in the other periods, the water can be managed as in today under present demands. With the varying demands in the future, the situation may be different and it is needed to be analysed in deep accounting all the future changes in the demands and with very high demands comparing with the current situation, there will be a water deficit in the dry months of the year (specially in months July and September) if the water is not managed properly.

5.2.3 Development of a water balance based hydrological model to analyse the impacts of climate change

A water balance based hydrological model was developed using the HEC-ResSim software as discussed earlier. Then with the observed reservoir water elevations, the model was verified. The basic purpose of generating this model was to see what will be the impact of climate change on the reservoir operations when using the future predicted streamflow data by the HEC-HMS model.

The annual streamflow is increased with climate change as discussed in the previous topic. The evaporation rates were also increased with the average temperature rise. Because of both reasons, it was not possible to directly guess what will happen to the reservoir’s annual total release as the increased inflow can increase the release while the increased evaporation rates can reduce the release from the reservoir. The construction of the Deduru Oya reservoir dam was started in 2006 and the construction was finished in 2014. Because of that reason, it is a very recently constructed reservoir where there is a higher possibility of considering the future demands of water into account when deciding the dimensions and sizes of the structures. Taking that into consideration, the design discharges which are considered as the maximum possible outflows from the structures were used with the future data to deal with the future varying demand in the drinking and irrigation water requirements as it will vary in the future with several factors like increased population. But the climate change data may not be considered when designing the structures as in general practice still the engineers do not stress about the changing climate when deciding the sizes and the dimensions of the structures, which is also a very crucial element that needs to be considered. Because of that reason, these kind of studies are really helpful to identify the climate change impacts on reservoir operations to be a guidance for the future constructions and to call attention to show the importance of considering climate change impacts in the new constructions especially like this kind of large reservoirs having considerably large design periods like 50-100 years (Rungee & Kim, 2017).

The total annual release of the reservoir was obtained using the predicted streamflow data sets and projected evaporation rates under 4 categories 20s-A2, 20s-B2, 50s-A2 and 50s-B2. Comparing with 20s-A2, a 7.88% reduction in the total annual release was observed in the 20s-B2. Comparing with 20s-A2, there was a significant increase in the total annual release as by 114.42% in the 50s-A2 scenario while 27.77% increase in the 50s-B2. Because of that, the highest release was observed under the A2 scenario in the 50s which can be explained with the reason for having the highest streamflow input.

When considering about the wet months, the increase in the evaporation rates does not act as a dominant factor and the priority was fallen to the increased streamflow inputs. It is fair to obtain that kind of variation as the evaporation amount considered from the reservoir topwater surface is a very low amount considering with the obtained rises in the streamflows. Most importantly it has been observed that there will be increased outflows from each outflow structure of the reservoir. When the left bank sluice and the right bank sluice release the maximum possible release from the gates (which is fair when considering the future increased demand), still the other outflows like the outflow from the eight radial gated spillways, outflow to generate power will also be increased at the same time. An increase in the outflow from the radial gated spillway and increase release in the power generation structure can cause downstream severe floods as they release the outflow to the downstream of the Deduru Oya river. But the highest increase was observed at the beginning of the year like in January and February which in the northwest monsoon season. In that period the flooding can occur severely in the downstream with more frequent releases from the reservoir. Many of the literature also came up with similar results of having extreme hydrological events like in the periods having monsoonal precipitations (Mukundan, Acharya, Gelda, Frei, & Owens, 2019). To mitigate this, it is very important to take actions to be alert at that time. Most importantly it is needed to analyse the vulnerability of the reservoir dam to the future situation with higher streamflow and ensure safety.

It is very significant to observe the behaviour of the monthly releases from the reservoir as it shows an increase in the wet months and a decrease in the dry months which shows the importance of storing water in the wet months to cover the demand in the dry months to avoid risks on severe floods and droughts.

As the future demand has considered in to account in the modelling process, the releases from the left bank canal and the right bank canal will be adequate for the future water requirements targeted from those structures even there will be slight reductions in the dry months. Furthermore, there will not be any flow deficit for power generation in the wet months as there will be higher releases in that time, but there can be a deficit in the dry months as the releases get reduced. But as the reduction in the releases in the dry months happens in very small amounts, and overall, it is possible to conclude that there will not be considerable adverse impacts on power generation. The modifications inflicted by climate change in total annual inflow affects the hydropower generation and the possible impact of climate change on varying electricity demand was identified as negligible in previous literature as well and it proves the findings in here (Gaudard, Gilli, & Romerio, 2013). Here, the maximum power generation was considered for the modelling process which was 1.5 MW, but in future, if there is a situation occurring which shows a higher demand than the capacity because of the higher electricity consumption by humans, it may need to go for an alternative method to generate the power. When considering the ecological flow, there will be increased flows at the beginning of the year and in the rest of time the flow will be nearly similar or slightly lower which may not adversely affect the ecosystem considerably.

5.2.4 Study about future water management options and make recommendations on mitigatory measures to resist climate change impacts

From all the results obtained, the total annual values of the rainfall and temperature are expected to be increased and the total annual streamflow will also be increased causing increased releases from the Deduru Oya reservoir under both scenarios in the considered future periods. Rainfall will show a considerable increase in the wet months and slight decreases in the dry months but overall, the annual rainfall value will get increased in the future. Seasonally, there can be some reductions in the mean minimum temperature in the Maha season, but the rest of the parameters will be increased as the maximum temperature experiences a higher increase which causes an increase in the average temperature as well. With the changed situations in the basin, it is very important to evaluate the methods of managing the water in the basin and making recommendations on the mitigatory measures. Increased streamflow can cause floods in the downstream as well as in the areas located on two sides of the Deduru Oya river. Building flood barriers to protect the water-related structures and relocating some of the possible structures to higher elevation are solutions for the rising issue with the increased streamflow. Apart from that, it is suitable to modify the land usage of the basin as if it is possible to increase the infiltration by managing the ecosystem and increase the retaining water amount in a location, it may help to reduce the increased streamflow. This can be accomplished by using some green infrastructures like using green roofs and also by increasing the vegetation cover of the land area in the basin other than increasing the impervious surfaces (Zhang & Peralta, 2019). As recently most of the sustainable concepts adopted for the new constructions, it may be easy and practical to use more green infrastructures which also can be a huge benefit to reduce the streamflow generation in the basin. Maintenance of proper drainage systems and river system will also be a help to avoid the flooding occurring as with proper drainage the water will easily flow in the constructed flow paths without stagnating in one location. One of the methods to improve the flow network is to redesign the culverts and water controlling gates for the increased streamflow which can regulate that flow effectively (Cross, Rowland, Long, Tully, & Dunning, 2017).

The water stress in the dry months can be increased more in the developing regions than the other regions and focusing more on supplying an adequate amount of water for those regions will help to do proper water management in the basin (Alcamo, Flörke, & Maerker, 2007). It is also recommended to make a trend towards the rational water allocation to manage the available water. Furthermore, water regulations can be improved to ensure water security as a sound early adaptation method (Andrew & Sauquet, 2017; Chen, Niu, & Sun, 2013).

Information based technology applications can be used to ensure the protection of water resources in advance (Chen, Niu, & Sun, 2013). With the use of modern technology, real-time reservoir operation data can be obtained and it will help the reservoir operators to do proper water management.

Increased release from a reservoir affects its operations and it can impose an impact on the surrounding area of the reservoir as well. Because of the increased release, it will be needed to operate the reservoir structures; spillways and sluice gates frequently to release the water to the downstream. Because of that reason, the availability of reservoir operators throughout the period of having high releases is very important to ensure the security of the structures. It is significant to give proper attention to the reservoir and monitor the water levels regularly to avoid the damages to the reservoir structures (Duan, et al., 2019). Taking water management into account, the additional streamflow input to the reservoir can be stored inside the reservoir by increasing the capacity of the reservoir by increasing the dam height. This may help to reduce the release from the reservoir and it will solve the issue of experiencing the downstream flooding. Also, the stored water can be used in the dry months to cover the demands if there is any deficit occurring. Apart from that, as there will be considerable increases in the release in wet months and only negligible decreases in the dry month releases overall, the power generation will not be adversely affected in the future. But the available power generation capacity may also not be adequate if there is a higher increase in the demand in the future. In that case, it is better to go for an alternative power generation method which can effectively generate power to coverup the increased demand. Floating solar power generation is a very sustainable solution for power generation using reservoirs (Sharma, Muni, & Sen, 2015). But the impact of the installation of floating solar on a reservoir is needed to be studied further as it can affect the reservoir in both hydrodynamical and water quality aspects (Karpouzoglou, Vlaswinkel, & Molen, 2019; Sudhakar, 2019). If the excess water in the wet months can be stored and released in the dry months, the ecological flow will not be reduced in the future and the drinking and irrigation water requirement is also possible to cover with the reservoir release in the future as the maximum discharge from the left bank and right bank sluices were considered under the modelling. On a long-term basis, conducting more systematic researches on climate change aspects will help to understand further, the ways of reducing climate change impacts to avoid the negative effects in the future.

6.0 CONCLUSION AND RECOMMANDATIONS

6.1 Conclusion

From all the results obtained, the total annual values of the rainfall and temperature are expected to be increased and the total annual streamflow will also be increased causing increased releases from the Deduru Oya reservoir under the scenarios A2 and B2 in the two periods considered the 20s (2011-2040) and 50s (2041-2070).

It has been observed that there is an increase in the total annual rainfall by 21% - 24% for the 20s (2011-2040) and 42% - 75% for the 50s (2041-2070). The average annual temperature indicates 0.08% - 0.14% increase for the 20s and 0.28% - 0.43% increase for the 50s under IPCC emission scenarios A2 and B2. Furthermore, the annual streamflow has shown a 62% -77% increase for the 20s (2011-2040) and it has increased further in the 50s (2041-2070). Under the B2 scenario, the relevant percentage for the 50s is 131.37%.

On a monthly basis, the rainfall shows an increase in the wet months and a reduction in the dry months. Even though the minimum temperature will get reduced in the Maha season, average temperature shows an increase throughout the year.

Streamflow will also show both increases and reductions on a monthly basis and in wet months the streamflow will get increased and in dry months it will get reduced. This variation affects the releases from the Deduru Oya reservoir and they vary following the same pattern as streamflow while showing increased releases in the wet months and decreased releases in the dry months.

With proper water management practices, the excess amount in the wet months can be stored and it can be used in the dry months and it may help to ensure the water supply-demand balance. The ability of power generation to cover the required demand, ability to cover the agricultural and drinking water demands, potential to supply the ecological flow can be ensured with the proper water management practices in the future.

The reservoirs in the region, especially in the intermediate zone as the Deduru Oya reservoir, will get similar kinds of impacts from climate change and it is needed to ensure proper water management in the future.

6.2 Recommendations

It is recommended to put more attention on the climate change impacts in detail as it can affect the streamflow and reservoir operations as discussed before. For future construction of water-related structures, it is needed to consider climate change impacts as well in the designing process.

It is recommended to conduct continuous assessments by the reservoir operators throughout the period to avoid severe floods and droughts.

Furthermore, it is recommended to follow a well structured irrigation guideline for reservoir operation in the future as it was not able to identify a specific guideline for the reservoir simulation model in the current study.

As climate change affects in different ways for different regions it is recommended to conduct more researches on a regional basis to identify the impacts for a specific region.

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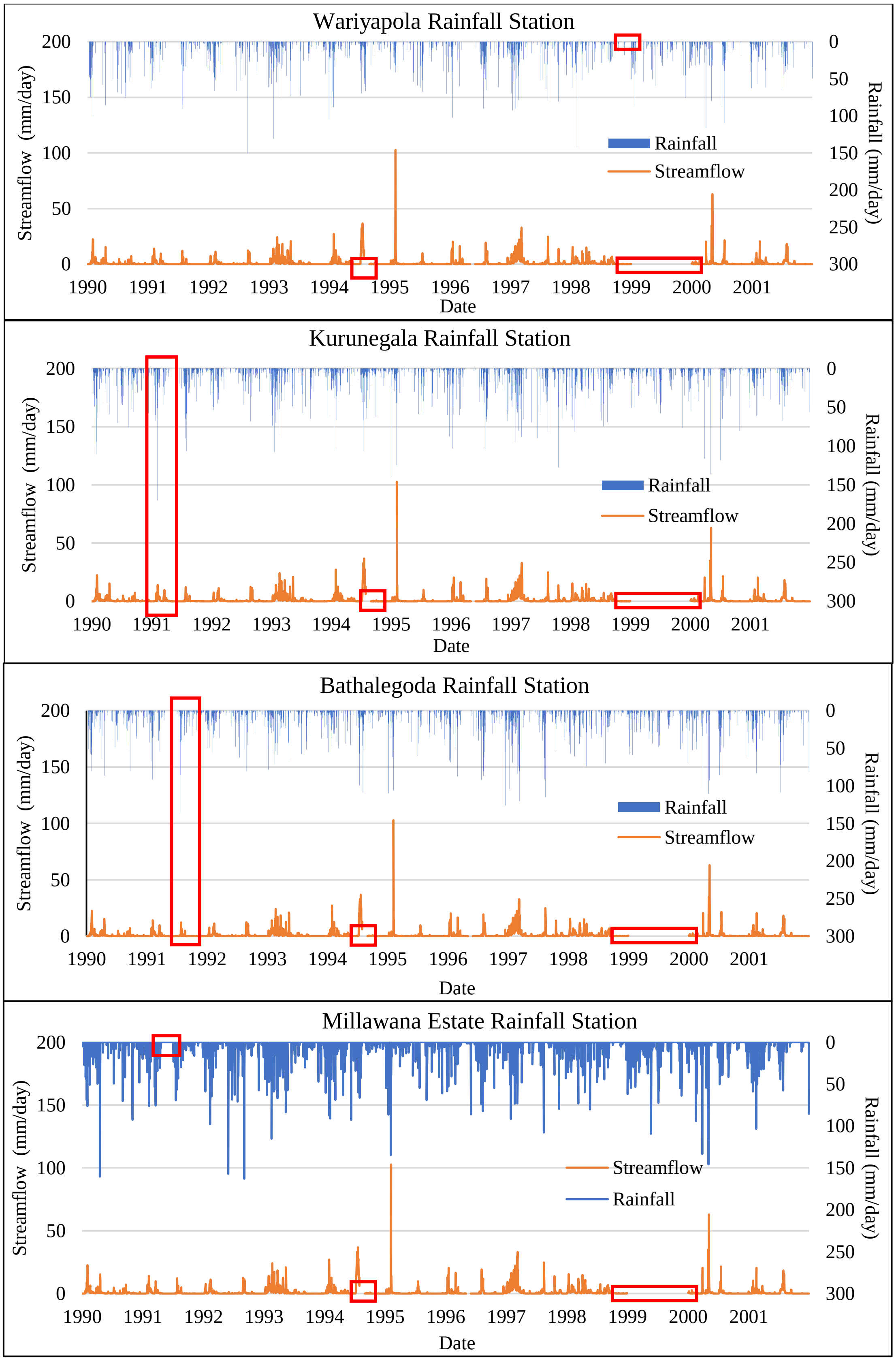
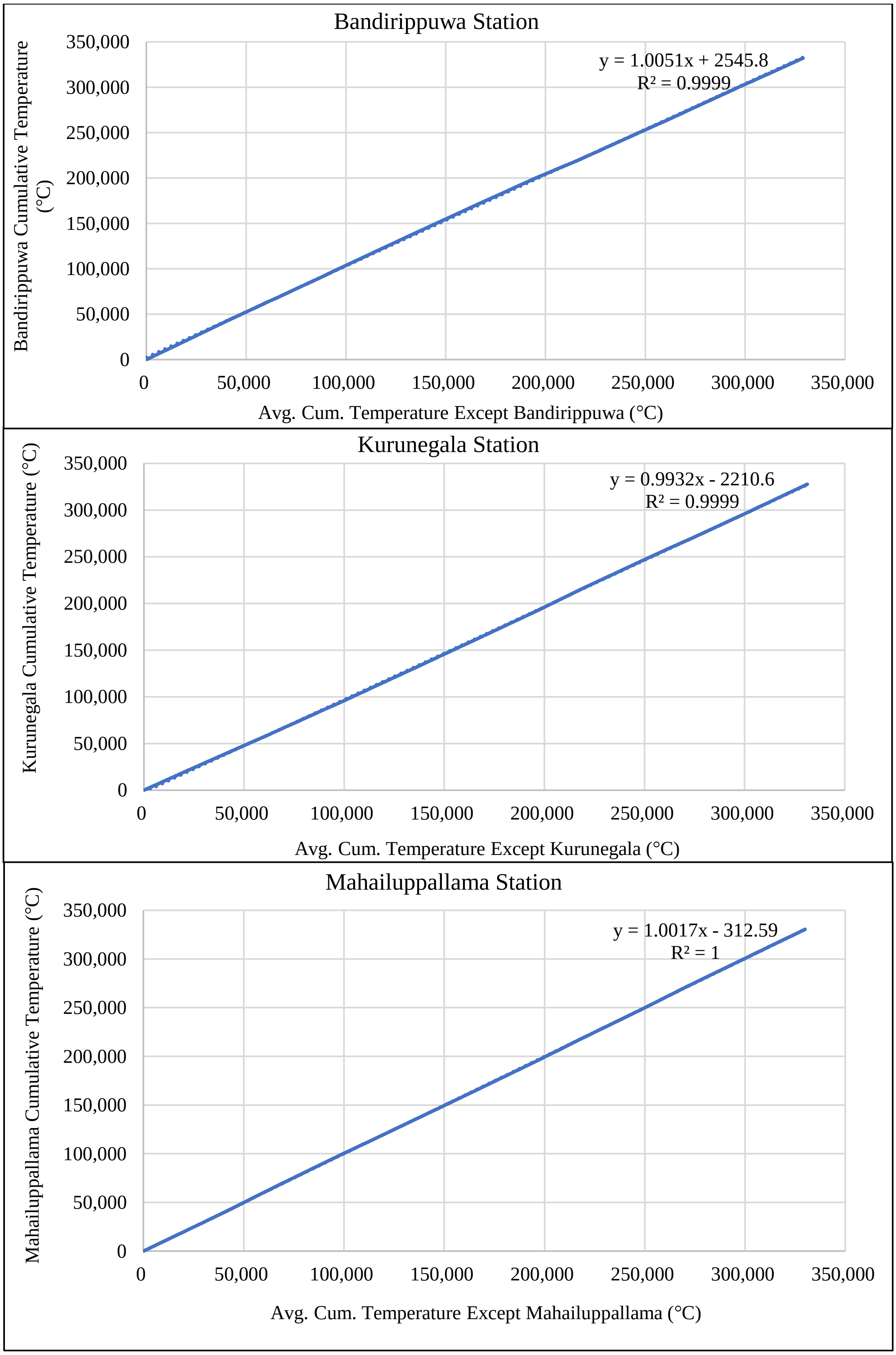
APPENDICES

Appendix I: Graphs of Visual Data Checking

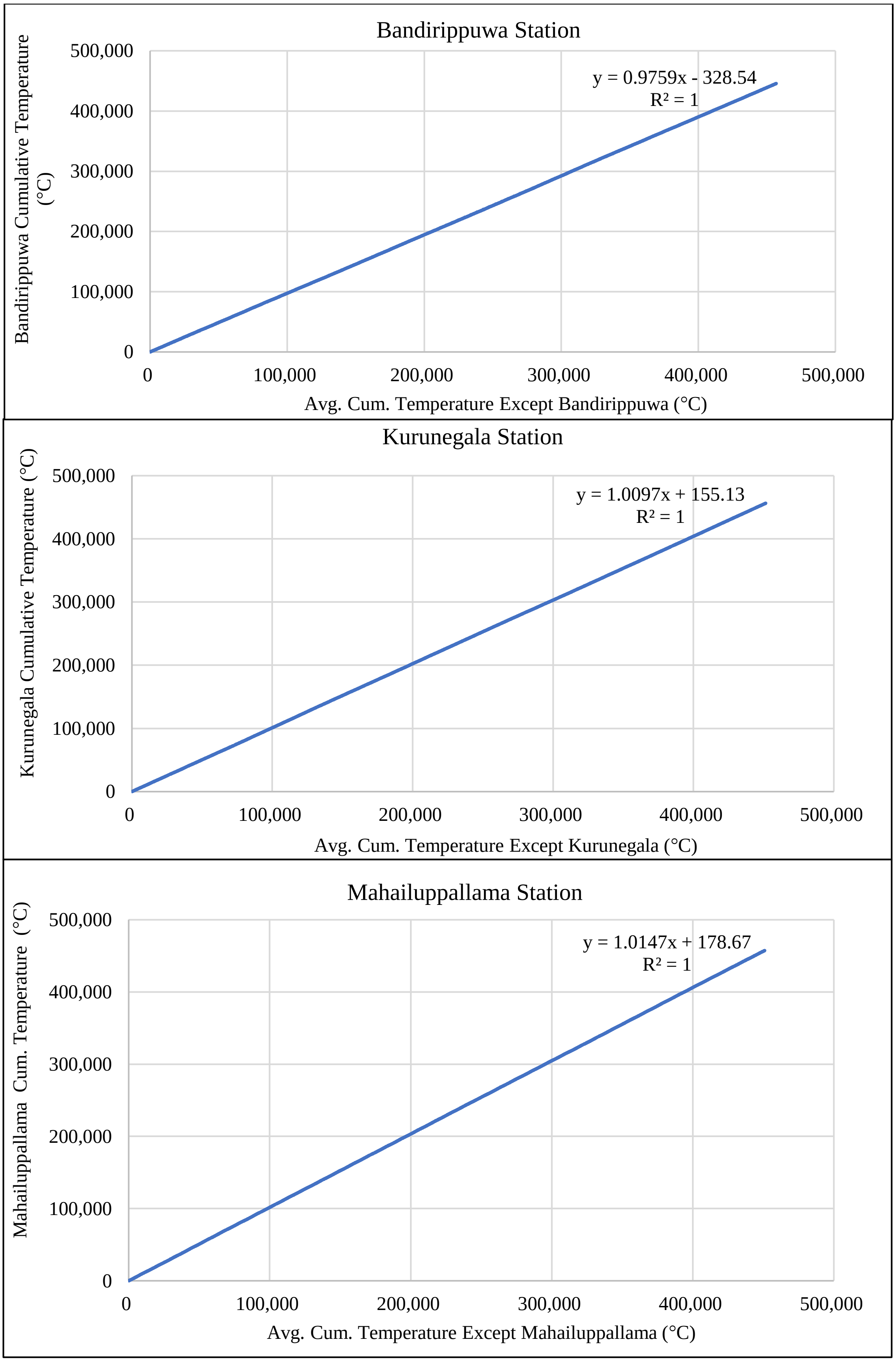


Appendix I-1: Graphs of visual data checking

Appendix II: Double Mass Curves



Appendix II-1: Double mass curves for minimum temperature stations



Appendix II-2: Double mass curve for maximum temperature stations