ESTABLISHMENT OF DRY WEATHER FLOW IN KALU GANGA UNDER CLIMATE CHANGE SCENARIOS

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Degree of Master of Science

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LIST OF ABBREVIATIONS

CCCma	Canadian Centre for Climate Modeling and Analysis
CSIRO	Commonwealth Scientific and Industrial Research Organization
DHI	Danish Hydraulic Institute
GC	Greater Colombo
GCM	General Circulation Model
GHG	Green House Gas
HadCM3	Hardley Center Coupled Model 3
IPCC	Intergovernmental Panel on Climate Change
MCM	Million Cubic Meters
NAM	Nedbør-Afstrømnings-Model
NCEP	National Center for Environmental Physics
NEM	North East Monsoon
NWSDB	National Water Supply and Drainage Board
RCM	Regional Climate Model
SDSM	Statistical Downscaling Model
SRES	Special Report on Emission Scenarios
SWM	South West Monsoon
WMO	World Meteorological Organization

1. INTRODUCTION

1.1 Background

Climate change refers to any significant change in the measures of climate such as temperature, precipitation, wind patterns lasting for several decades or longer. It is well established that rising global temperatures and warming earth have been accompanied by noticeable changes in weather and climate in the past decades. Many places have seen changes in rainfall, resulting in more floods, droughts, or intense rain. Climate change can create opportunities as well as risks worldwide. Through proper understanding of the issue, a frame work for the adaptation/minimizing risks for climate change can be developed. Vulnerability to climate change and variability is higher in poor developing nations than in the developed nations as the adaptive capacity to vulnerabilities is higher in the developed countries than in the developing countries.

"Sri Lanka expects that over the next two decades the sea-level will rise by 0.5m and rainfall variability with dry areas becoming drier and wet areas becoming wetter, leading to floods in some areas and drought in others" (Samath, 2008). "In April 2007, Rajendra Pachauri, Chairman of Intergovernmental Panel on Climate Change (IPCC), said at a press conference in New Delhi that up to 60 million coastal people in the low-lying areas of South Asia could be displaced by global warming by the end of the 21st century" (Samath, 2008).Those are some quotations which are frequently being heard all over Asia and the world which underlines the importance of being aware of climate change. The experts' talks warn that the world community faces many risks from climate change. It is important to understand the impacts and vulnerabilities due to climate change.

The Intergovernmental Panel on Climate Change (IPCC, 2007) defines Climate change as statistically significant variation either in mean state of the climate or in its variability, persisting for an extended period (typically for decades or longer). Climate change takes place due to natural internal processes or external forcing or due to persistent anthropogenic changes in the composition of the atmosphere or in land use.

As a result of human activities, which increase the greenhouse gas emissions such as burning of fossil fuels, change in land use practices specially deforestation and emission of industrial gases after the industrial revolution, changing climate has occurred in an alarming rate. All these actions resulted to the global warming of the earths' atmosphere causing the greenhouse effect thereby increasing the surface temperature. Climate change directly affects precipitation, temperature and potential evapo-transpiration. Consequently, some other main indirect impacts such as rise in seawater level, saltwater intrusion to inlands, unexpected flooding, droughts, and health problems have become dominant all over the world.

Especially with the climate change impacts, it is a must to be aware about the dry events and heavy rainfall events and prepare a national framework for adaptation for such situations. "Rainfall extremes are projected to increase more than the mean and the intensity of precipitation events are projected to increase. Although number of rainy days has decreased while reducing the water volume of watershed. The report "Summary for policy makers" released by IPCC in 2007 (IPCC, 2007) states, "It is very likely that hot extremes, heat waves, and heavy precipitation events will continue to become more frequent.

With respect to Sri Lanka, it has been determined that Sri Lanka also has undergone a significant climate change. Domroes (1996) has found that the variability of rainfall over Sri Lanka has very large fluctuations between the years of 1931-1993. The results showed a negative anomaly that indicates a decrease in rainfall over Sri Lanka. Furthermore, the trends were found to be varying, sometimes the trends are increasing and sometimes decreasing. However, for the period of 1961-1993 a very strong negative trend was observed in rainfall anomalies than over the last 140 years. Sri Lanka is an island of 65,600km^2 land area situated in the Indian Ocean between latitudes of 5° 55' and 9° 51' north and the longitudes of 79° 41' and 81° 54' east. The land area consists of central hills surrounded by low land area. It has a tropical climate with two distinct monsoons namely the northeast and southwest monsoons, which occur during December to February and May to September, respectively. The combination of the topographical features and the two monsoon rainfall patterns makes three climate zones mainly based on average annual rainfall. These are the wet zone in the southwest part of the country having more than 3,000mm of rainfall per year, the intermediate zone, and the dry zone in the north east part of the country having an average annual rainfall of less than 2000 mm. Due to climate change scenarios the dry zone of Sri Lanka undergoes drought conditions and the wet zones face unexpected flooding conditions frequently (how prepared are water & agriculral sector in Sri Lanka for climate change, IWMI).

Sri Lanka contains many water bodies in its 103 river basins with areas ranging from 60 km^2 to 10450 km^2. The four major river basins are the Mahaweli, Kelani, Kalu and Walawe which all originate from the central hills of Sri Lanka and flow to the Indian Ocean through the valleys and low land areas. Kalu Ganga basin is one of the most important river basins in Sri Lanka which receives very high rainfalls and annually discharges about 8180 MCM (Water; Global common and Global problem, Velma I. Grover) of water to the sea. Due to its hydrological and topographical characteristics, the lower flood plain suffers from frequent floods and it affects socio-economic profile greatly. During the past several years, many researchers have investigated climatic changes of main river basins of the country, but no studies have been done on climatic changes in Kalu Ganga basin.

While the Kalu Ganga basin has a decreasing trend of annual precipitation and it is clear that slight climatic changes may have affected the magnitude and timing of the precipitation within the study area (A.D.Ampitiyawatta & ShenglianGuo, 2009). It says negative trends of annual precipitation were found in all the analyzed rainfall gauging stations in kalu basin. As an average, -0.98 (Mann Kandall test statistics, S) trend with the annual rainfall reduction of 12.03 mm/year was found. April and August were observed to have strong decreasing trends. July and November displayed strong increasing trends. Kalu Ganga has decreasing trends of water volume in future (L Manawadu& N. Fernando, 2008). The study finds that the number of rainy days has decreased. This could indicate that the intensity of rainfall events may have increased together with increased durations of dry spells.

Sri Lanka being an island state is especially vulnerable to all identified impacts of climate change including rise in land and sea surface temperature, changes in precipitation amount and pattern, increase in extreme climate events, and sea level rise. These 'direct' impacts, in turn trigger a wide variety of secondary effects on water resources, agriculture, livelihoods, health and wellbeing, the economy and nature. It is critically important that these impacts are identified, quantified, and suitable action is initiated to adapt to them.

1.2Statement of the Problem

Sri Lanka faces number of challenges related to water sector and increasing water scarcity for domestic purposes has become prominent of amongst them. During the monsoon period some areas being severely affected by flood due to lack of storage facilities. However on the other hand again people are suffering during dry season due to lack of water. Therefore it is worth to study about the flow conditions in major rivers under various climatic conditions. Obviously such study would help for

- design of water control structures (bridges, weirs and drainages);
- estimating water abstraction rates;
- maintaining environmental flow and
- controlling flood hazards and effluent discharge

Greater Colombo (GC) area has been experiencing some massive all round development in almost every sphere involving housing, building, road, commercial and industrial activities coupled with a huge population growth during the past two to three decades, and naturally exerting demand for corresponding increase in public utility services and infrastructure. Consequently, the demand for pipe borne water supply too has increased manifold.

Potable water supply system in Colombo area mainly depends on water from the Kelani Ganga. At the moment, Kelani basin is the main basin which satisfies the domestic and industrial water demand in Greater Colombo area. However it is doubtful whether Kelani basin can further fulfill the increasing water supply demand as sea water intrusion is becoming a critical problem for that basin. Therefore, as an alternative, everyone in water sector pay their attention to the Kalu Ganga basin since it is rich with water resource. Hence it would be more appropriate to study about the dry weather flow and define the precautions that should be taken in such situation in future. This would be more advantageous for the water supply schemes as they should survive throughout the year.

Ellagawa and Millakanda are the main river gauges in Kalu Ganga maintained by Irrigation department. There are few rainfall stations being maintained by Meteorological Department close to Ellagawa and Millakanda gauging stations. Annual rainfall variation of few rainfall stations close to the above mentioned river gauging stations is shown in Table 1. According to the data shown in Table 1 a noticeable variation can be observed in annual rainfall.

Table 1: Annual Rainfall Variation

Year	Raigama	Halwatura	Galatura	Usk Valley
1994/1995	4131	5031	4530	4161
1995/1996	2673	3407	3353	3968
1996/1997	2799	2899	3805	2863
1997/1998	3126	2835	4756	5059
1998/1999	3862	3768	7030	4731
1999/2000	3661	5039	4322	4568
2000/2001	2638	3434	2598	3118
2001/2002	2393	3651	3456	3284
2002/2003	3416	5511	4918	4597
2003/2004	2634	5366	3856	4756
2004/2005	3201	5468	3636	3250
2005/2006	4327	4618	4006	4154
2006/2007	4209	3267	3628	4930
2007/2008	4342	2041	4362	5607
2008/2009	3300	3292	3727	5340
2009/2010	3731	4001	3489	4255

According to the recorded data, there is a variation in annual rainfall in every station. It can be effect on entire basin. Kalu Ganga basin has already under gone the impacts of climate and existing water availability could worsen due to effect of climate change in the future. Therefore, now is the time for analyzing future climatic condition to cater this problem.

1.3 Objective

The objective of this study is to pinpoint the dry weather flow (low flow) in Kalu Ganga in order to fulfill the future requirement of drinking water in Greater Colombo, because of the inadequate capacity of Kelani Ganga, which is the major source of potable water for Greater Colombo to meet future demand. Enhancing dry weather flow (low flow) of Kalu Ganga is also important because as it is the one of other major source of potable water to Greater Colombo.

The objective of this study is establishment of low flow condition in the Kalu Ganga basin under different climate change scenarios.

1.4 Scope of the Study

- Hydrological modeling for existing data
- Identify the suitable Global Circulation Method (GCM) for Sri Lanka
- Downscaling the GCM data and analysing future rainfall trends
- Hydrological modeling for future scenarios
- Low flow analysis and
- Identifies the significance of climate change on low flows.

1.5 Limitation of the Study

- Unavailability of Regional climate model data for the study area which can represent the climate change conditions better as Sri Lanka is an island.
- Inaccessibility to dynamically downscaled data and dynamical downscaling models for the study area which can determine daily data better than statistical methods.

2. LITERATURE REVIEW

2.1 General

This chapter presents concepts, principles and previous studies carried out in analyzing future climate and dry weather flow (low flow) due to climatic change conditions. It is mainly focused on timely necessity of this nature of study, climate change terminology, downscaling data from GCMs, hydrological modeling and low flow analysis.

2.1.1 Need of study

One of the most common uses of low flow information is, in designing and operation of public water supply schemes. There are three primary scenarios where low flow information is required.

- when designing the water supply scheme that is at the initial stage
- during operation phase and
- When it is necessary to make operational decision today, based on estimates of future river flows.

Diversion of base flow of rivers without impounding water had been in practice during the ancient hydraulic civilization in Sri Lanka. However, the analysis of low flow was not given much prominence by hydrologists, in comparison to flood peak analysis. More recently, a greater awareness of ecological factors concerning environmental degradation of river systems were taken place in various conferences worldwide, Specially during drought seasons, to conceive the idea of "river maintenance flow" and therefore pay more attention to the analysis of low flow in rivers. The recent emphasis on development of mini hydropower potential in Sri Lanka by diverting the base flow of streams put the dry weather flow issue in a vulnerable position.

The water demand for Greater Colombo for the year 2010 and 2020 have been estimated as 787,500m^3/d and 968,800 m^3/d respectively. Allowing 136,600m^3/d from Labugama and Kalatuwawa reservoirs, the balance water requirement has to be found from Kalani Ganga and other sources (Report on Water Supply Master Plan Update for Western Province Metropolitan Area, 2012). Due to salinity intrusion, it is not possible to extract the balance water volume from Kelani Ganga without enhancing the dry weather flow. Therefore, Kalu Ganga water supply projects intended to supply remaining water quantity to Greater Colombo Area. Usages of Kalu Ganga water for other purpose will be more in near future.

2.1.2Climate change terminology

The terminology commonly used in climate change scenarios are weather, climate, climate variability and change are the main words that needed to be known. Weather is described as atmospheric conditions at a particular place in terms of air temperature, pressure, humidity, wind speed and precipitation. Climate is defined as average weather over a time period, typically 30 years. Climate variability refers to the variations in the mean state of climate on all temporal and spatial scales beyond that of individual weather events. Extended drought, floods and conditions as a result of El Nino and La Nina events are some examples for the climate variability. Shifts in the mean state of the climate or in its' variability is referred as climate change.

2.2 Downscaling of Climate Data from GCMS

The future projection of weather data are normally done in very large special scales. In order to use them in basin scale analysis, the data needed to be made as sub grid scales of 10-100km. In order to achieve this, downscaling is done and currently there are many different methods available. Figure 1 is a schematic representation of downscaling process.

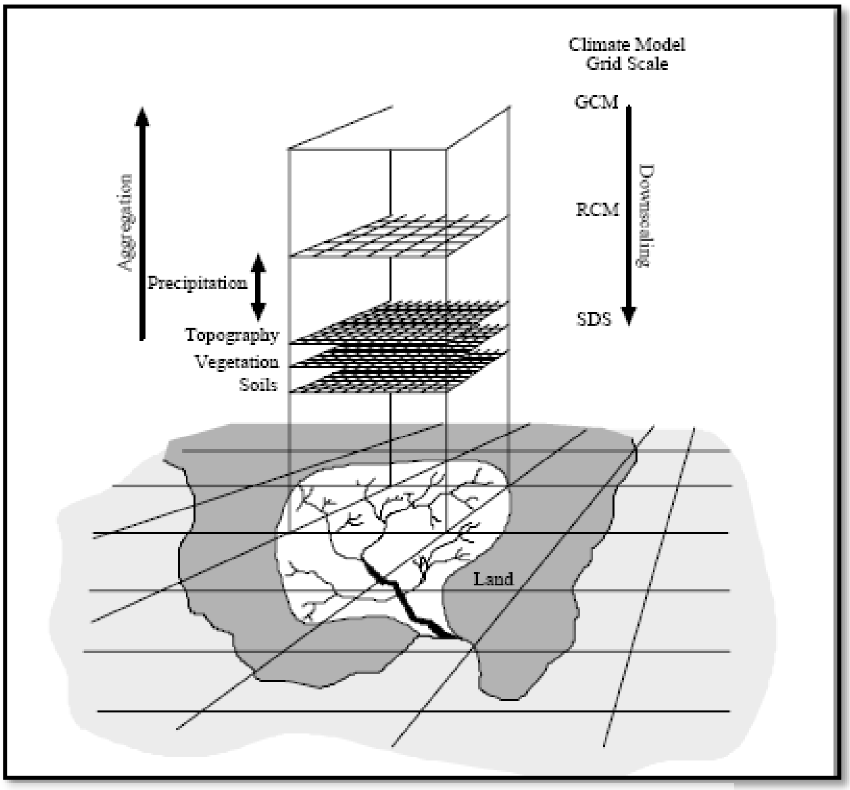


Figure 1-Schematic diagram of downscaling technique
(Source: Wilby and Dawson, 2007)

The literature shows that there are four main types of downscaling methods namely, Dynamical, Weather typing, Stochastic weather generators and Transfer functions method.

Dynamical downscaling involves the nesting of a higher resolution Regional Climate Model (RCM) within a coarser resolution GCM. The RCM uses the GCM to define time–varying atmospheric boundary conditions around a finite domain, within which the physical dynamics of the atmosphere are modelled using horizontal grid spacing of 20–50 km (SDSM user Manual, Wilby and Dawson, 2007). The main limitation of RCMs is that they are as computationally demanding as GCMs (placing constraints on the feasible domain size, number of experiments and duration of simulations). The scenarios produced by RCMs are also sensitive to the choice of boundary conditions (such as soil moisture) used to initiate experiments.

Weather typing approaches involve grouping local, meteorological data in relation to prevailing patterns of atmospheric circulation. Climate change scenarios are constructed, either by re–sampling from the observed data distributions or by generating synthetic sequences of weather patterns and then re–sampling from observed data. The technique is also valid for a wide variety of environmental variables as well as multi–site applications (SDSM user Manual, Wilby and Dawson, 2007).

Stochastic downscaling approaches typically involve modifying the parameters of conventional weather generators such as WGEN, LARS–WG or EARWIG. The WGEN model simulates precipitation occurrence. Climate change scenarios are generated stochastically using revised parameter sets scaled in line with the outputs from a host GCM (SDSM user Manual, Wilby and Dawson, 2007). The main advantage of the technique is that it can exactly reproduce many observed climate statistics and has been widely used, particularly for agricultural impact assessment. Furthermore, stochastic weather generators enable the efficient production of large ensembles of scenarios for risk analysis. The key disadvantages relate to the low skill at reproducing inter-annual to decadal climate variability, and to the unanticipated effects that changes to precipitation occurrence may have on secondary variables such as temperature.

Transfer-function downscaling methods rely on empirical relationships between local scale predictands and regional scale predictors. Individual downscaling schemes differ according to the choice of mathematical transfer function, predictor variables or statistical fitting procedure. Linear and non–linear regression, artificial neural networks, canonical correlation and principal components analyses have all been used to derive predictor–predictand relationships (SDSM user Manual, Wilby and Dawson, 2007). The main strength of transfer function downscaling is the relative ease of application, coupled with their use of observable trans–scale relationships. The main weakness is that the models often explain only a fraction of the observed climate variability. In common with weather typing methods, transfer methods also assume validity of the model parameters under future climate conditions, and the downscaling is highly sensitive to the choice of predictor variables and statistical form.

2.2.1 Climate change studies in Sri Lanka

Studies which spell out future climatic scenarios for Sri Lanka are scarce and even the ones that exist appear to project contradictory results, especially with respect to future rainfall. Rainfall projections for Sri Lanka within this century appear to be confusing and sometimes contradictory. While the majority of them project higher mean annual rainfall (MAR), some project lower MAR. AR4 models (Cruz et. al., 2007), regional climate models by Kumar et. al. (2006) and Islam and Rehman (undated) and statistically downscaled projections from the HadCM3 model by De Silva (2006) all show increases in MAR under a range of IPCC scenarios (A1F1, B1, A2, B2). De Silva (2006) further elaborates that these increases will be 14% for A2 and 5% for B2 by 2050 with reference to 1961-1990. While statistical downscaling of projections from HadCM3 and CSIRO models by Basnayake et. al. (2004) shows an increase in MAR, the CGCM model shows a decrease in MAR for scenarios A1F1, A2 and B1.

However, there is general consensus among them that Sri Lanka will become increasingly warmer during the 21st century, although the projected magnitude of temperature increase differs from study to study mainly due to differences in projection method and assumed future GHG emission scenarios.

Domroes (1996) has done a research on rainfall variability of Sri Lanka and found very large fluctuations during the periods of 1931-1993. Every year, rainfall in Sri Lanka gets decreased approximately by 10mm. However, the trend shows an inconsistency in annual totals with increasing as well as decreasing trends. The seasonal trends were controversial to that of annual though many similarities were noticed. It was noticed a very strong negative anomaly during the period of 1960-1993 and it was more striking decrease over the entire last 140 years.

The two regional climate models (Kumar et. al., 2006 and Islam and Rehman, undated), and downscaled projections from HadCM3 and CSIRO models by Basnayake et. al. (2004) suggested increases in both South West Monsoon (SWM) and North East Monsoon (NEM) rainfall (for a range of IPCC scenarios from A1 to B2). Further, with Basnayake et. al. (2004) has suggested higher increases in SWM than in NEM. They also envisage much higher increments of rainfall on the windward side of the central hills in each monsoon season and lesser increments on the leeward side by 2100. In contrast, Basnayake (2004) studied (downscaled CGCM model projections) on rainfall scenarios for Sri Lanka under the anticipated climate change with some model predictions. It depicted that the south west monsoon, Northeast monsoon and annual rainfall are projected to be decreased in the future.

De Silva (2006) envisaged a 26-34% decrease in the North East mean rainfall and a 16-38% increase in the South West Mean rainfall compared to 1961-1990 for scenarios B2 and A2.Recently a study had been carried out related to climate change data downscaling for Sri Lanka(De Silva et al., 2007). They have used the outputs from UK hardly center for climate prediction and research model (HadCM3) for selected scenarios for 2050. The scenarios were selected from special reports of IPCC on emission scenarios (SRES). Two scenarios, named A2 and B2 were mainly used. According to the results obtained, it is suggested that, during the wet season, average rainfall decreases by 17% (A2) and 9% (B2), with rains ending earlier and potential evapo transpiration increase by 3.5% (A2) and 3% (B2). Consequently, the average paddy irrigation water requirement increases by23% (A2) and 13% (B2). Moreover, the study suggested that the rainfall in Colombo during May to September period will increase by 43-57% (A2) and 19-27% (B2).

A.D. Ampitiyawatte and ShenglianGuo (2009) have envisaged negative trends of annual precipitation in all the analyzed rainfall gauging station in Kalu Basin. As an average, -0.98 trend with the annual rainfall reduction of 12.03 mm/year was found. April and August were observed to have strong decreasing trends. July and November displayed strong increasing trends. In conclusion, the Kalu Ganga basin has a decreasing trend of annual precipitation and it is clear that slight climatic changes may have affected the magnitude and timing of the precipitation within the study area.

The above literature data suggests that considerably amount of work is needed to be carried out to verify and further refine the available climate projections for Sri Lanka.

2.2.2 Statistical downscaling model (SDSM) for climate change data downscaling

SDSM is a decision support tool for assessing the local climate change impacts using a statistical downscaling technique. This can be used for development of multiple, low cost single site scenarios of daily surface weather variables under current and future climate forcing. However, at present there are several downscaling techniques available and SDSM can be only used for statistical downscaling.

Though both type of models (stastical and dynamic) show similar level of skill in estimating surface weather variables under current climate conditions. Table 2 highlights the main strengths and weaknesses of statistical and dynamic downscaling models (Wilby and Dawson, 2007).

Table 2: Main Strengths and weakness of statistical and dynamic downscaling

	Statistical downscaling	**Dynamical downscaling**
Strengths	Station–scale climate information from GCM–scale output	10–50 km resolution climate information from GCM–scale output
	Cheap, computationally undemanding and readily transferable	Respond in physically consistent ways to different external forcings
	Ensembles of climate scenarios permit risk/ uncertainty analyses	Resolve atmospheric processes such as orographic precipitation
	Applicable to ‘exotic’ predictands such as air quality and wave heights	Consistency with GCM
Weakness	Dependent on the realism of GCM boundary forcing	Dependent on the realism of GCM boundary forcing
	Choice of domain size and location affects results	Choice of domain size and location affects results
	Requires high quality data for model calibration	Requires significant computing resources

	Statistical downscaling	**Dynamical downscaling**
	Predictor–predictand relationships are often non–stationary	Ensembles of climate scenarios seldom produced
Weakness	Choice of predictor variables affects results	Initial boundary conditions affect results
	Choice of empirical transfer scheme affects results	Choice of cloud/ convection scheme affects (precipitation) results
	Low–frequency climate variability problematic	Not readily transferred to new regions or domains
	Always applied off-line, therefore, results do not feedback into the host GCM	Typically applied off-line, therefore results do not always feedback into the host GCM

(Source: Wilby and Dawson, 2007)

In SDSM, multiple regression methodology has used. The model includes several steps in statically downscaling daily weather series. Those are, screening of the predictor variables, model calibration, weather generation, synthesis of observed data, diagnostic testing and statistical analysis and scenario development. F 2Figure 2 shows the schematic view of the SDSM Process.

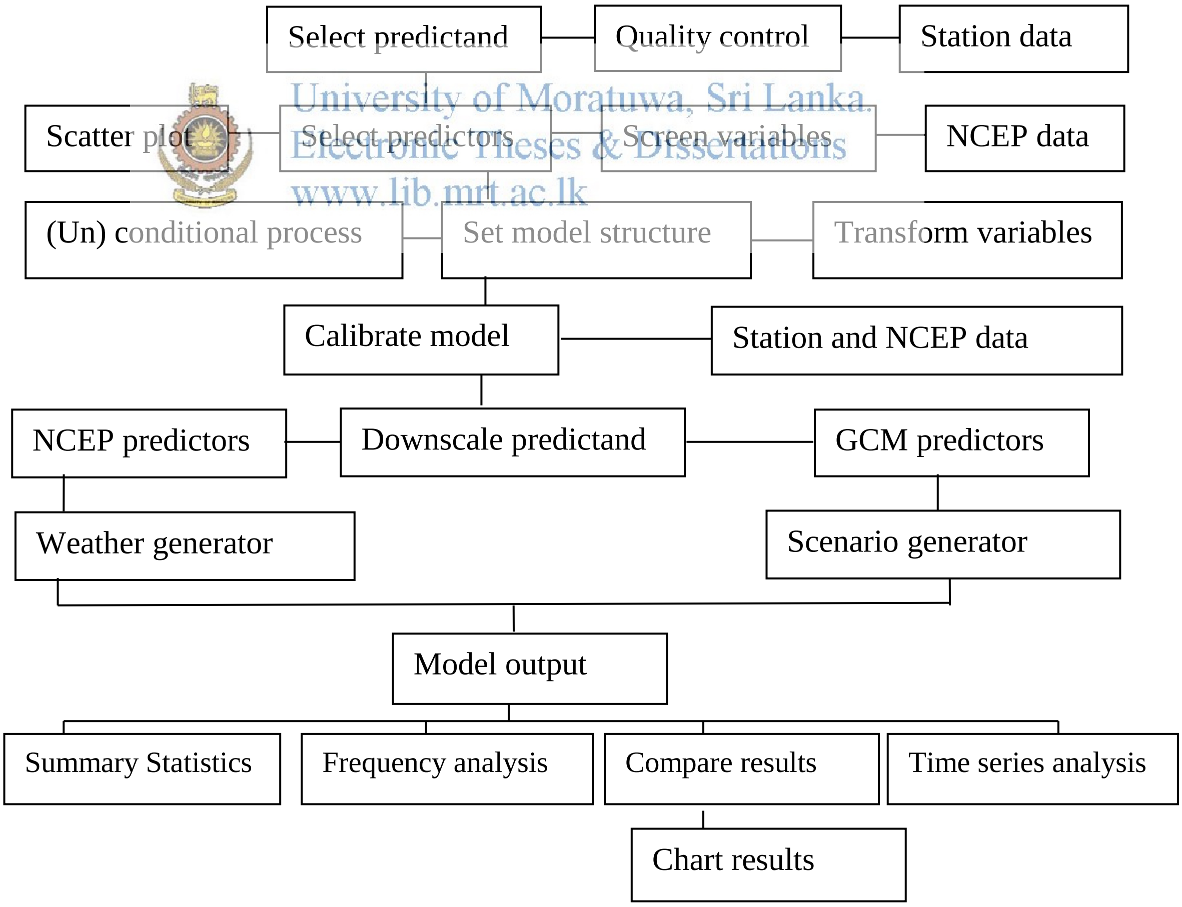


Figure 2: Schematic View of the SDSM Process

2.3 Hydrological Modelling

Variations in climate, topography, land types and land-use as well as various man-made interferences with the system make it difficult to construct general models that treat the whole hydrological cycle in any given catchment in the world. Most models only treat a part of the cycle, e.g., runoff or groundwater-flow. Models are simplified systems that represent real systems. In the case of hydrological models the real system may be an entire river basin or parts of it.

Hydrologic models are simplified, conceptual representations of a part of the hydrologic cycle. They are primarily used for hydrologic prediction and for understanding hydrologic processes. Hydrological models have become increasingly important tools for the management of the water resources of the basin. They are used for flow forecasting to support reservoir operation, flood protection, climate change impacts on water resources, in hydraulic structure design studies and for many other purposes.

Several models can be used for hydrological modeling. Mainly HEC-HMS developed by US Army Corps of Engineers and MIKE 11 NAM developed by Danish Hydraulic Institute are available for hydrological modeling. Mike 11 NAM was used in this study for hydrological modelling.

The rainfall-runoff module can be applied to represent one or more contributing catchments that generate lateral inflows to a river network. In this manner it is possible to treat a single catchment or a large river basin containing numerous catchments and a complex network of rivers and channels within the same modelling framework. NAM is the abbreviation of the Danish "Nedbør-Afstrømnings-Model", meaning precipitation-runoff-model. This model was originally developed by the Department of Hydrodynamics and Water Resources at the Technical University of Denmark. NAM represents various components of the rainfall-runoff process by continuously accounting for the water content in four different and mutually interrelated storages. Each storage represents different physical elements of the catchment. NAM can be used either for continuous hydrological modeling over a range of flows or for simulating single event. The NAM model can be characterized as a deterministic, lumped, conceptual model with moderate input data requirements. A description of the classification of hydrological models is given in Abbott and Refsgaard (1996). Refsgaard and Knudsen (1997) compare a number of different types of hydrological model, including the NAM model, in terms of both data requirements and model performance. The NAM model is a well-proven engineering tool that has been applied to a number of catchments around the world, representing many different hydrological regimes and climatic conditions.

A conceptual model like NAM is based on physical structures and equations used together with semi-empirical ones. Being a lumped model, NAM treats each catchment as a single unit. The basic input requirements for the NAM model are model parameters (surface root zone and groundwater zone), initial condition and meteorological data. The basic meteorological data required for NAM are rainfall and evaporation. That reproduces the effect of land-surface heterogeneity on circulation as imposed by such water balance model (D'Almeida et al, 2006). The parameters and variables represent in the NAM model are average values for the entire catchment. As a result, some of the model parameters can be evaluated from physical catchment data, but the final parameter estimation must be performed by calibration against time series of hydrological observations.

2.4 Low Flow

According to the World Meteorological Organization, Low flow is the "flow of water in a stream during prolonged dry weather". Low flows are not only of concern in water supply but are also important in water quality. Low flows affect the self-purification of a stream. Assessment of low flows is necessary in estimating the release of waters from upstream reservoirs to maintain minimum flow conditions in stream flows as well as to meet off stream uses. It is now recognized that there is a need to provide long term baseline monitoring and analysis of low flow to support integrated river basin management. This provides a framework for environmental agencies to make decisions regarding the catchment-wide development of water resources and prevents ad hoc decision making.

2.4.1 Estimation of low flow

Establishment of low flow condition is normally been based on the analysis of available data. The analysis should be focused on critical periods. Annual minimum and flow duration analysis can be carried out for specific months or seasons. It may be appropriate to consider annual minimum of different durations (7day, 10day, 30day and 90day etc).

The analysis of low flows must be based on probability theory. Frequency analysis provides a relationship between events and their probabilities of occurrences. In general this relationship is determined in the form of a theoretical probability distribution. There are several probability distributions suitable for low flow data (Transformation methods, Hypothetical Distribution-Based Methods and Plotting-Position Based Methods (Log-Boughton Distribution) (G.V.Loganathan, C.Y.Kuo and T.C. McCormick, 1985). Frequency analysis is the procedure for estimating the probability of occurrence of an event. Based on the recommendations of the Water Resources Council, the log-Pearson type III distribution has been widely used for the frequency analysis of floods and Weibul and Gamma distribution used for low flow analysis.

The first step required in frequency analysis is the collection of data to be analyzed. The sample for this type of analysis usually consists of a set of extreme values for each year. For low flows, the duration of the extreme value for each year is often taken to be something other than one day. Longer durations are used because the adverse impacts of low flows are often felt only after a prolonged period.

After generation of the sample, the second step in frequency analysis is the selection of the probability distribution to be utilized. A probability distribution is a functional relationship between events and the probability associated with their occurrence. A number of distributions have been used for the analysis of low flows. Those are transformation methods (Power Transformation, SMEMAX Transformation, Modified SMEMAX Transformation) , Hypothetical Distribution-Based Methods (Gumbel Type III Distribution, Gamma distribution, Pearson Type III(P3) Distribution , Weibull Distribution, Log-Pearson Type III Distribution) and Plotting-Position Based Methods (Log-Boughton Distribution) (G.V.Loganathan, C.Y.Kuo and T.C. McCormick,1985).

Nathan and McMahon (1990) considered some practical aspects concerning the application of the Weibul Distribution to low flow frequency analysis on 134 catchments located in southern Australia. They examined relative performance of the methods of moment, maximum likelihood and probability weighted moments. They found that different estimation methods provided distinct sets of estimates and the differences between estimation methods decreased as sample size increased.

Studies in the U.S. have shown that the Weibul and P3 (McMahon,1980; Matalas, 1963) and the Gamma (McMahon, 1980; Joseph 1970) distributions performed best for estimation of low flows. The Weibul distribution has been widely used in hydrology for fitting the frequency distribution of floods and low flow events. Matalas (1963) found the Weibul distribution as an appropriate distribution for the low flow analysis.

3. METHODOLOGY

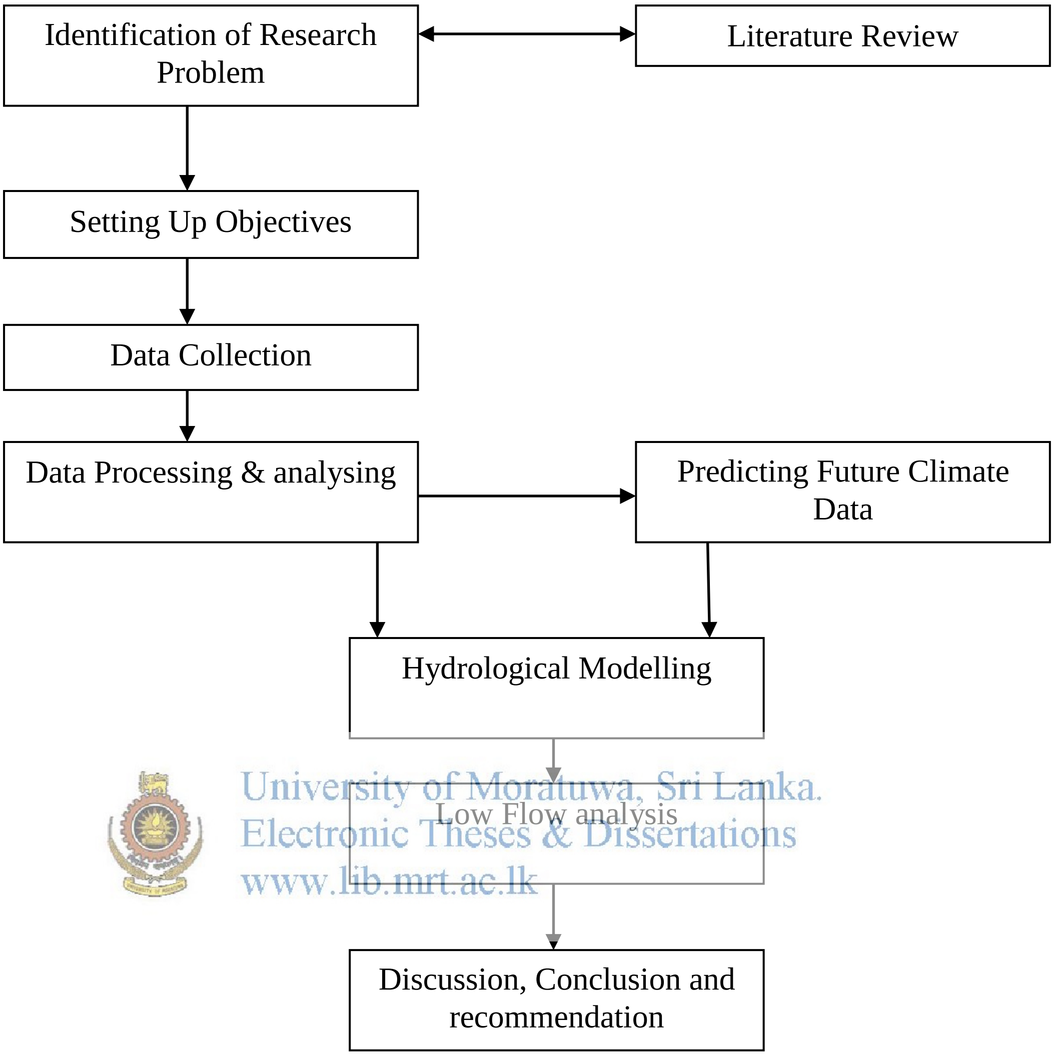


Figure 3: Methodology framework

As given in methodology framework, the main purpose of this study will be the finding the low flows for river gauging locations under future climatic scenarios. Main procedures were described in this chapter.

3.1 Data Collection

There are 34 numbers of meteorological and 5 numbers of flow gauging stations are available in Kalu Ganga Basin. Long term data was collected from selected stations to establish a well calibrated rainfall runoff model and to use for the low flow analysis. In addition, evaporation data, survey maps (1:50000 and 1:10000) and GIS maps were collected.

3.2 Hydrological Modelling

The main purpose of carrying out the hydrological analysis was to predict long term discharge and to use those data to determine the safe abstraction capacity under dry weather climatic conditions for Kalu Ganga basin. MIKE 11 Rainfall-Runoff (NAM) model which is developed by DHI was used for hydrological modelling. This model is a lumped, conceptual rainfall-runoff model simulating overland flow, interflow and base flow as a function of the water storage in each of four mutually interrelated storages representing the storage capacity of the catchment (Mike 11 user Manual, 2009). The basic input requirements for the NAM model consist of model parameters, initial conditions, meteorological data and stream flow data for model calibration and validation.

NAM is based on physical structures and equations used together with semi-empirical ones. Being a lumped model, NAM treats each catchment as a single unit. The parameters and variables represent, therefore, average values for the entire catchment. As a result some of the model parameters can be evaluated from physical catchment data, but the final parameter estimation must be performed by calibration against time series of hydrological observations.

The model structure is shown in Figure 4. It is an imitation of the land phase of the hydrological cycle. NAM simulates the rainfall-runoff process by continuously accounting for the water content in four different and mutually interrelated storages that represent different physical elements of the catchment. These storages are Snow storage, Surface storage, Lower or root zone storage and Groundwater storage. In addition NAM allows treatment of man-made interventions in the hydrological cycle such as irrigation and groundwater pumping. Based on the meteorological input data NAM produces catchment runoff as well as information about other elements of the land phase of the hydrological cycle, such as the temporal variation of the evapo-transpiration, soil moisture content, groundwater recharge, and groundwater levels. The resulting catchment runoff is split conceptually into overland flow, inter flow and base flow components.

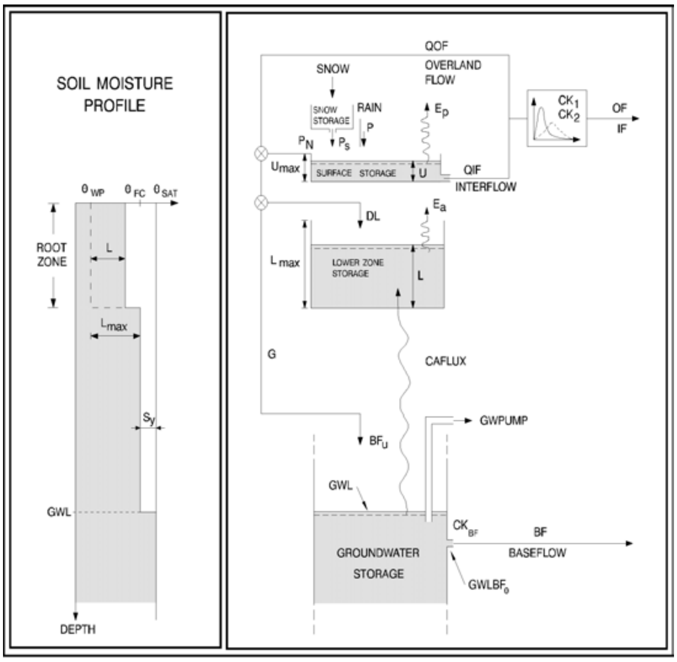


Figure 4: Structure of the NAM model
(Source: Mike 11 user manual, 2009)

This model was set up for each catchment and was calibrated using available discharge measurements for 3 year time period (1994-1997) and verified for another 2 year time period (1997-1999). The verified model was used to generate runoff time series for long periods for required sub basins. The runoff time series then was subjected to low flow analysis.

3.3 Downscaling and analysing the future climate with GCM data

Statistical Downscaling Model (SDSM) was used for the downscaling process. The predictor variables provide daily information concerning the large-scale state of the atmosphere, whilst the predictand describes conditions at the site scale. Since the processed data for SDSM was available only in Hardley Center Coupled Model 3(HadCM3) it was used for downscaling using SDSM. Downscaling of GCM data using SDSM Global Circulation Model (GCM) data of Hardley Center Coupled

Model 3 (HadCM3) was used under both A2 and B2 emission scenario as the raw data. A2 emission scenario was selected for hydrological modeling work, this as at present it has being identified that the most matching scenario for Sri Lankan conditions is A2 (De Silva et al, 2007).

The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuous increasing population. Economic development is primarily regional oriented, per capita economic growth and technological changes are more fragmented and slower than other storylines (IPCC, 2001).

The spatial resolution of HadCM3 is 2.5° x 3.75° (latitude x longitude) and the grid box resolution is 96 km x 73 km grid cells. The spatial resolution produced by this is about 417 km x278 km reducing to 295 km x 278 km at 45 degrees north and south. Downscaling was done for the precipitation data. Ellagawa and Millakanda sub basins in the Kalu Ganga basin were selected for the downscaling process. The rainfall data were downscaled for both basins.

The process of Statistical Downscaling Model (SDSM) involves multiple regression method. It requires 30 years of historical data and downscaled NCEP reanalysis data for 1961-2000 from National Center for Environmental Prediction (NCEP), HadCM3 data under A2 emission scenarios for the period of 1961-2099. The data was downloaded from Canadian Center for Climate a study which is globally available at http://www.cics.uvic.ca/scenarios/index.cgi?scenarios.The process of downscaling in SDSM involves,

- Screening of predictor variables

The most matching predictor variable combinations with observed data were selected from NCEP reanalysis predictors. The most matching combination was selected based on the partial correlation of reanalysis predictors.

- Calibration of the model

This is one of the most important tasks. The relationship between the observed predictands and the predictors of reanalysis data are combined here. The relationships of the predcitands are built as a multiple regression equation. Part of the observed data issued for calibration and the other part is used for the validation. Therefore, after the calibration with a part of data, a parameter file was created and it was used for next steps.

- Weather generator

This is the process of validation. Using the parameter file created in calibration process, the data for the validation period are generated from NCEP reanalysis data. A comparison of observed data and generated reanalyzed data was done after creating the summary statistics of them. This is the process of validation of the selected predictors.

- Scenario generator

This is the generation of downscaled GCM data. Here, using the parameter file calibrated and validated, the scenarios for the future from HadCM3 under A2 scenario was generated for the period of 1961-2099. The future climate data from the GCM was downscaled on daily basis and the daily data was used for the analysis.

3.4 Low flow analysis

The safe abstraction amount was determined using low flow frequency analysis. Reliable estimation/prediction of low-flows for rivers is vital for the proper planning and design of water supply projects. It is the flow rate in a stream during prolonged dry weather. The lowest recorded daily discharge may be referred to as ‘Absolute Minimum Flow’. Some of the commonly used low-flow indices are ‘annual minimum mean daily flow’ and ‘annual minimum N-day moving average flow’. In this study, the low flows were analyzed using ‘Annual minimum N-day moving average flow’ method. The analysis was performed for the two main gauges namely Ellagawa and Millakanda in Kaluganga where river flow data are available.

This was carried out using long term runoff time series which was generated using MIKE 11 RR (NAM) model. This was calibrated with long term flow records available at river gauging stations in Kalu Ganga river basin.

Weibull distribution is selected as the probability distribution function and due to the high probability of error in using graphical methods, Weibull parameters was analytically calculated. Weibull distribution is commonly used in low flow analysis and has been recommended (Manual on Low flow Estimation and Prediction, Operational Hydrology Report No. 50, 2009). For this purpose, one of the most commonly used technique 'Least square method' was used.

The Weibul distribution is an important distribution especially for reliability and maintainability analysis. The Weibull distribution density function (Mann et al. (1974)) is given by:

$$ln\, ln\left[\frac{1}{1-F(x)}\right] = \beta \ln x - \beta \ln \eta$$

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} ln\left\{ln\left[\frac{1}{\left(1-\frac{i}{n+1}\right)}\right]\right\}$$

$$\bar{y} = \frac{1}{n}\sum_{i=1}^{n} lnx_i$$

$$\hat{\beta} = \frac{\left\{n\,.\sum_{i=1}^{n}(lnx_i)\;.\left(ln\left\{ln\left[\frac{1}{\left(1-\frac{i}{n+1}\right)}\right]\right\}\right)\right\} - \left\{\sum_{i=1}^{n} ln\left\{ln\left[\frac{1}{\left(1-\frac{i}{n+1}\right)}\right]\right\}.\sum_{i=1}^{n} lnx_i\right\}}{\{n.\sum_{i=1}^{n}(lnx_i)^2)\} - \{\sum_{i=1}^{n}(lnx_i)\}^2}$$

$$\hat{\eta} = e^{(\bar{y}-\bar{x}/\hat{\beta})}$$

Where: β-Shape parameter
η-Scale parameter
F(x) – Weibul Density Function

4. STUDY AREA AND DATA COLLECTION

4.1 Study area

Sri Lanka has 103 river basins in which the largest river basins are Mahawali, Kelani, Malwathu Oya, Kalu Ganga and Deduru oya basins. Kalu Ganga basin is the third largest river basin in Sri Lanka which carries about 8180 MCM amount of water to sea annually. Kalu Ganga receives rain from both the northeastern and southwestern monsoons.

The catchment area of the Kalu Ganga basin is 2817 km^2. The Kalu Ganga originates from the central hills of wet zone at an altitude of 2250 m and falls out to the sea at Kalutara after traversing about 129 km. The basin has steep gradients in upper part and mild gradients in lower part. The annual rainfall in the basin is averaged to 3700 mm and leads to about 8180 MCM of annual flow. Due to these hydrological and topographical characteristics of the river basin, the excess water in the lower flood plain results frequent floods during the Southwest monsoon season. Therefore water resource planners are intended to utilize surplus water in Kalu Ganga basin in order to meet current and future water demands in various sectors. The study area is shown in Figure 5.

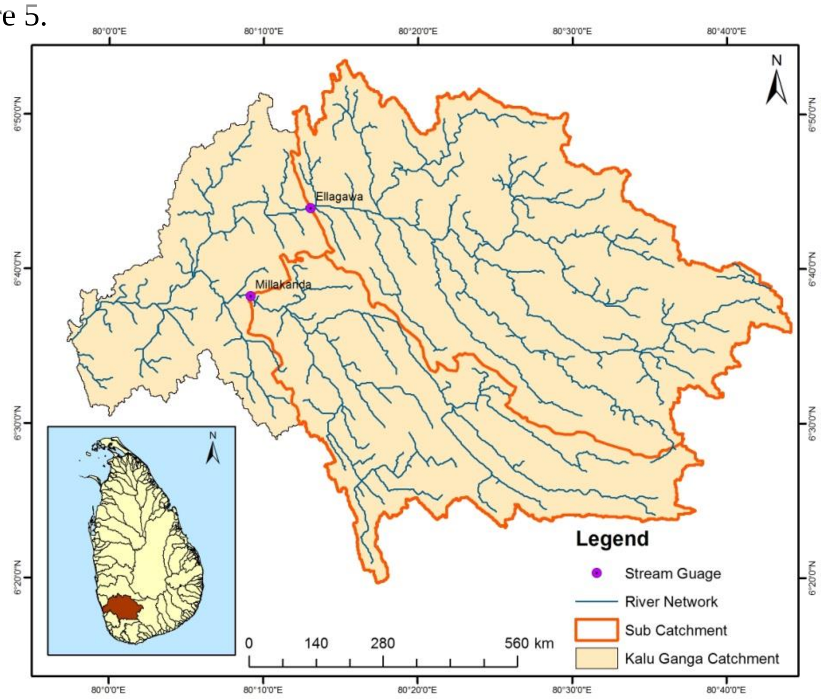


Figure 5: Study Area

Study area lies between latitudes of 06^0 19' 06'' – 06^0 54' 50'' and longitudes of 80^0 07' 55'' – 80^0 45' 33''. Ellagawa and Millakanda are the two main river gauging stations established in the lower reach of kalu ganga. According to the available information, two sub basins were considered for the study which is named as Ellagawa and Millakanda. Ellagawa sub basin covers $1425km^2$ of catchment area while Millakanda sub basin covers $793km^2$ of land extent.

Kalu Ganga also supplies small percentage of Colombo area water demand. The other major run off river intakes in Kalu Ganga supplies water to Kalutara district. The details of the run of river raw water sources including name of the river or tributary are shown in Table 3.

Table 3: Kalu Ganga raw water sources

Name	River/Tributary	Extraction (m^3/d)
Kandana	Kalu Ganga	315,000
Kethhena	Kalu Ganga	60,000
Horana	Kalu Ganga	4,000
Ingiriya	Nambapana Ela	25,000
Neboda (Proposed)	Kuda Ganga	161,000
Kudayala (Proposed)	Kalu Ganga	84,000

Further Kalu Ganga water also is affected by the salinity intrusion. In the late 1990s, extraction of water from Kalu Ganga from the intake at Kethhena, located about 17.4km from river mouth, was affected due to salinity intrusion. The maximum salinity intrusion length recorded is 21.2km during spring tide and 19.1km in neap tide for a low flow of $10.0m^3/s$. The threshold values of discharges to prevent salinity intrusion at the intake are $13.0m^3/s$ and $11.3m^3/s$ in spring and neap tides (Salinity Issues in Kalu River, LHI, 2003). In Sri Lanka, as the tidal variation is small compared with river discharge, they are low energy estuaries with very weak mixing. These estuaries are stratified, with very sharp interfaces between salt water and fresh water. The tide carries the saline wedge upstream during flood tide and downstream during ebb tide. The main reason to aggravate salinity intrusion in the river is the reduction of dry season flow.

4.2 Data Collection

4.2.1 Hydrological and meteorological data

The hydrological and meteorological data collected for the study area are given in Table 4. The rainfall and evaporation data were collected from the Department of Meteorology, Sri Lanka. The discharge data were collected from the Irrigation Department, Sri Lanka. The gauging stations are shown in Figure 6.

Mainly, data collected from twelve rainfall stations, one evaporation stations and two main river gauging stations in the study area. Summary of collected data is shown Table 4.

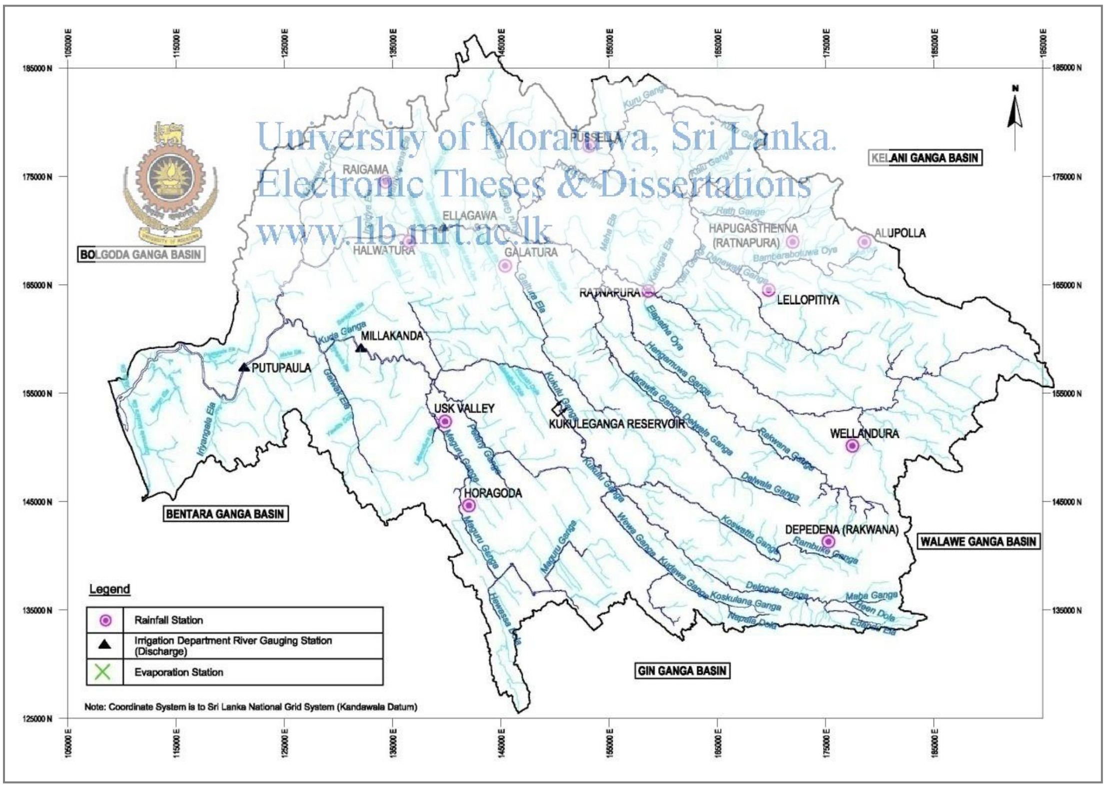


Figure 6: Meteorological gauging stations

The data collected from Internet sources for the downscaling process are given in Table 5.

Table 4: Hydrological and Meteorological data collected

Station	Period of observed data
Daily Rainfall	
Alupolla	1961-2010
Galatura	
Halwatura	
Hapugastanne	
Horagoda	
Lellopitiya	
Pussella	
Raigama	
Rakwana	
Ratnapura	
Usk Valley	
Wellandara	
Monthly Mean Evaporation	
Ratnapura	1995-2010
Daily Discharge	
Ellagawa	1969-2010
Millakanda	1994-2010

Since the total study area and the basin come under same grid of GCM, one set of data was downloaded as given in the table. An appropriate grid was selected for processed data for SDSM with HadCM3 data, as latitude 7.5 N and longitude 78.75 E as the data were in 2.50 km x 3.75 km resolutions.

Table 5: Data from internet sources

Data	Period	Source
HadCM3 A2 and B2predictor data	1960-2099	http://www.cics.uvic.ca/scenarios/index.cgi?scenarios
NCEP reanalysis data	1960-1990	http://www.cics.uvic.ca/scenarios/index.cgi?scenarios

4.2.2 Maps and Other Information

Digital maps of 1:50,000 and 1:10,000 topographic data from the survey department were used for this study. Catchment delineation was done using Arc GIS software. MIKE 11 NAM was used to develop the hydrological model.

The land use of the study area was obtained from Survey Department, Sri Lanka. These maps are in 1:50,000 scale and those are reclassified land use data in 1989. The land use of the study area varies such as built up areas consisting of home gardens, commercial and other non residential buildings, gardens, roads etc and agricultural lands as paddy coconut and other farm areas, water bodies, scrub lands, forest sand and rock etc.

4.2.3 Seasonal Distribution of Rainfall in Sri Lanka

It is known that Sri Lanka experience four main rain seasons, first inter monsoon, southwest monsoon, second inter monsoon and north east monsoon classified according to the amount of rainfall. The southwest monsoon rainfall brings the highest rainfall while the first inter monsoon brings lowest rainfall to the country. The average contributions of the seasonal rainfall to the annual rainfall in the country are given in Table 6.

Table 6: Contribution of the seasonal rainfall to the annual rainfall

Season	Period	Average Rainfall (mm)	Annual Contribution (%)
North east monsoon	December-February	479	26
First inter monsoon	March-April	268	14
Southwest monsoon	May-September	556	30
Second inter monsoon	October-November	558	30
Year (Total)	January-December	1861	

(Source: Mohottala, 2001)

4.2.4 Data preparation for the hydrological model set up

Rainfall data

- Filling Missing Rainfall Data

The missing rainfall data were filled in order to prepare the time series for the rainfall runoff model. It was done using simple arithmetic average and normal ratio method as described below.

Assume daily rainfall values for station 1 to *m* for a particular year is,

$P_1, P_2, P_3 \ldots\ldots\ldots\ldots\ldots\ldots P_x \ldots\ldots\ldots\ldots P_m$

P_x Missing data to be calculated

Assume, long-term average daily rainfall values for station 1 to *m* averaged over many years be $N_1, N_2, N_3 \ldots\ldots\ldots\ldots\ldots\ldots N_x \ldots\ldots\ldots\ldots N_m$

Method-1

If the average annual precipitation at each station of the adjacent stations differs from the average at missing data station by less than 10%, a simple arithmetic average is used. Then the missing value P_x can be taken as the average of $P_1, P_2, P_3 \ldots\ldots\ldots\ldots\ldots\ldots \ldots\ldots\ldots\ldots P_m$

Method-2

If the difference between average annual precipitation at any of adjacent stations and the missing data station is greater than 10%, a normal ratio method is used.

Ratio of P_1 to average, $N_1 = \dfrac{P_1}{N_1}$

Ratio of P_2 to average, $N_2 = \dfrac{P_2}{N_2}$

Ratio of P_m to average, $N_m = \dfrac{P_m}{N_m}$

Average ratio of $P_1, P_2, P_3 \ldots\ldots\ldots\ldots\ldots\ldots \ldots\ldots\ldots\ldots P_m$ to

$N_1, N_2, N_3 \ldots\ldots\ldots\ldots\ldots\ldots \ldots\ldots\ldots\ldots N_m$ is equal to $\dfrac{\left(\dfrac{P_1}{N_1} + \dfrac{P_2}{N_2} + \ldots\ldots\ldots\ldots\ldots\ldots \dfrac{P_m}{N_m}\right)}{(m-1)}$

Assuming the same average ratio would apply for the missing value

$$P_X = N_X \frac{\left(\dfrac{P_1}{N_1} + \dfrac{P_2}{N_2} + \ldots\ldots\ldots\ldots\ldots\ldots \dfrac{P_m}{N_m}\right)}{(m-1)}$$

(Guide to Hydrological Practices, Volume I: Hydrology – From Measurement to Hydrological Information, 2008, World Meteorological Organization).

Neighboring rainfall stations was used to fill the missing data and those used neighboring rainfall recoding stations is shown in Table 7.

Table 7: Neighboring Rainfall Stations used for Normal Ratio Method

Station with Missing Data	Stations used for Gap Filling
Usk Valley	Horagoda
Horagoda	Usk Valley
Rayigama	Halwatura
Pussellawa	Ratnapura
Lellopitiya	Allupolla
	Ratnapura (Hapugastenna)
Ratnapura (Hapugastenna)	Lellopitiya
	Allupolla
Wellandura	Rakwana (Depedena)
Rakwana (Depedena)	Wellandura
Galatura	Halwatura
	Pussellawa
Ratnapura	No missing data
Allupolla	No missing data
Halwatura	

Evaporation data

Monthly mean evaporation data of Ratnapura principal meteorological was used for the both sub basins in the hydrological model.

Discharge data

Ellagawa and Millakanda measured daily discharge data was used to calibration and verification of the model. Hydrological model Calibration was done for the daily data for the period of 1994 to 1997 and verification was done for the daily data for the period of 1997 to 1999.

Catchment Delineation

Main and sub-catchments pertaining to the respective locations were delineated using 1:50,000 topographical maps. Details of sub catchment are shown in Figure 7 and Table 8.

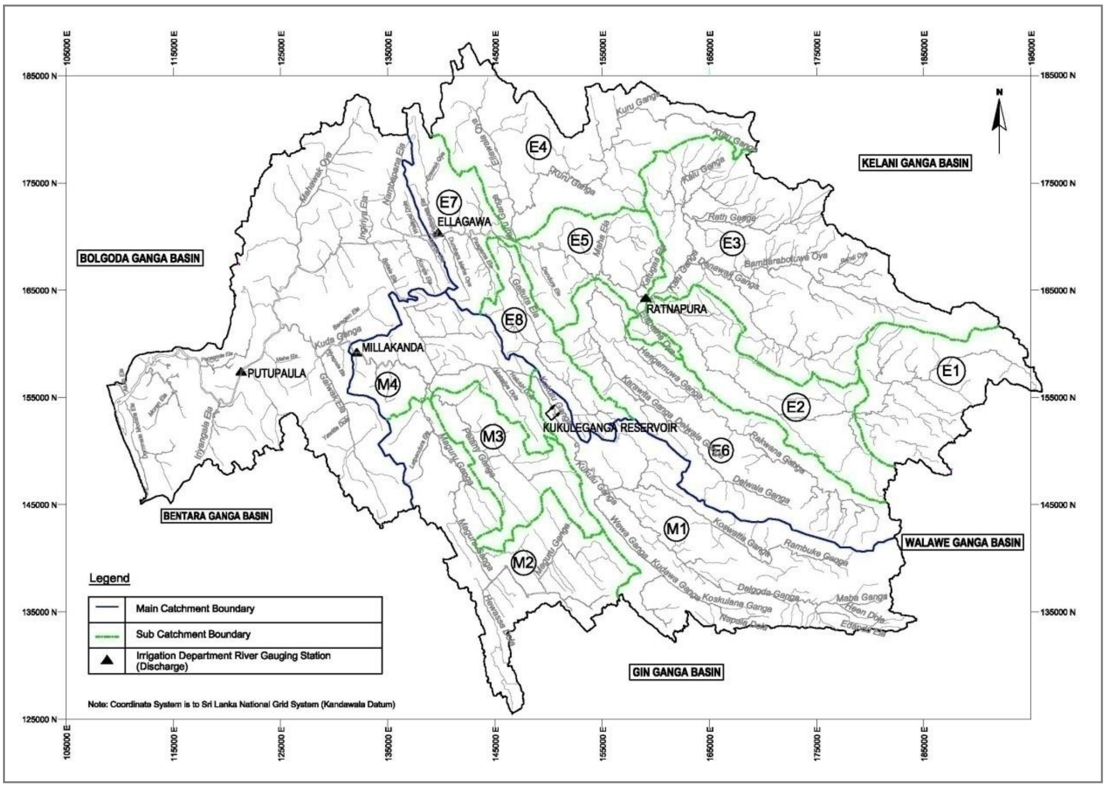


Figure 7: Catchment Delineation of Kalu Ganga

Table 8: Catchment area details

Main Gauged Catchment	Sub Catchments	Sub Catchment Area (km^2)	Cumulative Catchment Area (km^2)
Ellagawa (E)	E1	148.6	1424.9
	E2	145.3	
	E3	354.4	
	E4	246.1	
	E5	109.8	
	E6	253.3	
	E7	90.9	
	E8	76.5	
Millakanda (M)	M1	337.5	793.1
	M2	221	
	M3	98.3	
	M4	136.3	

5. RESULT AND DISCUSSION

5.1 Analysis of Past Metrological Data

In Table 9 illustrates the average daily rainfall data in each month from 1961 to 1990 data period. Data collected from twelve rainfall stations were considered for the calculation. Ellagawa and Millakanda basin rainfall were calculated using thiessen weights for the Kalu Ganga basin. Much difference could not be observed between basin mean rainfall and individual station's mean rainfall. Hence, basin rainfall was used to generate future rainfall.

Table 9: Daily mean rainfall (For period 1961 to 1990)

Station	Month											
	Jan	Feb	Mar	April	May	June	July	Aug	Sep	Oct	Nov	Dec
Alupolla	4.4	5.6	8.3	12.5	15.0	13.1	9.6	9.3	13.2	15.3	13.8	9.8
Lellopitiya	3.2	4.9	7.8	10.5	14.3	13.1	9.3	8.0	13.3	13.8	13.1	8.2
Wellandara	3.5	3.5	6.5	7.5	8.4	9.9	6.9	6.5	7.6	8.7	11.3	6.4
Ratnapura	3.4	5.0	6.8	11.5	14.7	14.3	9.8	8.8	13.1	13.6	12.5	7.5
Hapugastanne	4.0	6.1	8.2	13.3	20.1	19.9	14.6	13.4	18.7	16.9	15.7	8.4
Galatura	3.7	4.4	7.0	12.9	18.2	16.7	10.1	9.5	14.3	15.3	13.8	8.1
Pussella	3.0	4.4	8.0	14.7	17.1	15.7	9.9	9.9	14.0	16.7	14.2	7.6
Rakwana	3.8	3.9	7.2	10.1	11.6	11.3	7.1	6.6	9.6	11.7	13.5	7.1
Horagoda	4.2	4.2	9.4	11.8	15.6	14.5	10.2	9.4	11.7	14.1	14.1	8.8
Usk Valley	4.7	5.1	8.8	13.9	17.2	14.3	8.8	8.3	12.6	15.8	15.1	9.9
Halwatura	3.6	5.2	7.9	14.0	17.6	15.6	8.7	8.8	14.1	15.3	16.0	9.6
Raigama	4.3	5.4	8.6	14.4	17.4	14.0	8.0	8.3	12.5	16.0	15.3	10.3
Millakanda	4.1	4.3	8.4	11.8	14.8	13.6	8.9	8.2	11.4	13.8	14.1	8.5
Ellagawa	3.5	4.7	7.4	11.7	14.7	14.1	9.4	8.9	12.7	13.9	13.3	7.9

Figure 8 shows the annual river flow data in water year basis for Ellagawa, Millakanda and Putupaula river gauging stations in Kalu ganga. Referring to Figure 8, it can be clearly noticed that the amount of flow in Kalu River has been reduced within the period 98/99 to 01/02. But there is no decreasing trend in the flows after 01/02 as it appears to be stabilizing at an average flow lower than that prevailed before 98/99.

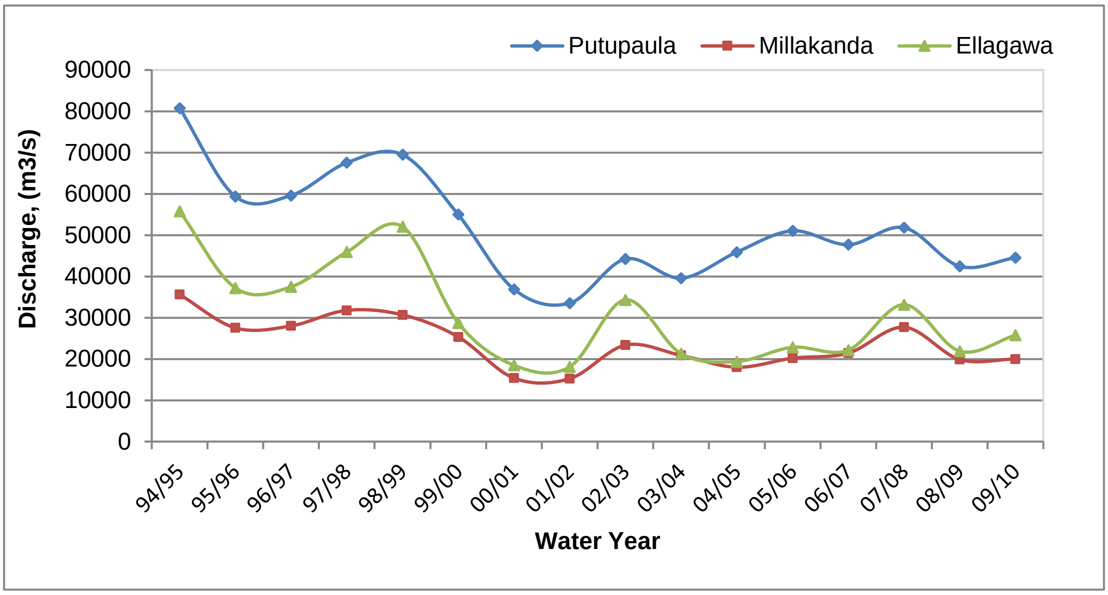


Figure 8: Annual Variations of River Flow Data in Kalu Catchment

Table 10 and Table 11 describe the recorded minimum flow for both Ellagawa and Millakanda river gauging stations.

Table 10: Recorded Absolute Minimum Flow at Ellagawa (1969 -1999)

Year	Daily Min Flow (m3/s)	Year	Daily Min Flow (m3/s)
69/70	19.00	84/85	13.00
70/71	17.00	85/86	15.00
71/72	9.00	86/87	11.33
72/73	9.00	87/88	12.35
73/74	8.00	88/89	10.00
74/75	15.00	89/90	8.00
75/76	9.00	90/91	4.22
76/77	10.00	91/92	9.91
77/78	12.00	92/93	4.41
78/79	8.00	93/94	9.15
79/80	12.00	94/95	11.75
80/81	13.00	95/96	10.47
81/82	12.00	96/97	18.40
82/83	11.00	97/98	15.67
83/84	13.00	98/99	22.72

(Source: Irrigation department, Sri Lanka)

The measured low flow value varies from 4 m^3/s to 23 m^3/s. Recorded absolute minimum flow has experience decreasing trend from 1989 to 1994.

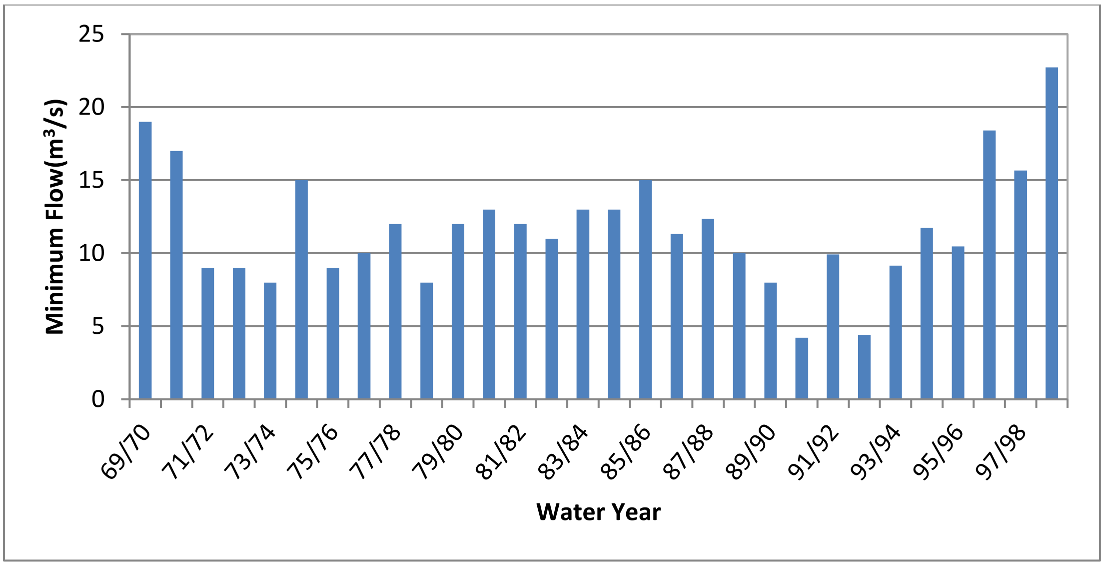


Figure 9: Recorded Absolute Minimum Flow at Ellagawa (1969 -1999)

Table 11: Recorded Absolute Minimum Flow at Millakanda (1994 – 2010)

Year	Daily Min Flow (m3/s)	Year	Daily Min Flow (m3/s)
94/95	20.52	02/03	5.44
95/96	21.57	03/04	11.63
96/97	17.89	04/05	12.53
97/98	18.05	05/06	13.7
98/99	21.57	06/07	10.62
99/00	14.78	07/08	12.61
00/01	12.78	08/09	10.03
01/02	10.31	09/10	11.24

(Source: Irrigation department, Sri Lanka)

The measured low flow value varies from 5 m^3/s to 22 m^3/s. Recorded absolute minimum flow has experience decreasing trend from 1999 to 2003. It shows considerable reduction after 1998. Te observed reduction was due to operation of Kukule ganga reservoir.

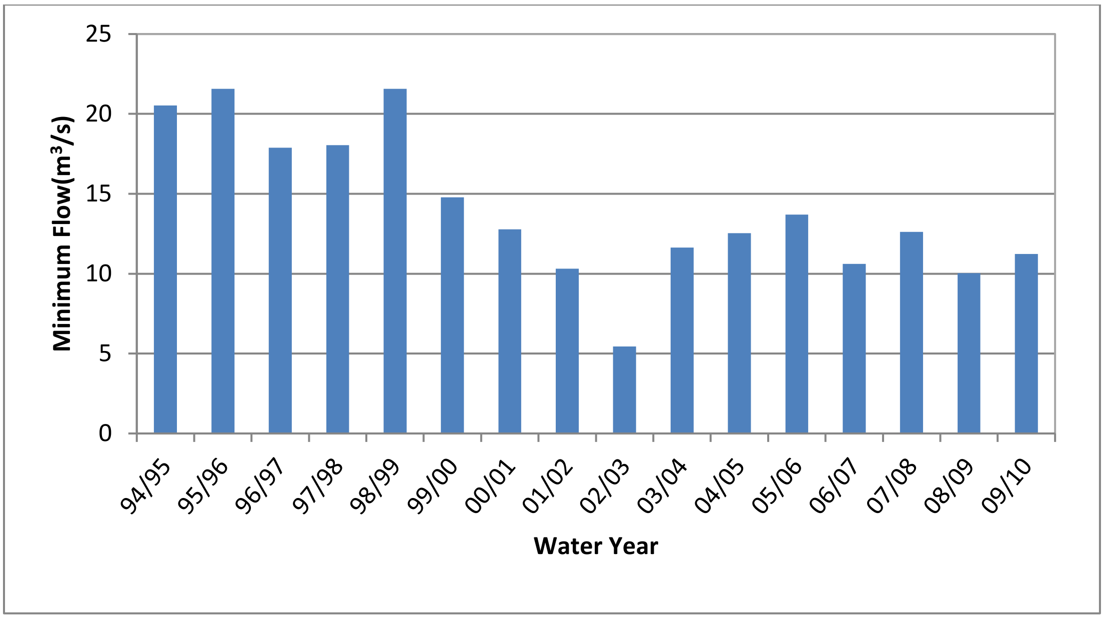


Figure 10: Recorded Absolute Minimum Flow at Millakanda (1994 – 2010)

Low flow values varying due to upstream abstraction during dry period for several activities such as villager's local demand, intake abstraction and other activities.

5.2 Hydrological Modeling

The MIKE 11 NAM models had been set up using the delineated sub catchments and 'combined catchment option'. Rainfall and evaporation data were assigned to the stations as mentioned in Tables 7. Theissen option in NAM model was used to determine the weighted rainfall at each catchment.

Model calibration was performed while adjusting the model parameters in order to reproduce the catchment characteristics well by mean of comparison of model output and observed/actual data. It involves adjusting the coefficients for the exchange of water between storage units and the storage unit depth. Calibrated model simulates the hydrological behavior of the catchment as closely and possible. During calibration, the catchment parameters were adjusted until a good fit between the simulated flow and gauged stream (observed) flow is obtained. Further, special attention was paid for the flood volume, flood peak and low flow volume.

The model calibration was performed for Ellagawa and Millakanda with observed data. Calibration period was 1994-1997 (water years) and validation period was 1997 – 1999 (water years) considering the different gradient in the observed cumulative discharge data after the year 1999 in Kalu River gauging stations. However, a warm up period of six months is recommended and therefore, the calibration results were given for two years (1995 – 1997). Ellagawa and Millakanda calibration plots are shown in Figure 11 to Figure 14.

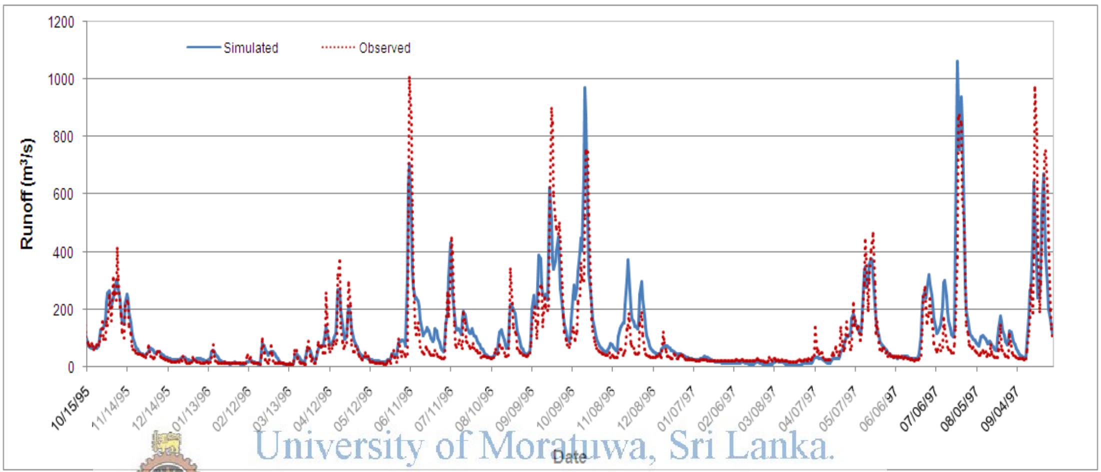


Figure 11: Ellagawa Calibration- Simulated vs. Observed Flow Comparison

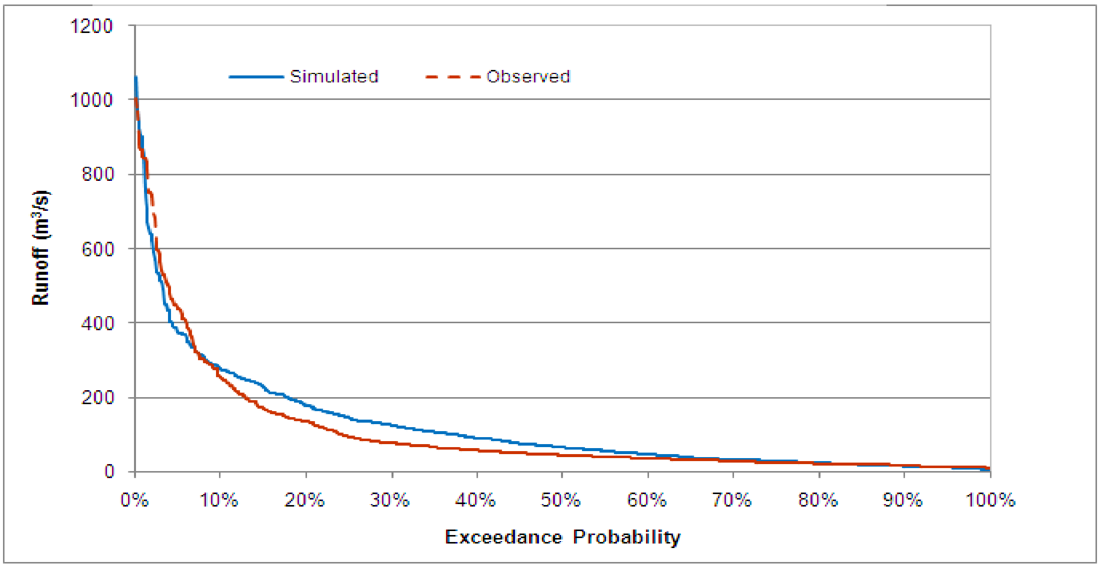


Figure 12: Ellagawa Calibration- Simulated vs. Observed Flow Duration Curves

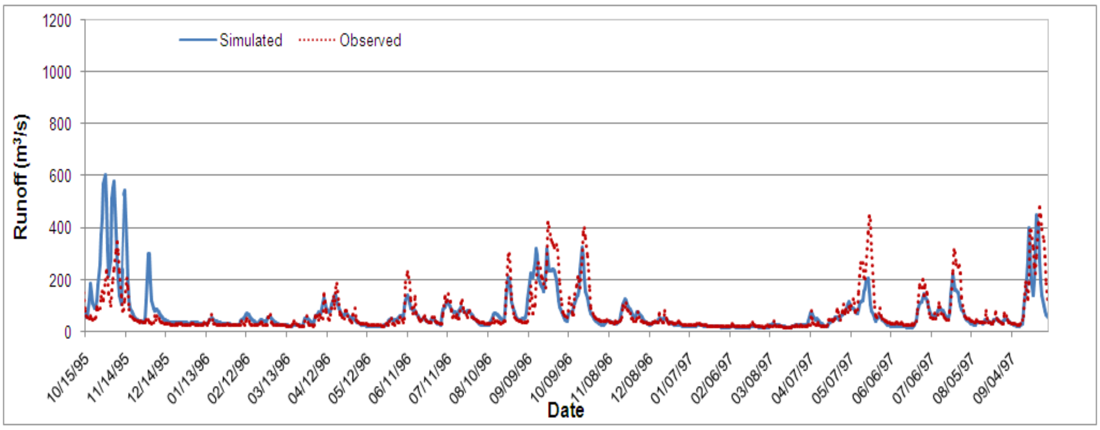


Figure 13: Millakanda Calibration - Simulated vs. Observed Flow Comparison

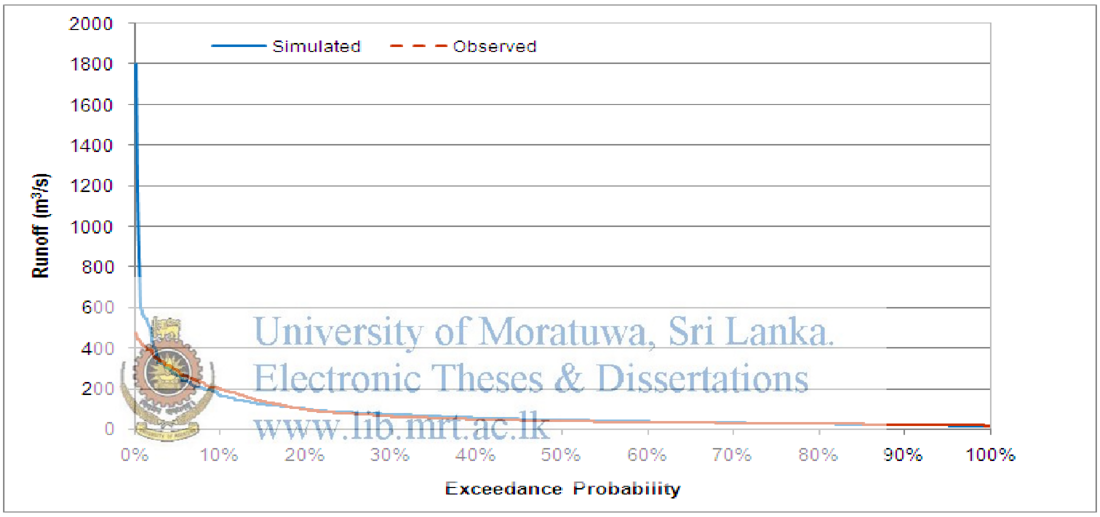


Figure 14: Millakanda Calibration - Simulated vs. Observed Flow Duration Curves

The model was calibrated mainly based on the high and low flow period. It is very difficult task to calibrate the model when both low and high peak flow events are present in the observed discharge. However the following objectives were considered during the model calibration:

- A good agreement between the average simulated and average observed catchment runoff, (i.e., a good water balance.)
- A good overall agreement of the shape of the hydrograph
- A good agreement of the peak flows with respect to timing, rate and volume
- A good agreement for low flows

Coefficient of determination (R^2) achieves 0.7 for Ellagawa station and 0.75 for Millakanda stations respectively for calibration. The model validation period is 1997-1999 and the plots during the validation period are also shown in Figure 15 to Figure 18.

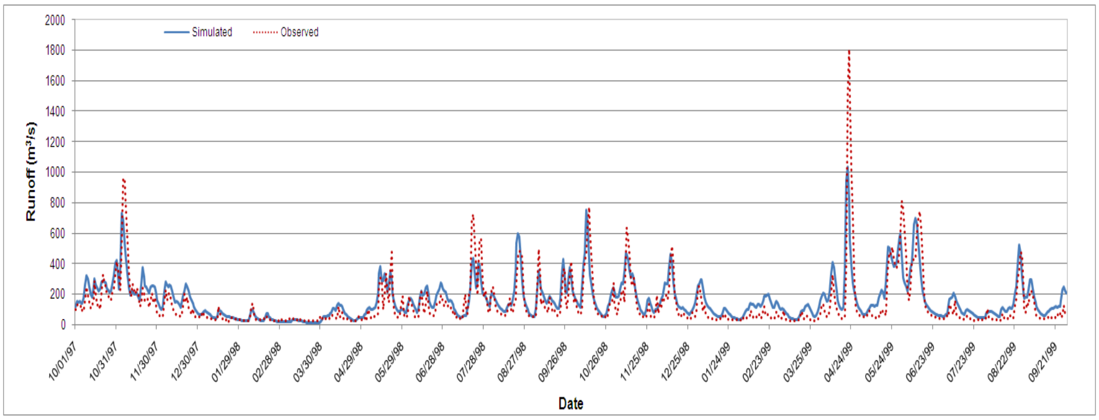


Figure 15: Ellagawa Validation - Simulated vs. Observed Flow Comparison

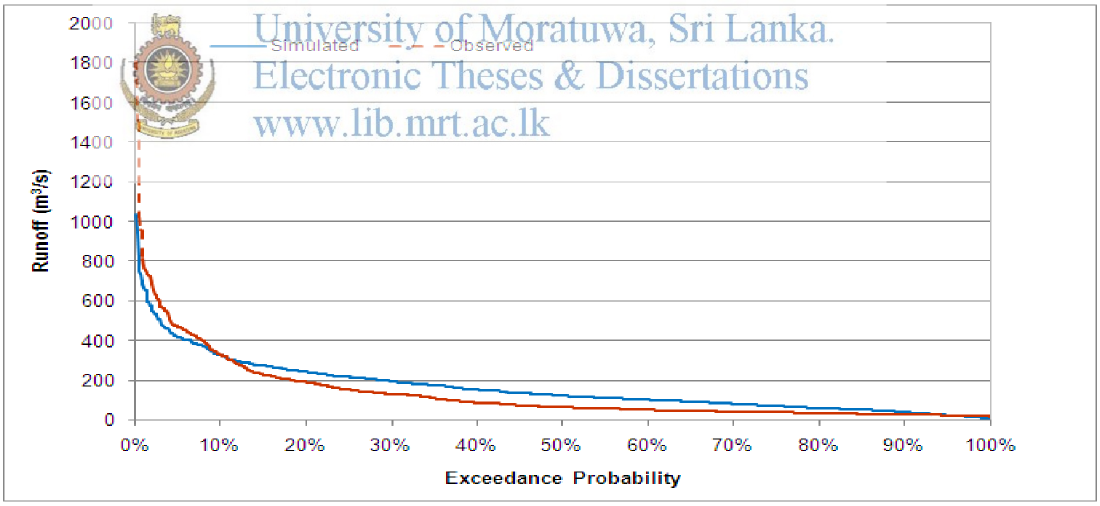


Figure 16: Ellagawa Validation- Simulated vs. Observed Flow Duration Curves

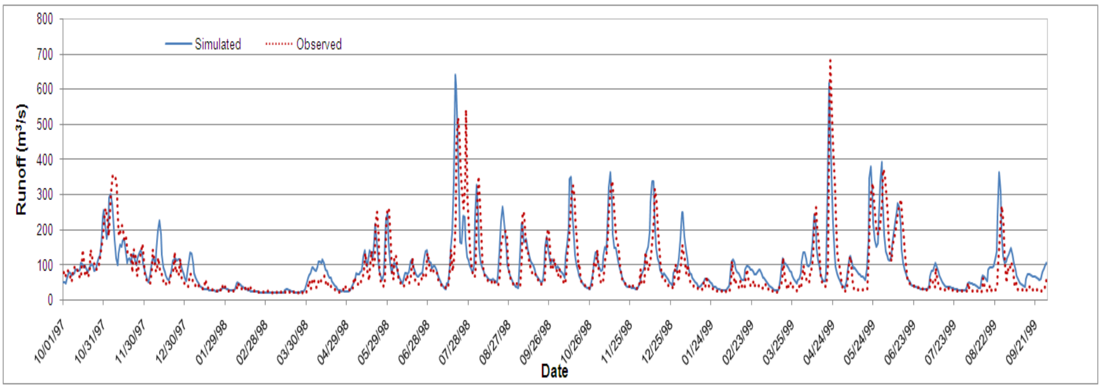


Figure 17: Millakanda Validation - Simulated vs. Observed Flow Comparison

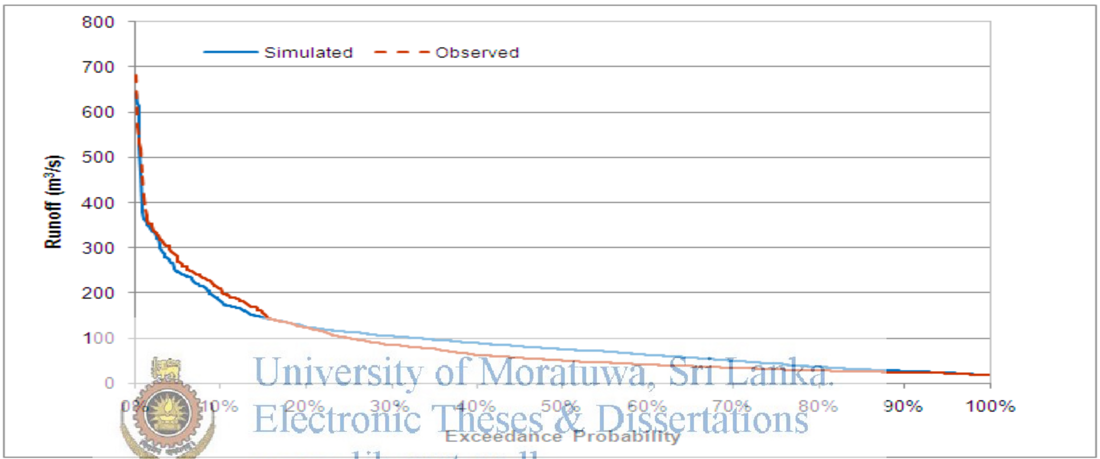


Figure 18: Millakanda Validation - Simulated vs. Observed Flow Duration Curves

For the model validation period coefficient of determination (R^2) achieves 0.7 and 0.6 for Ellagawa and Millakanda stations respectively. The calibrated rainfall runoff model was used to simulate the runoff for 50 years (2009/2010 to 2059/2060) time series due to predicted rainfall according to the climate change scenario.

5.3 Downscaling and analyzing of GCM data

The downscaled daily data under climate change were analyzed. Ellagawa and Millakanda basin rainfall were considered for downscaling. The minimum rainfall of the dry season was selected from the downscaled data at Ellagawa and Millaknda.

5.3.1 Selection of the Emission scenario for GCM data

The IPCC published a new set of scenarios in 2000 for use in the Third Assessment Report (Special Report on Emissions Scenarios - SRES). The SRES scenarios were constructed to explore future developments in the global environment with special reference to the production of greenhouse gases and aerosol precursor emissions.

The SRES team defined four narrative storylines (refer Figure 19), labelled A1, A2, B1 and B2, describing the relationships between the forces driving greenhouse gas and aerosol emissions and their evolution during the 21st century for large world regions and globally. Each storyline represents different demographic, social, economic, technological, and environmental developments that diverge in increasingly irreversible ways.

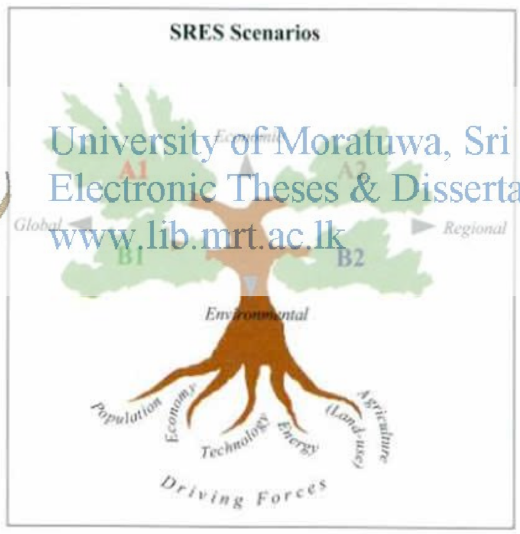


Figure 19: Schematic illustration of the four SRES storylines

In simple terms, the four storylines combine two sets of divergent tendencies: one set varying between strong economic values and strong environmental values, the other set between increasing globalization and increasing regionalization. The storylines are summarized as follows:

- A1 storyline and scenario family: a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and rapid introduction of new and more efficient technologies.
- A2 storyline and scenario family: a very heterogeneous world with continuously increasing global population and regionally oriented economic growth that is more fragmented and slower than in other storylines.
- B1 storyline and scenario family: a convergent world with the same global population as in the A1 storyline but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies.
- B2 storyline and scenario family: a world in which the emphasis is on local solutions to economic, social, and environmental sustainability, with continuously increasing population (lower than A2) and intermediate economic development.

In Sri Lankan climatic studies context, bothA2 and B2 scenarios can be used and the most matching scenario is A2 (De Silva et al., 2007). Hence, this analysis was initiated with both A2 and B2 scenarios and considered only A2 scenario to predict the future data.

5.3.2 Selection of the GCM data for the area

Being an island, it creates a lot of problems in GCM data for Sri Lanka. Most of the GCMs consider Sri Lanka as a sea area due to high spatial resolution of the models. However, as all the land areas are having data, some data can be obtained from the globally available GCMs. Most of the island countries such as UK and Taiwan etc. use regional climate models (RCMs) to generate the climatic change data (Fowler et al., 2005). The Sri Lankan situation is not developed well and at present no there is no any regional model available for the area. Only few studies have been carried out with climatic change data and they have used the proportional percentage changes given by the GCM where the changes to baseline data were applied (De Silva et al., 2007). This might be accurate enough for water availability studies. However, for the extreme rainfall analysis, these approaches are not very accurate. Very few GCMs have data for the Sri Lankan land area. The data sources availability is listed in Table 12.

Table 12: The GCM data sources for SRES A2 and B2

Model	Acronym	Center	Grid size (km x km)	Availability for Sri Lanka
CGCM2	CCCma	Canadian Center for Climate Modeling and Analysis, Canada	340 x340	Yes
HADCM3	HCCPR	Hadley Centre for Climate Prediction and Research, UK	417 x 278	Yes
CSIRO-Mk2	CSIRO	Australia's Commonwealth Scientific and Industrial research Organization, Australia	625 x350	Yes
NCAR-PCM	NCAR	National Centre for Atmospheric Research, USA	340 x340	No
CCSR/NIES AGCM	CCSR / NIES	Center for Climate System Research National Institute for Environmental Studies ,Japan		No

HadCM3 model was used with SDSM model to downscale the data, as processed data for SDSM is only available with HadCM3.

A comparison of averaged daily rainfall over 30 year period (1961-1990) with basin rainfall of Ellagawa is shown in Table 13. As shown in Table, the difference between the observed values and GCMs values shows no unique relationship. It shows GCM values are closely follows the observed values during dry period.

Table 13: Monthly averaged daily mean rainfall (1961-1990) at Ellagawa

Month	Monthly averaged daily mean rainfall (mm)		
	Observed	HadCM3 A2	HadCM3 B2
January	3.5	3.7	3.9
February	4.7	4.1	3.0
March	7.4	6.8	6.0
April	11.7	8.4	8.4
May	14.7	9.9	9.7
June	14.1	9.0	8.9
July	9.4	11.3	11.2
August	8.9	12.1	12.2
September	12.7	11.5	11.6
October	13.9	8.9	9.0
November	13.3	6.6	6.7
December	7.9	6.2	6.2

Table 14 shows a comparison of averaged daily rainfall values (averaged over 30years-1961-1990) with the basin rainfall of Millakanda station. In this comparison also, a better relationship can be observed during dry season.

Table 14: Monthly averaged daily mean rainfall (1961-1990) at Millakanda

Month	Monthly averaged daily mean rainfall (mm)		
	Observed	HadCM3 A2	HadCM3 B2
January	4.1	4.8	5.0
February	4.3	5.0	5.4
March	8.4	8.1	7.6
April	11.8	9.6	8.6
May	14.8	11.3	11.2
June	13.6	10.3	10.2
July	8.9	1.4	0.9
August	8.2	3.1	2.9
September	11.4	11.0	11.0
October	13.8	8.2	8.0
November	14.1	9.1	8.9
December	8.5	6.8	6.4

However, considering both situations, it can be observed that the GCM data does not represent the trend of rainfall in Sri Lanka reasonably well.

5.3.3 Downscaling of climate change data using SDSM

As mentioned in the methodology section, SDSM was also used for the downscaling process. Rainfall data was downscaled for Ellagawa and Millakanda basin rainfall. As rainfall is a conditional process, it was difficult to obtain a better correlation with the NCEP reanalysis predictors during the screening process. However, adequate relationship was obtained compared to the previous studies carried out (Dibike and Coulibaly, 2004). Table 15 shows the predictors selected and their correlations for the rainfall of the two basins. The predictor predictand relationship was lower in conditional process that is rainfall. This is due to that unconditional models assume a direct link between the regional scale predictors and the local predictand while conditional processes such as rainfall and sunshine depend on an intermediate variable such as the probability of wet day occurrence (Wilby et al., 2002).

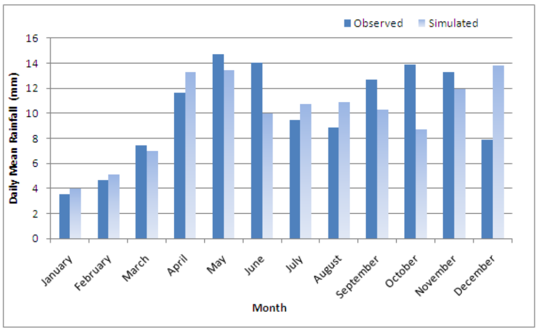
Table 15: Selected predictor variables and correlations with local predictands

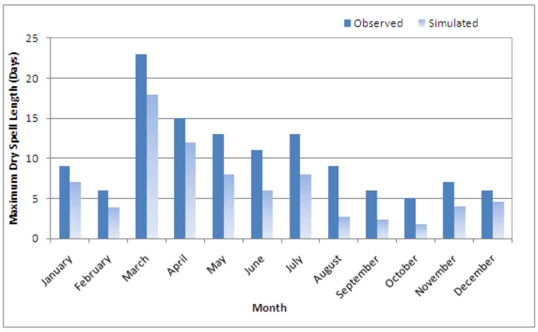
Predictor variables	Predictand and Predictor partial correlations	
	Ellagawa	Millakanda
Mean temperature at 2m	0.12	0.11
Near surface relative humidity	0.17	0.16
Relative humidity at 850 hPa	0.043	0.036
850 hPa wind direction	0.067	0.042
Surface divergence	0.046	0.047

After the selection of predictor variables, calibration of the model was done with a part of the observed data. During the calibration process, model computed a multiple linear regression equation with the predictor variables selected and the predictand (i.e. rainfall). The parameters of the linear regression equation were written to a standard format file *.PAR. Using the *.PAR file, weather data for the remaining period of the observed data were generated. The observed data and the generated data from the model using NCEP reanalysis data were compared and the validation was done.

Validation of the model for rainfall data at Ellagawa and Millakanda are as shown in Figure 20 and 21 respectively. Validation was done mainly for the monthly averaged daily mean, daily maximum, maximum dry spell length and mean dry spell length.

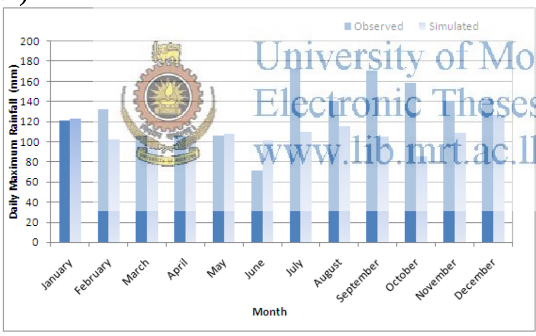
For the Ellagawa, the determination of coefficient (R2) between observed and modeled daily mean was 0.6, daily maximum was 0.65, maximum dry spell length was 0.6 and mean dry spell length was 0.8.

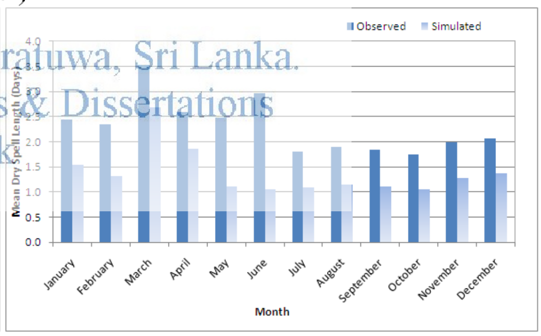




a)

b)





c)

d)

Figure 20 Validation of SDSM for Ellagawa a) Daily Mean Rainfall b) Maximum Dry Spell Length c) Daily Maximum Rainfall d) Mean dry Spell Length

As shown in Figure 21, it can be observed that the validation at Millakanda is also not good. The correlations between modeled and observed values were 0.6 for daily mean rainfall, 0.55 for daily maximum rainfall, 0.6 for maximum dry spell and 0.7 for mean dry spell length. However, in both cases mean dry spell lengths show better correlation with respect to the other.

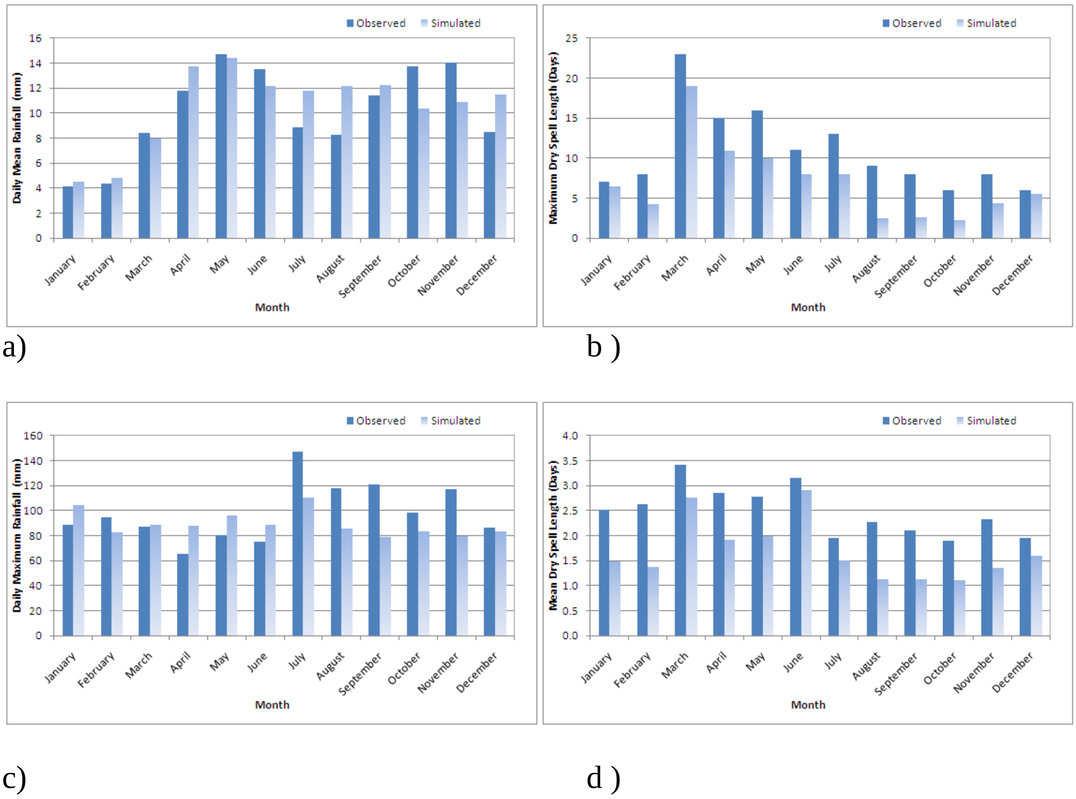


Figure 21 Validation of SDSM for Millakanda a) Daily Mean Rainfall b) Maximum Dry Spell Length c) Daily Maximum Rainfall d) Mean dry Spell Length

Though the mean dry spell length is in good agreement, others need to be improved. However, this might be the best calibration achievable. The discrepancies might due to the quality of the observed data as well as the GCM data. As Sri Lanka is a small island, the predictions on the atmosphere of it might not be exact. All the GCM s does not have data for the accurate enough Sri Lankan grid area. To avoid this kind of discrepancies happening due to being an island, RCMs need to be used instead of GCMs.

5.3.4 Low flow analysis

Through the downscaled values show some discrepancies, daily rainfall data was predicted from SDSM method. The low flow analysis was based on the method in Manual on Low flow Estimation and Prediction, Operational Hydrology Report No. 50, 2009, World Meteorological Organization (WMO). Weibull distribution was selected as the probability distribution function.

Low flow analysis was done both Ellagawa and Millakanda gauging stations with and without climate change impacts. Table 16 and Table 17 shows the result of Ellagawa and Millakanda Gauging stations low flow values without climate change impacts.

Table 16: Low flow values at Ellagawa without climate change impact

Return Period (Yrs)	Low Flow - Ellagawa Gauging Station (m^3/s)			
	Daily Avg	3 Days Moving Avg	5 Days Moving Avg	7 Days Moving Avg
5	8.82	9.5	9.94	10.25
10	7.18	7.72	8.07	8.25
20	5.90	6.34	6.61	6.69
50	4.58	4.90	5.10	5.11

Table 17: Low flow values at Millakanda without climate change impact

Return Period (Yrs)	Low Flow - Millakanda Gauging Station (m^3/s)			
	Daily Avg	3 Days Moving Avg	5 Days Moving Avg	7 Days Moving Avg
5	10.46	11.63	11.88	12.29
10	8.46	9.61	9.82	10.22
20	6.90	8.00	8.18	8.57
50	5.30	6.31	6.46	6.82

Table 18 and Table 19 shows the result of Ellagawa and Millakanda Gauging stations low flow values with climate change impacts.

Table 18: Low flow values at Ellagawa with climate change impact

Return Period (Yrs)	Low Flow - Ellagawa Gauging Station (m^3/s)			
	Daily Avg	3 Days Moving Avg	5 Days Moving Avg	7 Days Moving Avg
5	8.73	9.40	9.85	10.15
10	7.11	7.65	7.99	8.17
20	5.84	6.27	6.54	6.63
50	4.30	4.60	4.80	4.80

Table 19: Low flow values at Millakanda with climate change impact

Return Period (Yrs)	Low Flow - Millakanda Gauging Station (m^3/s)			
	Daily Avg	3 Days Moving Avg	5 Days Moving Avg	7 Days Moving Avg
5	10.36	11.51	11.76	12.17
10	8.38	9.51	9.72	10.12
20	6.83	7.92	8.10	8.49
50	5.10	6.00	6.10	6.50

Impact of climatic change is fairly less on events with less temporal resolution. As a percentage, it shows Ellagawa station about 6% in 50 year while other return period about 1% reduction of low flow values and Millakanda station about 4% in 50 year return period while other return period about 1% reduction of low flow values. It clearly shows impact of climatic change high for the events with high recurrence interval.

While allowing the environmental flow in Kalu Ganga Table 20 shows safe abstraction rate (m^3/d) of Ellagawa and Millaknda gauging locations. Environmental flow considered about 4 m^3/s for Ellagawa and 5 m^3/s for Millakanda gauging locations. It was considered 98 percentage of occurrence of river flow in both Ellagawa and Millaknda locations.

Table 20: Safe abstraction rate (m^3/d) for Ellagawa & Millakanda

Return Period (Yrs)	Safe Abstraction rate(m^3/d)			
	Ellagawa		Millakanda	
	Without Climate Change Impact	With climate Change Impact	Without Climate Change Impact	With climate Change Impact
5	416,500	408,700	471,750	463,100
10	274,800	268,700	298,950	292,000
20	164,200	159,000	164,200	158,100
50	50,100	25,900	25,900	8,650

Horana and Naboda intakes are located in Kalu Ganga basin close to Ellagawa and Millakanda river gauging stations. Both intakes are maintained by National Water Supply and Drainage Board. Horana intake is about 9km downstream from the Ellagawa gauging stations and it is design to abstract 36,000m^3/d in 2020. And also Naboda intake is about 4km downstream from the Millakanda gauging stations and it is design to abstract 161,000m^3/d in 2025 (Report on water Supply Master Plan Update for Western Province Metropolitan area, 2012).

Table 21 shows safe abstraction rates (m3/d) at the Horana and Naboda intake locations. It was predict by extrapolating low flow values at Ellagawa and Millakanda to the Horana and Naboda intake locations and allowing above considered environmental flow.

Table 21: Safe abstraction rate (m^3/d) for Horana and Naboda

Return Period (Yrs)	Safe Abstraction rate(m^3/d)			
	Horana		Naboda	
	Without Climate Change Impact	With climate Change Impact	Without Climate Change Impact	With climate Change Impact
5	446,900	438,850	594,309	585,315
10	299,600	293,300	414,579	407,381
20	184,550	179,170	274,399	268,118
50	59,600	35,450	130,626	113,166

According to the Table 21, required amount abstraction can be problematic in 50 year return period. Therefore, having an appropriate storage system to cater the required demand during dry season is needed to avoid disruptions to the distribution system.

Table 22 describes the percentage of success of Horana and Naboda intakes with respect to the different years. It considers demand and supply for different years varies from 2020 to 2050.

Table 22 : Percentage of Success

Intake	**2020**	**2025**	**2030**	**2050**
Horana	100	99.97	99.56	98.06
Naboda	-	100	99.67	99.39

Both intakes are not achieving 100 percent success. Horana intake can be fail in very less percentage after year 2025 and Naboda intake fail in very less percentage after year 2030. This happened due to demand is high and intake can't extract more water during dry seasons.

6. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

- Percentage reduction of low flow due to climate change in Ellagawa station about 6% and Millakanda Station about 4% in 50 year return periods. It is about 1% for other return periods in both stations.
- Impact of climate change on low flow is highly affected on the low flow with 50 year return period.
- Impact of climate change on low flow is less in 5 year, 10 year and 20 year return periods.
- Impact of climatic change is high for the events with high recurrence interval.
- Low flow rates (m^3/s) with and without climate change impact.

Table 23: Summary of Low Flow rates (m^3/s)

Return Period (Yrs)	Ellagawa (m^3/s)		Millakanda (m^3/s)	
	Without climate change impact	With climate change impact	Without climate change impact	With climate change impact
5	8.82	8.73	10.46	10.36
10	7.18	7.11	8.46	8.38
20	5.9	5.84	6.9	6.83
50	4.58	4.30	5.3	5.10

- Safe abstraction rates (m^3/d) with and without climate change impact.

Table 24: Summary of Safe Abstraction rates (m^3/d)

Return Period (Yrs)	Safe Abstraction rate(m^3/d)							
	Ellagawa		Millakanda		Horana		Naboda	
	Without Climate Change Impact	With climate Change Impact	Without Climate Change Impact	With climate Change Impact	Without Climate Change Impact	With climate Change Impact	Without Climate Change Impact	With climate Change Impact
5	416,500	408,700	471,750	463,100	446,900	438,850	594,309	585,315
10	274,800	268,700	298,950	292,000	299,600	293,300	414,579	407,381
20	164,200	159,000	164,200	158,100	184,550	179,170	274,399	268,118
50	50,100	25,900	25,900	8,650	59,600	35,450	130,626	113,166

Recommendations

- As Sri Lanka is a small island, the predictions on the atmosphere of it might not be exact. The Global Circulation Model (GCM) does not have data for the accurate enough Sri Lankan grid area. To avoid this kind of discrepancies, fine grid GCM with Regional Climate Models need to be developed.

- Safe abstraction rates with climate change impact at Ellagawa and Millakanda during the dry period 25900 m^3/d and 8650 m^3/d respectively in 50 year return period. For a run off river water extraction, risk of occurring water deficits during dry period in 50 return periods is high. Hence it is not recommended to extract water during dry periods. Therefore, having an appropriate storage system to cater the required demand during dry periods is recommended, to avoid disruptions to the distribution system.

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