OPEN TECHNOLOGIES BASED TANK MANAGEMENT MODEL FOR FLOOD RISK REDUCTION

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Abstract

Analysis of climate induced phenomenon is data intensive and the data collected from very sparse network of professional weather stations have become incapable to estimate the magnitude of the climate induced events. Manual stations, offline data, low spatial and temporal resolution of data, high cost of modelling software and state-owned stations' data, unavailability of pre-determined parameter values, lack of trust on technology and lack of expertise knowledge, are the barriers exist in most developing countries, which evade inclusion of hydrological modelling approaches for tank / reservoir water release decisions. Presently, in Sri Lanka, the reservoir water is released once it reaches to a particular threshold. The public is informed few hours prior to the opening of reservoir gates. This current practicing way of releasing water from the reservoirs increases the potential for dam failures and public outrage, and thus strains reservoir operators to open the spill gates during emergency periods. Therefore, for a low-income country, a total open-source solution, combined with low-cost open-source hardware, free and open-source software and open standards was seen as the only possible way to overcome the flood risk associated with reservoirs. Thanks to the 4ONSE (4 times Open and Non-conventional technologies for Sensing the Environment) project, a dense open-source sensor network has been deployed in Deduru Oya watershed following a new deployment approach. Deduru Oya reservoir was chosen to develop the tank management model, as it is the main player of controlling the floods in the lower basin. The tank management decision support system presented in this research is supported by a hydrological model developed from SWAT open-source tool, fed with 4ONSE big data. Further, this research introduces a novel approach to find the dominant parameters and their values at any spatial and temporal scale. The calibration and validation results have revealed the potential of the open technologies-based tank management approach in controlling the reservoir floods.

Keywords:

4ONSE, reservoir flood control, Deduru Oya, open-source technologies, hydrological modelling

DEDICATION

This thesis is dedicated to the memory of my beloved father.

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LIST OF ABBREVIATIONS

Abbreviation	Description
4ONSE	4 times Open and Non-conventional technologies for Sensing the Environment
ALPHA_BF	Baseflow alpha factor
ALPHA_BNK	Baseflow alpha factor for bank strorage (days)
ARMA	Autoregressive Moving Average Model
AAT	All-at-a-time global sensitivity analysis
AWS	Automated Weather Stations
CANMX	Maximum canopy storage
CeNSE	Central Nervous System for the Earth
CFSR	Climate Forecast System Reanalysis
CH_D	Depth of main channel from top of bank to bottom (m)
CH_K(1)	Effective hydraulic conductivity in tributary channel alluvium
CH_K(2)	Effective hydraulic conductivity in main channel alluvium
CH_L(1)	Longest tributary channel length in sub-basin
CH_L(2)	Length of main channel (km)
CH_N(1)	Manning’s “n” value for the tributary channels
CH_N(2)	Manning’s “n” value for main channel
CH_S(1)	Average slope of tributary channels
CH_S(2)	Average slope of main channel along the channel length
CH_W(1)	Average width of tributary channels
CH_W(2)	Average width of main channel at top of bank

CN	Curve Number
CN2	Initial SCS runoff curve number for moisture condition II)
CNCOEF	Plant evapotranspiration curve number coefficient
DEEPST	Initial depth of water in the deep aquifer
DEM	Digital Elevation Model
EPCO	Plant uptake compensation factor
ERA5	ECMWF Reanalysis 5th Generation
ESCO	Soil evapotranspiration compensation factor
EVRCH	Reach evaporation adjustment factor
FAO-UNESCO	Food and Agricultural Organization - United Nations Educational, Scientific and Cultural Organization
FFCB	Initial soil water storage
FREEWAT	Free and Open Source Software for Water Resources Management
GAML	Green and Ampt Mein Larson
GIS	Geographic Information System
GSMB	Geological Survey and Mines Bureau
GW_DELAY	Ground water delay time
GW_REVAP	Groundwater "revap" coefficient
GW_REVAP	Groundwater "revap" coefficient
GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur
HBV	Hydrologiska Byråns Vattenbalansavdelning
HBV-D	Hydrologiska Byråns Vattenbalansavdelning-D

HEC-HMS	Hydrologic Engineering Center - Hydrologic Modelling System
HEC-RAS	Hydrologic Engineering Center – River Analysis System
HP	Hewlett-Packard
HRU	Hydrological Response Unit
HRU_SLP	Average slope steepness
HYMOD	Hydrological MODel
IBM	International Business Machines
IFAS	Integrated Flood Analysis System
IHACRES	Identification of unit Hydrographs And Component flows from Rainfall, Evaporation and Streamflow data
IHDM	Institute of Hydrology Distributed Model
INSAT	Indian National Satellite System
IoT	Internet of Things
iRIC	International River Interface Cooperative
ISBA	Interaction Sol-Biosphère-Atmosphère
istSOS	Instituto scienze della Terra Sensor Observation Service
IWMI	International Water Management Institute
LAT_TTIME	Lateral flow travel time
MIKE-SHE	MIKE System Hydrologique European
MSK_CO1	Muskingum coefficient for normal flow
MSK_CO2	Muskingum coefficient for low flow
MSK_X	Weighting factor for wedge storage

NCEP	National Centers for Environmental Prediction
NN	Neural Networks
NSE	Nash-Sutcliffe Efficiency
OGC-SOS	Open Geospatial Consortium – Sensor Observation Service
OV_N	Manning's "n" value for overland flow
OAT	One-at-a-time local sensitivity analysis
PAWS	Process-based Adaptive Watershed Simulator
PCR-GLOBWB	PCRaster Global Water Balance
PET	Potential Evapotranspiration
PIHM	Penn State Integrated Hydrologic Modelling System
PRMS	Precipitation-Runoff Modelling System
QGIS	Quantum GIS
RCHRG_DP	Deep aquifer percolation factor
REVAPMN	Threshold depth of water in the shallow aquifer for percolation to the deep aquifer to occur
SCS	Soil Conservation Service
SHALLST	Initial depth of water in the shallow aquifer
SHE	System Hydrologique European
SUFI-2	Sequential Uncertainties Fitting Version 2
SLSOIL	Slope length for lateral subsurface flow
SLSUBBSN	Average slope length
SLURP	Semi-distributed Land Use-based Runoff Processes
SOL_ALB	Moist soil albedo

SOL_AWC	Available water capacity of the soil layer
SOL_BD	Moist bulk density
SOL_CRK	Potential or maximum crack volume of the soil profile expressed as a fraction of the total soil volume
SOL_K	Saturated hydraulic conductivity
SOL_Z	Depth from soil surface to bottom of layer
SRTM	Shuttle Radar Topography Mission
SURLAG	Surface runoff lag coefficient
SWAT	Soil and Water Assessment Tool
SWAT-CUP	SWAT-Calibration and Uncertainty Procedures
SWIM	Soil and Water Integrated Model
TOPMODEL	Topography based Hydrological Model
TRNSRCH	Fraction of transmission losses from main channel that enter deep aquifer
USDA	United States Department of Agriculture
USGS	United States Geological Survey
WEAP	Water Evaluation and Planning System
WMO	World Meteorological Organization
WUDEEP	Average daily water removal from the deep aquifer for the month
WUSHAL	Average daily water removal from the shallow aquifer for the month

CHAPTER 1
INTRODUCTION

1.1 Background of the study

Despite the development of modelling approaches over the past few decades, inclusion of these models for disaster management have rarely practiced by relevant decision makers, especially with regard to real time flood control in tanks / reservoirs. Many reservoir flood warnings are still issued when observed tank levels cross pre-defined threshold. Since the advent of computers, many efforts have been taken to establish a decision support system for reservoir flood control. However, application of these systems in developing countries is often not possible because of high costs and constraints pertaining to available technologies for data collection, transmission, modelling and forecasting.

The regional scale catchments are characterized typically by natural variability in climatic and land-surface features. The existing sparsely distributed weather network of Sri Lanka is strongly insufficient for adequately accounting for this climatic heterogeneity. As the communication network of the state-owned automatic stations are malfunctioned at present, obtaining continuous real time data for modelling purposes becomes an issue. Accordingly, in order to simulate the hydrological processes at sub-basin level, the observations are required to obtain at least sub-daily interval for parameters such as rainfall, as it varies more often spatially and temporarily. Hence, inadequate representation of rainfall distribution over a watershed may result in producing unreliable model outputs.

Thanks to the Internet of Things (IoT), weather data can now remotely collect from low-cost sensors implanted in open hardware development boards such as Arduino. These IoT based unmanned stations have the capability to collect, store and disseminate large amounts of data at regular intervals. As the proprietary software is typically expensive and may not compatible with some hardware, the open-source software, for instance, istSOS (Free and Open-Source Sensor Observation) can be used to obtain near-real-time sensor observations from central location based on OGC-SOS (Open Geospatial Consortium – Sensor Observation) standard. In this background, the combined open-source platforms facilitate decision makers and researchers to use the open big data effective management, modelling, and monitoring of environmental resources.

"4 times Open and Non-Conventional technologies for Sensing the Environment" (4ONSE), is a research project initiated in this context to support low economic nations to use near-real-time weather data for water resource management. This joint research project was launched in year 2016 by University of Moratuwa, Sri Lanka and University of Applied Sciences and Arts of Southern Switzerland to create a revolution in the country for environmental data viewing and sharing without any fee. The principle objective of the project is to development of an experimental, low-cost weather station network based on open source technologies and the use of open-big data in environmental management. The tank management application presented in this research demonstrates the capability of the 4ONSE's big data in estimating the inflows to the tanks during the rainfall events.

1.2 Research Problem

Still in most of the countries, reservoir flood warnings are threshold-based alerts which issue when the water level threshold is exceeded. This creates flash flooding in downstream areas due to large volume of water release from dam gates. Hence, water pre-release from reservoirs is an important strategy to reduce downstream flooding. Hydrological models can simulate river flows with sufficient lead time; thus, the resultant outputs can be effectively applied for reservoir pre-release decision making. Hence, by knowing the inflow to the reservoir with sufficient lead time let the reservoir operators to conduct the water pre-release decisions effectively to reduce the likelihood of a massive damage. As explained in the literature review, many efforts have been taken to establish a decision support system to control the for reservoir floods since the dawn of computer based applications (Albertini, t.al, 2020; Yang, et.al, 2019; Su and Chen, 2019; Chen, et.al, 2019; Awol, et.al, 2019; Huang, et.al, 2018; Zhao, et.al, 2016; Hashemi, et.al, 2014; Cohen Liechti, et.al, 2014; Shim, et.al, 2002; Huang & Yang, 1999; Ford & Killen, 1995; Robillard, et.al, 1979; Unver, et.al, 1987). However, application of these system in developing countries is often not possible due to constraints pertaining to state-owned hydro-meteorological network, data collection, transmission and modelling. In this background, a combined open-source technology-based approach has been proposed in this research. Research studies which have used open source hardware, software, standards and data have been limited to only few case studies recording real-time data on certain environmental parameters (Valenzuela, et.al, 2018; Daniele, et.al, 2016; Prescott, et.al, 2016; Mesas-Carrascosa, et.al, 2015; Sadler,et.al, 2014; . Samourkasidis & Athanasiadis, 2014). However, application of combined open technologies for reservoir flood control still remains as an unexplored area.

Nearly 90% of the land area of Sri Lanka is covered by 103 river basins, and two third of the country belongs to the dry zone which is featured by number of tanks. As a result of these significant hydrological features, river floods and reservoir induced floods are most commonly seen in Sri Lanka. In addition, urban floods are more common in urban areas of Sri Lanka due to increase amount of impervious surfaces. In dry zone, tanks are the most important and effective storage facilities to retain flood water. Flood control in tanks can effectively mitigate flood disasters and store water for use in the lean seasons. Out of the different reservoir flood control measures, non-structural measures have now been considered as more effective, compared to structural measures, due to its long-term sustainability and minimal cost for operation and maintenance. Establishment of flood warning system is one such non-structural measure where the warnings are issued primarily based on the hydro-meteorological observations or the outputs produced by hydrological models. Meteorological data, modelling software and methods are the main fuel to drive hydrological models. Out of them, application of any hydrological model is mainly determined by the availability of hydro-meteorological data and their quality. Offline data, low spatial and temporal resolution of data and high purchasing cost of state-owned data are the main reasons which hinder development of hydrological models for water related decision making. Besides, high cost of modelling software, lack of expertise knowledge on handling software, lack of trust on technology and non-availability or lack of pre-determined parameter values are the other factors which impede the use of hydrological models among water practitioners to control floods generated by tanks. Currently, Irrigation Department is the key organization of the country for issuance of flood warnings associated with tanks. Most of the time, these warnings are issued when the water levels of rivers and tanks / reservoirs exceed the threshold.

Hydrological modelling can be performed at various scales of global, regional and local. The required spatial and temporal resolutions of data usually get increase when downscaling of hydrological models from global to local level. Accordingly, regional scale hydrological models are an intermediate version where the requirement of intensive data and processing time is substantially low compared to local scale models. They are also the best kind to represent the river basin scale hydrological processes. In last few years, the use of proprietary and open-source software applications on hydrological simulations has grown dramatically with the development of computer models and Geographical Information System (GIS). Although open-source applications can be obtained with no cost for licensing, still in most of the developing countries, even in Sri Lanka, proprietary applications are more popular than open source, as they provide technical support and training to comfort buyers during an issue. Therefore, the government organizations of the developing countries pay substantial amount of money for venders of proprietary software for buying the software and renewal of license annually. As most of these proprietary software contain data-hungry modelling approaches, such software do not have long-establishment in the field of hydrological modelling in developing countries owing to the drawbacks of the hydro-meteorological data and lack of trust on technology. Since, open-source hydrological modelling software have their own advantages pertaining to licensing fees, voluntary contributions, accessing the source code and integration of innovative ideas (Tuomi, 2005), attention must be given to the factors like availability of documentation, manuals and publications, support receive from scientific community, availability of updated versions, types of applications and required data, when selecting appropriate open-source tool for modelling.

Any hydrological model starts with collecting relevant hydro-meteorological data to run the model. Despite the importance of hydrological models for water resource management and disaster risk reduction, the adequacy of the hydro-meteorological stations and their locations play a significant role in generating reliable model outputs ns (Chaplot, et.al, 2005; Andréassian, et. al, 2001; Faurès, et. al, 1995; Duncan, et.al, 1993). Although World Meteorological Organization (WMO) recommends minimum station densities (WMO, 2008) for different physiographic areas with some detailed standards on siting and calibrating the instruments used in the stations, they do not provide any guideline to select optimum locations to deploy the stations. Further, most of the approaches on automatic weather stations deployment are based on accessibility and network coverage (Azharuddin and Jana, 2016; Yang, et.al, 2016; Elhabyan and Yagoub, 2015; Sung and Yang, 2014; Yoon and Kim, 2013; Kulkarni,et.al., 2012; Argany, et.al, 2011; Ab Aziz, et.al, 2009; Seo, et.al, 2009; Zhang, et.al, 2008; Lai, et.al, 2007; So and Ye, 2005; Fan and Biagioni, 2004; Jourdan and de Weck, 2004;Viera, et.al, 2003), while other methods are based on assessing the adequacy and locational issues in the current network by analyzing the data of the network (Awadallah, 2012; Karimi-Hosseini, et.al, 2011; Yeh, et.al, 2011; Chen, et.al, 2008; Moulin,et.al, 2008). This creates subjectivity in location selection and ultimately results in disregarding the remote and ungauged locations where the hydro-meteorological condition mostly influences. Therefore, a new approach is required to select locations of the stations wisely to get maximum results from the hydrological models.

The long-term sustenance and simulation of accurate outputs by the hydrological models are primarily depended on continuous cycle of model parameterization and calibration. Hydrological models represent hydrological processes; each process contains set of equations with parameters. Model parameters are quantifiable features (Melone, et.al, 2005) which are spatially and temporally distinct owing to the variations in climate, topography, soil and land use. However, most of the time, pre-determined parameter values have been applied at catchment level to run the models. Owing to the constraints of identifying the dominant parameter values and disregarding their spatial and temporal variability increases the predictive uncertainty of hydrological models. Accordingly, the conventional deterministic modelling approaches have now been considered as outdated since they are failed to address the stochastic nature of model parameters. However, the model parameterization, which is the procedure of deciding the values of model parameters (Zeckoski, et.al, 2015) is a cumbersome task which involves long term field investigations and sometimes laboratory testing to find the dominant parameter values at different spatial and temporal scales. Therefore, the most convenient way is to indirectly identifying the dominant parameters and estimating their values through model calibration, by way of fitting model simulations to observations (Zhang, et.al, 2014). This inverse modelling approach is more appropriate for hydrological models which operates as continuous models with long-term runs. Unlike discrete hydrologic models, which function mostly as event-based models based on short term and discrete rainfall pulses, the continuous hydrologic models do not require initial river discharge value to upload into the model, at every occasion they operate. Instead, they have an option to assign model warm up period. Berthet, et.al (2009) have identified warm-up period has a significant impact on steadiness of the model. Depending on the saturation level of the soil, warm up period may range one to several years. Lesser warm-up period is required in wetter periods, while greater warm-up period is required in drier periods. As far as the hydrological simulation is concerned, the input data is underutilized within the warm-up period. However, the data is processed inside the model within this period to reach soil-moisture condition into a steady state. Hence, a novel approach is required for optimizing the hydrological model parameters of a river basin where a new open-source sensor network exists, under the constraint of limited data available for model warm-up period.

1.3 Research Questions

Based on the research gaps elaborated in section 1.2, the following five research questions have been developed:

1. What are the best means for a developing nation to overcome the drawbacks of the existing state-owned hydro-meteorological network for reservoir flood control?
2. Which open-source tools are more suitable for hydrological modelling at regional scale?
3. How to deploy weather stations for the purpose of hydrological modelling?
4. Do hydrological model parameters change at sub-catchment level and different temporal scales? If so, what are the dominant parameters and their values at sub-catchment level and different temporal scales?
5. How to apply the resultant outputs of the hydrologic models for water pre-release decision making?

1.4 Research Objectives

This research aims at developing open technologies-based tank management model for reservoir flood control. This is the main objective of this research. It is supported by five sub-objectives linked with the five research questions mentioned in section 1.3.

Main objective:

- To develop open technologies-based tank management model for reservoir flood control

Sub-objectives:

1. To develop a hydrological model operated by combined open-source technologies for reservoir flood control
2. To identify a suitable open-source hydrological modelling tool to simulate the hydrological processes at regional scale

3. To identify optimum locations for open-source weather station network for hydrological modelling
4. To identify the dominant parameters and their values based on sub-catchment level and different temporal scales
5. To apply the outputs of the hydrological model to estimate the amount of water that should be pre-released and to estimate the opening heights of the reservoir gates

1.5 Conceptual Framework

Figure 1 illustrates the conceptual framework of this research with reference to the overall research problems and gaps identified in section 1.2. Accordingly, the threshold-based flood warning in most of the countries creates flash floods in downstream areas which can be mitigated to considerable level by employing hydrological models for water pre-release decision making. In this research, four main problems have been identified with respect to direct use of hydrological models for reservoir flood control. The first problem is low resolution, offline and non-open data of existing state-owned hydro-meteorological network. The second problem is unavailability of a proper approach in research literature to decide the optimum number and locations for the hydro-meteorological stations for the purpose of hydrological modelling. The third problem is related to issues pertaining to hydrological modelling software. The fourth problem is non-availability and lack of pre-determined parameter values at sub-catchment level for different time intervals; hence requirement of developing an approach to optimize the model parameters, where a new open-source sensor network exists, under the constraint of limited data available for model warm-up period. Accordingly, the first four research questions in section 1.3 are related to the aforementioned four research problems. The fifth research question of how to apply outputs of hydrological models for reservoir pre-release decision making, has been answered after obtaining solutions for the first four research questions. The boxes of last two rows in the conceptual diagram show the main objective and sub-objectives of this research linked to the research questions.

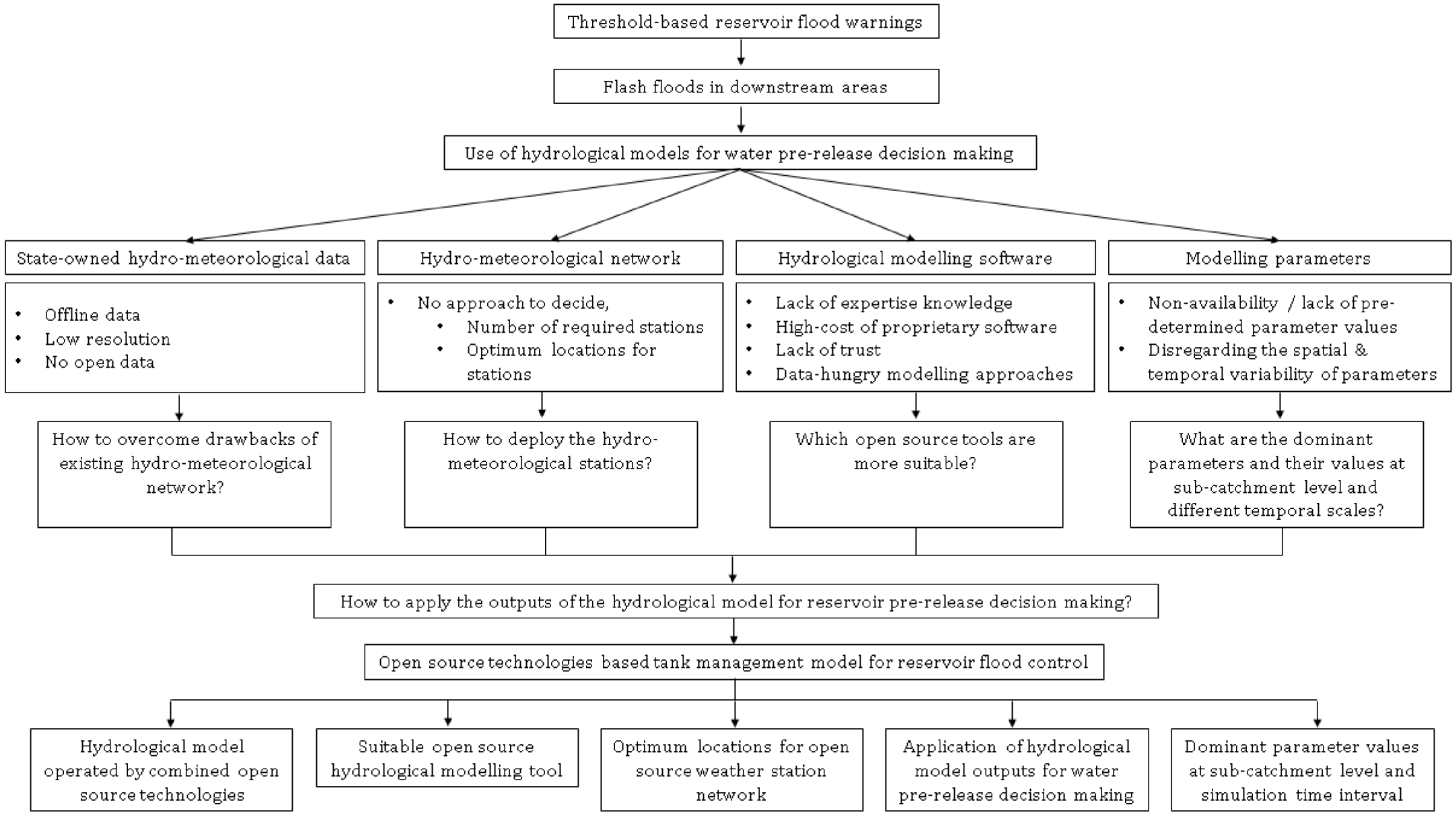


Figure 1: Conceptual Framework

1.6 Limitations of the Research

This study aims at developing open technologies-based model to simulate inflow to the Deduru Oya reservoir. The reservoir is located middle of the Deduru Oya basin and receives water from four streams (Deduru Oya, Maguru Oya, Hakwatuna Oya and Kimbulwana Oya). Based on the orientation of these four stream network and the topography, the upper watershed area divides into four sub-catchments. Out of them, Kimbulwana Oya sub-catchment and Hakwatuna Oya sub-catchment contains two tanks which are directly connected with the stream network. As explained in section 5.4.1, due to certain issues, these two sub-catchments could not be calibrated. Hence, this research presents optimized parameters with respect to Deduru Oya and Maguru Oya sub-catchments only.

Since it took considerable time to develop, test and install the 4ONSE sensor network in the Deduru Oya basin, only limited data was available to test the hydrological model. Hence, the performance of the model under different rainfall intensities could not be tested.

1.7 Organization of the other chapters

This thesis contains total of six chapters. The literature review is included in chapter 2, which includes comprehensive theoretical information about the research problem and gaps. The research presented in this thesis is a component of a recently completed joint research project called 4ONSE. Hence, chapter 3 elaborates the case study area of the research and the 4ONSE project. Chapter 4 contains the research design. Developing open technologies-based tank management model for reservoir flood control is the main objective of this study. This has been further subdivided into five sub-objectives. The methodological frameworks with respect to these five sub-objectives have been explained in chapter 4. The overall findings of the research with respect to these five sub-objectives have been presented in chapter 5. The conclusion has been presented in chapter 6, which explains contribution of the under objectives, limitations and directions for upcoming research.

CHAPTER 2
LITERATURE REVIEW

2.1 Overview

This chapter investigates the research questions and gaps through the literature review. The major findings of the literature review have been employed to develop the conceptual framework shown in Figure 1. The first research question has been explored in sections 2.2, 2.7 and 2.8, which discuss about the drawbacks of the existing state-owned hydro-meteorological network for reservoir flood control. The second research question of identifying suitable open-source tools for hydrological modelling has been investigated under sections 2.3, 2.4 and 2.5. Section 2.9 is more applicable for exploring the third research question of identifying suitable locations for deploying weather stations for the purpose of hydrological modelling. The fourth research question inquire about variation of parameter values at different spatial and temporal scales. This has been addressed in section 2.6. The fifth research question of applying resultant outputs of the hydrologic models for water pre-release decision making has been explored under sections 2.3, 2.4, 2.5 and 2.6.

2.2 Tank Management and Flood Control

Reservoir / tank is an artificial or natural lake or pond which is used to collect and store water for versatile activities such as portable water supply, irrigation, flood control, generation of hydropower and leisure activities. In Sri Lanka, reservoirs are called as tanks which is the direct translation of the Sinhala word “wewa”. The term “management” is defined in the Oxford dictionary as “the process of dealing with or controlling things or people”. Hence the “tank management” can be defined as the “process of controlling the operation of releasing water from the tanks”

Decisions pertaining to releasing water from tanks, is one of the hard tasks for reservoir operators to perform in heavy rainfall events (Wurbs, 1993). During the flood events, they need to release adequate water from the tanks, while ensuring the dam safety and the flood safety at downstream areas. Naturally, the tank water level rises when rainfalls occur at upstream. The gate opening decisions to release the water is crucial to make most of the time due to the unavailability of a proper decision support system to forecast the incoming flow with the aid of near-real-time weather data at upstream. Hence, a late decision might increase the flood risk at downstream areas and affect the dam’s structure.

In ancient Sri Lanka, floods associated with tanks mainly controlled through “Ellanga gammana” system which is also known as “Cascaded tank-village” system. This system still exists in the Dry Zone of Sri Lanka, which includes a network of small to large tanks in a micro or meso-scale catchment for storing, conveying and utilizing water from an ephemeral rivulvet (Madduma Bandara, 1995). Figure 2 illustrates this cascade system diagrammatically. This system operates as a buffer against seasonal flooding and store water during drought periods. This ensures continuous cultivation of paddy throughout the year and provides water supply for domestic and farming activities (Geekiyanage and Pushpakumara, 2013). Owing to its global significance, Food and Agricultural Organization (FAO) declared this system as a Globally Important Agricultural Heritage System (FAO, 2018). However, at present, this system is malfunctioned in most of the villages in Dry zone due to deforestation, sand mining, rural to urban migration, cultural changes and poverty related issues.

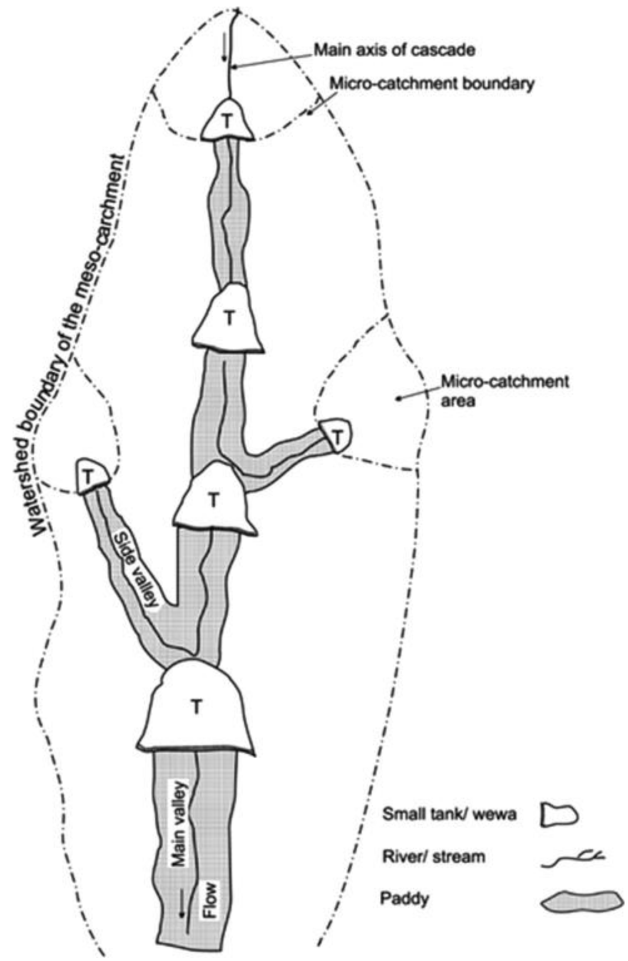


Figure 2: Schematic representation of a tank cascade system (Panabokke, et.al, 2002)

In present day, reservoir flood control measures can be broadly classified as structural and non-structural. Structural measures involve mitigation of flood through physical constructions such as creating detention reservoirs, construction of by-pass canals, enlarging the drainages, etc. These structural measures usually do not have a long-term sustainability and difficult to execute due to the social objections and financial constraints. Instead, non-structural measures on flood control have now been accepted as a proven method for reducing the flood risk and the damages due to its long-term sustainability and minimal cost for operation and maintenance. Establishment of flood warning system, development of flood emergency preparedness plans and flood resilient land use plans, enforcement of land use regulations, etc. are some of the non-structural measures that uses to reduce risks and impacts. Out of them, flood warning is the best measure to undertake for the areas deserve prompt attention.

Flood warnings are distinct from forecasts since they are issued when an event is imminent or already occurring (WMO, 2013). In Asian context, China and Japan have established reservoir flood control systems taking the advantage of advanced technologies. Reservoir Flood Forecasting and Control System (RFFCS) in China was developed in 1995 and its currently in operation (Guo, et,al, 2004). RFFCS was developed after the realization of that existing reservoir operation in China does not take the maximum utilization of advanced technology and management level need to cater the demands of the present community (Takeuchi, et.al, 1998). The RFFCS system uses satellite communication system to transfer real-time water level and rainfall data of stations to a central station. These data have been further processed and analyzed prior to use them for decision making. The river disaster prevention information system in Japan collects rainfall data from radar rain gauges and calibrates them online using ground telemetered data. These data are then analyzed through internet-based applications to produce flood forecasting and warning. The simulated information is finally disseminated to all user categories through Mobile applications. In most of the other countries, even in Sri Lanka, reservoir flood warnings are issued in circumstances where the reservoir’s storage capacity is already at full capacity and the dam gates are ready to release large amount of water. In most cases, the downstream areas face rapid flood like situation owing to the huge quantity of water released suddenly from dam gates during heavy rainfall events. Hence, by knowing the inflow to the reservoir with sufficient lead time let the reservoir operators to conduct the water pre-release decisions effectively to reduce the likelihood of a massive damage. The inflow is basically obtained through different approaches either applying real-time meteorological observations or forecasted meteorological observations.

2.3 Approaches on estimating the reservoir / tank water levels

Most of the studies done on reservoir / tank / lake water level estimation involve use of historical meteorological data as inputs to approximate the water levels or water discharge and calibration of results with historical gauge data, discharge data and flood data (Niu, et.al, 2019; Yue and Liu, 2019; Ashaary, et.al, 2015; Mokhtar,et.al, 2014; Khatibi, et al., 2014; Shrivastava, et.al, 2014; Muvundja, et al., 2014). These approaches are based on statistical methods such as Artificial Neural Network, Regression method and Auto-Regressive Integrated Moving Average.

The second approach involves application of Remote Sensing for measuring the reservoir / tank / lake volumes, especially in remote and ungauged areas, based on satellite radar altimetry (Carabajal and Boy, 2020; Cai, et.al, 2020; Wang, et.al, 2018; Pipitone, et.al, 2018; Ye, et al., 2017; Cretaux, et al., 2016; Silva, et al., 2014; Sima & Tajrishy, 2013).

The third cateogory is use of physically based hydrological models to estimate the reservoir / tank / water levels. Ever since the first computer based hydrological model developed by Freeze and Harlan in 1969, the use of computer applications for hydrological modelling have shown a dramatic development with the progress of the Geographic Information System (GIS). The modelling approaches which were in schematic form at the very beginning were started to transform into spatial form, due to the capabilities in GIS in representing and analysing number of overlapping layers of any discretization scheme. However, usage of such applications for water resources management was permitted to only several user groups as most of them were proprietary based. In last few decades, the evolution of open source GIS applications have enabled development of an increasing number of open source tools for water resources management. Tuomi (2005) have identified four reasons for rapid growth of open source applications among scientific community: (1) no license fees, (2) availability of multiple voluntary contribution for development of open source applications (3) possibility accessing the source code and modifying it (4) room for integration of innovative ideas compared to commercial packages and checking the reliability and functionally of the source code.

Table 1 shows the list of most widely used open-source tools / software supporting for water resources management. Accordingly, the relevant tools / software can be categorized based on three applications: hydrologic modelling, water resources management and hydraulic modelling.

Table 1: List of most widely used open-source tools for hydrologic modelling, water resources management and hydraulic modelling

Water resources application	**Software**	**Link**
Hydrologic modelling	HEC-HMS (Hydrologic Engineering Center - Hydrologic Modelling System)	http://www.hec.usace.army.mil/software/hec-hms/
	PRMS (Precipitation-Runoff Modelling System)	https://wwwbrr.cr.usgs.gov/projects/SW_MoWS/PRMS.html
	SWAT (Soil and Water Assessment Tool)	http://swat.tamu.edu
	IFAS (Integrated Flood Analysis System)	http://www.icharm.pwri.go.jp/research/ifas/
	PIHM (Penn State Integrated Hydrologic Modelling System)	http://www.pihm.psu.edu/
	PCR-GLOBWB (PCRaster Global Water Balance)	http://pcraster.geo.uu.nl/projects/applications/pcrglobwb/
Water resources management	FREEWAT (Free and Open-Source Software for Water Resources Management) and	http://www.freewat.eu/
	WEAP (Water Evaluation and Planning System)	https://www.weap21.org/
Hydraulic modelling	HEC-RAS (Hydrologic Engineering Center – River Analysis System)	https://www.hec.usace.army.mil/software/hec-ras/
	iRIC (International River Interface Cooperative)	https://i-ric.org/en/about/

2.4 Hydrologic Models, Hydrologic Cycle and Water Balance Equation

The heart of any flow forecasting system is a hydrological model (Askew, 1989). A model can represent any complex system in a simple manner. Thus, a hydrologic model represents parts of the hydrologic cycle such as precipitation, evapotranspiration, infiltration, surface runoff, routing and interflow / sub-surface flow (Figure 3) in a simple manner.

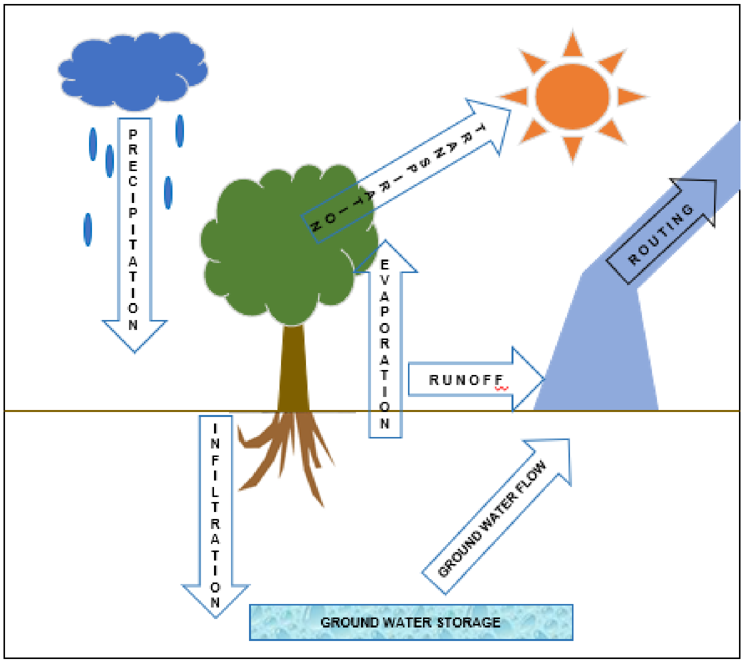


Figure 3: Hydrological Cycle

The quantitative measurements of the parts of the hydrological cycle can be expressed in the water balance equation as variables. The water balance equation is a fundamental equation applied in the science of hydrology. The equation expresses the balance between the water input and water output. In simplest form, water balance can be expressed as:

$$Water\ input = Water\ output + Change\ in\ storage$$

Equation 1: Basic water balance equation

As per the above equation 1, precipitation is the main basis for water input that falls from the atmosphere as rain, snow, freezing rain, sleet and hail. Evapotranspiration and surface runoff are the other processes caused for water output. The infiltration process influences for storing the water as ground water.

Evapotranspiration is the combined process of evaporation and transpiration which is the quantity of water released by the plants plus the water evaporated from the soil surface (Michael, 1978). This is also known as actual evapotranspiration. The rate of evapotranspiration is expressed in millimetres per unit time (Ex: mm/day, mm/hr, mm/month, mm/year). Temperature, wind speed, solar radiation and humidity are the main meteorological parameters influence for evapotranspiration. In addition, characteristics of the crops and management condition of the agricultural fields are also affected for increasing or decreasing the evapotranspiration. Analysts also use a concept called reference / potential evapotranspiration (PET) during the modelling. As defined by Doorenbos & Pruitt (1977), potential or reference evapotranspiration is the removal of water through transpiration and evaporation processes from a reference surface which has adequate amount of water. The reference surface is a hypothetical grass reference crop with specific characteristics. Actual evapotranspiration is generally less than the PET, and it is calculated based on the PET and crop coefficients.

The excess of the precipitation which runs over the surface is known as surface runoff. It's the primary source contributing for flooding, increasing the water levels of water bodies and sedimentation. Hence, the terms discharge and stream flow are also used to describe runoffs. Usually, it is measured in volume per unit of time (Ex: m^3/s) or depth per unit of time (Ex: mm/hour). The runoff is an important determinant used for calibrating the hydrological models. Although the hydrological models are termed in various names such as watershed models, river basin models, hydro-meteorological models, runoff models, etc., the typical approach is application of meteorological data as input data to simulate the runoff and stream flow.

The total runoff from a typically heterogeneous catchment area may be conveniently divided into three component parts: channel precipitation, overland flow and infiltration

(Ward, 1972). As shown in Figure 4, streams directly receive water from precipitation. In addition, the overland flow, which is the surplus of water travelling over the ground surface, also contributes to rise of the water level in streams. The process of seeping of water into the soil is known as infiltration. Intensity and duration of precipitation, characteristics of the land use / land cover and soil, slope, and base flow level of streams are the major factors which govern the infiltration. As per Figure 4, the process of infiltration further divides as interflow and ground water flow. Part of the water infiltrates to the soil layer travels through the upper soil layer as unsaturated flow. This process is called as interflow or lateral subsurface flow. The other part of infiltrated water travels through the deep soil layer as saturated flow. This process is called as groundwater flow. The water travels in this manner in underneath soil layers are called as subsurface runoff. Accordingly, the sum of channel precipitation, overland flow, interflow and groundwater flow clearly represent the total runoff generated during the storm periods.

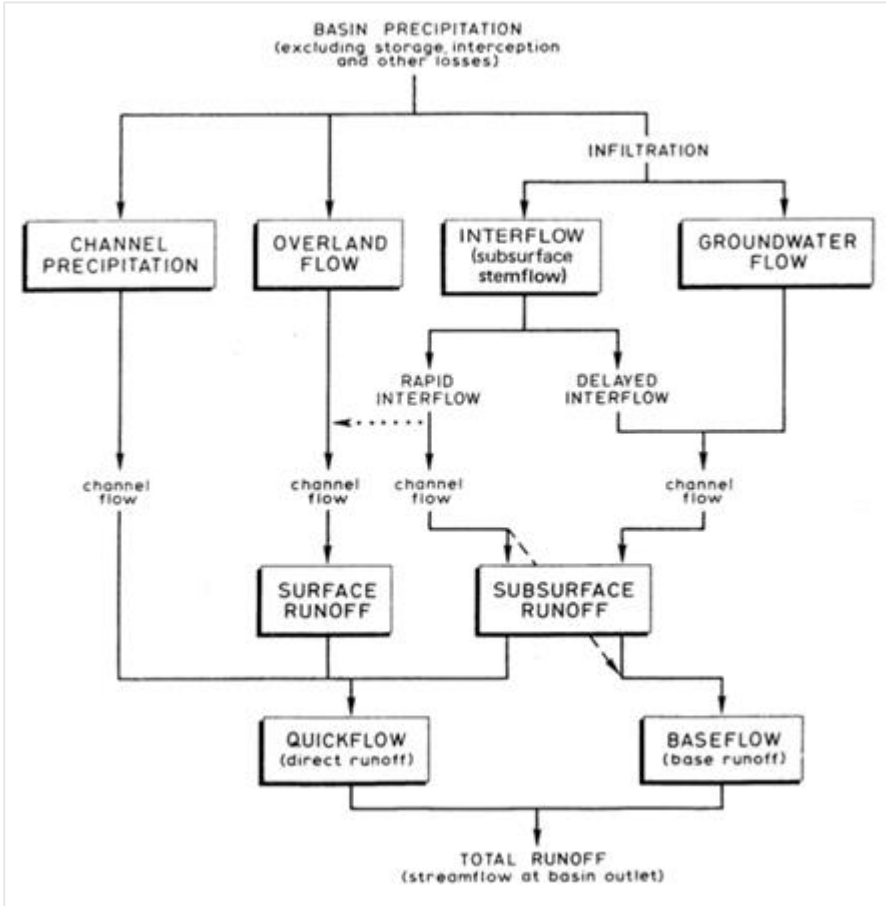


Figure 4: Diagrammatic representation of the runoff process (Ward, 1972)

2.5 Types of Hydrologic Models

The types of hydrologic models can be represented under several classification schemes. As demonstrated in Figure 5, Singh (1988) broadly divided the hydrologic models as symbolic and material models. Material models are physically based models tested in laboratories. Material models were primarily used by analysts prior to the advent of computer models. Symbolic models simulate the hydrological processes as mathematical and non-mathematical expressions. Mathematical models further classified into three groups as theoretical, conceptual and empirical. White box models, grey box models and black box models are the synonyms for above three groups respectively. Theoretical models are based on the laws in physics related to mass, momentum and energy balance which determine the behaviour of different phenomena.

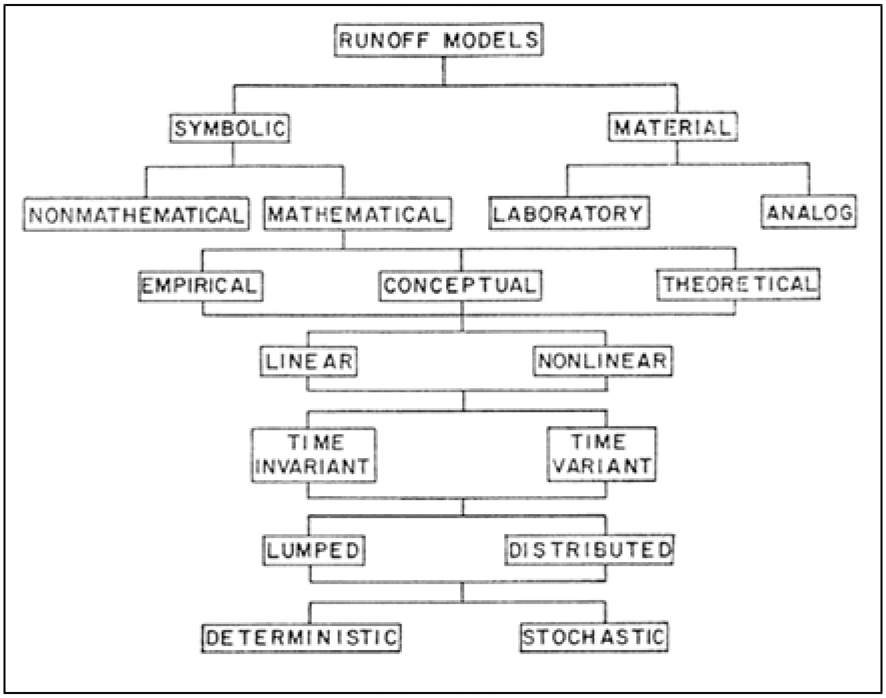


Figure 5: Types of hydrological models (Singh, 1988)

Theoretical models are also known as physical models since they are based on the laws in physics. The physical processes addressed by the physically based hydrological models include, evapotranspiration, snowmelt, infiltration, groundwater flow, surface runoff and water routing. The initial computer based physical model designed by Freeze and Harlan in 1969. Their model consists of two main components: (1) the storage component represents interception storage, soil-water storage, groundwater storage and channel storage (2) the second component is the transmission routes which are connected by a series of decision points. This model requires four inputs for the operation: (1) model definition input which is the size of the grid system (2) meteorological input (3) flow parameter input (4) mathematical input which represents the equations used in the model.

SHE model (Abbott et al., 1986) is an example for physically-based model. In empirical models, input data and parameters with little direct significance are used to compute the outputs. ARMA (Autoregressive Moving Average Model) and other time series models are examples for empirical models. The conceptual model is an intermediate version between empirical and theoretical models, which use laws in physics to understand the hydrological processes and the input data and parameters with significant influence are applied to compute the outputs. HBV (Hydrologiska Byråns Vattenbalansavdelning) model is an example for conceptual model.

In physically based distributed models, each hydrological process simulates inside the primary discretization scheme. Based on the discretization scheme, hydrological models can be classified as lumped, semi-distributed and distributed models. In here, the discretization refers to the division of watershed boundary into discrete units. Accordingly, lumped models, which consider entire watershed as a single system, is the simplest version of the hydrological models. Lumped-conceptual models were heavily used by the modellers to determine the surface runoff. Gosain, et.al (2009) have identified three processes related to lumped-conceptual models: (1) storing of water in soil, plants, aquifers and water bodies; (2) loss of water from storage (3) routing of water over the surface. As the lumped conceptual models do not take into account the spatial heterogeneities of landuse, soil, and input variables (Abbott, et.al., 1986), higher uncertainties are involved in calibration and validation of certain hydrological processes such as evapotranspiration (Beven, 1989) and their accuracies are primarily based on the meteorological and hydrological input data. Semi-distributed models are the intermediate version between lumped and fully-distributed models which usually consider sub-basins' boundaries as the discrete unit. Fully distributed models are more detailed than semi-distributed models, where watershed further divides into pixels or grids for modelling processes. Compared to semi-distributed models, fully-distributed models are data intensive and take substantial computation time. The schematic representations of three model types are illustrated in Figure 6.

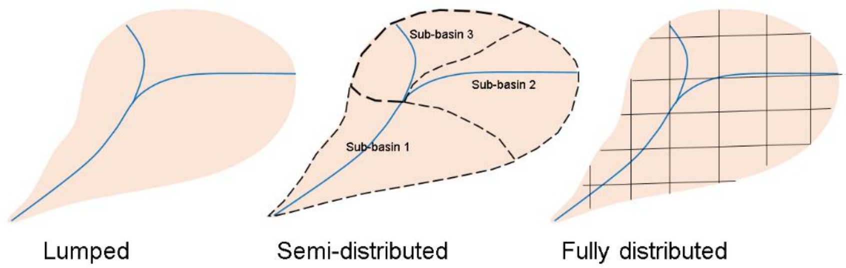


Figure 6: Schematic representation of watershed in lumped, semi-distributed and fully distributed models

In addition to the sub-basin level and pixel level discretization types, the distributed models also use another discretization type known as hydrological response unit (HRU). In this type, the entire watershed area divides into irregular shapes based on the similar geomorphological features (land use, soil type and slope). As semi-distributed models are less data demanding compared to fully distributed models, they are more fitting for modelling river basins at regional scale. TOPMODEL (Beven & Kirkby, 1976; Beven & Kirkby, 1979), SLURP (Kite, 1995) and SWAT (Arnold, et.al, 1998) are some examples for semi-distributed models. SHE (Abbott, et.al, 1986a; Abbott, et.al, 1986b), ISBA (Nolihan & Planton, 1989; Nolihan & Mahfour, 1996), IHDM (Beven, et.al, 1987; Calver & Wood, 1995), MIKE-SHE (Refsgaard & Storm, 1995) and PAWS (Shen & Phanikumar, 2010) are some examples for fully distributed models. Out of them, TOPMODEL was the foremost physically based distributed model which took into account the network topology and the concept of variable contributing area, when developing the model (Beven & Kirkby, 1979).

All hydrological processes are non-linear, although they are assumed as linear due to its modeling simplicity. Linear models usually have one basic form, while the non-linear models have many different forms. Therefore, flexibility is there in non-linear models to use different regression equations to measure the model fitness. Nash model or linear reservoir model (Nash, 1957) is an example for linear hydrological model which is widely used for cascade type tank network to calculate the outflow from each tank. The hydrological processes simulate through neural networks (NN) are considered as an example for non-linear hydrological modelling.

The other categories such as time variant and time-invariant, stochastic and deterministic and, event-based and continuous, can be represented in relation to time. In time-invariant models, hydrological parameters are assumed as unchanging with the time considering the model simplicity. However, in reality, hydrological parameters do not exist in constant form. Rather, they show temporal variation due to the changes in the climatic and geomorphological patterns. Correspondingly, the deterministic models consider same set of parameter values most of the time to simulate the outputs. However, in reality, hydrological parameters do not exist in constant form. Rather, they show temporal variation due to the changes in the climatic and geomorphological patterns. As any model parameter inherits a stochasticity due to random changes in the environmental condition, the time-invariant and deterministic modelling approaches have now been considered as obsolete. In contrary, time variant and stochastic models allow to incorporate range of parameters for different time scales. As stated by Abbaspour, et.al, (2018), "A stochastic model can be defined as a model that takes parameters in the form of a distribution and produces output variables in the form of a distribution". In event-based models, input weather data of a short period is considered to estimate the components of the water balance equation (Equation 1). These models, usually require the water flow at the beginning of the simulation, to run the model. In continuous process models, input weather data of a long period is uploaded into the model to simulate the runoff. Therefore, in addition to the weather data of the current period, these models require historical weather data at least during the past 1 year to run the model. Generally, these historical data are applied for the model warm-up period. Berthet, et.al (2009) have identified warm-up period has a significant impact on steadiness of the model. Depending on the soil's saturation level, warm up period may range one to several years. Lesser warm-up period is required in wetter periods, while greater warm-up period is required in drier periods.

However, the required time period varies with land use, climatic condition and size of the basin. As far as the hydrological simulation is concerned, the input data is underutilized within the warm-up period. However, the data is processed inside the model within this period to reach soil-moisture condition into a steady state. SWAT (Soil and Water Assessment Tool), HACRES (Identification of unit Hydrographs And Component flows from Rainfall, Evaporation and Streamflow data), HYMOD (Hydrological MODel), I, HBV-D (Hydrologiska Byråns Vattenbalansavdelning-D) and SWIM (Soil and Water Integrated Model) are some of the software which require model warm-up period. Hence, the above software do not require initial discharge value to upload into the model, at every occasion they operate.

2.6 Regionalization, Parameterization, Calibration, Validation and Uncertainty Assessment of Hydrological Models

Regionalization, parameterization, calibration, validation and uncertainty assessment are the terms which can be commonly found in the jargon of hydrology. In a nutshell, all of them are applied to improve and assess the model's performance. Generally, the terms regionalization, parameterization and calibration have similar meaning, which is adjusting the parameter values to reduce the difference between simulated result and observed values. Zeckoski, et al. (2015) defined the model calibration as a process of altering influential parameter values until simulated values (i.e. simulated river discharge) match with the observed measurements (i.e. actual river discharge) to an acceptable level. In the process of validation, the accuracy of the model further verified by applying the adjusted parameter values to a different time period, which have not used for the calibration.

Melone, et.al (2005) stated that a parameter represent process or feature in a model which is quantifiable. Hence, in the process of regionalization, approximate values are applied to the parameters considering its physical characteristics. Beck, et al. (2016) have identified six most widespread regionalization approaches to assign model parameters. They are:

(1) Catchment-by-catchment calibration
(2) Regression method
(3) Transfer of calibrated parameters to nearby catchments considering the geographic proximity
(4) Transfer of calibrated parameters considering the physiographic and climatic similarity
(5) Simultaneously calibration of multiple catchments with similar physiographic and climatic similarity
(6) Examination of stream flow signatures (shape of the hydrograph)

As per the definition suggested by Zeckoski, et.al. (2015), the term "parameterization" has a meaning similar to regionalization which is the course of action taken to quantify the model parameters. The parameters usually subject to change temporally and spatially owing to the changes in the climate, topography, land use / land cover and soil. Thus, identification of appropriate parameter sets and their values requires knowledge of hydrological processes and geomorphological features. Arnold, et.al. (2012a) has defined parameterization as "the process of imparting the analyst's knowledge of the physical processes of the watershed to the model". Inability to recognize correct parameters and their values increases the predictive uncertainty of the hydrological models.

Xuan, et, al (2009) stated most physically based hydrological models are highly complex and have multiple parameters due to the spatio-temporal dissimilarities of the hydrological processes. As the input parameters which govern the hydrological processes differ according to the climatic condition and geomorphological setup of the watershed, their level of uncertainty is obviously high. Lindenschmidt, et.al (2007) have identified model structure, input data and paramaters as the main factors which influence for uncertainty in hydrological modeling. Renard, et. al (2010) have identified four main sources for hydrologic modelling uncertainties. They are:

(1) Uncertainties of the conceptual model

Abbaspour (2008) have identified four issues for model uncertainties. They are:

a. Disregarding most important hydrological processes and parameters due to model simplicity.
b. Disregarding some most important hydrological processes occur in the watershed.
c. Uncertainties may arise when the modeler is unknown about occurrences of some processes in the hydrological model, although all the processes are included in the model.
d. Uncertainties may also create when some important hydrological processes are ignored and when their occurrences in the watershed are unknown to the modeler.

(2) Uncertainties in input data

The distinctive procedure applied in any hydrological model is to feed the model with meteorological observation or forecasts to simulate the runoff, stream flow and storage at waterbodies. Uncertainties in input weather data may occur as a result of measurement errors (i.e. underestimations), data gaps and sampling errors. In any hydrological model, rainfall is the foremost input data type. As the rainfall distribution and the intensity is varied across different geomorphological units, imprecise rainfall data represented in the model may generate erratic outputs. Further, errors associated with other ancillary data such as DEM, land use and soil layers can also contribute for producing inaccurate results.

(3) Uncertainty in parameterization

The uncertainties in the hydrological models may increase as a result of assigning incorrect values to model parameters and ignoring the dominant parameters that play a major role in hydrological processes.

(4) Output uncertainty

During the model calibration, the accuracy of the output result (i.e. simulated stream flow / runoff), is matched with the discharge of the stream at specific locations (i.e. river gauges). Measurements of the water level are continually recorded at the river gauge either manually or automatically. A stage-discharge rating curve is needed to convert this water level into a volume (or "discharge"). This curve is made by measuring the river discharge with respect to different water levels (stages). Schmidt (2002), pointed out that uncertainites in the stage-discharge relationship curve emerge as a result of: (1) natural uncertainties – changes in the river cross sections (2) knowledge uncertainties – lack of understanding of the actual physical processes (3) data uncertainties – errors associated with manually observing data and processing data.

Generally, the dominant parameters and their values are determined based on the previous field investigations and researches conducted within and around the particular watershed area. These methods of direct measurement of parameters are cumbersome, time consuming, labour-intensive and expensive most of the time. Therefore, the most convenient way is to indirectly identifying the dominant / sensitive parameters and estimating their values through model calibration, by way of fitting model simulations to observations (Zhang, et.al, 2014). This inverse modelling approach is more appropriate for hydrological models which operates as continuous models with long-term runs.

Unlike discrete hydrologic models, which function mostly as event-based models based on short term and discrete rainfall pulses, the continuous hydrologic models do not require initial river discharge value to upload into the model, at every occasion they operate. Instead, they have an option to assign model warm up period. Warm-up period is a mandatory option provided in some hydrological modelling tools such as SWAT (Soil and Water Assessment Tool), IHACRES (Identification of unit Hydrographs And Component flows from Rainfall, Evaporation and Streamflow data), HYMOD (Hydrological MODel), , HBV-D (Hydrologiska Byråns Vattenbalansavdelning-D) and SWIM (Soil and Water Integrated Model) to decide the initial condition of the catchment. Berthet, et.al (2009) have identified warm-up period has a significant impact on steadiness of the model. Depending on the soil's saturation, warm up period may ranges one to several years. Lesser warm-up period is required in wetter periods, while greater warm-up period is required in drier periods. However, the required time period varies with land use, climatic condition and size of the basin. As far as the hydrological simulation is concerned, the input data is underutilized within the warm-up period. However, the data is processed inside the model within this period to reach soil-moisture condition into a steady state.

2.7 Existing Hydrometeorological Network of Sri Lanka and the Decision-making Setup

The hydro-meteorological network is the key source of providing input data to run the hydrological model. However, like most developing countries, Sri Lanka lacks sufficient weather observing stations which provide continuous and near-real time data for decision making. Meteorological Department of Sri Lanka is the main government body in Sri Lanka, responsible for collecting weather records in conformity with the World Meteorological Organization's (WMO) standards. In addition, several government organizations such as Irrigation Department, National Building Research Organization and Disaster Management Center, maintain some weather stations for their own use.

The Meteorological Department owns 37 automated weather stations (AWS), 23 synoptic stations, 4 pilot balloon stations, 1 radiosonde station. In addition, the department has deployed 42 Agro-meteorological stations in collaboration with the Department of Agriculture. These stations mainly measure weather parameters such as evapotranspiration, sunshine hours, soil temperature and radiation which required for agriculture activities. Further, the department has located 510 rainfall measuring centers all over the country in collaborations with various organizations. These rain gauges operate manually and transmit data vocally over the phones. In 2018, 100 automatic rain gauge stations were also added to this network.

The 37 AWSs have been donated to Sri Lanka by the Japanese government. Usually, they measure all the surface weather parameters and the data is stored at one-minute interval. The collected data is sent to the Colombo at every 10 minutes via satellite INSAT 3-E. This satellite communication network is malfunctioned at present. Hence, no AWS sends real-time data to the department. Therefore, during an emergency weather condition, getting a series of high temporal and spatial resolution dataset for modelling purposes become an issue. Since those AWSs were developed with sophisticated technologies, replacing sensors and other electronic components during a breakdown, is unbearable for a developing nation (Senevirathna and Jayawickrama, 2014). Further, the available resources to maintain the weather stations, especially at remote locations, are inadequate most of the time. As identified by Snow (2013), the commonly found challenges for a developing nation to maintain their weather network are inadequate funds, lack of locally available expertise knowledge, infrastructure and spare-parts and corrosion of electronic components.

Irrigation Department is the main government body in Sri Lanka responsible for hydrological issues. Flood monitoring and forecasting, planning, designing and construction of structural measures, operational and maintenance of flood control systems and operation of reservoirs to minimize to downstream floods are some of the key functions of Irrigation Department related to flood management. The present flood warning system is primarily based on monitoring the water levels and rainfall at certain gauges. These observations are recorded at 3 hourly interval and the data is transmitted to the Divisional Irrigation office over the phone. Hence, under a bad weather condition, the transfer of data over the phone, can be obstructed due to issues in the transmission lines. Most of the time warnings are issued based on the past experience and estimating the stream flow through stage-discharge rating curves. Nevertheless, certain divisional irrigation offices uses HEC-HMS open source application to simulate the river flows at certain occasions. However, this is not often practiced owing to the limited meteorological stations, offline data, outdated model parameter values and limited resource persons in handling the software. In addition, reservoir floods are primarily monitored by observing the water levels of the reservoirs and incoming flows. Therefore, during the heavy rainfall periods, water pre-release decisions become crucial due to the difficulties in estimating the inflow of the reservoir with sufficient lead time.

Currently, the water resources data and meteorological data pertaining to river basins are collected by five state organizations as per their own procedures - Meteorological Department, Irrigation Department, Water Resources Board, Central Environmental Authority and National Water Supply and Drainage Board. As these organizations operate as independent bodies, data sharing is occasionally occurred. Most of the stations are operated manually and the digital data is not readily and freely available. Therefore, every time, the decision makers and researchers need to purchase data or need to conduct data collection surveys for their studies. Hence, data interoperability, which is the exchanging of data, is not still practiced among these five state organizations.

In this background, this study reveals the necessity of a novel and cost-effective approach to fill the big vacuum in the fields of weather monitoring and disaster management, especially in developing countries. Thus, as described in the subsequent section, thanks to the IoT (Internet of Things) enabled technologies, the future of weather station industry has now been made a significant turning point from its high-cost sophisticated devices into low cost IoT enabled solutions. Now most of IoT platforms are open source-oriented. Open source makes it possible to solve issues pertaining to data interoperability and assist to develop solutions towards environmental monitoring.

2.8 Internet of Things (IoT), Open-Source Technologies and Environmental Monitoring

Evans (2011) defined the term Internet of Things (IoT) as a moment where more things are connected to the internet than people. Wireless connectivity and smart sensors are the two technologies which shape-up the IoT network. Hence, IoT usually does the collecting of data through smart sensors and sharing them through internet. Although there is no universally accepted definition for IoT, its meaning in the viewpoint of environment could be expressed as "An open and comprehensive network of intelligent objects that have the capacity to auto-organize, share information, data and resources, reacting and acting in face of situations and changes in the environment" (Madakam, et,al., 2015).

Hart & Martinez (2015) have stated that most of the IoT based applications and IoT oriented researches have been applied in cities and indoor environments where the relevant infrastructure facilities such as internet connectivity, accessibility and electric power supply are available. Therefore, the most essential requirement to form a global environmental monitoring sensor network is to introduce IoT to remote environments where the IoT systems are powered by energy harvesting systems composed of sustainable energy source/s and energy storage unit and wireless internet connectivity. Several world's most recognized companies such as IBM and HP have already started some initiatives in this respect (IBM,2010; HP, 2013; Liang & Huang, 2013).

Most cost effective IoT applications have been started to popular after the addition of low cost sensors, open source hardware platforms (i.e. Arduino), open source software and standards in system development (Prescott, et.al, 2016; Rao, et.al, 2016; Saini, et.al, 2016; Bitella, et.al, 2014; Formisano, et.al, 2015; Chemin, et.al, 2015; Sadler, et.al, 2014; Van de Giesen, et.al, 2014; Chemin, et.al, 2014; Samourkasidis & Athanasiadis, 2014). Thanks to the open-source software for instance istSOS (Instituto scienze della Terra Sensor Observation Service), all the sensor observations, including near-real-time and historical data, can now access from central location based on the OGC-SOS (Open Geospatial Consortium – Sensor Observation Service) standard. OGC is an international consortium composed of more than 530 businesses, universities, government and research organizations to facilitate finding and accessing geospatial information and services in an interoperable and reusable ways. The consortium has introduced OGC member approved specification and standards for building open interfaces and encodings. OGC-SOS is one such standard web service interface which provides interoperable facilities to query observations and sensor metadata and to represent observed features. Further, it has standards on removing existing sensors and registering new sensors (Open Geospatial Consortium, 2012).

In this background, the combined open-source platforms facilitate decision makers and researchers to use the open big data effective management and monitoring of environmental resources. However, combination of open hardware, open software and open standards has been limited to only few cases focusing on recording real-time data on certain environmental parameters. Valenzuela, et.al (2018) developed a turbidity data acquisition system using Arduino as open hardware and MyOpenLap free software as open source software. Sabatini (2017) has presented an approach of step by step installation of automatic weather station in remote sites. Daniele, et.al (2016) have developed an open hardware device based on Arduino to monitor the soil water potential for irrigation activities. Similar kind of application was developed by Bitella, et.al (2014) to monitor the soil water content integrating the soil, vegetation and atmosphere parameters. Prescott, et.al (2016) discussed a hydro-climatic monitoring station which observes six water quality parameters. Mesas-Carrascosa, et.al (2015) developed an open source hardware device to record environmental parameters and a smart phone application to analyse the data. Sadler, et.al (2014) developed a low-cost environmental monitoring system which measures air temperature and relative humidity and automatically sends the collected to Hydrologic Information System. Samourkasidis & Athanasiadis (2014) demonstrated an automated data archival system integrated with OGC-SOS, low-cost sensors and Raspberry Pi as open hardware. Therefore, application of combined open technologies in tank management in catchment areas, especially with regard to flood control in tanks still remains as an unexplored area.

2.9 Deployment of an experimental weather station network in a river basin

Although, WMO has set standards and guidelines for setting weather observing instruments, they haven't set any specific standard for number of stations required for an area. Nevertheless, they have set minimum coverage area per rain gauge station for different physiographic areas (Table 2). However, the standards recommended in Table 2 is extremely insufficient for a tropical country like Sri Lanka as the rainfall is significantly varying even with short distance.

Table 2: Recommended minimum coverage area per rain gauge

Physiographic unit	**Area in km^2 per station**	
	Non-recording	**Recording**
Coastal	900	9000
Mountains	250	2500
Interior plains	575	5750
Hilly/undulating	575	5750
Small islands	25	250
Urban areas	-	10 - 20
Polar / arid	10,000	100,000

Source: (WMO, 2008)

Uneven distribution and inadequate number of weather stations over the watershed area generally lead to produce undesirable results during the modelling process (Chaplot, et.al, 2005; Andréassian, et. al, 2001; Faurès, et. al, 1995; Duncan, et.al, 1993). In absence of adequate stations for hydrological modelling, different methods for areal averaging of rainfall are usually employed to estimate the missing rainfall data. Arithmetic average method, thiessen polygon method and isohyetal method are some of the methods used for areal averaging of rainfall.

As shown in Figure 7, to find the average rainfall (P_{avg}) of the watershed, arithmetic average method can be applied. In arithmetic average method, rainfall values of all the stations in the watershed are summed up and divided by the number of stations to decide the average rainfall for that watershed (Equation 2).

$$P_{avg} = \frac{\sum_{i=1}^{n} P_i}{n} \quad \text{Equation 2}$$

As per the Equation 2, P_{avg} is the arithmetic average of rainfall, P_i is the precipitation of the i^{th} station and n is the number of stations. This method is mostly appropriate for lumped hydrological models and mostly recommended to apply for an area where stations are uniformly distributed. As a rule of thumb, the arithmetic average method considered as an accurate estimator if $\frac{\sigma_p}{P_{avg}} < 10\%$, where σ_p is the standard deviation of precipitation. However, this method does not take into account the topographic influences which significantly accounts for variation of rainfall.

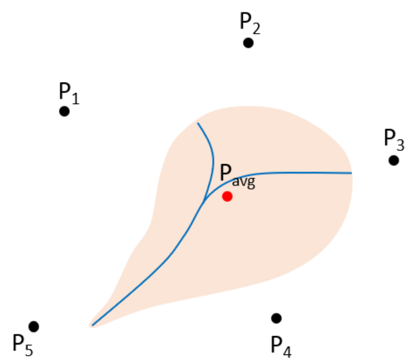


Figure 7: Schematic representation of estimating the Px using arithmetic average method

Thiessen polygons are Voronoi diagrams which designed by intersecting perpendicular bisector lines between points (Thiessen, 1911). Though this method was originally used for averaging precipitation over large areas, now it is applied even in transportation and population studies. Through this method, it is possible to estimate the rainfall values of an ungauged area based on the rainfall values of surrounding stations (Figure 8). The formula for estimating the missing rainfall values of the ungauged station can be written as:

$$P_x = \frac{\sum_{i=1}^{n} [(A_j - A_i) P_i]}{\sum_{i=1}^{n} (A_j - A_i)} \qquad \text{Equation 3}$$

Where P_x is the estimated rainfall value of the ungauged area, n is the number of surrounding stations, A_j is the extent of the Thiessen polygon represents the ungauged area, A_i is the extent of the Thiessen polygon with reference to i^{th} station, P_i is the precipitation of the i^{th} station. Thiessen polygon method is more appropriate for a flat terrain, as it does not account for topographic influences.

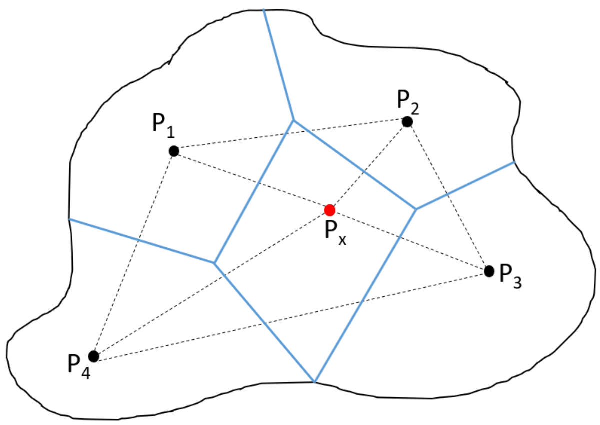


Figure 8: Schematic representation of estimating Px based on the Thiessen polygon method

In Isohytel method, rainfall over a catchment is estimated based on a map which shows contours of equal rainfall distribution (Figure 9). To execute this method, rainfall values of a well distributed station network is required. As per the equation 4, P_i is the average rainfall in-between consecutive isohyetes which is calculated as $\frac{P_1+P_2}{2}$. A_i is the area below isohyetes.

$$P_{avg} = \frac{\sum_i^n P_i}{\sum_i^n A_i} \qquad \text{Equation 4}$$

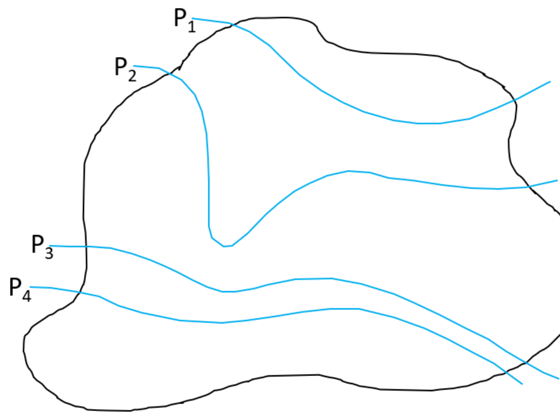


Figure 9: Schematic representation of estimating P_{avg} based on the Isohyetal method

In isohyetal method, isohyets can be drawn while also considering topographical influences. As depicted in Figure 9, closely-spaced isohyets could be areas of steeper slopes while spaced isohyets could be flat terrain. Hence, isohyetal method is more accurate compared to arithmetic average method and Thiessen polygon method. However, this method becomes tedious and time consuming as new isohyets are required to make for each rainfall event.

Moreover, several methods on deploying weather station networks can be found in the literature. The most popular method is aimed at finding optimal sensor node deployment to minimize total energy spent in the network, while maximizing the connectivity. Voronoi approach (Di, et.al, 2020; Boubrima, et.al, 2019; Singh, et.al, 2019; Van Wesemael, et.al, 2019), Particle Swarm Optimization algorithm (Murillo-Escobar, et.al, 2019; Pannu, et.al, 2019; Azharuddin and Jana, 2016; Elhabyan and Yagoub, 2015) and Genetic algorithm (Moreno-Carbonell, et.al, 2020; Sobhani, et.al, 2019; Vanderstar, et.al, 2018; Hao & Xie, 2018) are some of the most widely used approaches in this regard. However, unlike in the past when Automatic Weather Stations (AWSs) are placed where the electricity lines and telecommunication network is available, nowadays the technological advancements in renewable electricity generation technologies and cellular communication technologies have let AWSs to operate without directly connected to the electricity grid or telecommunication network. Therefore, site selection, primarily based on availability of electricity and telecommunication network is not a necessity for sensor networks operating nowadays.

The second approach is concerned with investigating the adequacy of the existing network and deciding some new locations for the weather stations based on the measurements of the existing stations using Geostatistical tools such as Kriging and Shannon's entropy method (Joo, et.al, 2019; Li, et.al, 2019; Wang, et.al, 2019; Xu, et.al, 2018; Pourshahabi, et.al, 2018; Werstuck & Coulibaly, 2017; Awadallah, 2012; Karimi-Hosseini, et.al, 2011; Yeh, et.al, 2011). By placing stations in the higher entropy areas, the overall variance in precipitation, for example can be reduced. The limitation in this method is, it requires measurements of the stations already exist on the basin. Therefore, the most challenging task is to find the optimum locations for sensor networks in an ungauged river basin where the meteorological data lacks or unavailable.

CHAPTER 3
STUDY AREA

3.1 Overview

This chapter elaborates the study area of the research which is the Deduru Oya river basin of Sri Lanka. Since this study is a component of a recently completed joint research project called "4ONSE", this chapter also includes information about the 4ONSE project. Accordingly, section 3.2 contains introduction about the 4ONSE project, system architecture of the 4ONSE sensor network and the quality of data. Section 3.3 describes the case study area of the 4ONSE project and this research. Section 3.4 includes the timeline with respect to deployment of open sensor network in Deduru Oya basin.

3.2 4ONSE Project

3.2.1 Introduction to 4ONSE project

This study of developing a tank management model is a part of a joint research project between University of Moratuwa and University of Applied Sciences and Arts of Southern Switzerland, which was commenced in October, 2016. The name of the project is "4ONSE", which stands for "4 times Open and Non-conventional technologies for Sensing the Environment". In here, open hardware, open software, open data and open standards are the 4 open and non-conventional technologies. The project was funded by Swiss Agency for Development and Cooperation and Swiss National Science Foundation. Mainly there are two concrete objectives of the project:

(1) Develop an experimental sensor network to measure environmental parameters based on open source technologies (open hardware, open software, open standards and open data) and deploy them in a selected river basin of Sri Lanka
(2) Application of 4ONSE weather stations' data to develop a tank management model
(3) Application of 4ONSE weather stations' data to develop a drought model

Accordingly, the main intention of conducting this research was to address the 2nd objective of the 4ONSE project. Malwathu Oya river basin area was the originally selected area to install the stations. However, IWMI (International Water Management Institute) and some other organizations have already installed similar type of weather stations in Malwathu Oya river basin area for research and monitoring purposes. Further, a special request was made by the Irrigation Department to select a river basin area where a weather station network is seriously needed. Accordingly, they suggested to select Deduru Oya river basin to launch this project. The state-owned weather network of Deduru Oya basin is confined to certain locations of the basin and most of the rain gauges are manually operated. Hence, disaster warning with respect to reservoir floods have become a challenging task due to the absence of real time, dense and continuous meteorological dataset. Further, several studies done for Deduru Oya river basin have revealed the constraints of conducting researches owing to the limitations of the existing state-owned weather station network in the basin (Lankadhikara, et.al, 2015; Katupotha, 2009; Wickramaarachchi, 2004).

3.2.2 System Architecture of the 4ONSE Open-Source Stations

All the 4ONSE stations were built on Arduino Mega 2560 open hardware platforms. In addition to the weather stations, several river gauges were built using the same Arduino Mega version to measure the water levels of the streams. Each station is powered by 30W solar panel and 12 V 35Ah rechargeable battery. Table 3 shows the sensors used for building the stations, measured parameters, units, accuracy and measuring range. These parameters were decided by consulting the stakeholders during the first policy workshop of the 4ONSE project, which was held on 21st of November 2016 at hotel Ozo, Colombo, Sri Lanka. All the sensors, except soil moisture sensors and the light sensors were purchased from the international market, while DS18B20 and BME280 sensors were purchased from both international and local market. When selecting sensors for the stations, cost, WMO standards, accuracy and durability are the main factors considered. Figures 10 (a) & (b) shows photo of a 4ONSE weather station and 4ONSE river gauge respectively.

Table 3: Sensors of the 4ONSE stations

Sensor	**Parameter**	**Unit**	**Accuracy**	**Measuring range**
DS18B20	Temperature	Degrees Celsius (℃)	±0.5℃	-10 to 85 ℃
BME280	Relative Humidity	Percentage (%)	±3%	0% - 100%
BME280	Barometric pressure	Hectopascals (hPa)	±1 hPa	300 – 1000 hPa
ZHIPU wind speed sensor	Wind speed	Meters per second (ms^{-1})	±1m/s	0-32.4m/s
Anemometer 485 wind direction sensor	Wind direction	Degrees	±3º	16 different directions and any angle values can be identified
6465 Davis AeroCone Rain Gauge with Mountable Base	Precipitation	Millimeters (mm)	0.2mm	N/A
BH1750 light sensor module	Light intensity	Lux (lx)	1.44 times, Sensor Out / Actual lx	(1-65535lx)
Soil moisture module	Soil moisture	Percentage (%)	±2%	0 to 22%
River gauge module MB7062 XL-MaxSonar-WR1 Ultrasonic sensor	Water Level	Meters	±0.5cm	0 - 10m

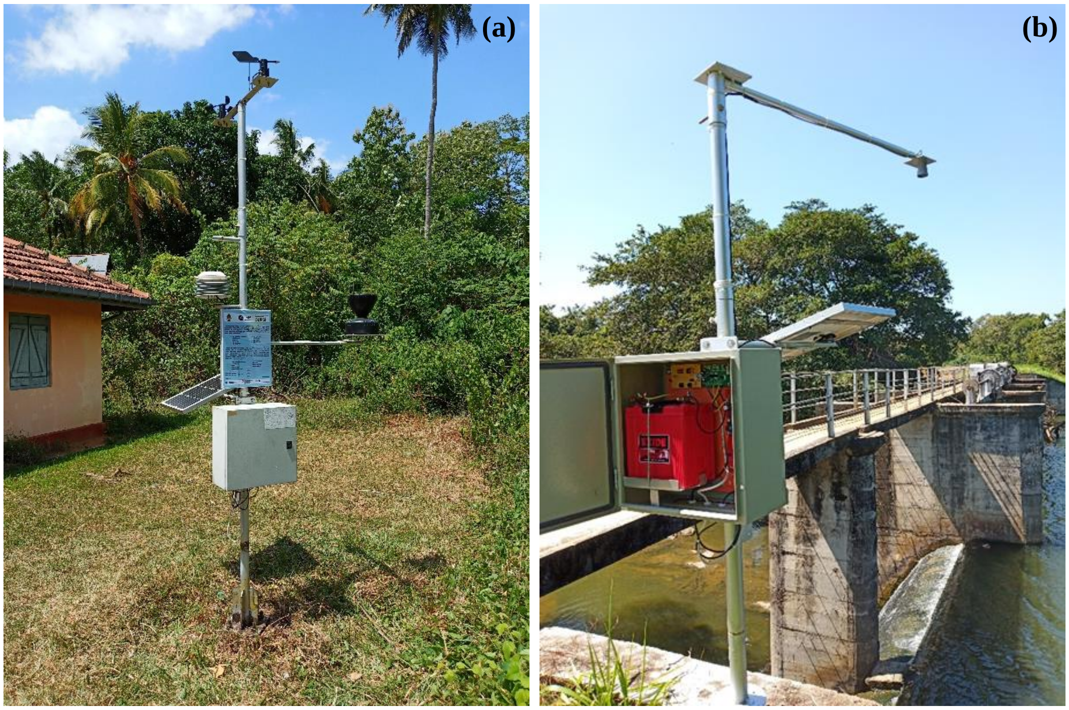


Figure 10: 4ONSE (a) weather station and (b) river gauge

Table 4 shows the cost incurred in building 4ONSE weather station and 4ONSE river gauge. Accordingly, the 4ONSE weather station and river gauge can be built at a cost about 766USD and 633USD respectively.

Table 4: Average cost incurred in building 4ONSE weather station and river gauge

4ONSE weather station	
Component	**Total cost (USD)**
Processing and controlling unit	51.63
Power supply unit	97.17
Sensors	195.26
Housing	194.12
Miscellaneous items*	153.33
Average shipping cost	74.86

Total cost to build 4ONSE weather station =	**USD 766.37**
=	**LKR 130,282.90**
4ONSE river gauge	
Component	**Total cost (USD)**
Processing and controlling unit	47.87
Power supply unit	95.76
Water level sensor	174.95
Housing	194.12
Miscellaneous items[a]	120.18
Average shipping cost	19.28
Total cost to build 4ONSE river gauge =	**USD 632.88**
=	**LKR 110,867.98**

Miscellaneous Items* - resistors, capacitors, transistors. ICs, heat Sink, wires, nut & bolt, sleeving, battery bracket & plate, Perspex sheet, laser cutting, SIM card, SD card, reset switch, buzzer, terminals, spacers, grease, cable tie, headers, soldering iron, I2C, etc.

Compared to professional weather stations in Meteorological Department, the cost of 4ONSE weather station is approximately 50 times lower. As shown in Table 5, when compared to other portable wireless weather stations available in the international market, the cost of the 4ONSE station is relatively low. However, the cost of the 4ONSE station can be further reduced by producing some of the sensors locally without importing them.

Table 5: Cost of the other portable wireless weather stations available in the international market

Cost of the station in USD (including shipping cost)			
4ONSE weather station	Vantage Pro Plus	MetPak RG	Rainwise PORTLOG 805-1018
766	1665	2734	5036

The communication side of the 4ONSE network has been built using the istSOS (www.istsos.org) open source software, which manages and dispatches observations of the stations as per the OGC-SOS (Open Geospatial Consortium-Sensor Observation Service) standard, which allows to manage the data in an interoperable way. The data are visualized in istSOS at a rate of 10 minutes. Figure 11, shows the screenshot of the istSOS application.

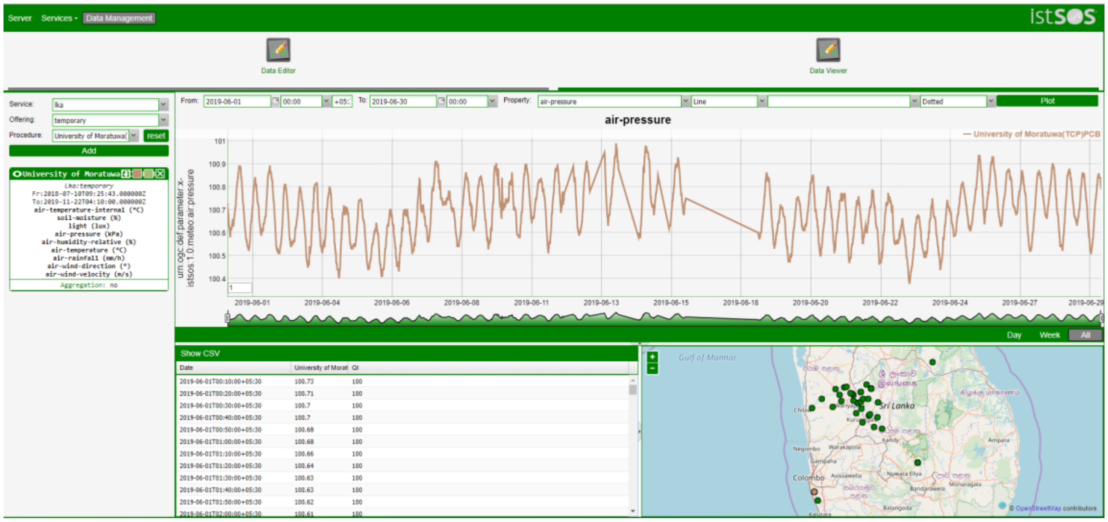


Figure 11: Screenshot of the istSOS application

3.2.3 Quality of the 4ONSE weather data

The quality of the 4ONSE weather stations' data were checked using some reference weather stations' data. For that, three Davis Vantage Pro2 stations were bought and deployed in both low-altitude and high-altitude areas where 4ONSE stations are located (Table 6).

Table 6: Locational information of 3 Davis Vantage Pro2 stations

No	Latitude and Longitude (decimal degrees)	Nearest 4ONSE station	Elevation (m)
1	7.4586, 80.3639	Lyceum adventure park	243 (high altitude)

2	7.6058, 80.0782	Hettipola Mahindodaya Maha Vidyalaya	48 (low altitude)
3	6.7969, 79.9018	Testing station located at University of Moratuwa	37 (low altitude)

Relative humidity, rainfall, temperature and air pressure are the parameters tested at daily and 10 minutes intervals. Figures 12 to 16 show data comparison results of aforementioned parameters. Table 7 shows the R-squared (coefficient of determination) values with respect to the comparison results represented in Figures 12 to 16. R-squared is a benchmark for fitness of observations, which ranges 0 - 1. If the R^2 is closer to 1, better the fitness between 4ONSE data and Davis Vantage Pro2 station's data. The formula to calculate the R squared is expressed in Equation 5.

$$R^2 = \{(\frac{1}{N}) \times \sum[(x_i - \bar{x}) \times (y_i - \bar{y})]/(\sigma_x \times \sigma_y)\}^2 \text{ Equation 5}$$

Where:

R^2 = Coefficient of determination

N = number of observations

x_i = x value for observation i

$\bar{x}$ = mean x value

y_i = y value for observation i

$\bar{y}$ = mean y value

σ_x = standard deviation of x

σ_y = standard deviation of y

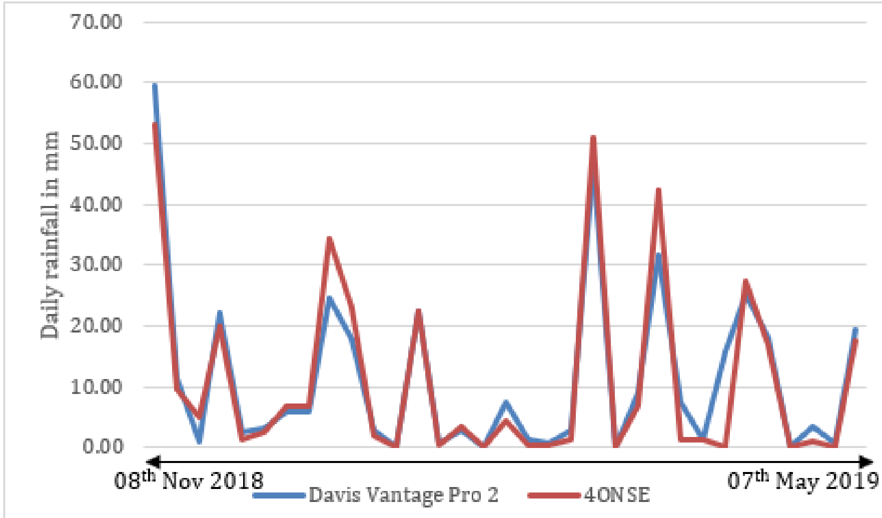


Figure 12: Comparison of rainfall at low altitude – daily interval

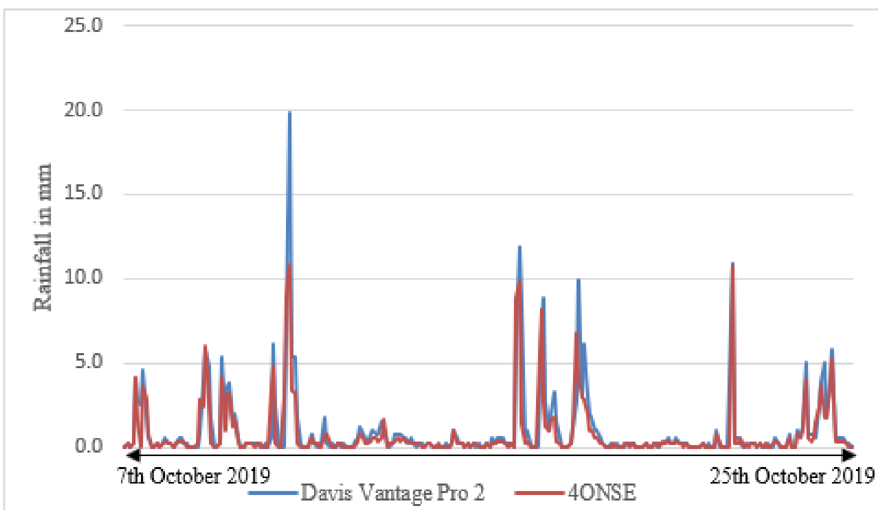


Figure 13: Comparison of rainfall at high altitude – 10 minutes interval

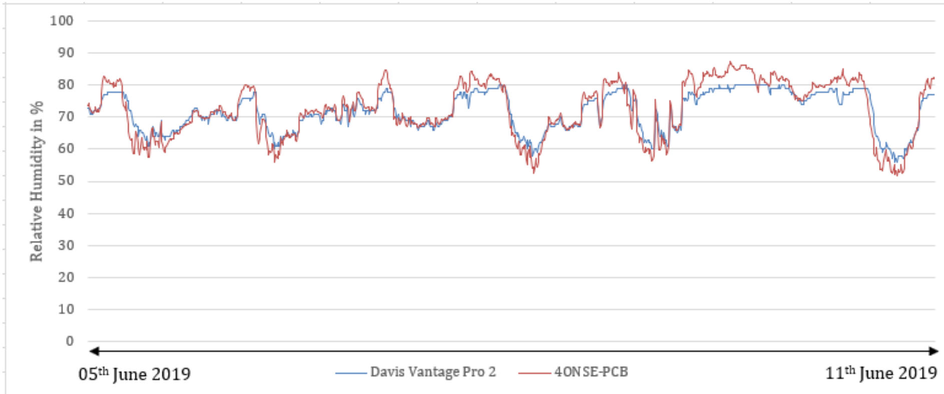


Figure 14: Comparison of relative humidity - 10 minutes interval

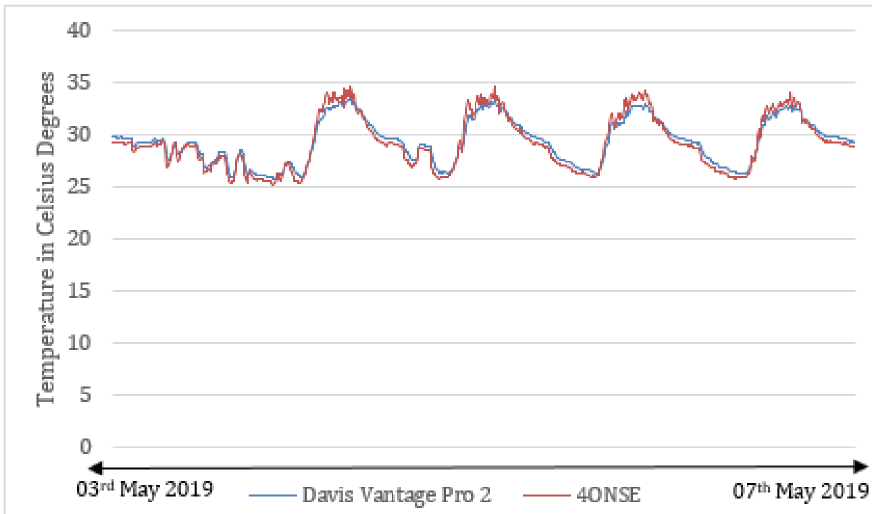


Figure 15: Comparison of temperature - 10 minutes interval

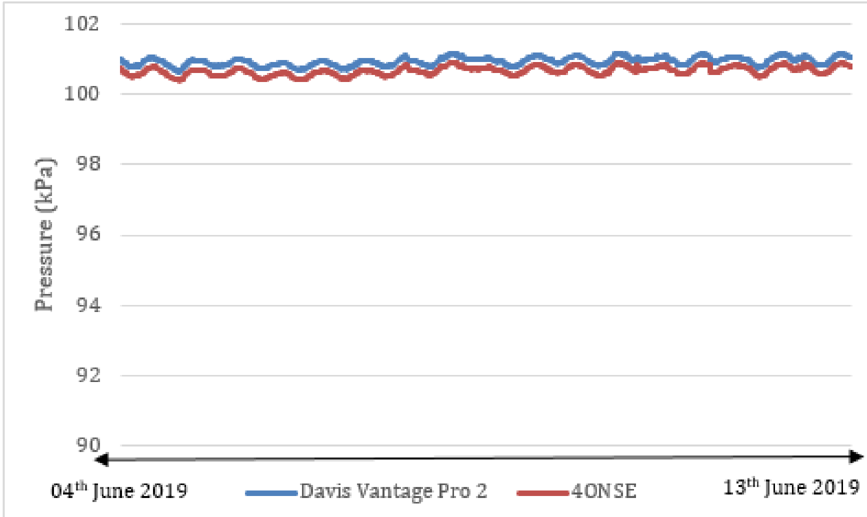


Figure 16: Comparison of air pressure - 10 minutes interval

As shown in Table 7, R-squared value of rainfall is relatively low compared to other weather parameters. In 4ONSE weather station, the rainfall is measured by 6465 Davis AeroCone Rain Gauge. As stated in the user manual of Davis rain collector, it has an error percentage of ±4% for rain rates up to 50mm/hour and ±5% for rain rates within the range of 50mm/hr to 100mm/hr (Davis Instruments, 2017). Therefore, during the intensive rainfall events, the rainfall measured by the rain collector is lower than the actual rainfall.

Table 7: R^2 values with reference to 4ONSE weather data comparison

Parameter	**Interval**	**Analysis period**	**R^2 value**
Temperature	10 minutes	3rd May 2019 - 7th May 2019	0.9678
	Daily	8th Nov 2018 - 7th May 2019	0.9921
Rainfall – Low altitude	10 minutes	8th Nov 2018 - 7th May 2019	0.7292
	Daily	8th Nov 2018 - 7th May 2019	0.7784
Rainfall – high altitude	10 minutes	7th Oct 2019 - 25th Oct 2019	0.7448
Relative humidity	10 minutes	5th June 2019 - 11th June 2019	0.9184
	Daily	5th June 2019 - 11th June 2019	0.9811
Air pressure	10 minutes	4th June 2019 - 13th June 2019	0.9771

	Daily	4^{th} June 2019 - 13^{th} June 2019	0.9929

3.2.4 Quality of the 4ONSE water level data

Two 4ONSE river gauges (river gauges at Amunugama bridge and Maspotha bridge) are installed at the places where the Irrigation Department's river gauges are located. Therefore, the water level data of those two places were compared with Irrigation Department's water level data. Figures 17 to 21 show comparison results of Amunugama and Maspotha river gauges at daily and 10 minutes interval. The 10 minutes interval water level data in istSOS were averaged to daily interval prior to the comparison. However, when viewing water level data in istSOS an unusual pattern has been observed. The river gauges are equipped with MB7062 Ultrasonic sensor to measure the water level. As indicated in Figure 17, a decreasing trend of water level can be observed especially during the day time (around 07:00 to 16:00). As expressed by the technical support specialists who sell MB7062 Ultrasonic sensor, the sensor has been affected by solar loading / heating. The sensor does speed of sound compensation based on temperature. If the sensor is directly in the sunlight, or making contact with something being heated by the sun, it can mess up the speed of sound calculations to cause a wavy pattern like in Figure 17. This issue doesn't create any impact for comparison of water level data at daily interval, as the data is averaged prior to the comparison. However, when conducting the hourly comparison, the data which have been affected by the solar loading (data during the period of 07:00 to 16:00) were removed prior to the comparison.

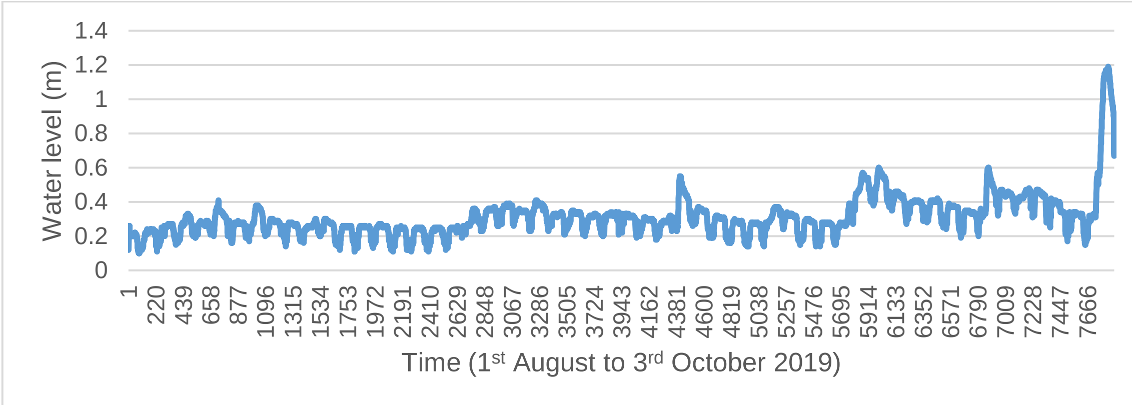


Figure 17: Measurements of the MB7062 Ultrasonic sensor at 10 minutes interval

As shown in Table 8, the R^2 values at both Amunugama and Maspotha river gauges at both daily and hourly interval are closer to 1 indicates, better fitness of 4ONSE river gauge data with Irrigation Department's river gauge data. However, both Amunugama and Maspotha river gauges have shown approximately 10cm and 15cm respectively difference of water level data, due to the small shift in the origin which starts from the river bedrock.

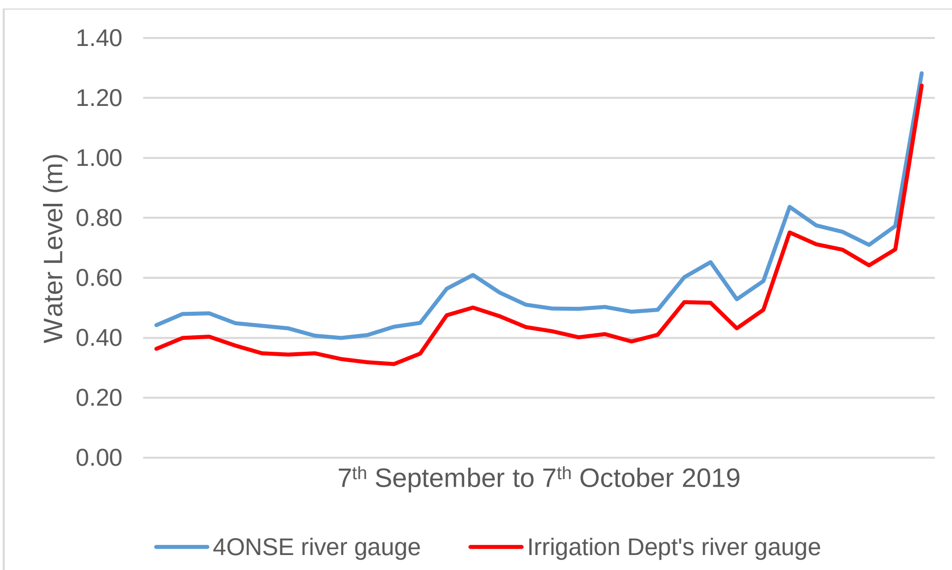


Figure 18: Comparison of water level data at Amunugama – daily interval

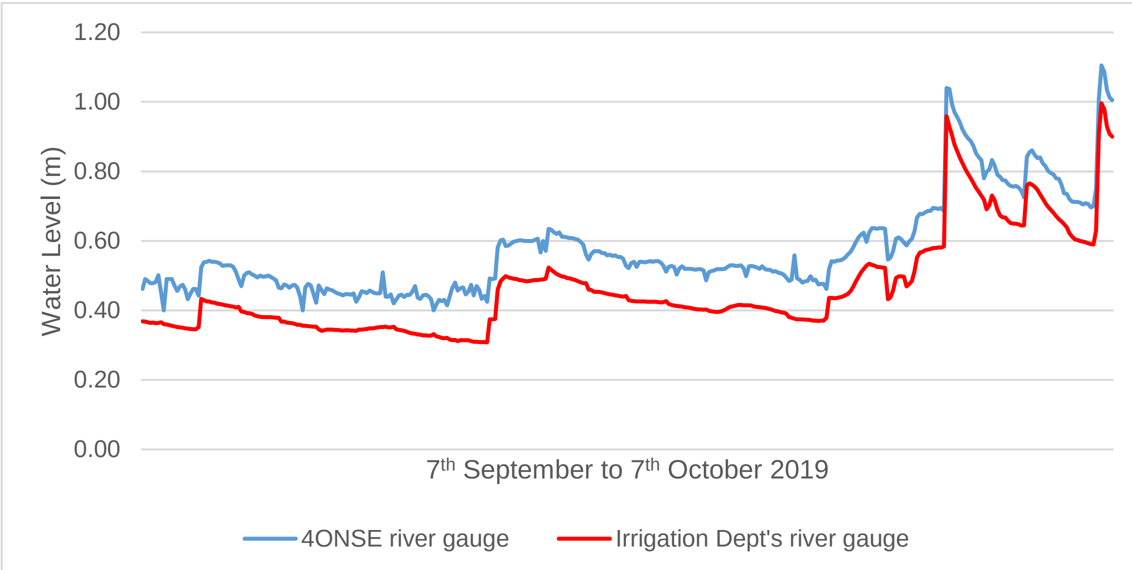


Figure 19: Comparison of water level data at Amunugama – 10 minutes interval

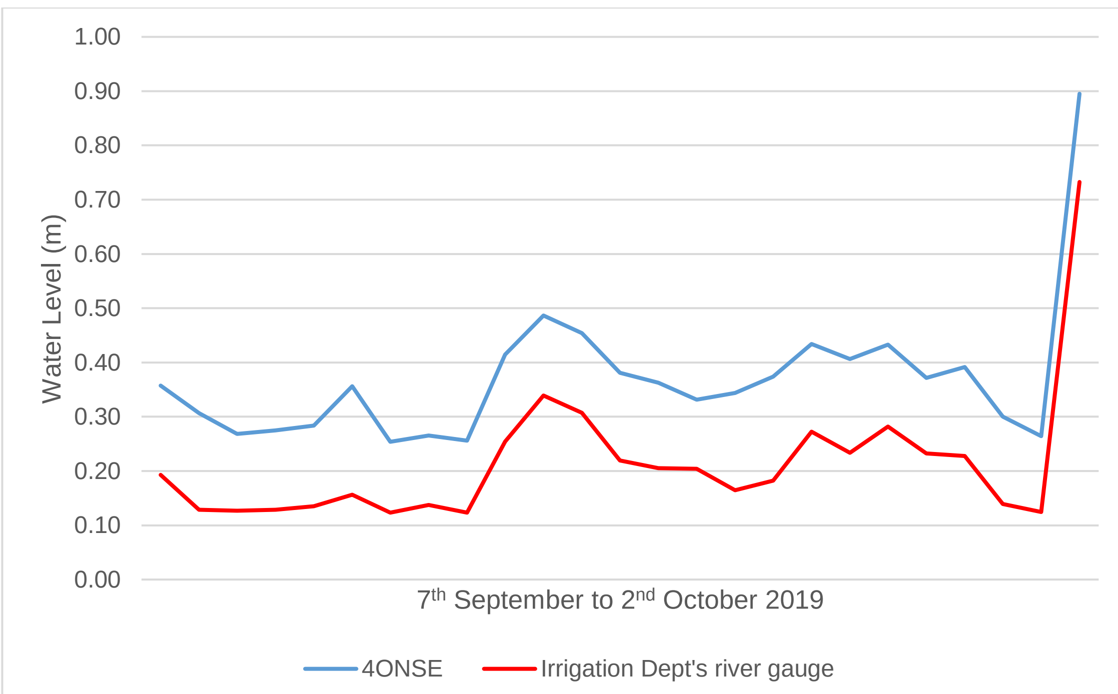


Figure 20: Comparison of water level data at Maspotha - daily interval

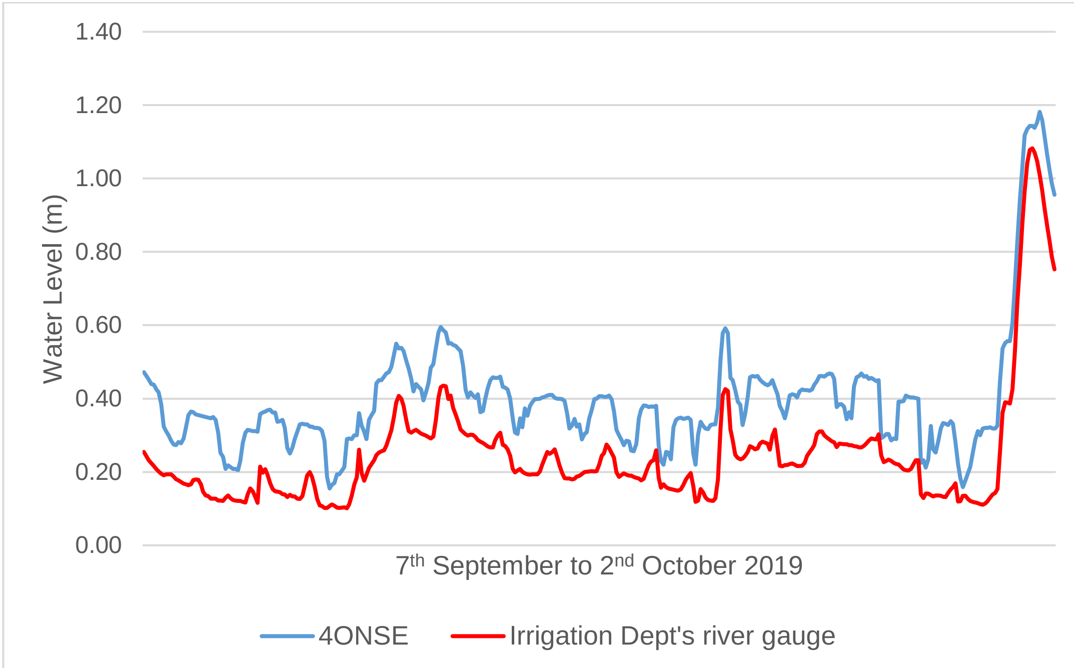


Figure 21: Comparison of water level data at Maspotha - 10 minutes interval

Table 8: R^2 values with reference to 4ONSE river gauge data comparison

Location	**Interval**	**Analysis period**	**R^2 value**
Amunugama bridge	10 minutes	7th September to 7th October 2019	0.9889
	Daily	7th September to 7th October 2019	0.9916
Maspotha bridge	10 minutes	7th September to 2nd October 2019	0.9781
	Daily	7th September to 2nd October 2019	0.9347

3.3 Case Study Area

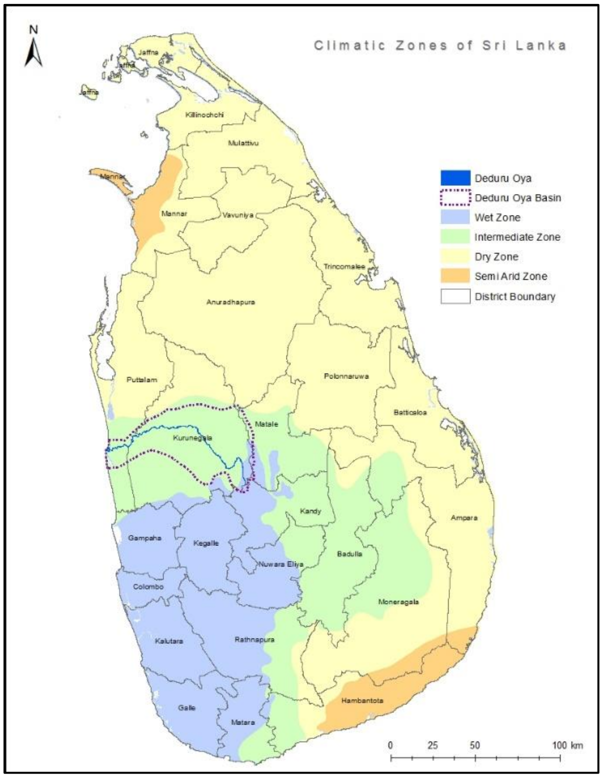


Figure 22: Climatic zones of Sri Lanka

The main objective of this study is to develop cost effective, open source-based tank management model to alleviate the reservoir flood risk in the Deduru Oya basin, which is considered as the 4th largest river basin of the country. The extent of the catchment is approximately 2687km^2 and the length of the main channel is 115km. Kutopotha (2009) has stated that the Deduru Oya basin is located in a very susceptible area due climate change. Figure 22 shows the main climatic zones and the location of Deduru Oya basin. As depicted there, the basin intersects with wet zone and intermediate zone. The major part of the basin (97%) belongs to Puttalam and Kurunegala districts and the remaining part (3%) belongs to Matale and Kandy districts. The upper basin receives nearly 2600mm of rainfall while the lower basin receives nearly 1100mm of rainfall. Presently, the Deduru Oya stream releases nearly 1600 MCM of water to the sea annually (Environmental Impact Assessment Report, 2003). Drought is the most predominant natural disaster existing in the basin. However, during the heavy rainfall seasons, the lower basin gets flooded as a result of opening reservoir gates. The very low catchment gradient of the main stream which is about 0.0089, influences for creating rapid floods in the downstream areas.

There are 8 major reservoirs and 2408 minor reservoirs in the basin (Figure 23). Most of them locate as cascades. The selected tank to develop the tank management model is Deduru Oya reservoir, which is the principal tank in the basin. The capacity of the tank is about 75,000,000m^3. Construction of dam across the Deduru Oya river was begun in 2006 and completed in 2014. The reservoir is located at the center of the basin and the four streams (Deduru Oya, Kimbulwana Oya, Hakwatuna Oya and Maguru Oya) which start from the central highlands merged at the reservoir. Due to its geographical location, Deduru Oya reservoir is a major determinant of controlling the floods in the lower basin.

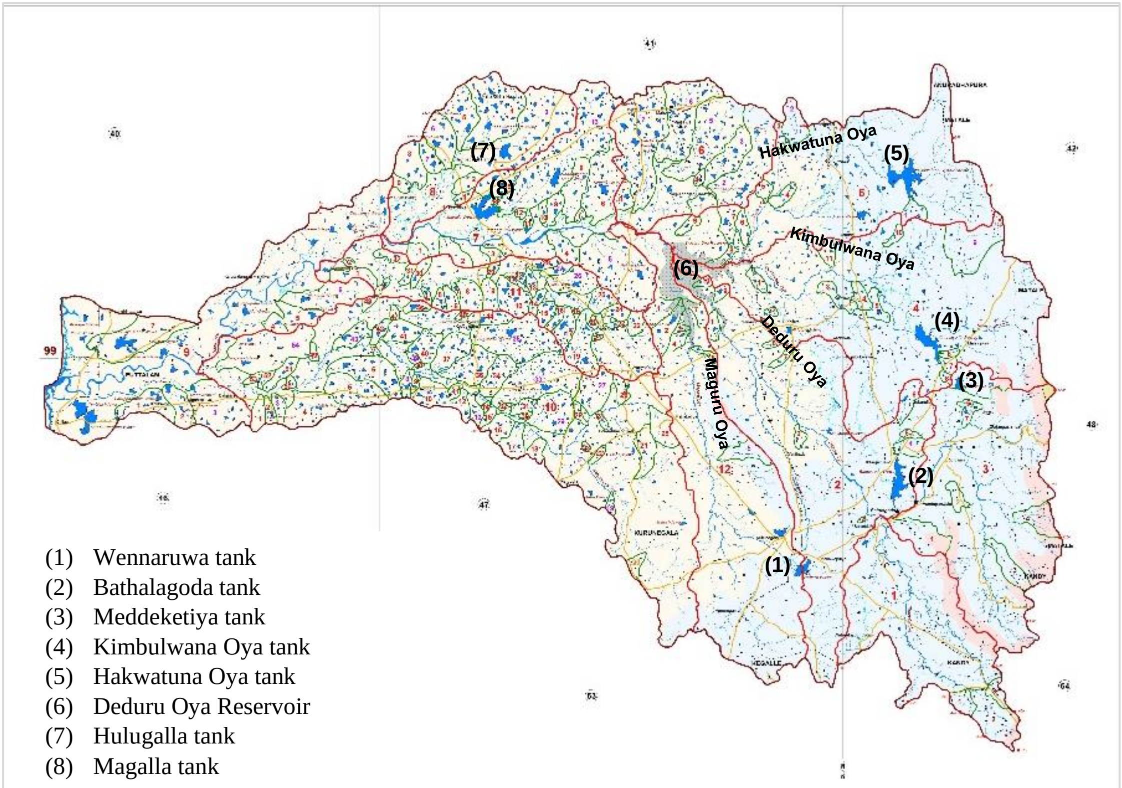


Figure 23: Deduru Oya basin and its major tanks

Source: Department of Agrarian Development

The existing hydro-meteorological network of Deduru Oya river basin has some weather stations and river gauges belong to Irrigation Department, Meteorological Department and Bathalagoda rice research institute. Figure 24 shows the regional automated weather stations belong to Meteorological Department which locate in and around the basin and the locations of manual rain gauges belong Irrigation Department. Accordingly, one regional station (Kurunegala) is located inside the basin and the other four regional stations (Puttalam, Mahailuppallma, Katugastota and Katunayake) are located outside the basin. In addition, 12 manually operating rain gauges are located inside the basin. The Bathalagoda rice research institute is also located inside the upper watershed of the basin.

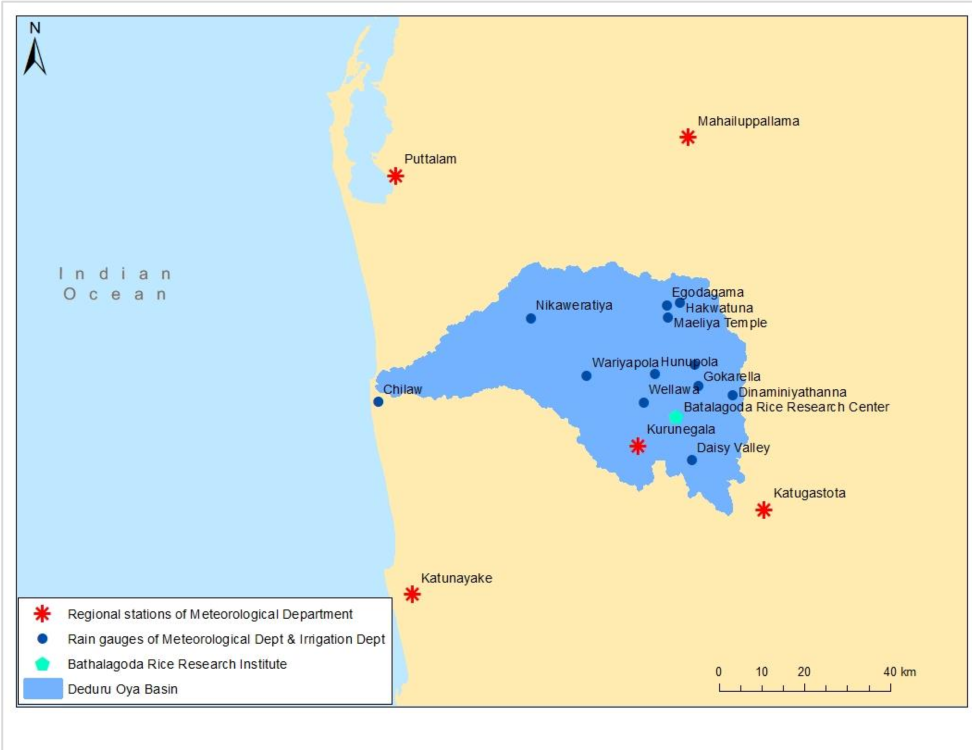


Figure 24: State-owned weather stations of Deduru Oya basin

The seasonal rainfall pattern of Sri Lanka commands in the periods of March - April & October – November as inter-monsoon, December – February as Northeast monsoon and May – September as Southwest monsoon (Figure 25). Out of the total annual rainfall, approximately 50% of the rainfall receives in the inter-monsoon, 35% receives in the Southwest monsoon and the balance 15% receives in the Northeast monsoon (Sampath, et.al, 2015). Figure 26 shows the monthly average rainfall of Deduru Oya basin calculated by averaging the long-term (1950 – 1999) rainfall values of Wariyapola, Chilaw, Batalagoda, Hakwatuna Oya, Magalla, Kurunegala and Nikaweratiya stations in the basin (Table 9). Accordingly, the basin receives highest rainfall during the periods of April to May and September to December.

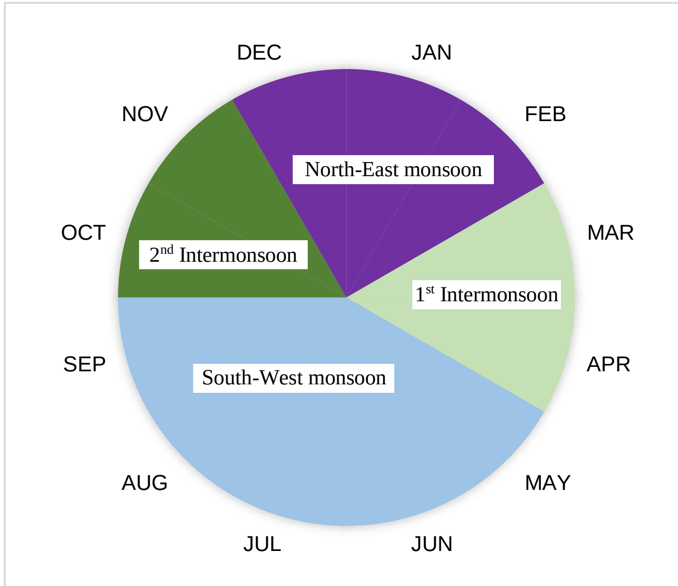


Figure 25: Monsoons and Inter-monsoons of Sri Lanka

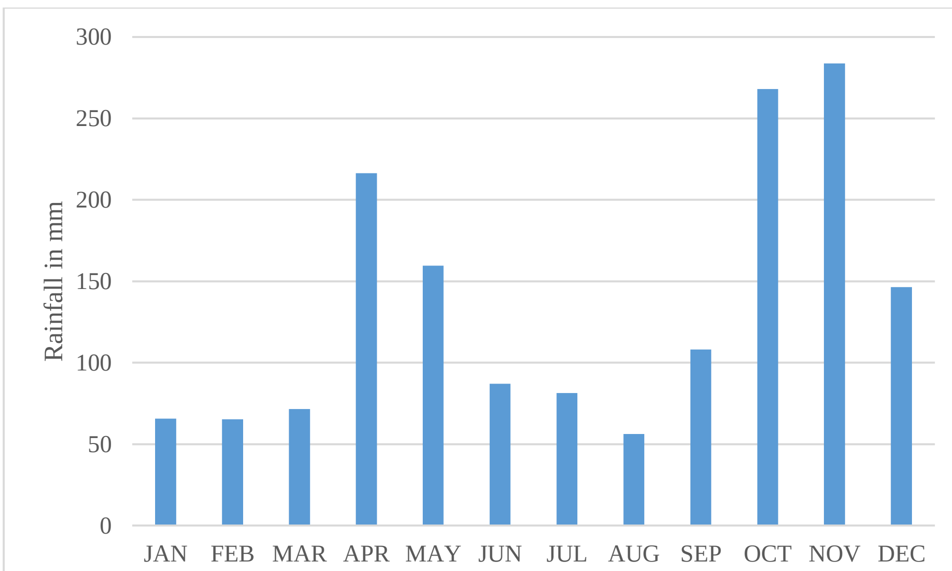


Figure 26: Monthly average rainfall of Deduru Oya basin

Source: Meteorological Department

Table 9: Monthly average rainfall of several stations in Deduru Oya basin

Location	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**NOV**	**DEC**
Wariyapola	122	89	72	212	135	112	113	85	127	288	308	236

Chilaw	39	49	94	232	193	69	70	25	92	277	260	125
Batalagoda	70	66	80	211	155	114	89	69	125	277	256	151
Hakwatuna Oya	66	63	19	218	178	36	81	86	107	210	314	175
Magalla	59	58	29	182	118	63	65	17	65	202	252	104
Kurunegala	59	73	124	262	211	160	112	85	156	359	334	132
Nikaweratiya	45	59	83	198	127	55	40	26	84	263	262	102

Source: Meteorological Department

During the rainy periods, the reservoir managers face difficulties in taking timely decision on deciding the magnitude of flood flows for the safe disposal of excess flow. In a nutshell, there are several reasons behind non-application of data of existing state-owned weather stations for reservoir management:

(1) Manual stations

As the upper basin mostly contains manually operating rain gauges, getting near-real-time data at sub-hourly or hourly interval is problematic.

(2) Offline data

Since the communication network of existing automated regional stations belong to Meteorological Department is malfunctioned at present, no station sends data to relevant offices.

(3) Uneven distribution of stations

As shown in Table 9, the precipitation is not uniformly distributed over the basin and the state-owned rain gauges are not uniformly distributed throughout the upper catchment (Figure 24) to account the sub-basin level rainfall measurements. Owing to this arrangement, estimating the sub-basin level runoff and the incoming flow to the Deduru Oya reservoir is difficult.

(4) Less or no dependency on using hydrological modelling tools for estimating the incoming flow to the reservoir due to cost of proprietary software, lack of expertise

knowledge, lack of trust on technological outputs and unavailability of reliable weather data.

(5) As shown in Figure 24, only the automated regional station at Kurunegala and weather devices at Bathalagoda rice research institute measure the other weather parameters such as wind speed, temperature, solar radiation and relative humidity, which requires to operate hydrological models. Hence, obtaining those parameters only from two stations are insufficient for generating an accurate representation for the entire watershed.

Currently, the reservoir managers release water from the reservoir once it comes to a particular level. This creates floods in the downstream areas due to the massive water flow receives to the downstream. The flood warnings are usually issued via radio and television, few hours prior to the flooding, sometimes after the opening of spill gates. In addition, the river water levels, status of the reservoirs and rainfall measurements of certain locations are daily issued by the Irrigation Department, through their website. Therefore, in the context of disaster risk reduction, the current practicing way of releasing water from the reservoir certainly leads for public outrage, which further strains reservoir operators to open spill gates during emergency periods. Accordingly, the flood risk in the downstream areas can be managed to a considerable level, if the reservoir mangers take prior judgments about the amount of water that should be pre-released at different time. The importance of near-real-time weather data for reservoir pre-release decisions have been pointed out by Valdes & Marco (1995) as the anticipated drawdowns are very seldom feasible unless flood forecasting is reliable for a sufficient lead time. As showed by them, the real time flood management have many advantages such as:

(1) Avoiding or reducing the losses to lives and damages to properties
(2) Possibility of mitigating dam failures
(3) Consideration of short time scale prevent use of tedious techniques on decision making
(4) Reducing the stress levels of dam operators to a considerable level

Table 10 shows some of the reported news items where the Deduru Oya sluice gates were opened as a result of the heavy showers. Accordingly, heavy showers for the Deduru Oya basin usually starts during the second inter-monsoonal period and persists until the North-East monsoon period. In some years, heavy rainfall also recorded in the month of May where South-West monsoon begins.

Table 10: Reported news items on heavy showers occurred in Deduru Oya basin

Date	**Link**
01st December 2019	https://www.newsfirst.lk/2019/12/01/extreme-weather-tanks-overflowing-electricity-outages-roads-blocked/
20th October 2019	https://www.newsradio.lk/local/rajanganaya-deduru-angamuwa-spill-gates-opened/
24th October 2018	http://www.dailymirror.lk/article/Two-spill-gates-of-Victoria-reservoir-opened-157311.html
05th October 2018	http://www.adaderana.lk/news.php?nid=50505
21st May 2018	http://www.colombopage.com/archive_18A/May21_1526923702CH.php
30 November 2017	https://www.newsfirst.lk/2017/11/30/extreme-weather-river-reservoir-water-levels-rise/
17th May 2016	https://www.pressreader.com/sri-lanka/daily-mirror-sri-lanka/20160517/282484297987157
3rd November 2015	http://www.dailymirror.lk/93799/sluice-gates-of-deduru-oya-opened
07th January 2015	https://www.news.lk/news/business/item/5570-reservoir-water-levels-rise-up-to-to-91
06th November 2014	https://www.newsfirst.lk/2014/11/06/deduru-oya-spill-gates-opened/

Figure 27 shows the discharge (m^3/s) at Amunugama, Maspotha and Ethiliyagala river gauge locations pertaining to Deduru Oya, Maguru Oya and the combined flow of Hakwatuna and Kimbulwana Oya respectively. The discharge volumes of year 2015, 2017 and 2018 were plotted in the graphs. The discharge volumes of year 2016 was not plotted in the graphs due to missing data. Thus, the graph further affirms the information about the periods, where Deduru Oya basin receives heavy showers and the discharge volume of Deduru Oya stream, compared to other 3 streams.

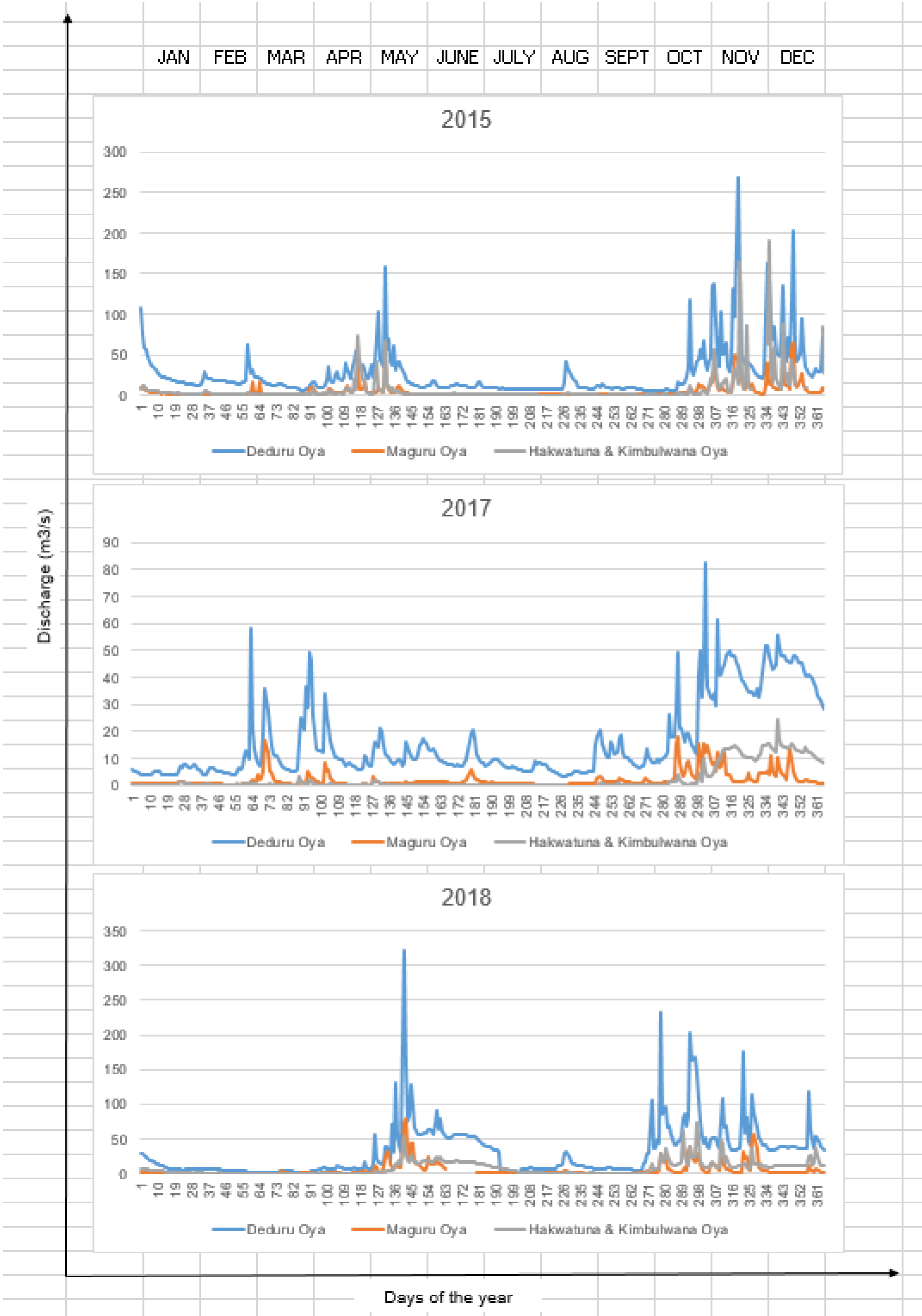


Figure 27: Discharge volumes measured at Amunugama, Maspotha and Ethiliyagala river gauges during 2015, 2017 & 2018

Source: Irrigation Department

3.4 Installation of 4ONSE sensor network in Deduru Oya basin

As illustrated in Figure 28, installation of weather stations in the basin was commenced on 6th March 2018 and completed on 21st July 2018. Installation of river gauges in the basin was commenced on 4th January 2019 and completed on 21st March 2019. Due to the calibrating difficulties, weather data during the period of 21st July 2018 to 4th January 2019 could not be utilized in the model, as the river gauges were not installed in that period. When testing the rainfall data, it was found that the rain collector is not properly calibrated to measure the rainfall. Accordingly, all the rain collectors in the basin were re-calibrated during the period of 17th to 23rd May 2019. Thus, the weather data after 1st June 2019 were used to run the model. The basin area had relatively dry period during the months of June & July in 2019 with some sporadic rainfall. The heavy rainfalls were occurred in the area after the month of July. Hence, the performance of the model for dry and wet weather conditions were tested with the 4ONSE weather data during the period of June-July and August-October respectively.

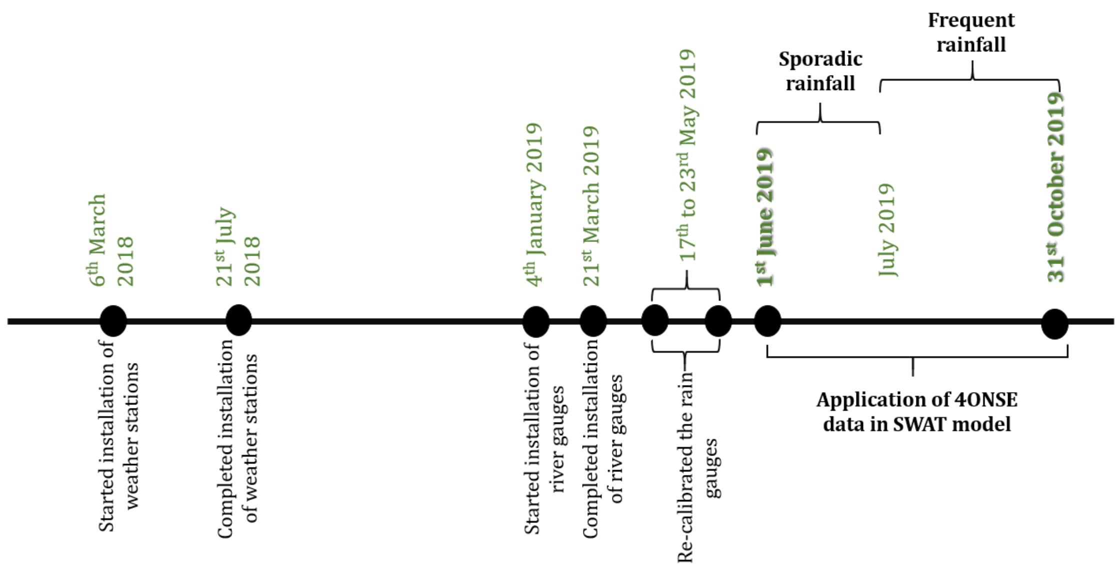


Figure 28: Timeline representing the 4ONSE deployment and application 4ONSE data in the model

CHAPTER 4
RESEARCH DESIGN

4.1 Overview

This chapter includes the overall research design with respect to the main research objective and five sub-objectives. Section 4.2 elaborates the method of applying combined open technologies to develop the hydrological model (sub-objective 1) and the process of selecting a suitable open source software for the model development (sub-objective 2). The approach of identifying optimum locations for 4ONSE weather stations and river gauges (sub-objective 3) has been discussed in section 4.3. Section 4.4 contains the approach of optimizing parameters for each sub-catchment at hourly and daily time intervals and for dry and wet periods (sub-objective 4). This section includes two subsections: the first sub-section includes the methodology of model development and the second sub-section includes the methodology of parameter optimization. The application of outputs of the hydrologic model for water pre-release decision making is explained under section 4.5 (sub-objective 5).

4.2 Application of combined open source technologies and selection of suitable open source hydrological modelling tool for reservoir flood control

This section elaborates the way of achieving sub-objectives 1 and 2. The first sub-objective is "to develop a hydrological model operated by combined open source technologies for reservoir flood control" and the second sub-objective is "to identify a suitable open source hydrological modelling tool to simulate the hydrological processes at regional scale".

This research's main intention is to develop a tank management model using hydrologic modelling tools to support reservoir flood control. Hence, open source tools relevant to hydrologic modelling and water resources management has been explored first. Out of the tools presented in Table 1, among the present scientific community, HEC-HMS and

SWAT are the most popular open-source tools for hydrologic modelling, while WEAP is the most popular open-source tool for water resources management. Accordingly, HEC-HMS, SWAT and WEAP were compared to identify the best tool for developing the model (Annexure 1). Out of them, SWAT (Soil and Water Assessment Tool) was finally selected to develop the hydrologic model. As a summary to Annexure 1, the main reasons behind selection of SWAT tool are as follows:

- SWAT is an existing, readily available and well documented water resources modelling tool.
- SWAT is a physically based semi-distributed model. Hence, the regional scale hydrological processes can easily represent in SWAT.
- SWAT's graphical user interface is available in 3 famous GIS software – ArcGIS, QGIS and MapWindow. In ArcGIS, QGIS and MapWindow, SWAT plugin / extension is available as ArcSWAT, QSWAT and MWSWAT respectively. Among them, QGIS and MapWindow are open-source GIS applications which can be freely downloaded.
- Availability of many supportive plugins and tools in QGIS and MapWindow for watershed delineation
- Availability of global gridded weather data, land use data and soil data in the SWAT website (https://swat.tamu.edu/)
- Availability of estimated parameter values for different land use and soil types.
- Availability of good manuals and user forums to assist in troubleshooting
- Availability of SWAT-CUP standalone program for parameter optimization (model calibration, validation and uncertainty assessment) and possibility of operating the model as a stochastic model through SWAT-CUP.
- As the SWAT operates as a continuous model, it doesn't require initial discharge like in most of the hydrological models (i.e. HEC-HMS) at every occasion when the model runs.

SWAT was developed by Dr Jeff Arnold for the USDA (United States Department of Agriculture) Agriculture Research Service. QGIS and Map Window are the two open-source GIS applications which support to run QSWAT and MWSWAT respectively. In this study, the model was developed using QSWAT plugin version 1.9 (Dile, et.al., 2016) (Figure 29). Out of different QGIS versions, QSWAT plugin successfully works in QGIS 2.6.1 Brighton version. The processing of input data such as DEM, land use and soil were performed using QGIS Brighton version. As shown in Figure 29, QSWAT has three main steps to perform: (1) Delineate watershed (2) Create HRUs (3) Edit inputs and run SWAT. The fourth step of "Visualization" is only useful for visualizing the stream flows graphically.

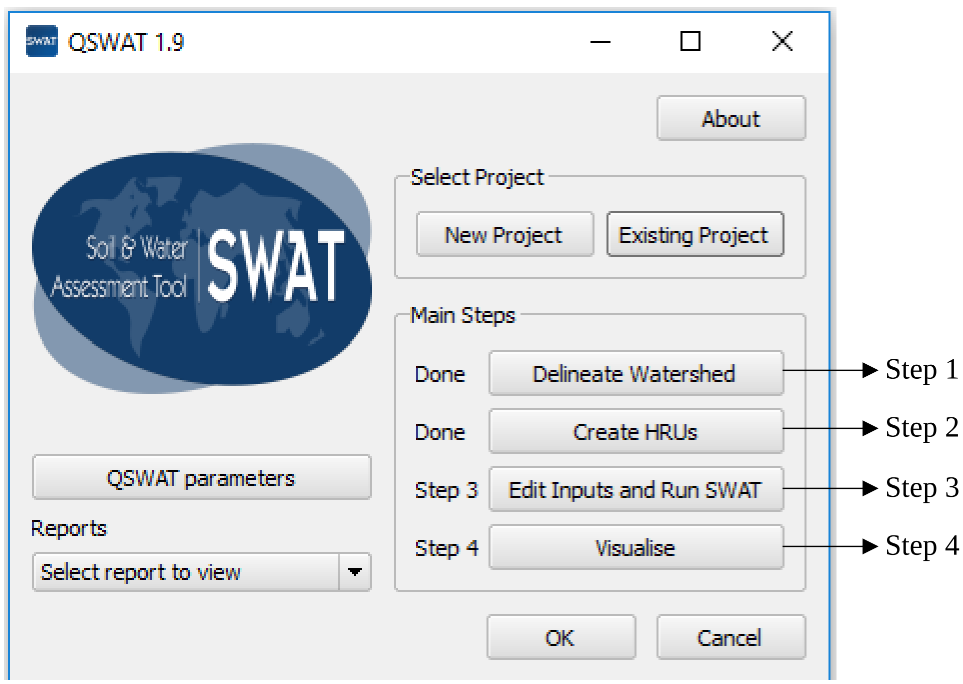


Figure 29: QSWAT version 1.9 interface

Identification of hydrological processes of the watershed is a prerequisite to perform model calibration. In hydrological models, processes refer to the main parts of the hydrological cycle: precipitation, evapotranspiration, runoff and infiltration. The dynamic processes of hydrological cycle can be represented by equations. SWAT uses the water balance equation given in Equation 6 to represent the soil water content at basin level:

$$SW_t = SW_0 + \sum_{i-1}^{t}(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}) \text{ Equation 6}$$

where SW_t is the final soil water content, SW_0 is the initial soil water content on day i, t is the time, R_{day} is the amount of precipitation on day i, Q_{surf} is the amount of surface runoff on day i, E_a is the amount of evapotranspiration on day i, w_{seep} is the amount of water entering the vadose zone from the soil profile on day i, and Q_{gw} is the amount of return flow on day i.

Weather, Hydrology, Sedimentation, Nutrient Cycle, Pesticide Dynamics, Management and Bacteria are the main aspects considered in SWAT model. For the purpose of this research, only the weather and hydrology aspects were taken into consideration. Table 11 shows the associated input variables and processes with respect to weather and hydrology aspects. Accordingly, the required weather inputs in the SWAT model are precipitation, air temperature (maximum and minimum), solar radiation, wind speed and relative humidity.

Table 11: Input variables / processes of weather and hydrology aspects of SWAT model

Aspect	**Input variables / Processes**
Weather	Precipitation Air temperature Solar radiation Wind speed Relative humidity
Hydrology	Canopy storage Infiltration Redistribution Evapotranspiration

	Lateral subsurface flow Surface runoff Ponds Tributary channels

SWAT model can be operated at yearly, monthly, daily and sub-daily time steps. Although SWAT literature database includes more than 1500 research papers on SWAT model, starting from 2016 to date, sub-daily applications remain limited (Duan, et.al, 2019; Jodar-Abellan, et.al, 2019; Li, et.al, 2018; Yu, et.al, 2018; Yang, et.al, 2016; Jang and Kim, 2016). The SWAT model cannot be directly used for simulating the flood levels. However, the sub-daily simulation capabilities embedded in the software allows analyst to estimate the stream flow at flood peaks, which is directly useful in real time flood management. SWAT's algorithms for infiltration, surface runoff, flow routing, impoundments, and lagging of surface runoff have been modified to allow flow simulations with a sub-daily time interval as small as one minute and, evapotranspiration, soil water contents, base flow, and lateral flow are estimated on a daily basis and distributed equally for each time step (Jeong, et.al, 2010). Therefore, it is adequate to use precipitation at sub-daily time step while the other input data (maximum and minimum temperature, relative humidity, solar radiation and wind speed) at daily time step.

The SWAT Editor tool (Figure 30) of SWAT reads the above input data and the database and allows to run the model. SWAT database includes some pre-determined parameter values with reference to land use types and soil types. In addition, it also contains some monthly statistical parameters with reference to several locations of the basin (Annexure 4). These statistics are used by the SWAT weather generator to estimate the missing weather data. Table 12 shows the models and methods used in the SWAT-weather generator to estimate the missing weather data.

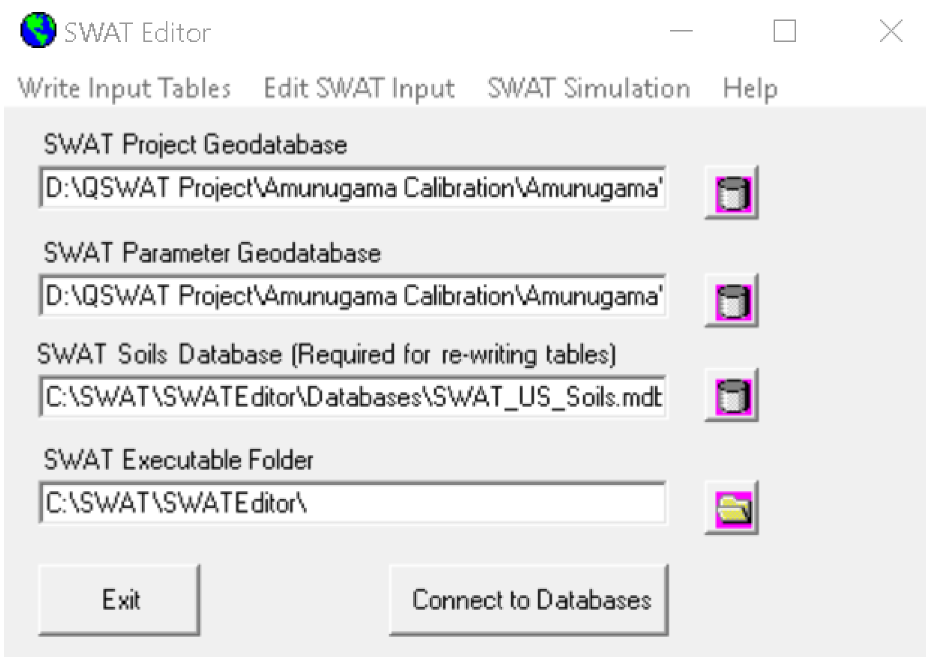


Figure 30: Interface of the SWAT-Editor Tool

Table 12: Models and methods used in SWAT weather generator

Climatic variable	**Model / Method**
Daily precipitation	Model developed by Nicks (1974)
Sub-daily precipitation	Double exponential function
Daily maximum and minimum air temperature	Normal distribution
Daily average relative humidity	Triangular distribution
Daily solar radiation	Normal distribution
Daily mean wind speed	Modified exponential equation

In this study, both daily and sub-daily (hourly) simulations were performed. Hence, both daily and hourly precipitation data have been used in the model. All the other weather data were applied in daily time step. As the 4ONSE weather stations measure the light intensity instead of solar radiation, SWAT's weather generator was used to estimate the required daily solar radiation values. Table 13 shows the applied data in the model for both daily and hourly simulations.

Table 13: Simulation type and required data

Simulation type	**Time interval**	**Required data**	**Source**
Daily simulation	Daily	Precipitation	4ONSE weather stations
	Daily	Minimum and maximum temperature	
	Daily	Relative humidity	
	Daily	Wind speed	
	Daily	Solar radiation	SWAT weather generator
Hourly simulation	Hourly	Precipitation	4ONSE weather stations
	Daily	Minimum and maximum temperature	
	Daily	Relative humidity	
	Daily	Wind speed	
	Daily	Solar radiation	SWAT weather generator

The istSOS open source application was used to download 4ONSE weather stations' data. The istSOS itself has an automatic data validation procedure to identify the quality near-real-time data. This validation procedure assigns a code for each data after the validation test (Table 14). When applying data for the hydrological model, the data with code 100 and 110 were only used.

Table 14: istSOS quality indexes

Code	**Name**	**Description**
-100	Aggregation no data	No values are present for this aggregation interval
0	Outbound	Gross error

100	Raw	The format is correct
110	Acceptable	The value is acceptable for the observed property
200	Reasonable	The value is in a reasonable range for that observed property and station
300	Timely coherent	The value is coherent with time-series
400	Spatially coherent	The value is coherent with close by observations
500	Manually adjusted	The value has been manually corrected
600	Correct	The value has not been modified and is correct

All the weather data which directly applied from 4ONSE weather stations need to be stored in txt format. The locational information of the stations (ID, name of the station, latitude (decimal degrees), longitude (decimal degrees), elevation (meters)) should be stored in separate txt files related to four parameters (Figure 31). Figure 32 and Figure 33 shows an example for pcp.txt and tmp.txt file which includes the information about the locations which measure precipitation and temperature respectively. In here, bat, ram, par and sb are the short names given for corresponding 4ONSE weather stations located at Batalagoda Rice Research Institute, Rambadagalla Central College, Paragahadeniya National College and SB Herath National School. Since both temperature and precipitation data are obtained from a single station, the latitude, longitude and elevation values of both files are same. p_bat, p_ram, p_par and p_sb are names of the files which include precipitation data, while t_bat, t_ram, t_par and t_sb are names of the files which include maximum and minimum temperature data related to aforementioned four 4ONSE stations. rh and wind txt files also have relative humidity and wind data in a similar format as described above.

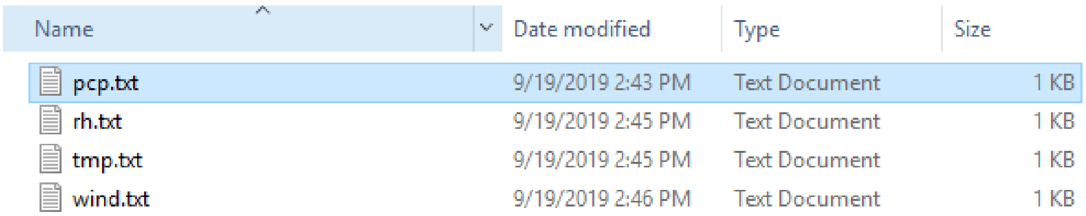


Figure 31: Txt files of four weather parameters

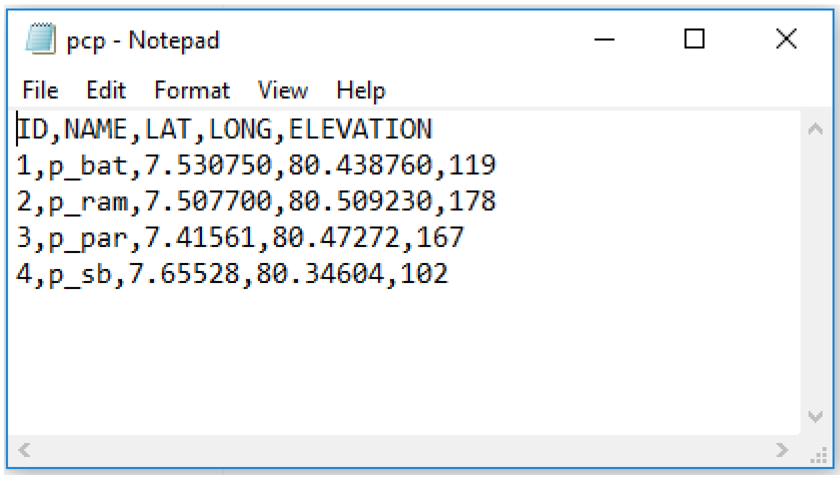


Figure 32: An example for pcp.txt file

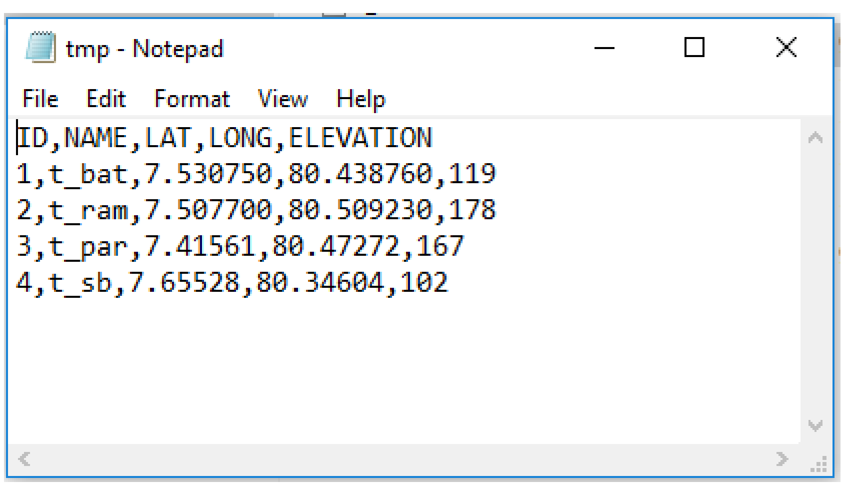


Figure 33: An example for tmp.txt file

Since SWAT is a continuous-process model, it requires model warm-up period of at least more than one year to reach the soil-moisture condition into a steady state. As depicted in Figure 28, obtaining an accurate and continuous dataset to optimize the model parameters were started from 1st June 2019 onwards. Therefore, the available continuous data collected by the 4ONSE network was inadequate to assign at least 2 years warm-up period in the model. SWAT-weather generator has been used to estimate the data required for the 2 years warm-up period and to estimate the other missing data of the 4ONSE stations. If any data record of weather txt files contains "-99" value, the model commands SWAT-weather generator to fill using SWAT weather generator. As shown in Figure 28, 4ONSE weather data have been applied for the period of 1st June 2019 to 31st October 2019. Accordingly, "-99" value was applied for all the records prior to 1st June 2019. This study can be considered as the first application of SWAT model, where the SWAT weather generator has been used to produce the sub-basin level data required for the warm-up period.

Figures 34 (a) and (b) show some example txt files representing the hourly precipitation and daily temperature (maximum and minimum) data of weather station located at Batalagoda Rice Research Institute. As shown in Figure 34 (a), the first row indicates the starting date (year, month, day) and time interval (in minutes) of the Batalagoda station's precipitation records. Since the model requires the temperature data in daily time-step, the txt file represented in Figure 34 (b) does not need time interval to mention at the first row.

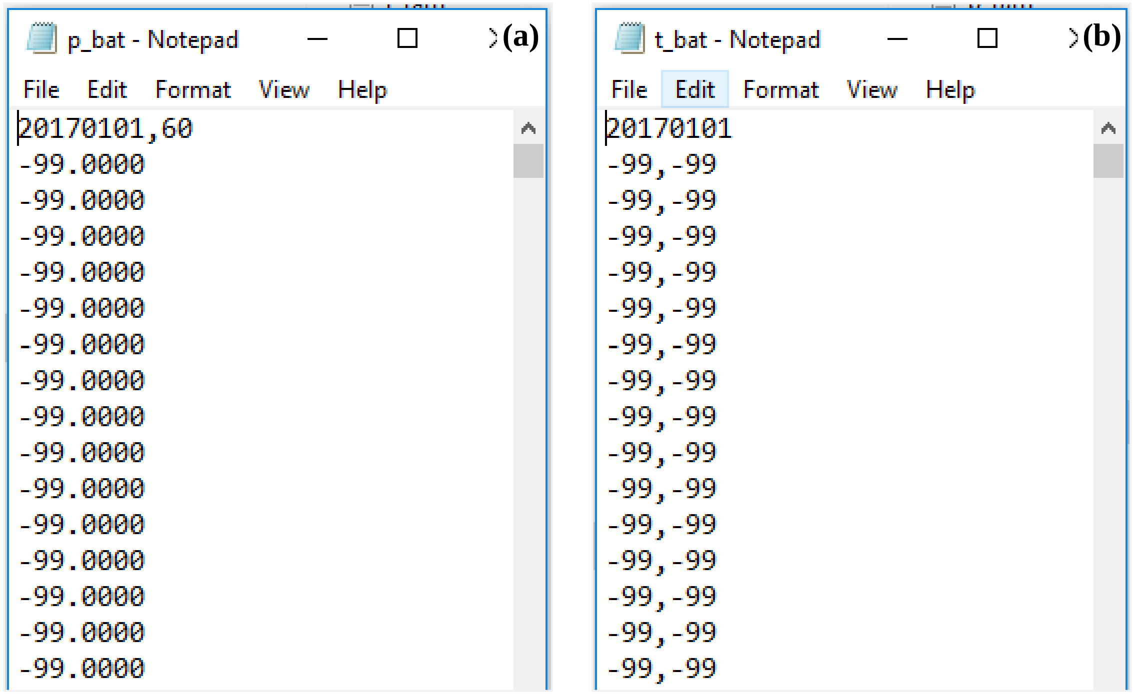


Figure 34: (a) Format of the hourly precipitation file of Batalagoda station (b) Format of the temperature file of Batalgoda station

The regionalization, parameterization, calibration, validation and uncertainty assessment of the model was done through SWAT-CUP (SWAT-Calibration and Uncertainty Procedures) standalone program (Figure 35).

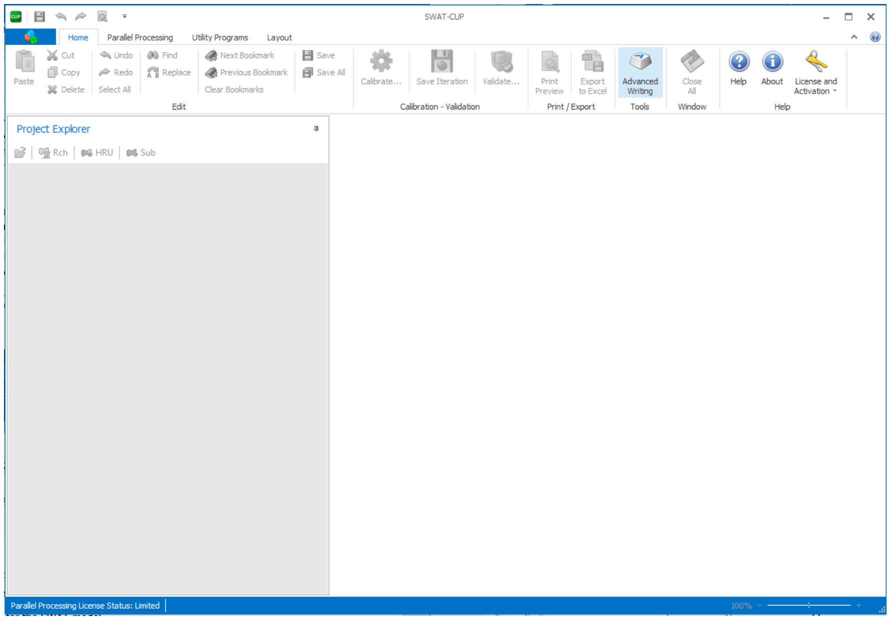
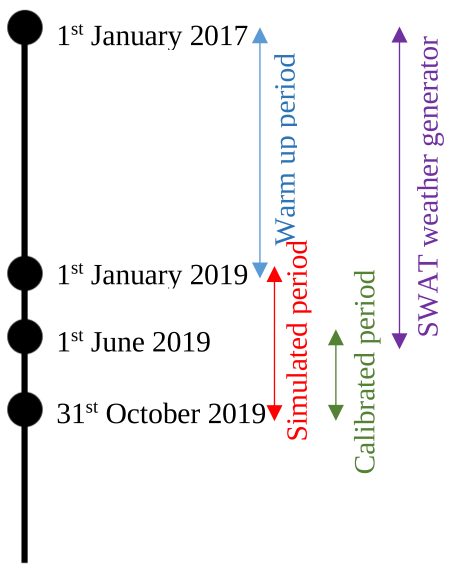
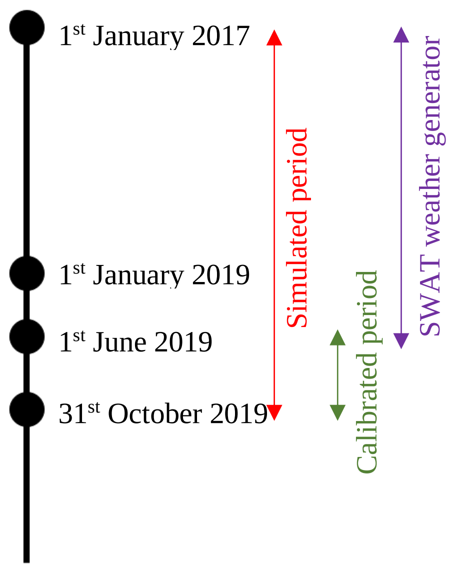
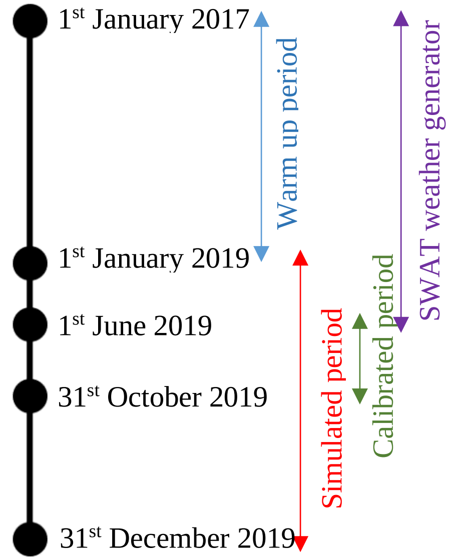


Figure 35: SWAT-CUP 5.2.1 interface

Several test runs were done prior to the identification of error free model configuration to run and calibrate the model (Table 15). In all three test runs, 4ONSE data was applied for the period of 1st June 2019 to 31st October 2019. SWAT's weather generator has been used to estimate the missing data prior to 1st June 2019. In the 1st test run and 3rd test run, 2 years (2017 – 2019) of warm up period was applied and the 2nd test run was performed without any warm-up period. During the 1st test run, an error was occurred during the process of calibrating the model through SWAT-CUP. The 2nd test run produced a low discharge when running the model without warm-up period. Accordingly, the 3rd test run was selected as the ideal configuration to run the model, as it did not produce any errors. The difference of 3rd test run than to 1st test run is, in the 3rd test run, simulated period was extended until 31st December 2019, by letting the SWAT weather generator to produce weather data after 31st October 2019.

Table 15: Tested model configurations

1st Test Run	**2nd Test Run**	**3rd Test Run**
		
Result: An error was occurred during the calibration process of the model	**Result:** When running the model without any warm-up period gave low flows	**Result:** The model was run and calibrated without any errors

As a summary, Table 16 lists all the open-source tools used in this research, their main function and the link to download them.

Table 16: Open-source tools used in this research

Open-source tool	**Function**	**Link**
QGIS Brighton Version	To process vector and raster input data GIS interface to run the SWAT model	http://qgis.org/downloads/QGIS-OSGeo4W-2.6.1-1-Setup-x86.exe
QSWAT	SWAT plugin used to run the model in QGIS software	https://swat.tamu.edu/software/qswat/
SWAT-Editor	Reading project databases Generating missing weather data Executing SWAT run Calibrating the model	https://swat.tamu.edu/software/swat-editor/
SWAT-CUP	Identifying the dominant parameters & their ranges Calibrating the model Validating the model	https://www.2w2e.com/home/SwatCup
istSOS	To view and download the data of 4ONSE stations	https://geoservice.ist.supsi.ch/4onse/admin/

4.3 An approach to determine the optimum locations for open-source weather station network for hydrological modelling

This section elaborates the methodology related to 3rd sub-objective of "identifying optimum locations for open-source weather station network for hydrological modelling".

As explained in section 2.9, although World Meteorological Organization (WMO) recommends minimum station densities for different physiographic areas with some detailed standards on siting and calibrating the instruments used in the stations, they do not provide any guideline on selecting optimum locations to deploy the stations. The recommended densities are extremely insufficient, since some of the most widely used parameters in hydrological modelling, such as precipitation can vary greatly with small distances. Moreover, different areal averaging methods have their own limitations when employing them to estimate missing rainfall data. In the presence of renewable electricity generation technologies and cellular communication technologies, directly connecting to the electricity grid or telecommunication network is unnecessary. Therefore, optimum locations for the 4ONSE weather stations have been identified by applying Geostatistical tools and Shannon's entropy method. However, this approach requires some historical rainfall data of the basin to calculate the spatial distribution of rainfall entropy values.

The runoff is simulated in SWAT model at sub-basin level and the required weather data to run the model is obtained from the station which locates closer to the sub-basin's centroid. This is a one reason behind why the 4ONSE deployment was done at sub-basin level. For that, the watershed and sub-basin boundaries were delineated first. As the watershed and sub-basin boundary delineation process usually takes into account the topographic condition, sub-basin level deployment was considered as the best way to deploy the 4ONSE stations, owing to the constraints in the areal averaging of rainfall.

The word 'watershed' is used interchangeably with drainage basin, basin, sink or catchment. It is an area of land that drains all the storm water runoff and stream flow to a common point called as 'outlet'. The outlet usually locates at the remote point of the watershed. It can be an ocean, a reservoir, a lake, a lagoon or a bay. The boundary of the watershed is usually formed by mountain ridge. As illustrated in Figure 36, sub-basins, stream network, watershed boundary, drainage divides and outlets are the main components of a watershed. Sub-basin is the basic unit of the watershed based on the size. A collection of sub-basins forms the watershed.

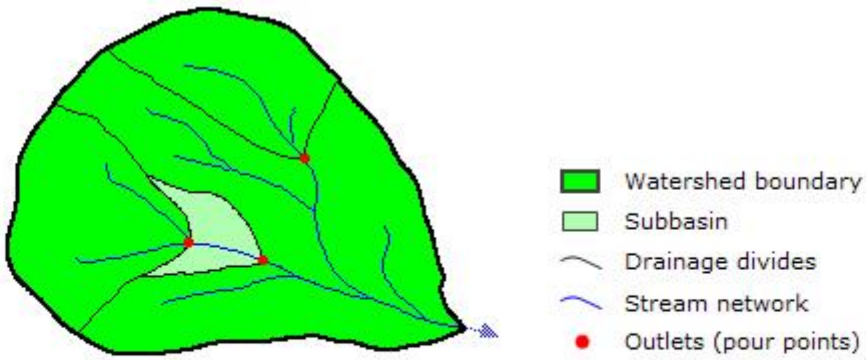


Figure 36: Components of a watershed

Source: ESRI

Most of the hydrological models, even SWAT, start with watershed delineation. Watershed delineation is important to identify the exact area where the precipitation can influence and to understand the sequence of storm water flow starting from upper watershed to outlet. Luo, et.al. (2011) highlighted the importance of water delineation, as it supports to bring reliable results with respect to modelling surface runoff, sediments and water quality.

Generally, watershed boundaries are based on elevation. In the past, watershed boundaries have been identified and drawn manually using topographic maps. The availability of Geographic Information Systems and digital elevation data called as Digital Elevation Models (DEMs) have now enabled users to generate watershed and sub-basin boundaries automatically. The watershed delineation has been done using the QSWAT plugin. Two methods are available in SWAT model for watershed delineation: (1) based on the Digital Elevation Model (DEM) (automatic delineation) (2) manual delineation (pre-defined method). In this research, DEM based method was used to delineate the watershed (Figure 37). Table 17 shows the required data to delineate the watershed and sub-basin boundaries.

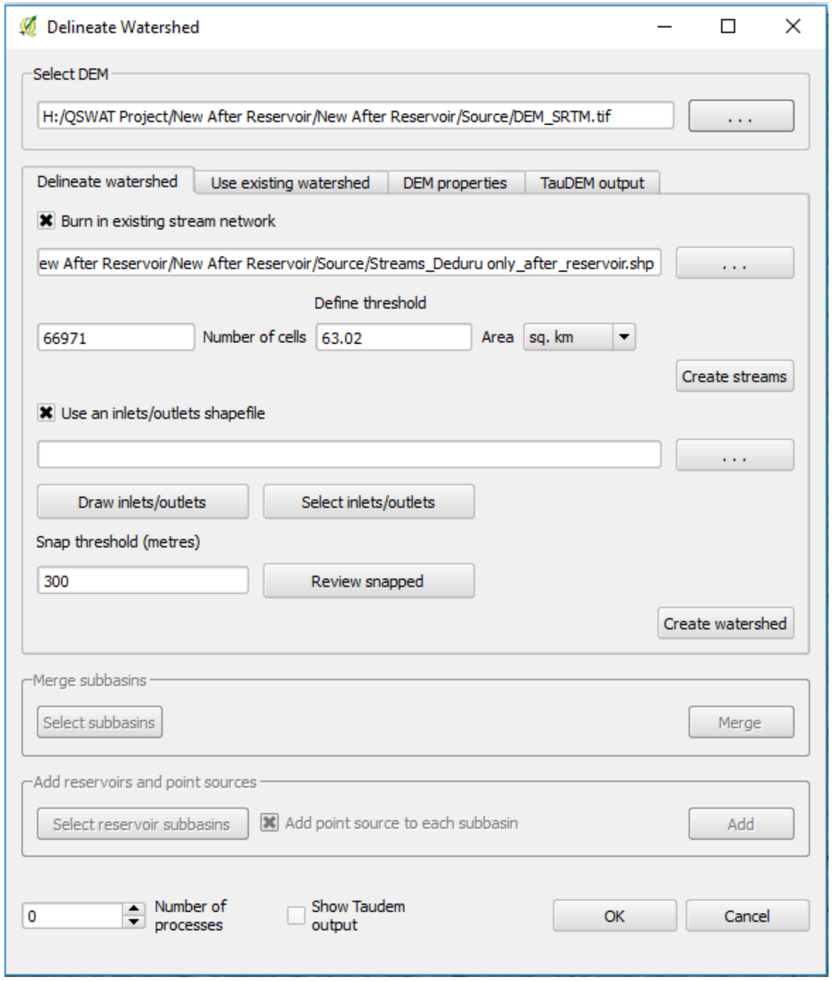


Figure 37: DEM based watershed delineation in QSWAT

Table 17: Required data to delineate the watershed and sub-basin boundaries

Input Data	**Source & link**	**Resolution**
Digital Elevation Model (DEM)	Shuttle Radar Topography Mission (SRTM) https://earthexplorer.usgs.gov/	1 arc second (approximately 30m)
Stream Network	Produced by the Author	1:10,000

Digital Elevation Model (DEM) and the digitized stream network was used to delineate the boundary of the entire Deduru Oya basin and the other sub-basins. The Digital Elevation Model (DEM) was downloaded from the USGS Earth Explorer website. The DEM was originally come in Geographic Coordinate System. Hence, it was projected to Universal Transverse Mercator (UTM) coordinate system. Next, the projected DEM was clipped to the extent of the study area. The two cross sections depicted in Figures 39 and 40 show the variation of topography over Deduru Oya basin.

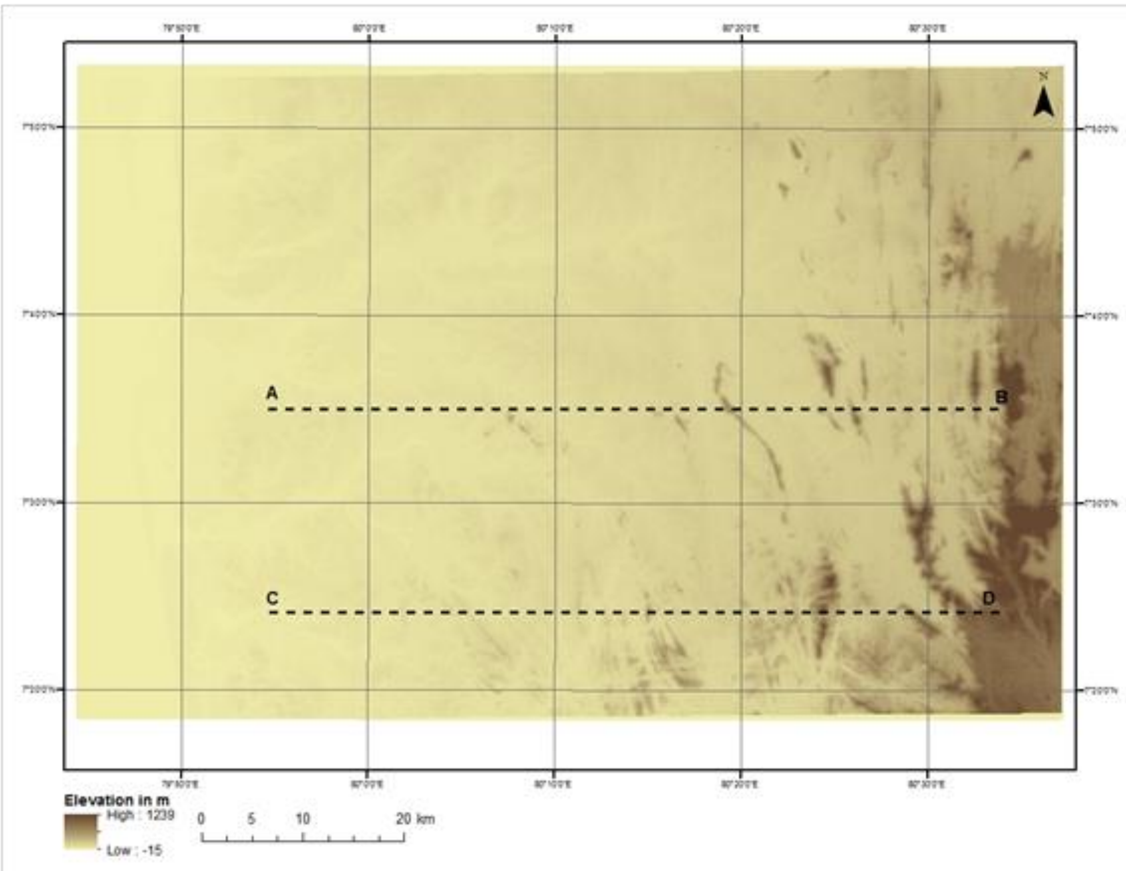


Figure 38: SRTM DEM representing the study area

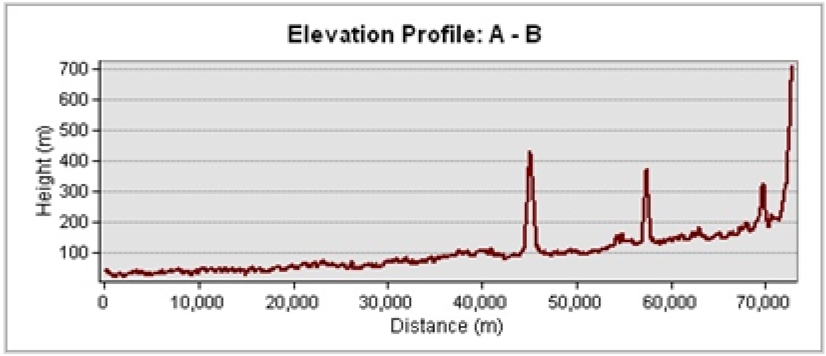


Figure 39: Elevation profile: A-B

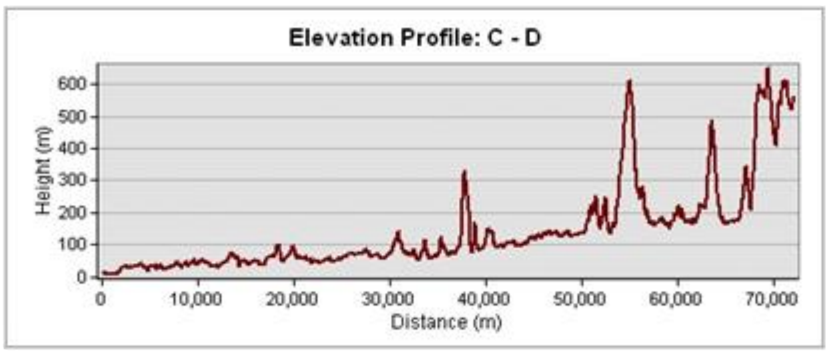


Figure 40: Elevation profile: C-D

The entire stream network was digitized for the purpose of boundary delineation. Figure 41 shows the stream network and the major tanks of the study area.

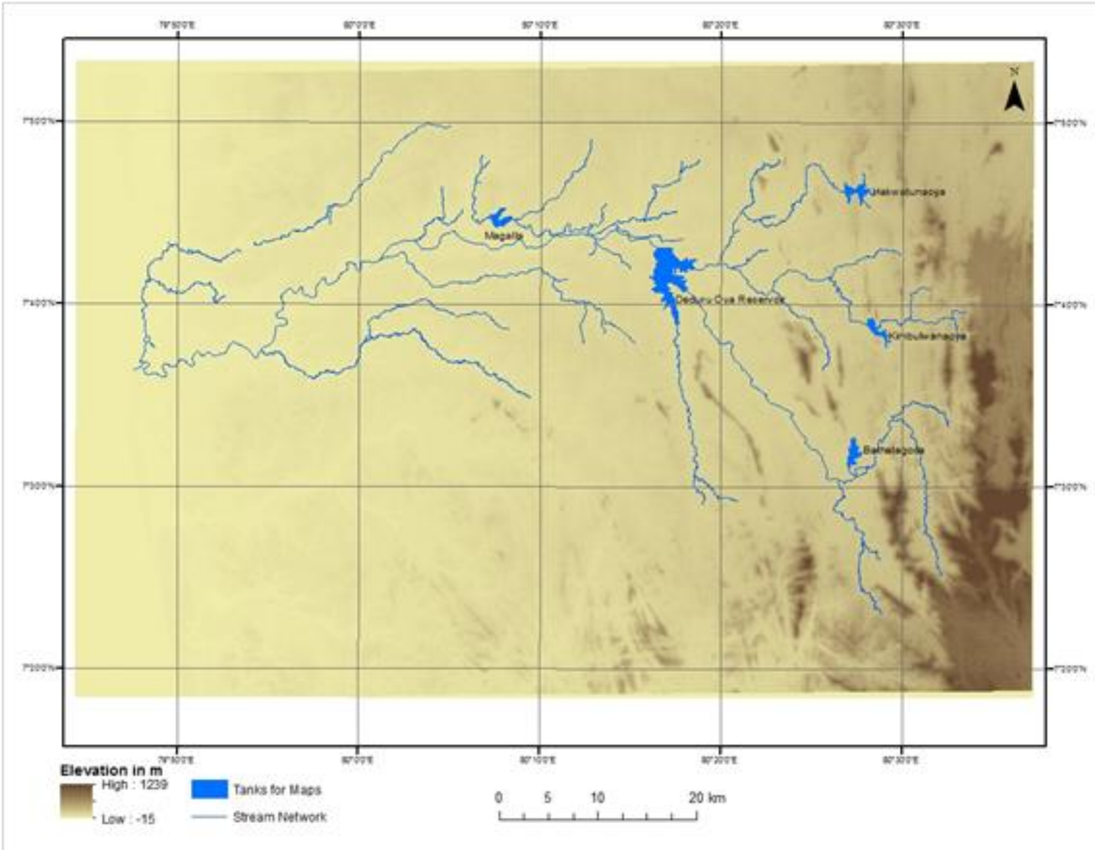


Figure 41: Stream network and major tanks of the study area

First the DEM was uploaded into the SWAT model. Then using the option “Burn in existing stream network”, the digital stream network can trace on the DEM layer. “Burn in” algorithm helps to locate stream network correctly on the DEM by reducing the elevation of the cells corresponding to the stream network by little value. The stream network layer which used for this process should be a continuous set of stream lines, in which lines should be drawn through tanks, lakes and ponds. The isolated lines should be removed prior to the use them in the model. Further, the stream network should be digitized in a manner in which only one stream segment is shown in between two confluences. After performing the “Burn-in” function the next step is to delineate the stream network specifying a threshold value. The default value in SWAT model is 1% from the entire drainage area. Even tiny tributaries can be visualized for small threshold value, while only the main stream network can be visualized for larger threshold values. Any watershed modelling tool can generate large number of sub-basins in presence of tiny tributaries in the stream network. The model becomes complex and increases the executing time when there are more sub-basins. Hence different threshold values ranging from 0.25% to 3% were applied to choose the ideal threshold value for the basin. The next step in the SWAT model is to locate the outlet of the basin. The outlet of the river mouth was located at the place, where the river enters the ocean.

After locating the outlet, "Review snapped" option was selected to check whether they are correctly positioned on the delineated stream network. To avoid the very small sub-basin, the small sub-basins which have land area less than 25% of the mean area were selected and merged. In the merging process, sub-basins which have an outlet or reservoir were ignored. Then the three reservoir sub-basin were introduced into the model selecting the "Select reservoir sub-basins" option. In a nutshell, the process of watershed and sub-basin boundary delineation with QSWAT is illustrated in Figure 42.

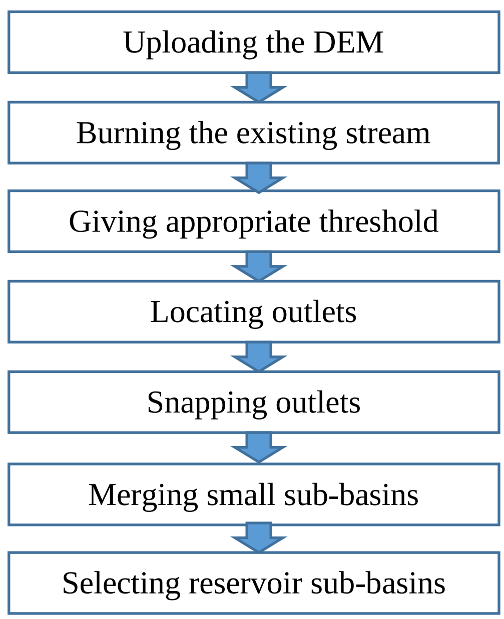


Figure 42: Overall Process of watershed delineation in QSWAT

After the delineation of watershed and sub-basin boundaries, several other factors were also considered to identify the most suitable locations within the sub-basins. They are:

(1) Rainfall entropy values
(2) Distance to sub-basin's centroid
(3) Accessibility
(4) Safety
(5) WMO standards on siting weather measuring instruments
(6) Signal strength

Rainfall is the main input for any hydrological model which varies greatly with small distances. Spatially distributed rainfall entropy values are a good indicator of identifying areas with uncertain rainfall occurrences. Hence, such locations can be considered as more demanding spaces for weather stations. Shannon's entropy method is mostly widely used approach for measuring the uncertainty of rainfall quantitatively.

Entropy is discussed under the domain of Information theory. In information theory, entropy is defined as the quantity of information possessed by a signal (Shannon, 1949). The quantity of information can be measured indirectly based on the degree of the reduction of uncertainty (Lee, 2013). Accordingly, with reference to rainfall measurement, larger the entropy means greater the lack of information and higher uncertainty. Shannon entropy of a discrete random variable x with n possible outcomes can be calculated as per the Equation 7. In here, the symbol p denotes the probability.

$$H_x = -\sum_{i=1}^{n} p(x_i) \, . \, log_{base} p(x_i) \quad \text{Equation 7}$$

Equation 7 requires pixel wise probabilities of occurrence of rainfall. The rainfall data required for this study was obtained from National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) database (link: https://globalweather.tamu.edu) for the period of 2000 to 2013. The CFSR is a third-generation reanalysis product, which involves use of observations and mathematical models to simulate weather and climate parameters. The general purpose of conducting reanalysis is to produce multiyear global state-of-the-art gridded representations of atmospheric states, generated by a constant model and a constant data assimilation system

(Saha, et.al, 2010). In this study, 0.5^0 resolution precipitation dataset was used. The dataset has been constructed through the interpolation of quality-controlled rain gauge reports from nearly 31,000 stations collected from the Global Telecommunication Network and many other national and international collections (Sun, et.al, 2018). Figure 43 shows the selected grid points to obtain CFSR data.

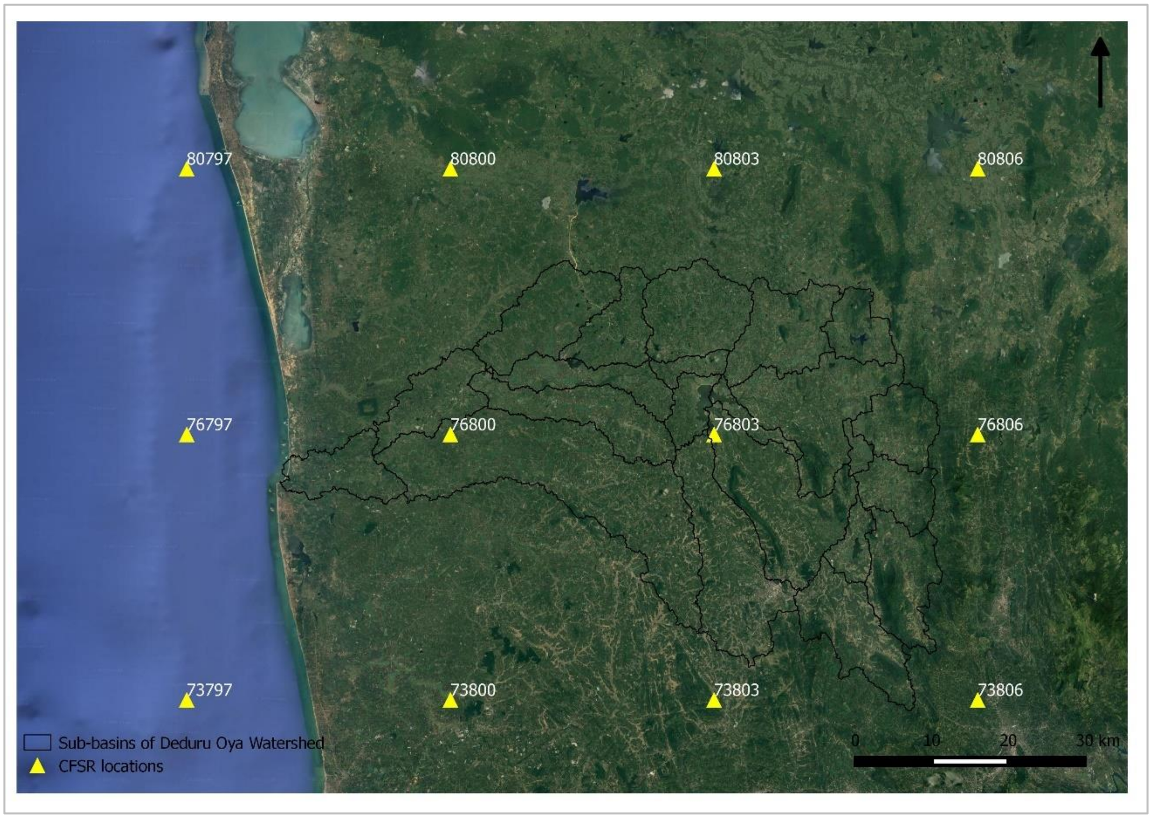


Figure 43: Selected CFSR locations at Deduru Oya basin

As the CFSR dataset is confined to single locations, Kringing method (Equation 8) was applied to calculate the pixel wise rainfall values for the entire basin. The calculation was performed in monthly basis for the period of 2000 - 2013.

$$\hat{Z}(s_0) = \sum_{i=1}^{N} \lambda_i Z(s_i) \text{ Equation 8}$$

Where, $Z(s_i)$ is the measured value at the i^{th} location, λ_i is an unknown weight for the measured value at the i^{th} location, s_0 is the prediction location and N is the number of measured values. Following the Equation 8, 168 Kriging layers were produced for the

Deduru Oya basin. The Kriging layers were classified as per classification given in Table 18, to calculate the pixel wise probabilities of rainfall rate. Then the raster analysis was performed to calculate the entropy values of each pixel as per the Equation 8.

Table 18: Classification scale of Kringing layers

Rainfall range (mm)	**Weight**
0-50	1
50-100	2
100-150	3
150-200	4
200-250	5
250-300	6
300-350	7
350-400	8
400-450	9
450-500	10
500<	11

Figure 44 shows the overall process of finding optimum locations for the 4ONSE weather stations.

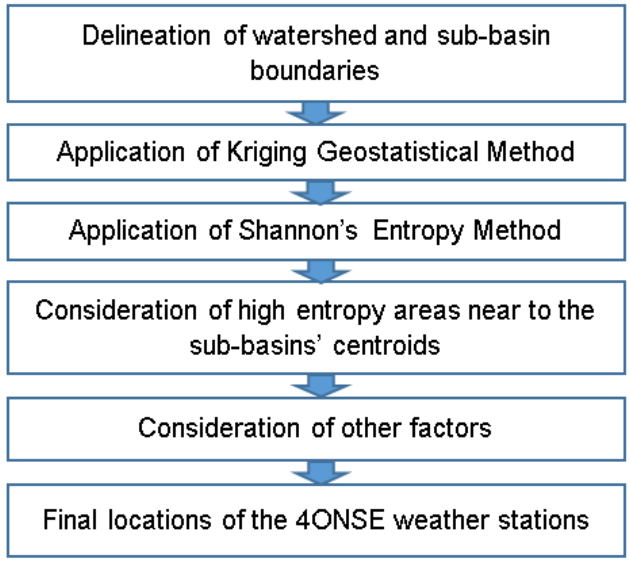


Figure 44: Overall approach of finding optimum locations for the weather stations

4.4 Parameter optimization at sub-catchment level and different temporal scales

This section elaborates the way of achieving the 4th sub-objective, which is the "identification of dominant parameters and their values based on sub-catchment level and different temporal scales".

4.4.1 Development of SWAT model

The tank management model of this study was developed for Deduru Oya reservoir which is located at the center of the Deduru Oya basin. Hence, the water level of the reservoir is controlled by the runoff generated in the upper watershed area. Hence, considering the convenience of calibrating the model, the sub-basins of the upper watershed were grouped under 4 sub-catchments, based on the stream network that they belong. Maguru Oya, Deduru Oya, Kimbulwana Oya and Hakwatuna Oya are the four sub-catchments in the upper watershed (Figure 45).

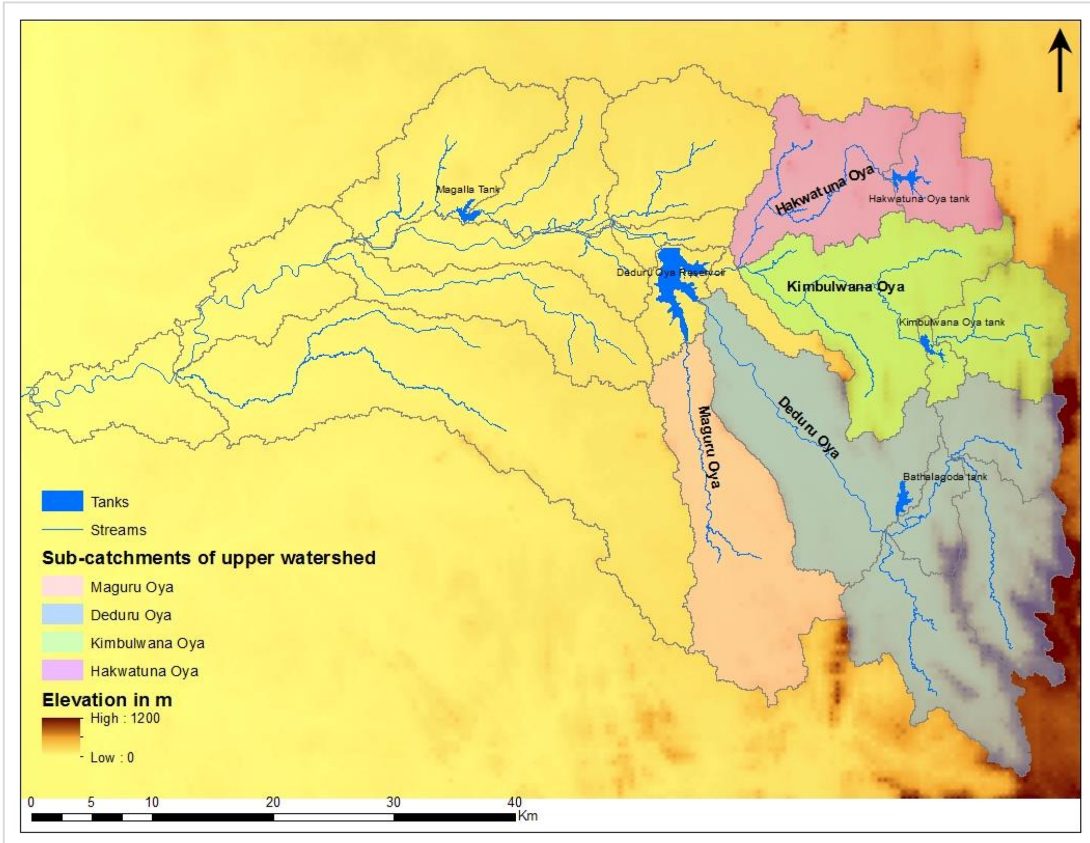


Figure 45: Sub-catchments of upper watershed

Thus, four separate QSWAT models have been created for the aforementioned four sub-catchments. Maspotha bridge, Amunugama bridge, Deegama bridge and Moragoda anicut are the outlets considered when determining the sub-catchment boundaries of Maguru Oya, Deduru Oya, Kimbulwana Oya and Hakwatuna Oya respectively. The required data to develop the models are given in Table 19.

Table 19: Required data for the SWAT model

No	Input Data	Source & link	Resolution	Purpose
01	Digital Elevation Model (DEM)	Shuttle Radar Topography Mission (SRTM) https://earthexplorer.usgs.gov/	1 arc second (approximately 30m)	To delineate the watershed and sub-basins boundaries

02	Stream Network	Produced by the Author	1:10,000	
03	Land use	Survey Department of Sri Lanka	1:50,000	To generate the Hydrological Response Units (HRUs)
04	Soil	FAO-UNESCO http://www.fao.org/geonetwork/srv/en/metadata.show?id=14116	1:5,000,000	
05	Historical weather data	Climate Forecast System Reanalysis (CFSR) https://globalweather.tamu.edu/	0.5 degree (approximately 55km) gridded dataset for the period of 1993 to 2013	To calculate the statistics to use in the SWAT's weather generator
06	Daily and hourly weather data	4ONSE weather stations https://geoservice.ist.supsi.ch/4onse/admin/	Sub-basin level	To run the model
07	Daily and hourly stream water levels	4ONSE river gauges https://geoservice.ist.supsi.ch/4onse/admin/ Irrigation Department	-	To calibrate the model

SWAT requires DEM, land use and soil layers to be uploaded into the model in raster format. DEM is originally in raster format. Land use and soil vector layers were converted to raster format of 30m resolution (to the same resolution of the DEM), prior to upload them in the model. According to Waldo Tobler's rule (Tobler, 1963), the detectable size in meters for 1:50,000 scale land use layer is 25m. As the converted resolution is greater than the detectable size, it doesn't bring any negative impacts to the model.

As explained in section 4.3, DEM and stream network data have been used to delineate the watershed and sub-basin boundaries. Then, land use and soil data were used to generate the Hydrological Response Units (HRU) of the basin, which is the smallest unit used in the SWAT model to compute the runoff. In the model, the runoff is calculated separately for each HRU and summed together to determine the total runoff for the respective sub-basin (Arnold, et al., 2012a). Each HRU is composed of similar land use, soil and slope classes. SWAT has several databases to store information on land use properties, soil properties and land management. The parameters and their values which use to describe this information are important to parameterize and calibrate the model. Hence, to identify the values of the parameters with respect to land uses of the Deduru Oya basin, the land use classes of the Survey Department's land use layer was reclassified according to the SWAT land use scheme (Table 20). Figure 46 shows reclassified land uses of the Deduru Oya basin area to the SWAT's land use scheme. Annexure 2 shows the parameter values of the land uses in the study area.

Table 20: Land uses of the basin and the corresponding SWAT land use categories

Land use classes of the basin	**SWAT land use class**	**SWAT code**
Coconut	Coconut	COCO
Stream, Canal, Lagoon, Reservoir, Tank, Waterholes and Sea	Water	WATR
Home gardens	Residential low density	URLD
Built up area	Residential-Medium Density	URMD
Marsh	Wetlands – Mixed	WETL
Prawn farms	Wetlands-Non-Forested	WETN
Scrub land, Grassland and other unclassified land	Range – Grasses	RNGE
Paddy	Rice	RICE
Chena	Pasture	PAST
Rubber	Rubber	RUBR
Sand	Barren land	BARR
Tea	Agricultural land - Generic	AGRL
Forest	Forest - Mixed	FRST
Rock	South Western Range	SWRN

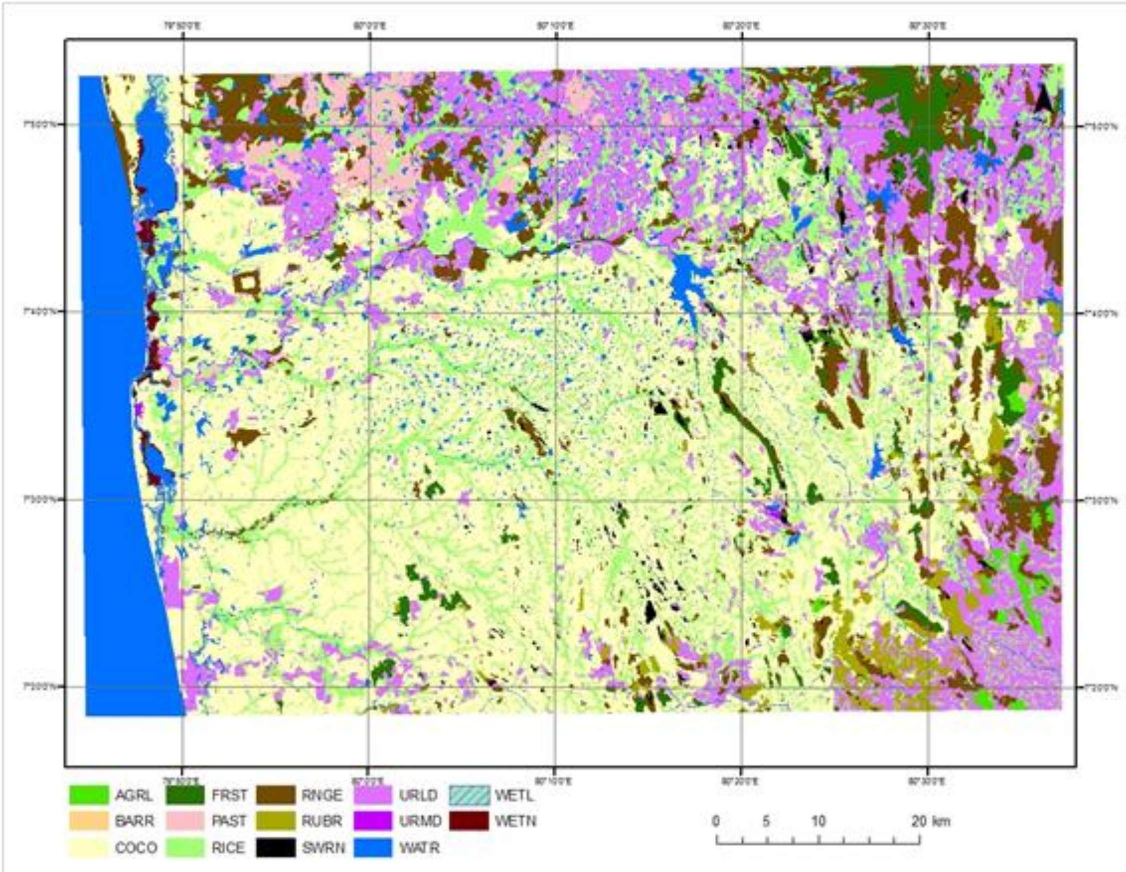


Figure 46: Reclassified land uses of the Deduru Oya basin as per the SWAT land use classes

Soil data is important to determine the hydrologic characteristics of each sub-basin. The soil database in the SWAT model was classified according to the FAO's (Food and Agricultural Organization) supra-national classification. This is also called as World Soil Classification. However, the available soil layer for Sri Lanka was produced by Geological Survey and Mines Bureau (GSMB) to the scale of 1:50,000 and it follows a different classification scheme (Figure 47). Therefore, FAO's soil layer was used in this study (Figure 48). Prior to the application of FAO's soil layer in the SWAT model, the GSMB's soil layer and FAO's soil layer were cross checked with each other in order to verify that the spatial distribution of soil types in both layers were same. Some minor soil types in the GSMB's soil layer were ignored during this comparison. Annexure 3 shows the parameter values of the soil properties in the study area.

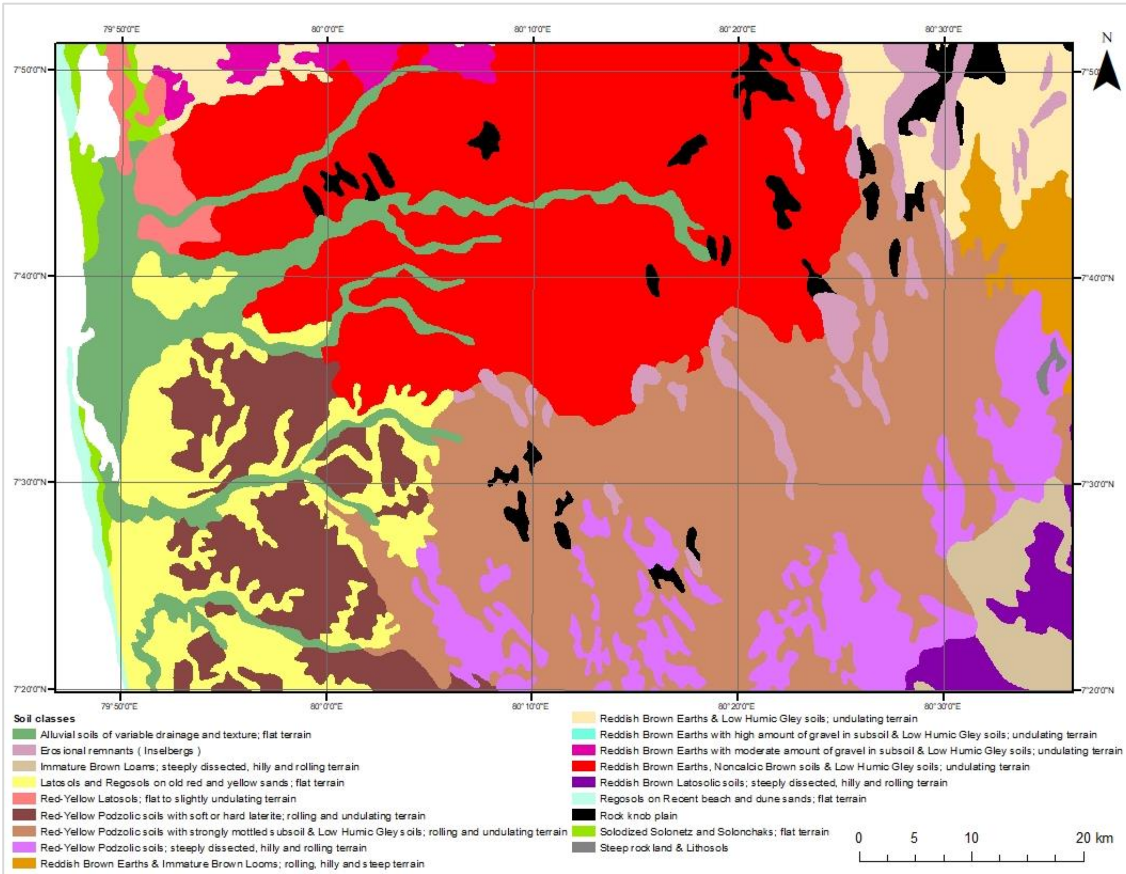


Figure 47: GSMB's soil classes for Deduru Oya basin

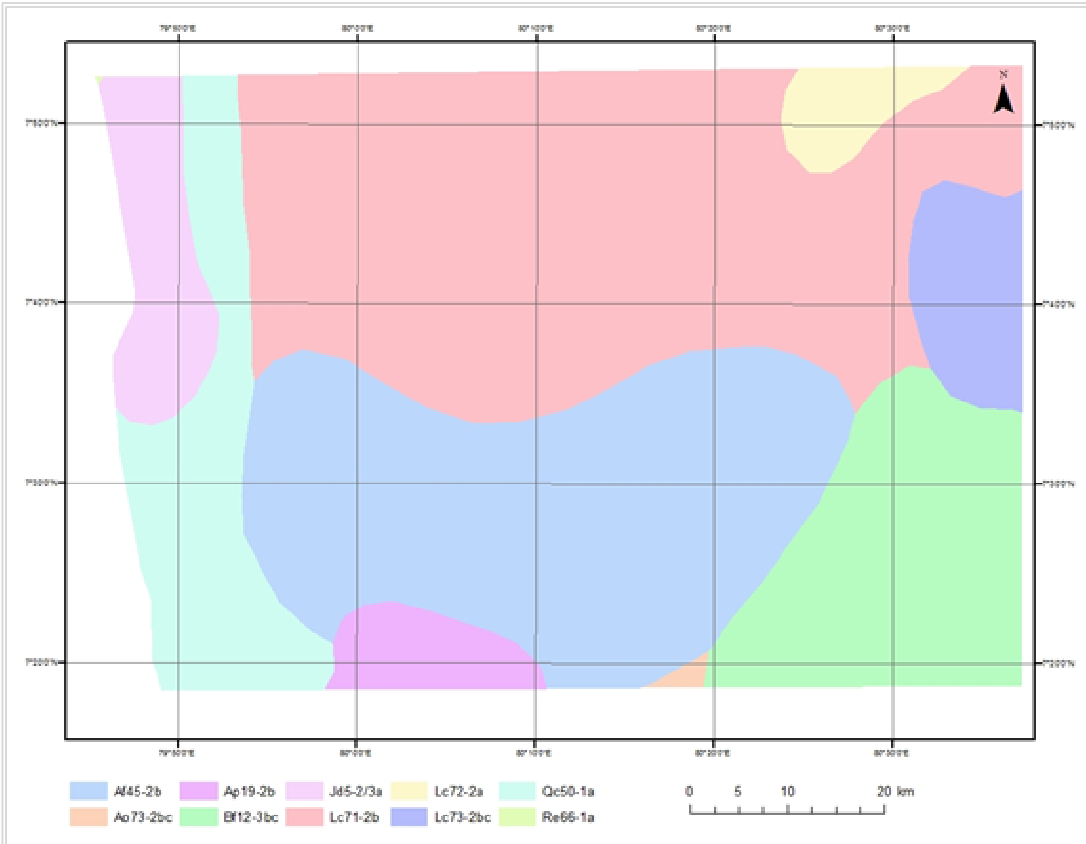


Figure 48: World soil classes for Deduru Oya basin

Like land use and soil, slope is also an important spatial element which determines the movement of water. When creating HRUs, slope of the basin was categorized into four groups (0–11%, 11-33%, 33-86% and 86% <), based on the natural breaks of the slope values. Figure 49 shows the snippet of the generated HRU report related for Deduru Oya watershed. Accordingly, the watershed has total of 845 HRUs for the 22 sub-basins.

```
HruLanduseSoilSlopeRepSwat.txt - Notepad
File  Edit  Format  View  Help
Landuse/Soil/Slope and HRU Distribution        21 September 2018 10.07

Using percentage of subbasin as a threshold
Multiple HRUs Landuse/Soil/Slope option        Thresholds: 0/0/0 [%]
Number of HRUs: 845
Number of subbasins: 22

Numbers in parentheses are corresponding values before HRU creation

------------------------------------------------------------------------------------------------------------
                                    Area [ha]
Watershed                           261281.12
------------------------------------------------------------------------------------------------------------
                                    Area [ha]                        %Watershed

Landuse
                          COCO      113878.02    (113878.02)          43.58 (43.58)
                          RICE       54837.74     (54837.74)          20.99 (20.99)
                          URLD       44279.23     (44279.23)          16.95 (16.95)
                          WATR       12107.58     (12107.58)           4.63  (4.63)
                          RNGE       18942.25     (18942.25)           7.25  (7.25)
                          RUBR        4940.90      (4940.90)           1.89  (1.89)
                          AGRL         349.04       (349.04)           0.13  (0.13)
                          FRST        6887.47      (6887.47)           2.64  (2.64)
                          SWRN        2084.34      (2084.34)           0.80  (0.80)
                          PAST        2624.59      (2624.59)           1.00  (1.00)
                          BARR           2.63         (2.63)           0.00  (0.00)
                          WETL         225.57       (225.57)           0.09  (0.09)
                          URMD          55.05        (55.05)           0.02  (0.02)
                          WETN          66.72        (66.72)           0.03  (0.03)

Soil
                       Lc71-2b      150010.56    (150010.56)          57.41 (57.41)
                       Lc72-2a        2167.53      (2167.53)           0.83  (0.83)
                       Qc50-1a        3125.05      (3125.05)           1.20  (1.20)
                       Jd5-2-3a       3233.74      (3233.74)           1.24  (1.24)
                      Lc73-2bc        8069.43      (8069.43)           3.09  (3.09)
                       Af45-2b       58464.93     (58464.93)          22.38 (22.38)
                      Bf12-3bc       36209.89     (36209.89)          13.86 (13.86)

Slope
                       0-11.11      206529.96    (206529.96)          79.05 (79.05)
                   11.11-33.21       37557.48     (37557.48)          14.37 (14.37)
                   33.21-86.13       15557.19     (15557.19)           5.95  (5.95)
```

Figure 49: Snippet of the HRU report of Deduru Oya sub-catchment

SWAT's weather generator needs some statistical data to estimate missing weather data in the model. For that, SWAT model requires some historical weather data on rainfall, temperature, solar radiation, wind speed and relative humidity, at least during a decade, to calculate the statistics required to run the model. The historical weather data (rainfall, minimum and maximum temperature, relative humidity, wind speed and solar radiation) required to calculate these statistics were obtained from the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) database. The same dataset has been used to calculate the pixel wise probabilities of occurrence of rainfall described in section 4.3. Annexure 4 shows the relevant variables and statistics required for SWAT weather generator, their definitions and the calculated values for 12 grid points of Deduru Oya river basin

The relevant weather data to run the model were obtained from 4ONSE weather stations. Figure 50 shows the 4ONSE weather stations located in each upper sub-catchment.

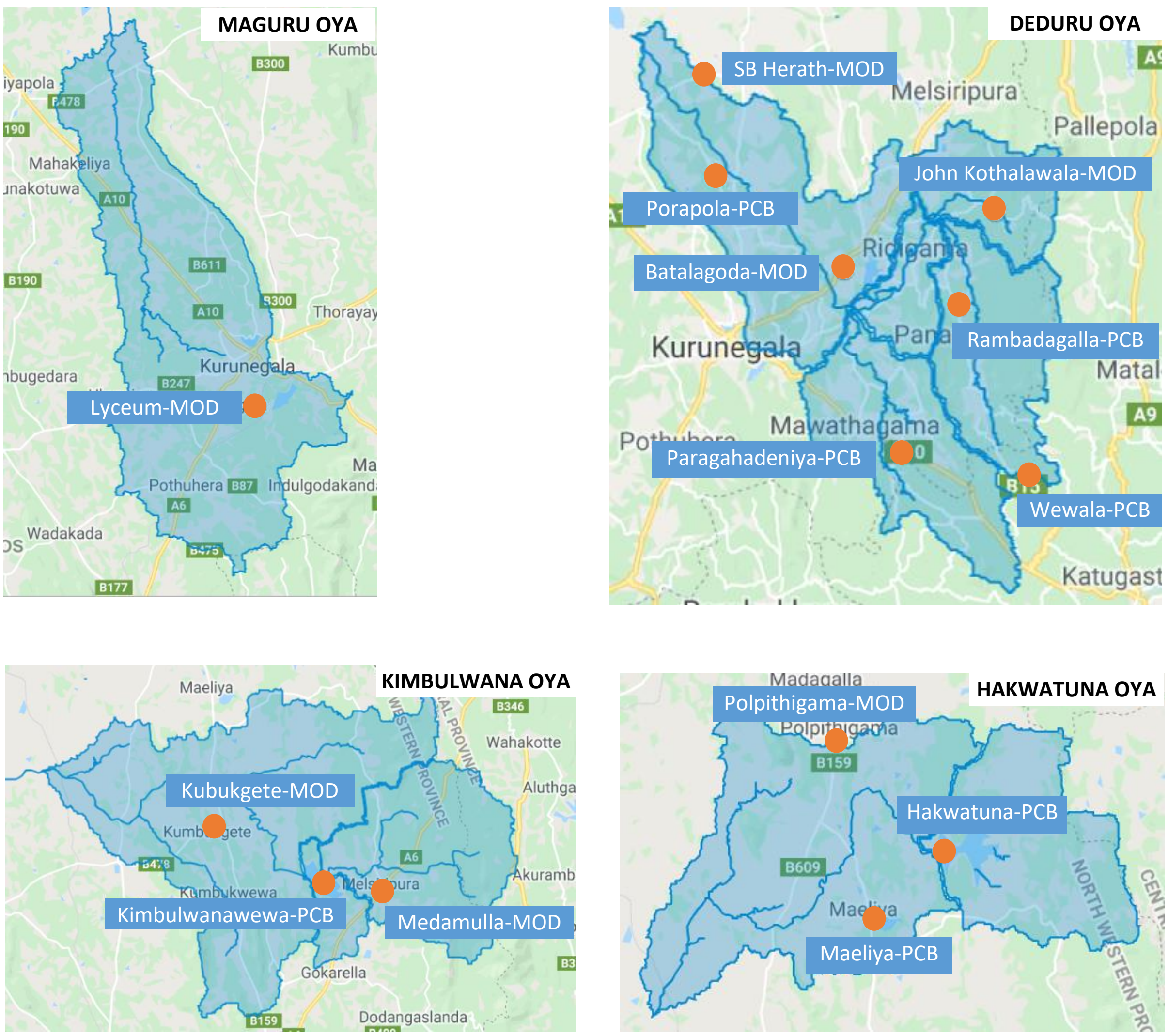


Figure 50: 4ONSE weather stations belong to four upper sub-catchments

Canopy storage, infiltration, redistribution, evapotranspiration, lateral subsurface flow, surface runoff are the processes model under hydrology aspect in SWAT model. In addition, ponds and tributary channels are also represented under hydrology aspect as input elements. Considering the convenience of running and calibrating the model, ponds are not incorporated in this modelling approach. Ponds usually obstruct surface runoff movement. SWAT assumes ponds do not receive water from the upper catchment as they are located off the main channel. The processes of infiltration, evapotranspiration, lateral subsurface flow and surface runoff are elaborated in section 2.4 of this report. Other processes of canopy storage and redistribution are explained in the subsequent paragraph.

Canopy storage / interception is simply the process of storing the water received from precipitation by plants. The stored water in this manner release to the atmosphere during the process of evapotranspiration. Redistribution is the process of movement of water through the soil layers after the occurrence of rainfall. It will stop once the soil layers are fully saturated with water.

Table 21 shows the options available in SWAT model to simulate aforementioned hydrological processes.

Table 21: Options available in SWAT model to simulate the hydrologic processes

Process	**Options**
Redistribution	• Storage routing technique
Potential Evapotranspiration (PET) Estimation	• Penman – Monteith (Monteith, 1965) • Priestley – Taylor (Priestley & Taylor, 1972) • Hargreaves (Hargreaves, et.al, 1985)
Lateral subsurface flow	• Kinematic storage model
Runoff	Rainfall / runoff / routing option • SCS curve number (SCS, 1972) • Green and Ampt Mein Larson (Mein and Larson, 1973)
	Daily curve number (CN) calculation method • Soil moisture method • Plant ET method
Canopy storage	• SCS curve number method – canopy storage is automatically taken into account (SCS, 1972)

	• Green and Ampt Mein Larson method – canopy storage must be modelled separately (Mein and Larson, 1973)
Infiltration	• SCS curve number method – models the infiltration indirectly (SCS, 1972) • Green and Ampt Mein Larson method – directly models infiltration (Mein and Larson, 1973)
Channel flow	• Variable storage coefficient (Williams, 1969) • Muskingham Cunge (Cunge, 1969)

In this study, Penman-Monteith method, Green and Ampt Mein Larson method, Soil moisture method and Muskingham cunge method were applied for potential evapotranspiration estimation, surface runoff routing, daily curve number calculation and estimating the channel flow respectively. Compared to Priestly-Taylor method and Hargreaves method, in the Penman – Monteith method, four types of input weather data (air temperature, relative humidity, solar radiation and wind speed) are used to estimate the Potential Evapotranspiration (PET). The Priestley-Taylor method needs air temperature, relative humidity and solar radiation, while the Hargreaves method uses only air temperature to estimate the PET. The Penman-Monteith equation is given in Equation 9.

$$\lambda ET = \frac{\Delta(R_n - G) + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma(1 + \frac{r_s}{r_a})} \quad \text{Equation 9}$$

Where λET is the latent heat density, R_n is the net radiation, G is the soil heat flux, $(e_s - e_a)$ represents the vapor pressure deficit of the air, where e_s is the saturation vapor pressure and e_a is the actual vapor pressure, ρ_a is the mean air density at constant pressure, c_p is the specific heat of the air, Δ represents the slope of the saturation vapor pressure temperature relationship, γ is the psychrometric constant, and r_s and r_a are the (bulk) surface and aerodynamic resistances.

SWAT includes two methods to calculate the retention parameter in SCS curve number method: soil moisture method and plant ET method. During the modelling process, it was found that the soil moisture method is more appropriate to calculate the retention parameter of the Deduru Oya basin, as it is more dependent on the soil storage. Equation 10 is used to estimate the retention parameter when the soil moisture method is applied.

$$S = S_{max}\left(1 - \frac{SW}{[SW + exp(w_1 - w_2)SW]}\right) \text{ Equation 10}$$

Where S is the retention parameter of a particular day measured in mm, S_{max} is the maximum value for the retention parameter, which is calculated as per the Equation 11, SW is the soil water content, w_1 and w_2 are shape coefficients.

$$S_{max} = 25.4\left(\frac{1000}{CN} - 10\right) \text{ Equation 11}$$

Where CN is the curve number.

SWAT provides two methods for estimating surface runoff: the SCS curve number (CN) method (SCS, 1972) and the Green and Ampt Mein Larson (GAML) excess rainfall method (Mein and Larson, 1973). CN method is an empirical model, which is based on the basic rainfall-runoff relationships of different land uses and soil types in small rural watershed of United States. GAML method is a physically based model, which considers direct relationship between infiltration and rainfall based on physical parameters allowing continuous surface runoff simulation (Jeong, et.al, 2010). Garen and Moore (2005) revealed, CN method is not suitable for simulating the continuous surface runoff at sub-hourly interval, since it estimates the direct runoff using empirical relationships between the total rainfall and watershed properties. King et al. (1999) also suggests GAML is more appropriate for sub-hourly simulation than CN method, due to its less biasness over model prediction. Further, several studies (Wang & Yang, 2019; Yu,et.al, 2018; Shannak, 2017; Boithias, 2017; Bauwe, et.al, 2017; Yang,et.al, 2016) have revealed the better performance of GAML in simulating the peak flows during flashy storms. Hence, GAML method has been chosen for sub-hourly surface runoff simulation. When applying the GAML method to simulate the runoff, the interception of rainfall by the plants need to be modelled separately. The GAML infiltration model can be expressed in Equation 12.

$$f(t) = K_e\left(1 + \frac{\psi\Delta\theta}{F(t)}\right) \text{ Equation 12}$$

Where, $f(t)$ is the infiltration rate for time t (mm/hour), K_e is the effective hydraulic conductivity, ψ is the wetting front matric potential (mm), $\Delta\theta$ is the variation of moisture content, $F(t)$is the cumulative infiltration (mm).

To simulate the runoff, Muskingham method was applied as the stream network of Deduru Oya basin follows a meandering pattern. The Muskingham method formula to estimate the downstream outflow is expressed in Equation 13.

$$O_{j+1} = C_1 I_{j+1} + C_2 I_j + C_3 O_j \quad \text{Equation 13}$$

Where:

$$C_1 = \frac{\Delta t - 2KX}{2K(1-X)+\Delta t}, \; C_2 = \frac{\Delta t + 2KX}{2K(1-X)+\Delta t}, \; C_3 = \frac{2K(1-X) - \Delta t}{2K(1-X)+\Delta t}, \; C_1 + C_2 + C_3 = 1$$

O_{j+1} = downstream outflow at time $(j+1)$

O_j = downstream outflow at time (j)

I_{j+1} = upstream inflow at time (j)

K = storage constant

X = weighting factor

Δt = time interval

The SWAT model itself has a reservoir management tool, which allows to simulate the reservoir capacity based on four ways: (1) annual average release rate of the reservoir (2) measured monthly outflow of the reservoir (3) simulated target release (4) measured daily outflow of the reservoir. Out of these four approaches, type 3 is usually applied for natural and uncontrolled reservoirs or minimally controlled reservoirs such as natural lakes. All the other 3 options are applied for controlled reservoirs. As the intention of this study is to simulate the total inflow to the reservoir prior to the reservoir gate opening decision making, the reservoir management tool available in the SWAT has not been used in this study.

The overall approach developing the hydrological model through SWAT tool has been showed in Figure 51.

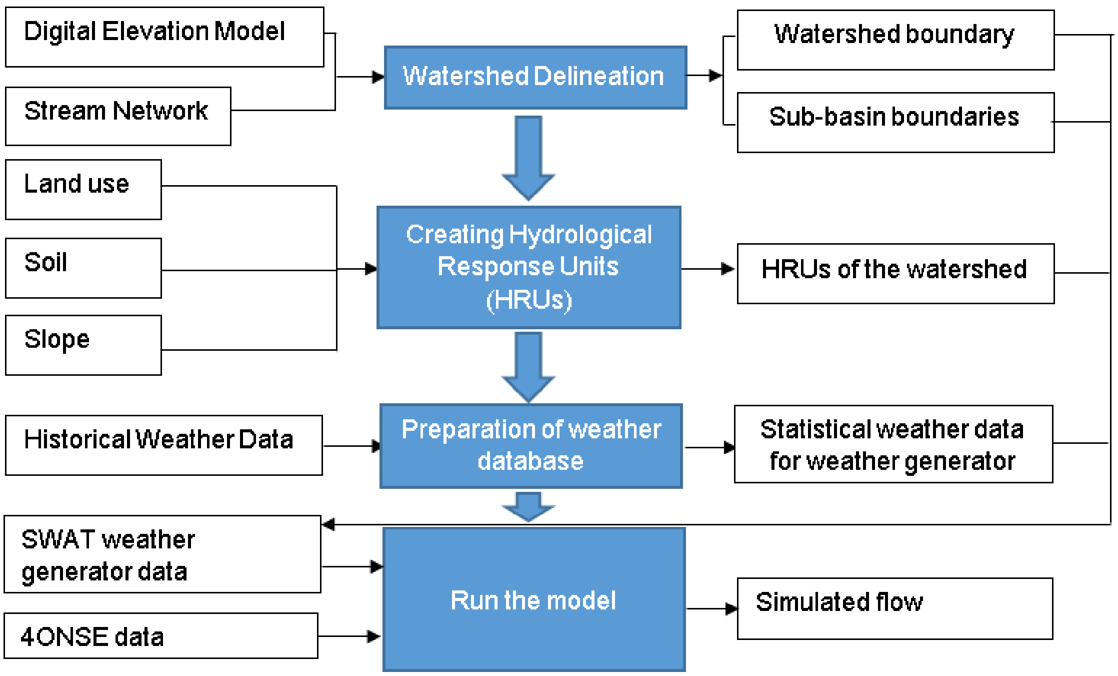


Figure 51: Approach of developing the hydrological model

4.4.2 Parameter optimization with SWAT-CUP

SWAT input data can be inserted to the model at 3 levels: watershed level (.bsn), sub-basin level (.sub) and HRU level (.hru). Watershed level inputs are used to model processes of the entire watershed. Sub-basin level inputs are applied to all HRUs in that particular sub-basin. Since there are only one reach per sub-basin, input data for main channels are also defined at the sub-basin level. HRU level inputs are applied only for the selected HRU in the watershed. In addition, the below main files are also considered in the model:

1. .sol (soil input file) - contains the information about the physical characteristics of the soil in the HRU
2. .gw (ground water input file) - contains the information on shallow and deep aquifer in the sub-basin.

3. .rte (main channel input file) - contains parameters governing water and sediment movement in the main channel of a sub-basin
4. .mgt (management input file) – contains input data on tile drains, urban areas, planting, harvesting and irrigation applications.

Annexure 5 shows SWAT's main input parameters, their ranges specified in the SWAT database, their associated levels, units and definitions. As shown in Annexure 5, SWAT model has more than 50 parameters and not all of them are useful in developing the hydrological model. Therefore, identification of dominant / sensitive parameters and their values are important to identify, prior to calibrate the model. This can be done through the SWAT manual calibration tool and SWAT-CUP open-source tool. Figure 52 shows the SWAT manual calibration tool. As shown there, value of each parameter can be modified by applying suitable mathematical operation (multiplying, adding, replacing). In addition, the tool has four filters to apply the changes based on sub-basin number, land use type, soil type and slope category. Whatever the changes apply in this tool changes the final result of the SWAT output files. Therefore, the variation of stream flow can be checked. Table 22 shows the output files created by SWAT. As the requirement of the model is to simulate river discharge data, only output.rch file is useful in the model.

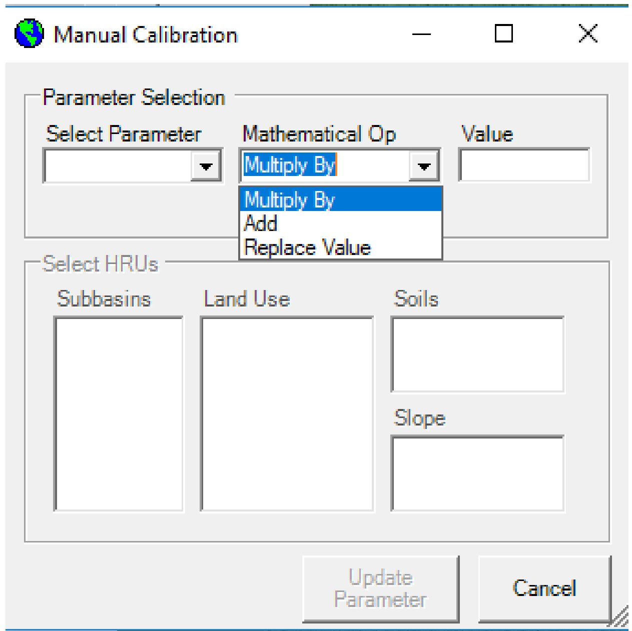


Figure 52: Manual calibration with SWAT

Table 22: Output files of SWAT

File name	Description
output.rch	Main channel output file
output.sub	Sub-basin output file
output.hru	HRU output file
output.snw	Snow output file
output.sed	Sediment loads output file
output.rsv	Reservoir output file
output.pst	Pesticide output file
output.wtr	HRU impoundment output file
output.swr	Soil water output file
output.snu	Soil nutrient output file
output.pot	Pothole output file
output.vel	Velocity of water output file
output.wql	Water quality output file
output.mgt	Management output file

The other tool which is specifically designed to automate SWAT manual calibration procedure is SWAT-CUP (SWAT Calibration and Uncertainty Procedures) open-source application. It can be used to calibrate, validate, sensitivity analysis and uncertainty analysis of SWAT models. The parameterization / regionalization scheme of SWAT-CUP tool is as follows:

$$x\_ < parname >. < ext > \_ < hydrogrp > \_ < soltext > \_ < landuse > \_ < subbasn > \_ < slope > \qquad \text{Equation 14}$$

As per the scheme represented in Equation 14, $x\_$ represents the type of change to be applied to the parameter. The same mathematical operations and the filters illustrated in Figure 52 are applied in this scheme. In addition, the scheme also lets users to parameterize based on the soil hydrologic group. Accordingly, the components, $parname$, ext, $hydrogrp$, $soltext$, $landuse$, $subbasn$ and $slope$ represents the name of the parameter (as it appears in SWAT), extension of the parameter, soil hydrologic group, land use type, sub-basin number and the slope respectively. The type of changes represented by $x\_$ are as follows:

1) $V\_$ - replacing the existing parameter value
2) $A\_$ - given value is added to the existing parameter value
3) $R\_$ - existing parameter (spatial parameters) value multiplied by (1+ given value)

In this study, several rules have been applied when selecting the appropriate $x\_$ type. SWAT_CUP usually recommends to apply the type R_ for spatial parameters (parameters related to land use and soil properties). In addition, considering the convenience of examining more parameter space (value range), type $R\_$ have been applied in this study for parameters with large range. For all the other parameters, type V_ have been applied.

One-at-a-time (OAT) local sensitivity analysis and All-at-a-time (AAT) global sensitivity analysis are the two methods available in SWAT to perform sensitivity analysis with respect to model parameters. OAT shows sensitivity of a selected parameter if all the other parameters are kept constant at some value, while AAT shows sensitivity of each parameter while allowing all other parameters to change. These two methods are used in SWAT to identify the sensitive / dominant parameters in the catchment. Accordingly, the dominant parameters were identified for each sub-catchment based on the hourly and daily time interval. Further, this model has used 4ONSE data during the period of 1st June 2019 to 31st October 2019. In June and July months, the basin area had dry weather condition with sporadic rainfall and July to October, the area had wet weather condition with some frequent rainfalls. Therefore, variation of parameter values within these two periods were also examined in this approach.

Figure 53 shows an example of resultant graph produced by SWAT-CUP after performing the OAT sensitivity analysis. The selected parameter is CN2 (Initial SCS runoff curve number for moisture condition II). As CN2 is a spatial parameter, type *R_* was applied. The range applied for CN2 parameter is -0.2 (min) to 0.2 (max). Three runs were performed to examine the local sensitivity of CN2 parameter. The green colour line in Figure 53 shows the default outflow without applying any change to the existing CN2 value. The other two lines are referenced to multiplying the default CN2 values by 1.1333 (1+0.1333) and 0.8667 (1 – 0.1333). As the outflow significantly changes with respect to changes in the CN2 value, the CN2 parameter can be considered as a sensitive / dominant parameter.

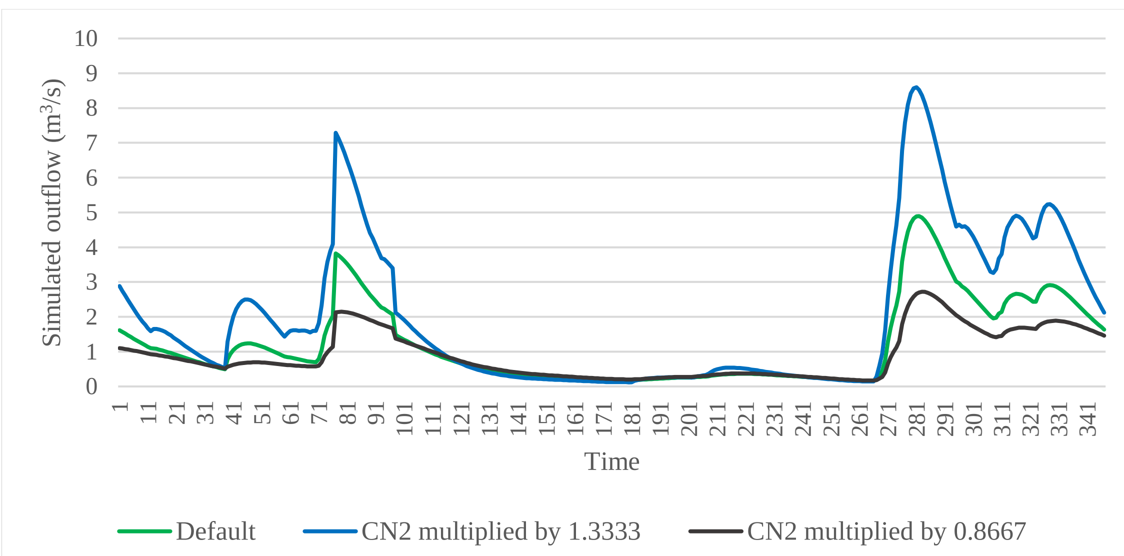


Figure 53: Local sensitivity of CN2 parameter

Global sensitivity analysis requires to perform large number of runs to produce an acceptable result. SWAT-CUP automatically calculates global sensitivities after performing many runs. In this study, 500 runs were performed for each iteration. In AAT approach, multiple regression equation (Equation 15) is used to quantify the sensitivities of parameters.

$$g = \alpha \sum_{i=1}^{n} \beta_i b_i \text{ Equation 15}$$

Where g is the sensitivity value represented in the objective function, α is the regression constant, β_i is the coefficient of parameters and b_i is the parameter value. In AAT analysis, sensitive parameters are decided based on the $t - test$. As per the results of the $t - test$, the parameters are considered as sensitive / dominant, if the t-stat value (absolute value) is large and p-value is small (usually less than 0.05).

Compared to AAT analysis, OAT analysis is much convenient to apply to decide the important parameters at the beginning of the model. However, the limitation of OAT is that the sensitivity of one parameter is more often depends on the values of other parameters and the parameter values which need to fix at the beginning are unknown (Abbaspour, et.al, 2018). The other limitation is, OAT requires considerable time to decide whether a parameter is sensitive or not, by specifying different parameter ranges. For an example, suppose the range of a parameter is 0 – 20. The parameter might sensitive for 0 – 1 range, although it is insensitive for entire 0 -20 range. Therefore, a considerable time was taken to identify the sensitive parameters and their suitable parameter ranges. Although AAT produces much reliable result compared to OAT, the parameter ranges and the number of runs affect the relative sensitivity of parameters (Abbaspour, et.al, 2018).

SWAT-CUP contains several methods to calibrate and uncertainty analysis of SWAT models. They are:

1) SUFI-2 (Abbaspour et.al, 2015)
2) GLUE (Beven and Binley, 1992)
3) ParaSol (Van Griensven and Meixner, 2006)
4) MCMC (Kuczera and Parent, 1998)
5) PSO (Kennedy and Eberhart, 1995)

In this study, SUFI-2 (Sequential Uncertainties Fitting Version 2) algorithm was used to calibrate the model. The SUFI-2 algorithm performs as an Inverse Modeling approach, where the suitable parameters and their values are decided by the observed stream flow / discharge. As it follows a stochastic modelling approach, range of values are applied to parameters instead of single values. Hence, the uncertainties in the model with reference to the parameters can be expressed as ranges. Prior to the application of water level data in the model, they were converted into flow using the stage-discharge relationship equations developed by the Irrigation Department. The equations for the sub-catchments are as follows:

Deduru Oya sub-catchment at Amunugama:

$$y = 34.408x^{1.7938}$$ Equation 16

Maguru Oya sub-catchment at Maspotha:

$$y = 5.3727x^{1.4492}$$ Equation 17

Kimbulwana & Hakwatuna Oya sub-catchment (combined flow) at Ethiliyawela:

$$y = 4.9804x^{2.5847}$$ Equation 18

There are several objective functions available in SWAT-CUP to determine the fitness of the model statistically. Multiplicative, summation, coefficient of determination, Chi-Square, Nash-Sutcliffe, Modified Nash-Sutcliffe are some of the available forms of objective function is SWAT-CUP. These objective functions measures of how well a model simulation fits the available observations. In this study, Nash-Sutcliffe Efficiency (NSE) method was used. The objective function proposed by Nash and Sutcliffe (1970) is defined in Equation 19. The NSE value ranges between $-\infty$ and 1. It indicates the match between observed and predicted values. Values between 0 – 1 are generally viewed as acceptable levels of performance, whereas values less than 0 indicate unacceptable performance.

$$Maximize: \qquad NSE = \frac{\sum_{i=1}^{n}(O_i-\bar{O})^2-\sum_{i=1}^{n}(P_i-O_i)^2}{\sum_{i=1}^{n}(O_i-\bar{O})^2} \qquad \text{Equation 19}$$

In addition, SWAT-CUP also measures the goodness of fit (R^2), which ranges between 0 and 1 (Equation 20). This indicates the proportion of the variance in the measured data. The higher value indicates less error variance. Usually, $R^2 > 0.5$ is considered as acceptable (Santhi, et.al., 2001; Van Liew, et.al., 2003).

$$R^2 = \frac{\sum_{i=1}^{n}(O_i-\bar{O})(P_i-\bar{P})}{\sqrt{\sum_{i=1}^{n}(O_i-\bar{O})^2}\sqrt{\sum_{i=1}^{n}(P_i-\bar{P})^2}} \qquad \text{Equation 20}$$

Where n is the number of observations in the period under consideration, O_i is the i^{th} observed value, $\bar{O}$ is the mean observed value, P_i is the i^{th} model-predicted value and $\bar{P}$ is the mean model predicted value.

In SUFI-2 algorithm, the fitness between the simulated result and the observed values are expressed as 95PPU – 95% prediction uncertainty. Each simulation produces two statistics: P-factor and R-factor. P-factor is the percentage of observed data simulated in the model. Hence, (1 – P factor) is the percentage of observed data not simulated well in the model, in other words “model error”. R-factor is the thickness of the 95PPU envelop. It is calculated as follows:

$$R - factor = \frac{\frac{1}{n_j}\sum_{t_i=1}^{n_j}\left(x_s^{t_i,97.5\%}-x_s^{t_i,2.5\%}\right)}{\sigma_{oj}} \qquad \text{Equation 21}$$

Where $x_s^{t_i,97.5\%}$ and $x_s^{t_i,2.5\%}$ are the upper and lower boundary of the 95PPU at time step t and simulation t.

For model outputs related to discharge, SWAT-CUP recommends P-factor greater than 70%, while having R-factor of around 1. It gives the P-factor and R-factor of the best simulation. SWAT tool becomes a stochastic hydrological model, when using SWAT-CUP for model calibration. Each iteration of the model selects the best parameter values and their ranges. Model parameters cannot have a single value due to their diversity and temporal variation. Further, the selected model calibration algorithm of this study, which is SUFI-2, is an inverse modeling approach. Hence, the measured observations can be produced with different parameter sets. Therefore, the best way to show the modeling result is by means of parameter distributions which fit with the observed data. If the model result is unsatisfactory, another iteration can be made using the new parameter ranges produced in the previous iteration.

The overall approach of optimizing the model parameters has been demonstrated in Figure 54.

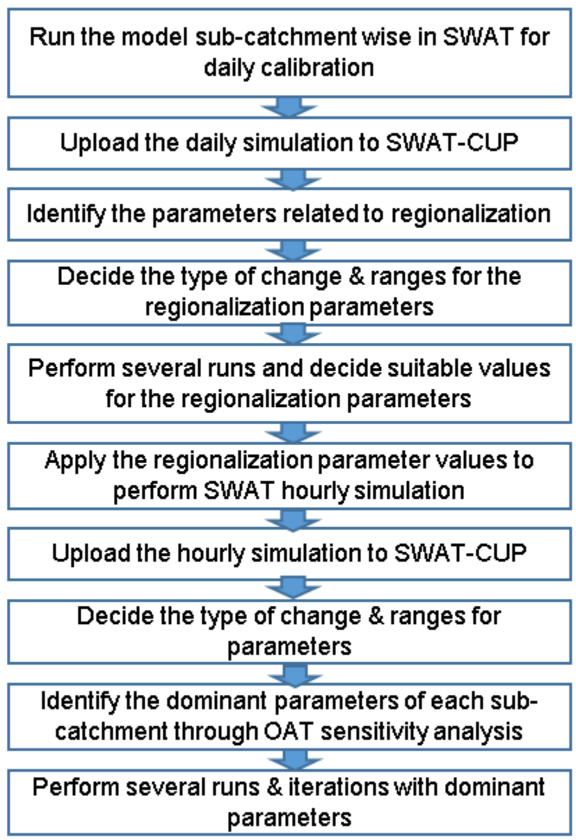


Figure 54: The approach of parameter optimization

4.5 The approach of applying outputs of the hydrological model for reservoir flood control

This section elaborates the way of achieving the 5th sub-objective, which is the "application of outputs of the hydrological model to estimate the amount of pre-release water and opening heights of the reservoir gates".

In the previous section, an approach has been presented to optimize the model parameters at sub-catchment level, daily and hourly time intervals and for dry and wet periods. However, only the hourly flows are important for reservoir pre-release decision making. Therefore, the optimized hourly parameters can be applied in the SWAT model to simulate the hourly flows. The required steps to follow are elaborated below:

(1) Step 1 – Fill the weather data files in the model with real time 4ONSE data

The hydrological model developed in this study requires 4 weather parameters (rainfall, maximum and minimum temperature, relative humidity and wind speed) to run the model. The istSOS application visualizes 4ONSE weather data at 10 minutes interval. They have to arrange into hourly and daily formats as explained in section 4.2. The default model contains 4ONSE weather data during the period of 1st June 2019 to 31st October 2019. Follow the below steps when uploading 4ONSE data after 31st October 2019.

Currently, the weather files of the model are filled with "-99" value for the period after 31st October 2019. Those values should be replaced with new data when running the model for the future.

To upload new rainfall data to the model, open the relevant station file and go to the relevant record where you want to start uploading rainfall data. To find the row number to start entering rainfall data, Equation 22 can be used. The number of the day in that year can be obtained from the table given in Annexure 6.

$$17521 + (previous\ number\ of\ day\ of\ that\ year\ \times 24) + hour \quad \text{Equation 22}$$

Example: Row number related to 1st December 2019 at 02:00 is,

$$17521 + (335 \times 24) + 2 = 25563$$

The Equation 22 is valid only for finding the relevant precipitation file's row number for year 2019. For year 2020, another 8760 should be added to the equation. 8760 is the total number of hourly records per year. The reason for using 17521 value in Equation 22 is the use of 2 years of warm period (8760 x 2) in the model with 1st row reserved for indicating the starting date of the model.

The Equation 23 can be used to find the relevant row number of the other weather parameters (relative humidity, temperature, wind speed) at daily time step.

$$731 + number\ of\ the\ day\ of\ that\ year \quad \text{Equation 23}$$

Like Equation 22, the Equation 23 is valid only for finding the other weather files' row numbers for year 2019. For year 2020, another 365 should be added to the equation. 365 is the total number of daily records per year. The reason for using 731 value in Equation 23 is the use of 2 years of warm period (365 x 2) in the model with 1st row reserved for indicating the starting date of the model.

(2) Step 2 – Uploading the weather data files into the model

After filling the weather data files, click on the "Edit Inputs and Run SWAT" button (Refer Figure 29) in QSWAT window to open the "SWAT Editor". Do the following steps to upload the weather data files to the model.

Click on "Connect to databases" → Go to "Write Input Tables" menu → Select "Weather Stations" → Go to "Weather Generator Data" tab → Select "WGEN Deduru" from "Locations Table" → Go to "Rainfall Data" tab → Click on the option "Raingauges" → Select "Precip Timestep as "Sub-Daily" give the Timestep as "60" and browse to the "pcp.txt" file → Then go to the "Temperature Data" tab → Click on the option "Climate Stations" → Browse to the "tmp.txt" file → Do the same for "Relative Humidity" and "Wind speed" data → Then go to "Solar Radiation Data" tab and select the "Simulation" option → Click "OK"

(3) Step 3 – Writing the input files

Click on the "Write Input Tables" menu of SWAT Editor → Select "Write SWAT Input Tables" → Click on "Select All" button → Click on "Create Tables" → Except the message on "Use weather database to calculate heat units to maturity (US only)?", for all the other messages select "Yes"

After writing the SWAT Input Tables, the model may arrange its settings to default options provided for hydrological simulation. To change them, go to the "Edit SWAT Input" menu of SWAT Editor → Go to "Watershed Data" → Select "General Data (.BSN)" → Apply the following options given in Table 23.

Table 23: Options need to apply in the model for hourly simulation

Hydrologic Process	**Option need to select**
Rainfall – Runoff Method	Sub-daily/G&A/Hourly Route (1)
ICN	Soil Moisture Method
Channel Routing	Muskingum

After applying the above option, click on "Save Edits" button → Click on "Exit" button

If needed, the parameters can be changed. For that, go to "SWAT Simulation" menu in SWAT editor → Select "Manual Calibration Helper" → the relevant sensitive parameters found through the SWAT-CUP can be selected from "Select Parameter" drop down menu → Then the relevant change (multiplying / adding / replacing) can be applied from the "Mathematical Op" menu → The parameter value can be entered in "Value" text box → The four filters (Subbasins, Land Use, Soil, Slope) can be applied at the end → Finally update each sensitive parameter by clicking "Update Parameter" button

The Figure 55 shows an example of applying the CANMX parameter value for HRUs contain Coconut land use. The CANMX values obtained during the model calibration process are given in Table 29. Since CANMX is a parameter sensitive only for Deduru

Oya sub-catchment, the subbasins' numbers (numbers 7, 9, 11, 15 & 16) of the Deduru Oya sub-catchment were only selected.

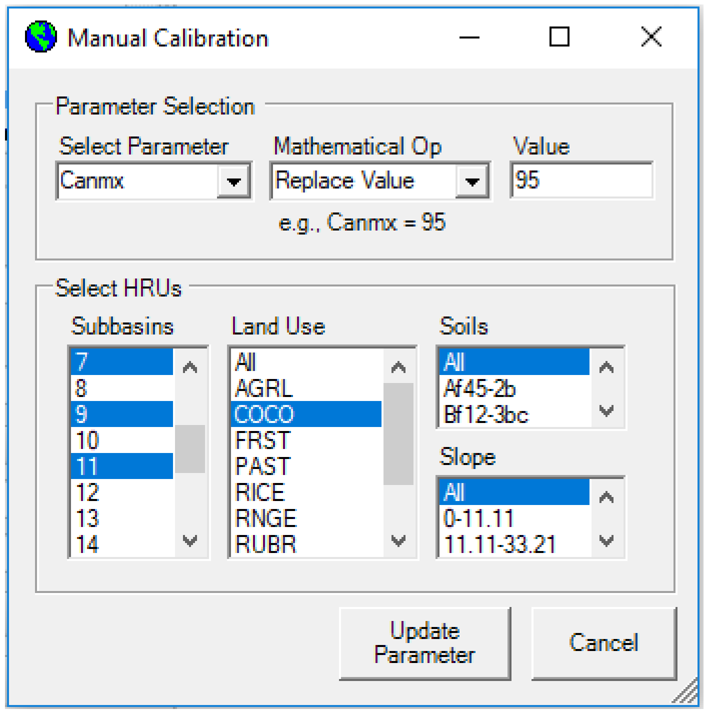


Figure 55: An example of applying CANMX value for HRUs contain with Coconut landuse in Deduru Oya sub-catchment

After parameterization, go to "Edit SWAT Input" menu in "SWAT Editor" window → select "Re-Write SWAT Input Files"

(4) Step 4 – Run the model

To run the model, go to "SWAT Simulation" menu in "SWAT Editor" window → Select "Run SWAT" → Give the "Starting Date" and "Ending Date" → Select the "SWAT.exe" Version as "64 bit, release" → Select the option "Daily" and give the "NYSKIP" (Number of Years to Skip) as "2" in the "Prinout Settings" → Click on "Setup SWAT Run" button → After that click on "Run SWAT" button

(5) Step 5 – Read the SWAT Output

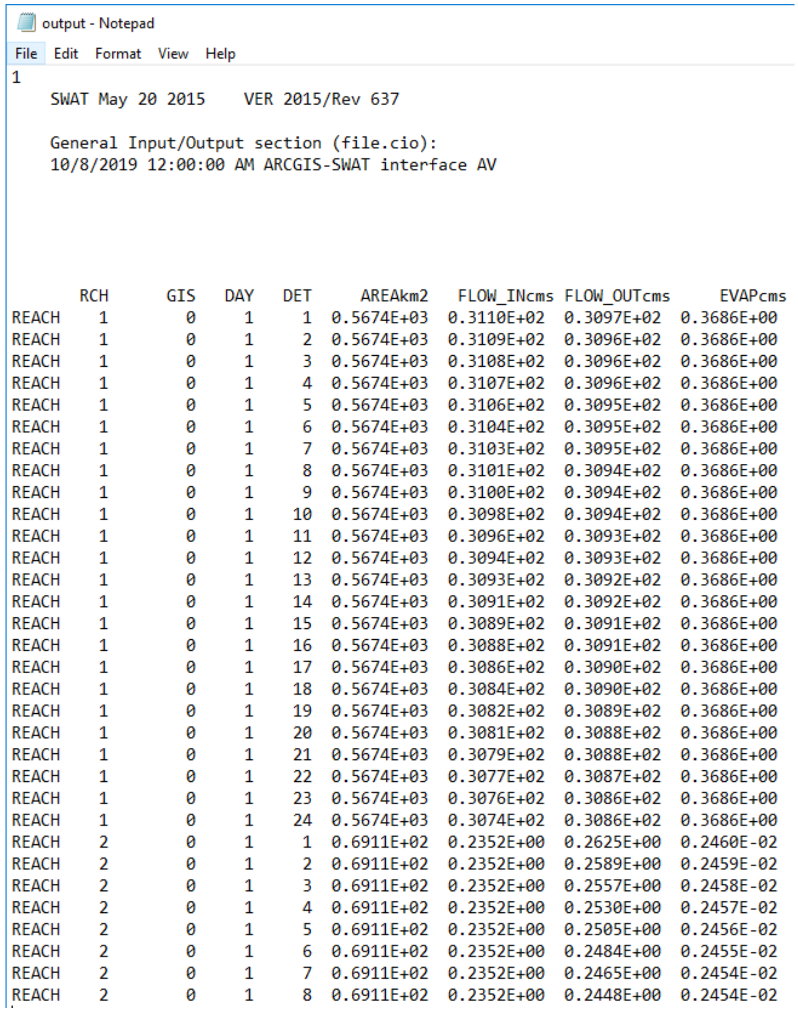
Go to the “SWAT Simulation” menu in “SWAT Editor” → Select “Read SWAT Output” → Check the “output.rch” → Click the button “Import Files to Database”. The relevant simulation can also be saved separately by giving a name in the bottom text box and by clicking the button “Save Simulation”

To view the output file, go the relevant project folder and open the “Scenarios” folder → Go to the “Default” folder or the folder that you saved separately in the above step → Open the “TxtInOut” folder → Open the file.CIO → Change the “IPRINT” to “3” and save the file → Double click on the “SWAT_64rel” execution file in the TxtInOut folder (If the SWAT_64rel is not in the TxtInOut folder, copy it from the SWAT’s SWAT Editor folder and paste it inside the TxtInOut folder) → Double click on the “output.rch” file in the TxtInOut folder to view the results.

By filtering the relevant reach (RCH) numbers (the ID number of the streams which provide water to the Deduru Oya reservoir), the total outflow (Figure 56) from the upper streams to the Deduru Oya reservoir can be calculated. Table 24 shows the ID numbers of the relevant reaches.

Table 24: RCH numbers to streams which provide inflow to the Deduru Oya reservoir

RCH number	**Stream**
10	Maguru Oya
16	Deduru Oya
17	Combined streams of Kimbulwana and Hakwatuna Oya



```
output - Notepad
File  Edit  Format  View  Help
1
    SWAT May 20 2015    VER 2015/Rev 637

    General Input/Output section (file.cio):
    10/8/2019 12:00:00 AM ARCGIS-SWAT interface AV




       RCH      GIS   DAY   DET     AREAkm2   FLOW_INcms FLOW_OUTcms    EVAPcms
REACH    1        0     1     1  0.5674E+03  0.3110E+02  0.3097E+02  0.3686E+00
REACH    1        0     1     2  0.5674E+03  0.3109E+02  0.3096E+02  0.3686E+00
REACH    1        0     1     3  0.5674E+03  0.3108E+02  0.3096E+02  0.3686E+00
REACH    1        0     1     4  0.5674E+03  0.3107E+02  0.3096E+02  0.3686E+00
REACH    1        0     1     5  0.5674E+03  0.3106E+02  0.3095E+02  0.3686E+00
REACH    1        0     1     6  0.5674E+03  0.3104E+02  0.3095E+02  0.3686E+00
REACH    1        0     1     7  0.5674E+03  0.3103E+02  0.3095E+02  0.3686E+00
REACH    1        0     1     8  0.5674E+03  0.3101E+02  0.3094E+02  0.3686E+00
REACH    1        0     1     9  0.5674E+03  0.3100E+02  0.3094E+02  0.3686E+00
REACH    1        0     1    10  0.5674E+03  0.3098E+02  0.3094E+02  0.3686E+00
REACH    1        0     1    11  0.5674E+03  0.3096E+02  0.3093E+02  0.3686E+00
REACH    1        0     1    12  0.5674E+03  0.3094E+02  0.3093E+02  0.3686E+00
REACH    1        0     1    13  0.5674E+03  0.3093E+02  0.3092E+02  0.3686E+00
REACH    1        0     1    14  0.5674E+03  0.3091E+02  0.3092E+02  0.3686E+00
REACH    1        0     1    15  0.5674E+03  0.3089E+02  0.3091E+02  0.3686E+00
REACH    1        0     1    16  0.5674E+03  0.3088E+02  0.3091E+02  0.3686E+00
REACH    1        0     1    17  0.5674E+03  0.3086E+02  0.3090E+02  0.3686E+00
REACH    1        0     1    18  0.5674E+03  0.3084E+02  0.3090E+02  0.3686E+00
REACH    1        0     1    19  0.5674E+03  0.3082E+02  0.3089E+02  0.3686E+00
REACH    1        0     1    20  0.5674E+03  0.3081E+02  0.3088E+02  0.3686E+00
REACH    1        0     1    21  0.5674E+03  0.3079E+02  0.3088E+02  0.3686E+00
REACH    1        0     1    22  0.5674E+03  0.3077E+02  0.3087E+02  0.3686E+00
REACH    1        0     1    23  0.5674E+03  0.3076E+02  0.3086E+02  0.3686E+00
REACH    1        0     1    24  0.5674E+03  0.3074E+02  0.3086E+02  0.3686E+00
REACH    2        0     1     1  0.6911E+02  0.2352E+00  0.2625E+00  0.2460E-02
REACH    2        0     1     2  0.6911E+02  0.2352E+00  0.2589E+00  0.2459E-02
REACH    2        0     1     3  0.6911E+02  0.2352E+00  0.2557E+00  0.2458E-02
REACH    2        0     1     4  0.6911E+02  0.2352E+00  0.2530E+00  0.2457E-02
REACH    2        0     1     5  0.6911E+02  0.2352E+00  0.2505E+00  0.2456E-02
REACH    2        0     1     6  0.6911E+02  0.2352E+00  0.2484E+00  0.2455E-02
REACH    2        0     1     7  0.6911E+02  0.2352E+00  0.2465E+00  0.2454E-02
REACH    2        0     1     8  0.6911E+02  0.2352E+00  0.2448E+00  0.2454E-02
```

Figure 56: Snippet of the output.rch file

The expected water capacity of the Deduru Oya reservoir at a particular hour could be calculated as shown in Equation 24.

$$C_E = C_0 + 3600(I_D + I_M + I_K + I_H) \quad \text{Equation 24}$$

Where, C_t is the expected capacity, C_0 is the existing capacity, I_D is the inflow to the reservoir from Deduru Oya stream, I_M is the inflow to the reservoir from Maguru Oya stream, I_K is the inflow to the reservoir from Kimbulwana Oya stream and I_H is the inflow to the reservoir from Hakwatuna Oya stream. The hydrological model calculates the inflow to the reservoir in m^3/s. Accordingly, the total flow required multiply by 3600 to find the inflow to the reservoir within one hour.

As illustrated in Figure 27, stream flow of the Deduru Oya stream is approximately $2/3^{rd}$ of the Maguru Oya stream and combined flow of Kimbulwana Oya and Hakwatuna Oya streams. This assumption can be used to decide the total inflow to the Deduru Oya reservoir, since the Hakwatuna Oya sub-catchment and Kimbulwana Oya sub-catchment has not been parameterized and calibrated in this study.

Table 25 shows the approximate time taken to reach water to the Deduru Oya reservoir from each sub-catchment, after the occurrence of rainfall in the upper catchment area. As explained in section 5.4.1, the Deduru Oya is the most significant sub-catchment out of them, since the reservoir receives the largest inflow from it. As per the Table 25, approximately 6 hours have been taken to reach water to the reservoir from the Deduru Oya upper sub-catchment after a rainfall event. Therefore, application of near-real-time data of 4ONSE weather stations in the hydrological model is only applicable if the time taken for reservoir pre-release decision is less than 6 hours. If not, forecasted data of the numerical weather prediction models needs to apply to simulate the inflow to the reservoir with sufficient lead time.

Table 25: Approximate time of concentration of each sub-catchment

Sub-catchment	**Time of concentration**
Deduru Oya	6 hours
Maguru Oya	2 hours
Kimbulwana Oya	2 hours
Hakwatuna Oya	1 & 1/2 hours

Further, prior to the application of this model for reservoir flood control, it is essential to test the performance of the model under different rainfall frequencies. The accuracy of the results also depends on the precision of the sensors used in the 4ONSE system. Therefore, 4ONSE network and as well as the tank management model requires to be tested by the relevant experts in the Meteorological Department and Irrigation Department and issue an authentic report, prior to use this system in disaster management.

The overall methodology of parameter optimization is illustrated in Figure 57.

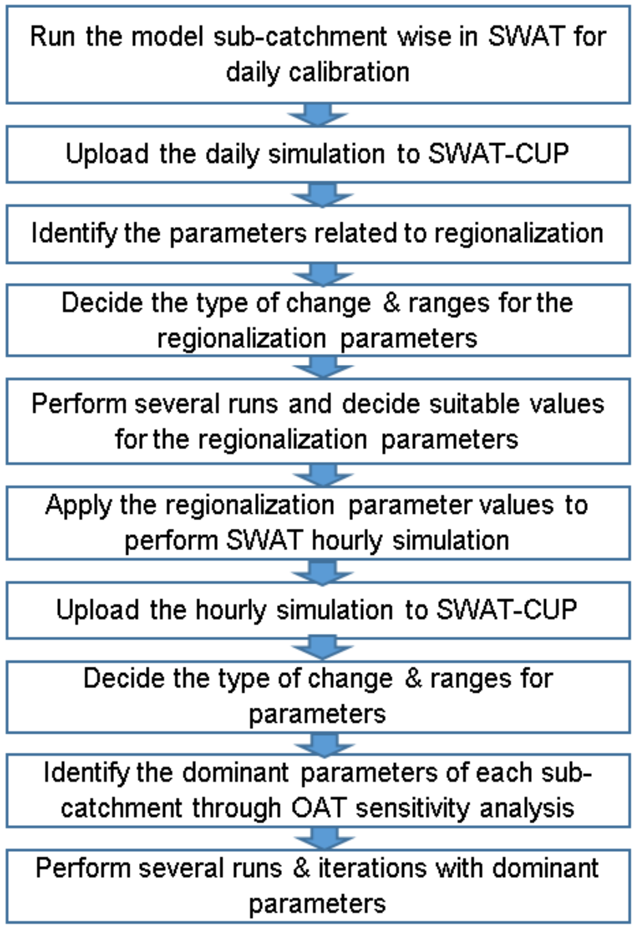


Figure 57: Overall methodology of parameter optimization

CHAPTER 5
ANALYSIS & FINDINGS

5.1 Overview

The main objective of this research is to develop open technologies-based tank management model for reservoir flood control. This chapter includes the analysis and findings of the research with respect to the five sub-objectives. The first sub-objective is to develop a hydrological model operated by combined open-source technologies for reservoir flood control and the second sub-objective is to identify a suitable open-source hydrological modelling tool to simulate the hydrological processes at regional scale. The approach related to these two objectives are elaborated in section 4.2. Hence, in this chapter, the overall framework related to these two sub-objectives is graphically represented in section 5.2. Section 5.3 describes the optimum locations identified in this study to deploy the 4ONSE sensor network, which is the third sub-objective of this research. The results related to the fourth sub-objective of parameter optimization have been discussed in section 5.4. This section includes five sub-sections on calibration issues, parameter optimization at daily time step, parameter optimization at hourly time step, comparison of parameters between daily and hourly time steps and wet and dry periods. The final result of application of tank management model relates the fifth sub-objective. This has been elaborated under section 5.5 as application of 4ONSE data in the hydrological model to estimate the inflow to the reservoir and to decide the height of the radial gate opening, application of tank management model to a different river basin and a demonstration of obtaining numerical weather prediction data from ERA5 data portal to run the model.

5.2 Hydrological model operated by combined open-source technologies

This section includes the graphical framework of application of combined open-source technologies to develop the hydrological model. Hence, the outcome related to sub-objectives 1 and 2 is graphically presented in this section (Figure 58).

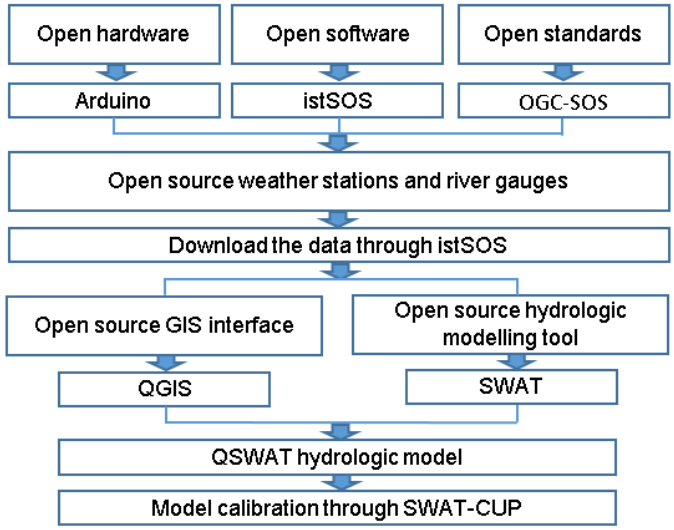


Figure 58: Framework of application of combined open-source technologies

Accordingly, the hydrological model obtains the input data from weather stations and river gauges which have been developed through amalgamating open-source hardware (Arduino), software (istSOS) and standards (OGC-SOS). This has been elaborated in section 3.1.2. SWAT open-source hydrologic modelling tool which has been embedded in QGIS open-source software as QSWAT plugin, has been used to develop the hydrologic model. The model was calibrated by SWAT-CUP open-source program. Thus, the entire approach of loading data into the model, developing the model and calibrating the model was done in an open-source platform.

5.3 Optimum locations of the 4ONSE open-source sensor network

With reference to second sub-objective, this section elaborates the final locations which have been identified to deploy the 4ONSE weather stations and river gauges.

During the process of watershed and sub-basin boundary delineation, several boundaries were delineated by applying the 0.25%, 0.5%, 1%, 2% and 3% thresholds (Figure 59). Accordingly, 3% of threshold was considered as the ideal size for the Deduru Oya basin, as most of the sub-basins coincide with the delineated boundaries prepared by Department of Agrarian Development (Figure 60). Therefore, the boundary coincided with the boundary delineated by Department of Agrarian Development consists of 15 sub-basins.

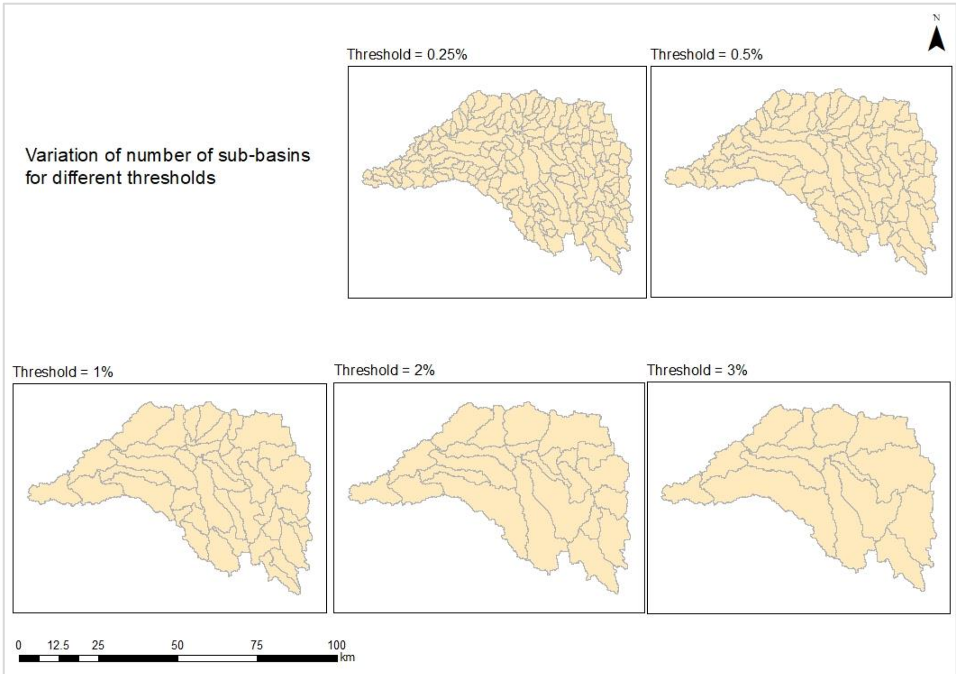


Figure 59: Variation of number of sub-basins for different thresholds

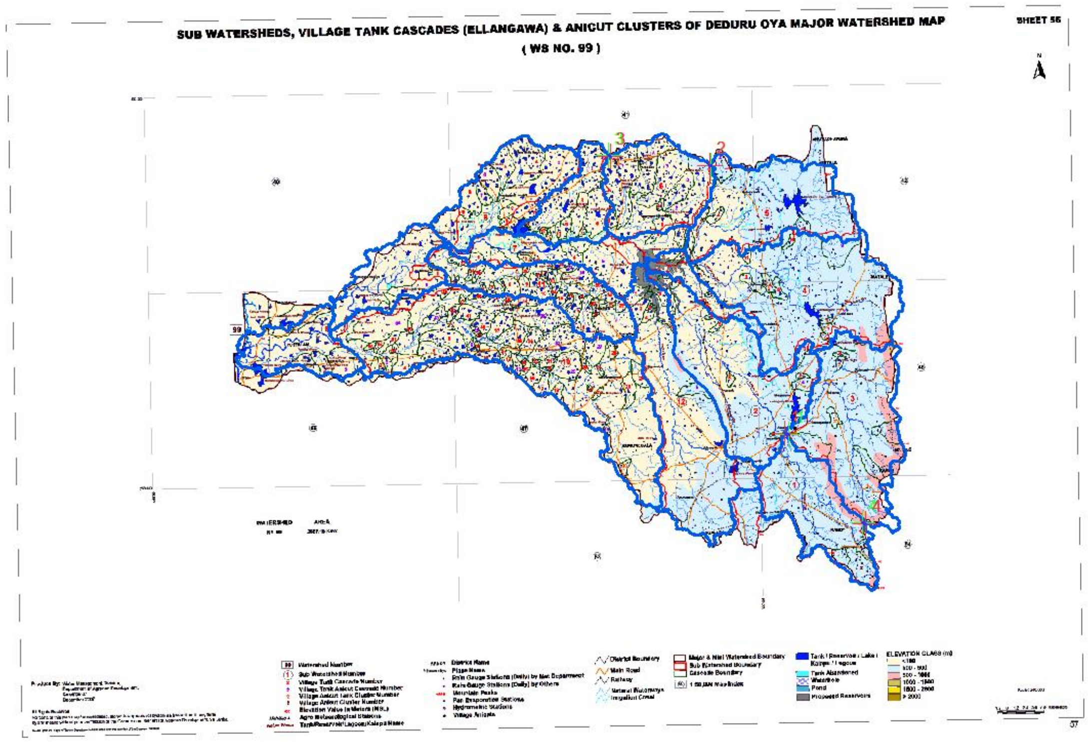


Figure 60: Coincided boundary with map prepared by Department of Agrarian Development

As per the delineated boundary shown in Figure 60, only 15 stations are enough, if they deploy at sub-basin level. However, the intention of 4ONSE project is to deploy denser weather station network in Deduru Oya basin. Therefore, it was decided to increase number of sub-basins by decreasing the threshold up to 1%. When delineating this new boundary as per the threshold of 1%, the sub-basins were delineated in a manner to incorporate reservoirs of the upper catchment into single sub-basins. SWAT considers the water bodies located on the stream network, both natural and manmade as “reservoirs”. They should receive runoff from sub-basins in the upper catchment. As explained in section 3.3, there are 8 major reservoirs and 2408 minor reservoirs in the Deduru Oya basin. In this research, only the major reservoirs were taken into consideration when developing the model. Out of the major reservoirs, the largest reservoir, which is the Deduru Oya tank is located center of the basin, two tanks (Hulugalla tank and Magalla tank) area located at the lower basin and the remaining five tanks (Wennaruwa tank, Bathalagoda tank, Meddeketiya tank, Kimbulwana Oya tank and Hakwatuna tank) are located at the upper basin. Since the tank management model of this research is developed for the Deduru Oya tank, the five major tanks in the upper basin are influenced for the variation of tank levels in Deduru Oya reservoir. Out of those five tanks, the tanks which are directly connected with the delineated stream network were taken when delineating the watershed. Accordingly, Kimbulwana Oya and Hakwatuna Oya are the tanks which directly connect to the main stream network. Hence, they were marked as reservoirs in the QSWAT interface. Other tanks – Wennaruwa tank, Bathalagoda tank and Meddaketiya tank, were considered as impoundments as they locate off from the main stream network. Considering the convenience of running the model, the selected reservoirs were taken into a single sub-basin. For that, as shown in Figure 61, outlets were located at the places where the streams of the upper basin meet the reservoir and the reservoir point was placed at the outlet of the reservoir. Figure 62 portrays the new sub-basin boundaries received for the Deduru Oya basin for the threshold of 1%. Consequently, the new watershed with 22 sub-basins were used to deploy the 4ONSE stations.

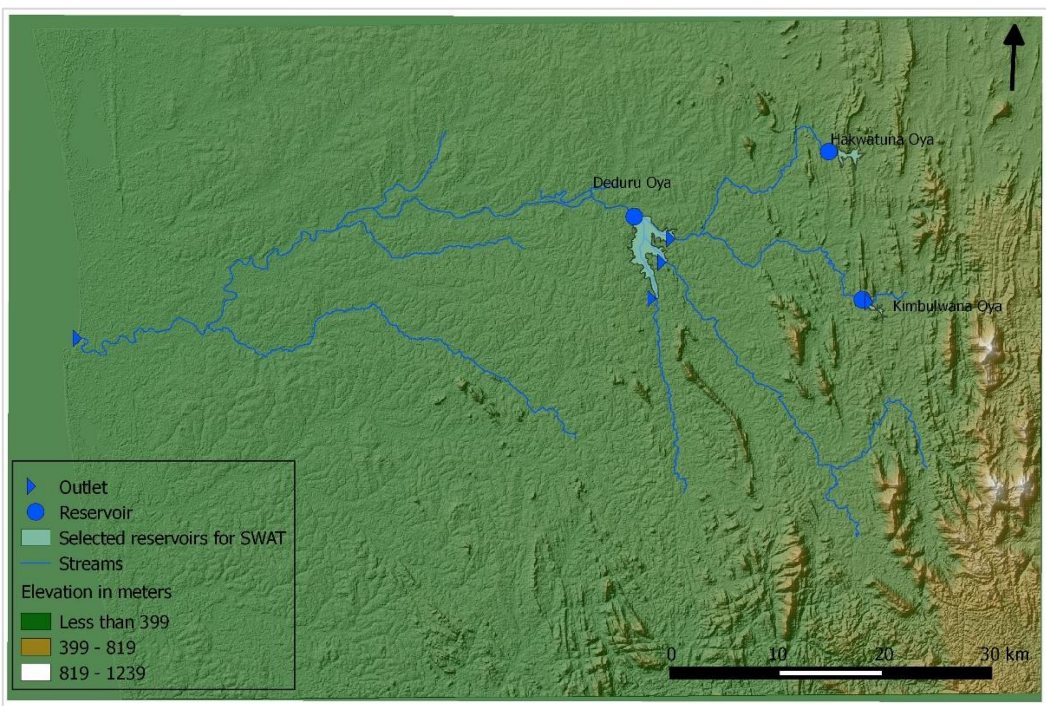


Figure 61: Outlets and reservoir points marked in the QSWAT model

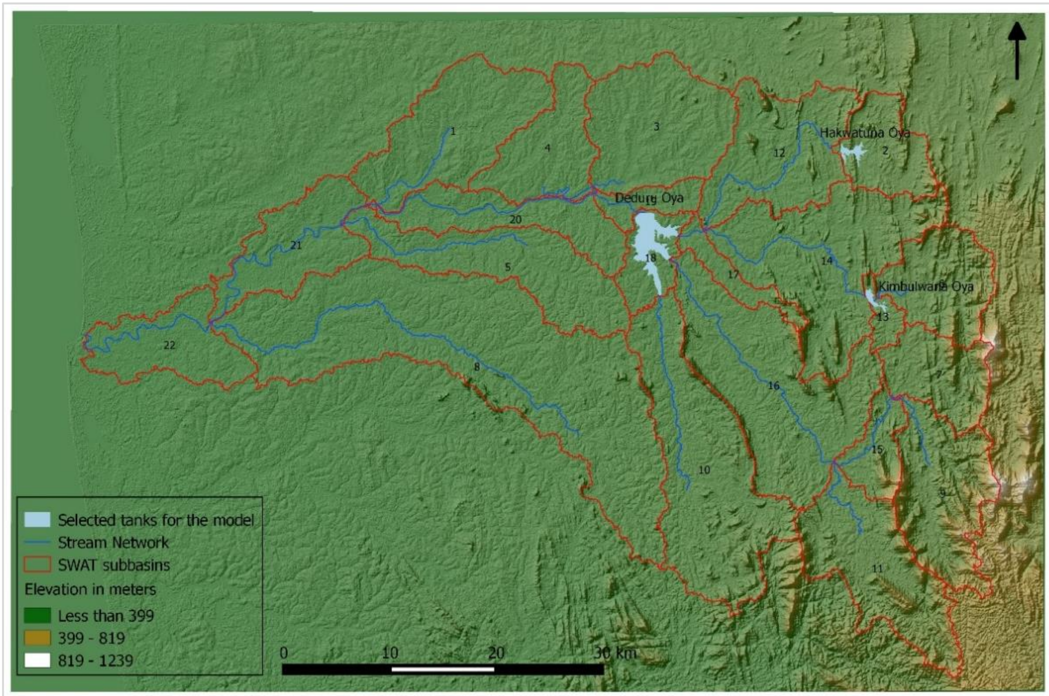


Figure 62: Delineated boundary to deploy the 4ONSE stations

After obtaining the appropriate sub-basin boundaries for the Deduru Oya watershed area, spatial distribution of rainfall entropy values was calculated for the basin using CFSR rainfall data. As a sample, Figure 63 shows the variation of entropy values related to Sub-basin number 3, 4 and 22. Entropy is higher in red color areas while the value is lower in blue color areas.

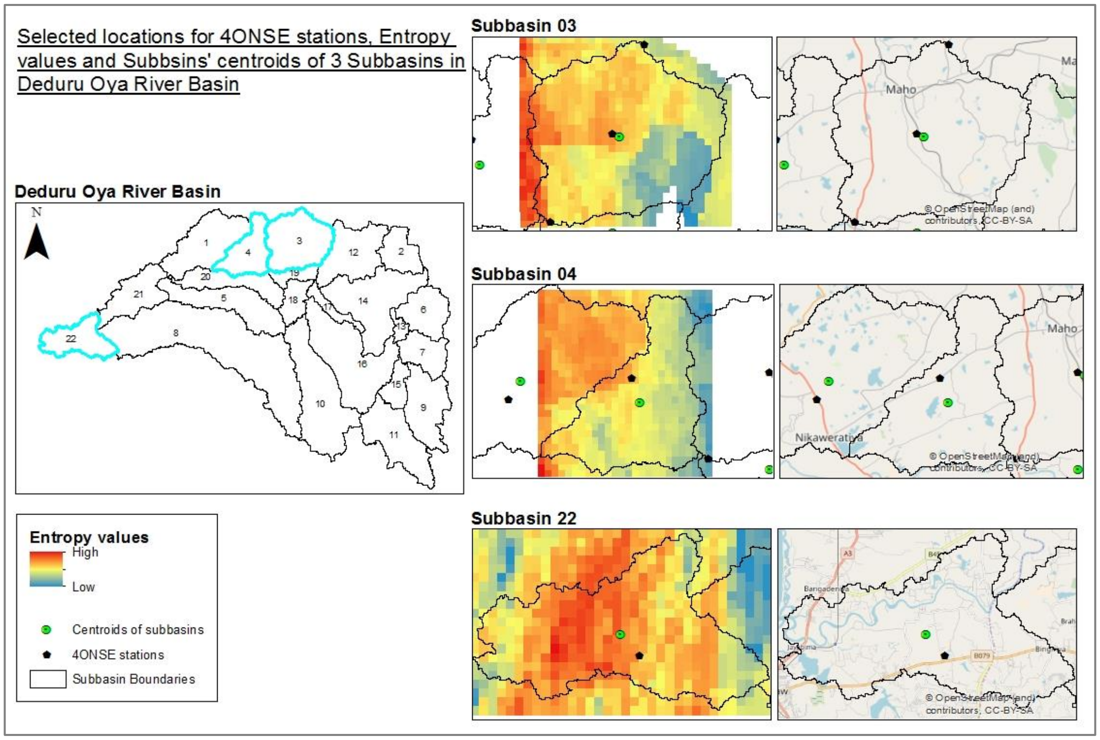


Figure 63: Selected locations for 4ONSE stations, variation of entropy values and locations of sub-basins' centroids of some sub-basins

SWAT model takes the required weather data at sub-basin level, from nearest station to the relevant sub-basin's centroid. Therefore, in addition to the rainfall entropy, distance to the sub-basin centroid was also taken as a factor to determine the optimum location for the 4ONSE stations. Accessibility (availability of road network to reach to the stations), safety (government or public places with security officers), availability of open spaces, distance to water bodies (more than 100m away from water bodies), extent of the sub-basins (it was decided to install more than one station for sub-basins greater than 2 ha), signal strength and conformity with WMO standards (WMO, 2006) on siting weather measuring instruments were the other factors considered in identifying suitable locations for the 4ONSE stations.

However, several locations were selected while disobeying the aforementioned criteria. They are:

- The extent of sub-basin 9 is less than 2 hectares. However, it was decided to install one more station at the upper area of the sub-basin 9 where the Deduru Oya stream is originated.
- It was decided not to install any station in sub-basin 15, due to the location of two nearby stations at sub-basin 9 and 16, within less than 5km distance.
- Upon the request of Irrigation Department two stations have been installed closer to two tanks called Hakwatuna and Kimbulwana and one more station has been installed at the Dam of Deduru Oya reservoir

Figure 64 shows the final locations of the 4ONSE weather stations. Table 26 includes the information of the 4ONSE weather stations installed in Deduru Oya basin.

Table 26: Information of the 4ONSE weather stations installed in Deduru Oya basin

No	**Name of the location**	**Code**	**Location type**	**Sub-basin Number**	**Coordinates**
01	Sri Sudarshanaramaya	SSR	Temple	01	7.77609, 80.10723
02	Maeliya Maha Vidyalaya	MEL	School	12	7.74501, 80.4189
03	Polpithigama Central College	PPG	School	12	7.81619, 80.40497
04	Hakwatuna Irrigation Office	HKW	Irrigation Department 's premises	02	7.77067, 80.44662
05	Gunapala Malasekara Model Primary school	GMM	School	03	7.79459, 80.28381
06	Bakmeegahawatta College	BMG	School	03	7.85393, 80.30532
07	Hulogedara Maha Vidyalaya	HGR	School	04	7.79054, 80.19073
08	Bamunugama Maha Vidyalaya	BMG	School	08	7.65746, 80.16155

09	Kubukgete Central College	KPG	School	14	7.67338, 80.41995
10	Medamulla De Mel Maha Vidyalaya	MDM	School	06	7.64323, 80.5093
11	Kimbulwanawewa Irrigation Office	KMB	Irrigation Department's premises	09	7.64871, 80.47782
12	Sir John Kothalawala Central College	SJK	School	07	7.56845, 80.53221
13	Kedapathwehera Primary School	KDW	School	08	7.54703, 80.2529
14	Hettipola Mahindodaya Maha Vidyalaya	HTP	School	08	7.60583, 80.07815
15	Rambadagalla Central College	RBG	School	09	7.50758, 80.50921
16	Wewala Parakrama Kanishta Vidyalaya	WWL	School	09	7.39998, 80.55304
17	Paragahadeniya National School	PGD	School	11	7.41561, 80.47272
18	Lyceum adventure park	LAP	Park belongs to Lyceum international school	10	7.45965, 80.36421
19	Bathalagoda Rice Research Institute	RRI	Research institute	16	7.53148, 80.43538
20	Porapola Kanishta Vidyalaya	PPL	School	16	7.59081, 80.35303
21	S.B. Herath National School	SBH	School	16	7.65528, 80.34604

22	Dam of Deduru Oya reservoir	DAM	Irrigation Department's premises	18	7.71934, 80.27471
23	Malagane Maha Vidyalaya	MLG	School	18	7.66651, 80.27807
24	Gajanaggegama Maha Vidyalaya	GJM	School	19	7.73613, 80.24267
25	Withikuliya Central College	WTK	School	20	7.71783, 80.14575
26	Wellangiriya Govipola	WLG	Farm	21	7.68275, 79.97235
27	Kokkawila Kanishta Vidyalaya	KKW	School	22	7.59464, 79.88334

In addition to the weather stations, six river gauges also deployed in the basin to calibrate the model. Out of them, five river gauges were deployed in the upper catchment and one was deployed in the lower catchment in proximity to Deduru Oya reservoir. The river gauges of Deduru Oya stream are located at Amungama bridge and Thoraya bridge. The other upstream river gauges of Maguru Oya, Kimbulwana Oya and Hakwatuna Oya are located at Maspotha bridge, Deegama bridge and Moragoda anicut respectively. The river gauge of the lower basin was installed at Ridie Bandi Ella anicut where the water is released from the Deduru Oya reservoir. Figure 64 shows the locations of the six river gauges in the basin and Table 27 includes their information.

Table 27: Information of the 4ONSE river gauges installed in Deduru Oya basin

	Name of the location	**Location type**	**Name of the stream**	**Coordinates**
01	Maspotha	Bridge	Maguru Oya	7.54687, 80.30708
02	Amunugama	Bridge	Deduru Oya	7.64433, 80.32288
03	Deegama	Bridge	Kimbulwana Oya	7.67834, 80.37039

04	Moragoda	Anicut	Hakwatuna Oya	7.74578, 80.34725
05	Ridie Bandi Ella	Anicut	Deduru Oya	7.72775, 80.26457
06	Thorayaya	Bridge	Deduru Oya	7.52101, 80.42811

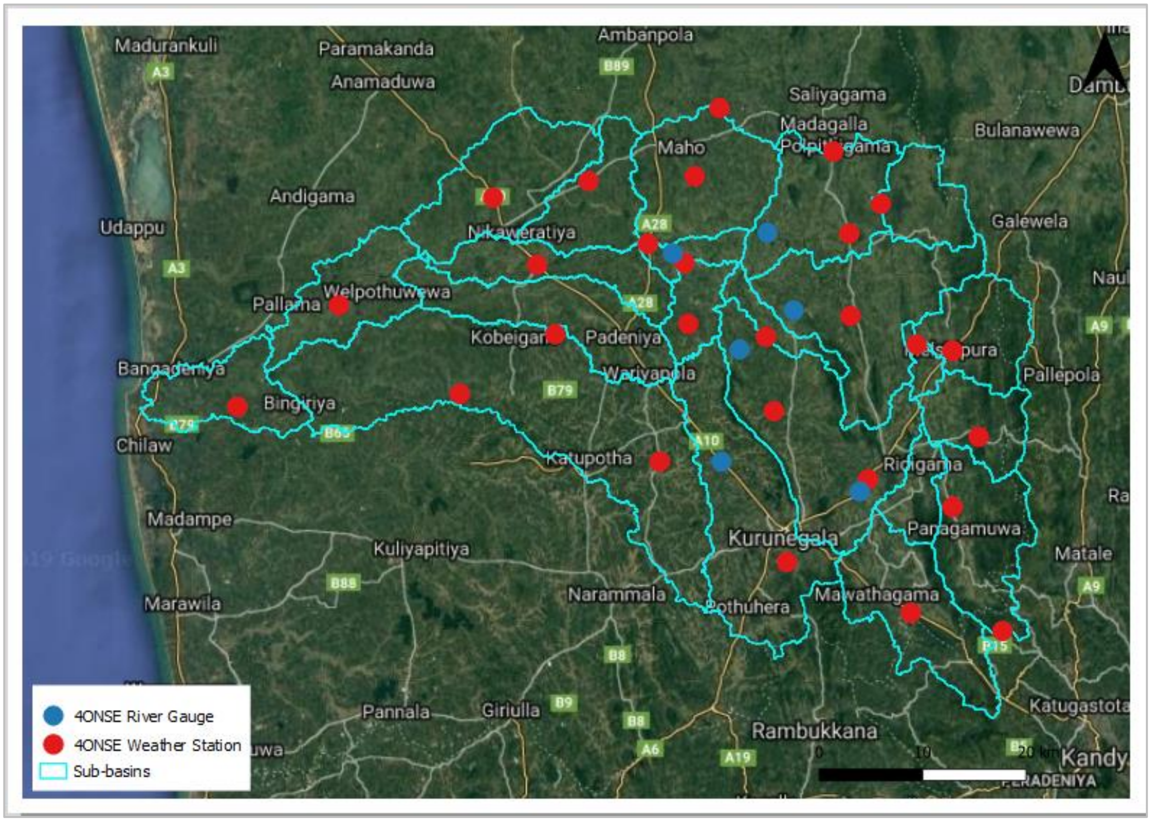


Figure 64: Locations of the 4ONSE stations in Deduru Oya basin

5.4 Optimization of model parameters

5.4.1 Issues encountered when calibrating the model

The four upper-sub-catchments in Deduru Oya basin have been separately calibrated in this study by developing four separate SWAT models. However, certain issues were encountered when calibrating the Kimbulwana Oya and Hakwatuna Oya sub-catchments. The total runoff generated in the Hakwatuna sub-catchment collect at the Moragoda anicut and distribute to surrounding agricultural lands (Figure 65). Therefore, only a small portion of flow is received to the Deduru Oya reservoir from there. Accordingly, the Hakwatuna sub-catchment doesn't make a significant contribution to the inflow of Deduru Oya reservoir. In addition, the water level of Hakwatuna Oya is measured at the 4ONSE river gauge installed at Moragoda anicut. Since the river gauge is located at the place where the Moragoda anicut collects the discharge of Hakwatuna Oya stream, the water level measurement remained unchanged at the value 1.87m throughout the selected simulated time period (Figure 66). Further, the reservoir discharge data of Hakwatuna Oya reservoir is not available at hourly basis. Owing to these reasons, Hakwatuna Oya sub-catchment could not be calibrated neither hourly nor daily.

Figure 65: Google map view of Moragoda anicut and Hakwatuna Oya

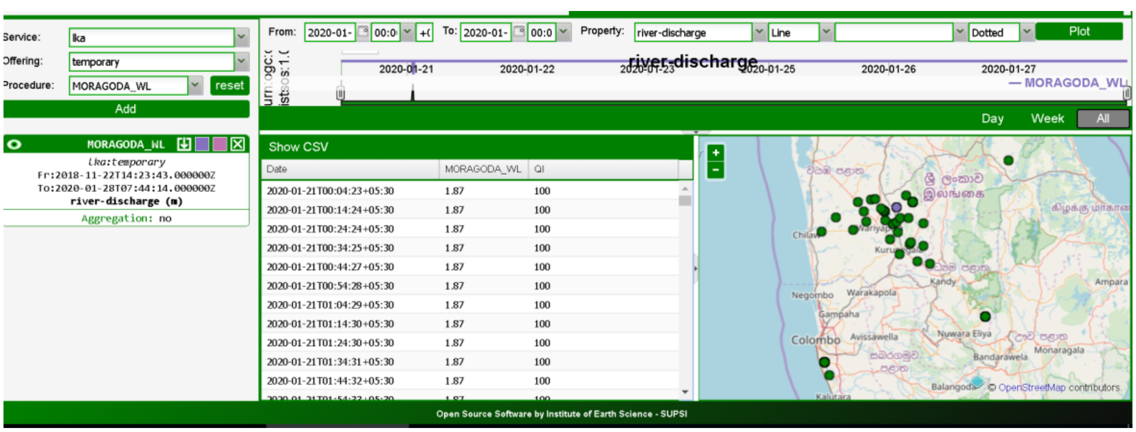


Figure 66: Water level measurement at Moragoda anicut

Like Hakwatuna Oya reservoir, discharge data of Kimbulwana Oya reservoir is not available at hourly basis. Therefore, the model was run for Kimbulwana Oya sub-catchment using daily weather data of Kimbulwanawewa station. As shown in Figure 50, three 4ONSE weather stations have been installed at Kimbulwana Oya sub-catchment in the locations of Kubukgete Central College, Kimbulwanawewa Irrigation Office and Medamulla De Mel Maha Vidyalaya. Considering the continuity of data, only the Kimbulwanawewa weather station's data have been used to run the model related to Kimbulwana Oya sub-catchment. Figure 67 shows the simulated and observed flow of Kimbulwana Oya sub-catchment at daily time step. Although the pattern is same, a gap of approximately 2.5m^3/s of flow rate is there between two flows. The main reason for this low level of simulation is the underestimation of rainfall by the rain gauge at Kimbulwanawewa station. Owing to this reason, the rainfall measurements at Kimbulwanawewa station couldn't be further applied for simulating the discharge at Kimbulwana Oya sub-catchment.

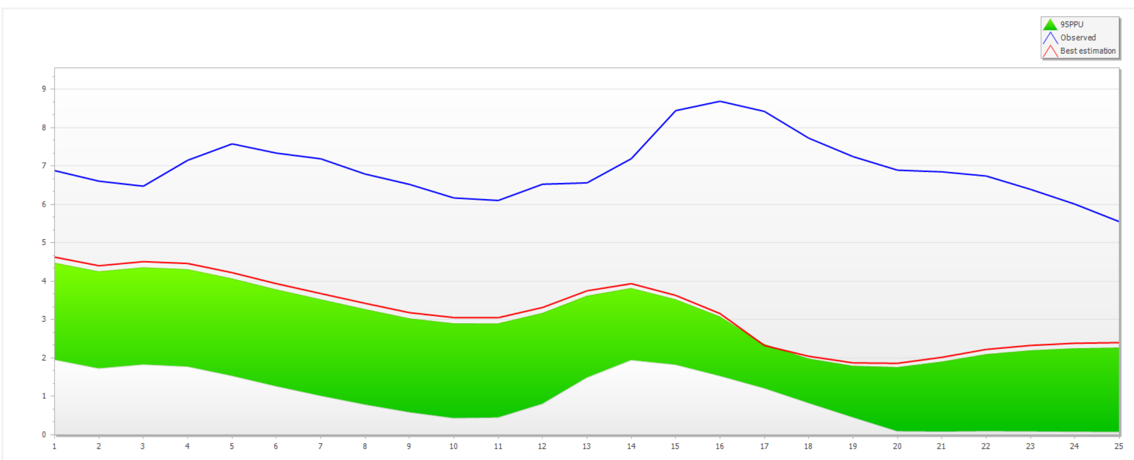


Figure 67: Simulated and Observed flow of Kimbulwana Oya sub-catchment at daily time step

Accordingly, both Hakwatuna Oya and Kimbulwana Oya sub-catchments could not be calibrated neither daily nor hourly. Therefore, in this research, only Deduru Oya and Maguru Oya sub-catchments were calibrated. As shown in Figure 27, Deduru Oya reservoir receives largest inflow from Deduru Oya stream. The discharge of Deduru Oya stream is approximately three times greater than the discharge of other upper streams.

Moreover, Irrigation Department's main concern is also to know about the discharge of the Deduru Oya sub-catchment to decide the height of the reservoir gate opening.

During the rainfall events, the discharge from the Hakwatuna and Kimbulwana oya sub-catchments could be controlled to a certain extent through the Moragoda anicut and Hakwatuna Oya & Kimbulwana Oya tanks. Further, it was unable to find hourly tank release data related to Hakwatuna Oya & Kimbulwana Oya tanks. Hence, the model calibration and validation could not be performed to Hakwatuna & Kimbulwana Oya sub-catchments. Therefore, calibration and validation were performed only to remaining two sub-catchments. Out of those two sub-catchments, Deduru Oya is the major determinant in managing the water level of the reservoir during the heavy rainfall events.

5.4.2 Optimization of model parameters at daily time step

Initially, the performance of the hydrological model was tested at daily time step. The default parameter values in the SWAT model and the daily 4ONSE data were used for this initial run. However, due to the significance difference in the simulated flow and observed flow, the model was regionalized first by examining the stream flow signatures. Figure 68 (a) and (b) show the simulated and observed daily stream flow patterns for Deduru Oya and Maguru Oya sub-catchments respectively. In here, the observed flow was obtained by averaging the 10 minutes interval water level data into daily interval and converting the water level into flow through Irrigation Department's stage-discharge relationship equations (Equation 16 and 17). Table 28 shows the reasons for the differences and influencing parameters for each observation in two sub-catchments. The highlighted parameters in ash colour show the causal parameters with reference to each observation. The causal parameters were identified by performing OAT sensitivity analysis.

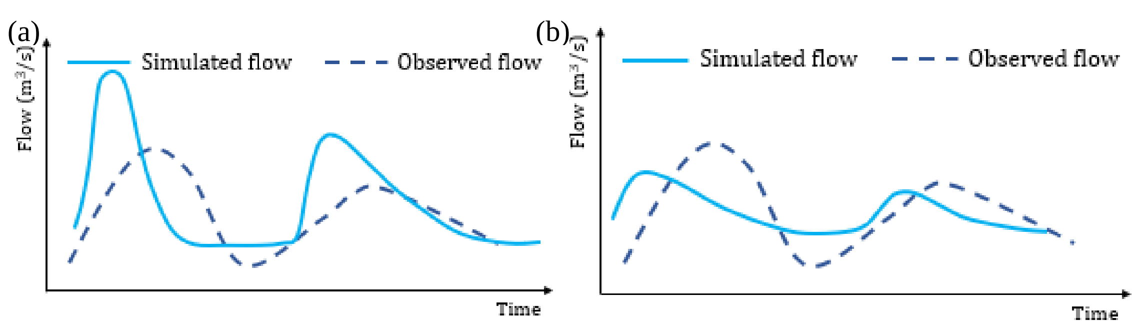


Figure 68: Observed and simulated flow patterns of (a) Deduru Oya sub-catchment (b) Maguru Oya sub-catchment

Table 28: Regionalized parameters of Deduru Oya and Maguru Oya sub-catchments

Sub-catchment	**Observation**	**Reason**	**Related parameters**	**Change need to apply**
Deduru Oya sub-catchment	High peaks	High surface flow	Curve number (CN2), Soil available water (SOL_AWC), Soil evaporation compensation factor (ESCO), Maximum canopy storage (CANMX)	Increase CANMX
	Model over predicts the flow	High baseflow and / or little evapotranspiration	Deep percolation parameter (GWQMN), Groundwater revap coefficient (GW_REVAP), Threshold depth of water in shallow aquifer (REVAPMN)	Increase GWQMN & GW_REVAP
	Discharge was shifted to left	Simulated flow leads the actual flow	Slope (SLOPE), Manning's roughness coefficient (OV_N), Overland flow length (SLSUBBSN), Manning's "n" value for the main channel (CH_N2)	Increase CH_N2
Maguru Oya sub-catchment	Model over predicts the flow	High baseflow and / or little evapotranspiration	Deep percolation parameter (GWQMN), Groundwater revap	Increase GWQMN & GW_REVAP

			coefficient (GW_REVAP), Threshold depth of water in shallow aquifer (REVAPMN)	
	Discharge was shifted to left	Simulated flow leads the actual flow	Slope (SLOPE), Manning's roughness coefficient (OV_N), Overland flow length (SLSUBBSN), Manning's "n" value for the main channel (CH_N2)	Increase CH_N2

Table 29 shows the regionalized parameters and their optimal values. 50 runs were performed to get the optimal values.

Table 29: Regionalized parameters and their optimal values

Sub-catchment	**Parameter**	**Optimal value**
Deduru Oya sub-catchment	CANMX (Coconut)	95mm
	CANMX (Rice)	71mm
	CANMX (Low density residential)	43mm
	CANMX (Rubber)	43mm
	GWQMN	1900mm
	GW_REVAP	0.1016
	CH_N2	0.3
Maguru Oya sub-catchment	GWQMN	5565mm
	GW_REVAP	0.02
	CH_N2	0.0.087

CANMX (Maximum canopy storage) parameter is used to indicate maximum amount of water that can be retained by the trees. This value is zero by default in SWAT database.

However, CANMX has become a sensitive parameter only for Deduru Oya sub-catchment. During the OAT analysis, variation of sensitivity levels was observed among dominant land use categories (Coconut, Rice, Low density residential, Rubber) of Deduru Oya sub-catchment. As CANMX is a parameter which introduces water into the system, it was calibrated separately for dominant land uses of Deduru Oya sub-catchment.

For Deduru Oya sub-catchment, GWQMN and GW_REVAP are the parameters sensitive for processes related to baseflow and evapotranspiration. GWQMN shows the threshold depth of water in the shallow aquifer, while GW_REVAP is a coefficient to represent the approach of water from the shallow aquifer to root zone. GWQMN's and GW_REVAP's default value in SWAT database is 1000mm and 0.02 respectively. Approach of groundwater to stream occurs when the depth of water in the shallow aquifer is identical or larger than to GWQMN value. GW_REVAP coefficient ranges 0 – 1. By increasing the GW_REVAP value, the rate of movement of water from the shallow aquifer to the upper surface can be improved. Hence, after performing 50 runs in SWAT_CUP, the optimal values received for GWQMN and GW_REVAP parameters were higher than its usual default values. Therefore, by increasing the GWQMN and GW_REVAP parameter values, the problem of over-predicting the flow could be solved.

In both Maguru Oya and Deduru Oya sub-catchments, the simulated flow leads the actual flow. This shift could not be corrected by changing the SLOPE, OV_N and SLSUBBSN values. The only parameter which sensitive to this shift was CH_N(2). CH_N(2) parameter represent the Manning's "n" value for the main channel. The value changes with the channel type. The default CH_N(2) value in the SWAT database is 0.014. As per the Manning's n value suggested by Chow (1959) for channels, the value is low for channels which allow smooth flow of water, and vice versa. Both Maguru Oya and Deduru Oya stream presence of large rocks, bushes and trees along the stream flow path which hinders the smooth flow of water. Hence the actual CH_N(2) value of two streams are greater than the default CH_N(2) value in the SWAT database.

The next task was, daily calibration of the model to examine the performance of the model to simulate the daily stream flow. For that, OAT sensitivity analysis was performed to identify the sensitive / dominant parameters of Deduru Oya and Maguru Oya sub-catchments with reference to daily time step. Accordingly, Tables 30 and 31 shows all the sensitive / dominant parameters of Deduru Oya and Maguru Oya sub-catchments selected through OAT analysis. The ranges applied for the 1st iteration have been carefully selected by examining the sensitivity of the parameters related to different ranges. SWAT-CUP suggests new parameter ranges at the end of each iteration. These new parameter ranges are used to perform another iteration if the performance of the previous iteration is unsatisfactory. Both sub-catchments have produced acceptable result (both visually and statistically) during the 4th iteration. Accordingly, the uncertainty levels of parameters can be obtained at the 4th iteration. Number of runs performed at each iteration were 500. When performing more iterations, the parameter ranges become smaller and enlarge better region of the parameter space (Abbaspour, 2008). The visual result of simulated and observed daily flow is illustrated in Figure 69 and 70 and the statistical result is shown in Table 32.

Table 30: Sensitive parameters & their ranges related to daily simulation at Deduru Oya sub-catchment

Parameter	**Type of change**	**Category**	**Ranges applied at 1st iteration**	**Ranges applied at 4th iteration (Parameter uncertainties)**	**Optimum value**
CN2	R_	HRU management level parameter	(-0.2) – 0.2	0.14 – 0.25	0.23
SOL_AWC	R_	Soil parameter	(-0.2) – 0.2	(-0.14) – 0.03	(-0.09)

ESCO	V_	HRU level parameter	0.3 - 1	0.68 – 0.95	0.69
SOL_BD	R_	Soil parameter	(-0.2) – 0.2	(-0.12) – 0.06	(-0.05)
MSK_X	V_	Watershed level parameter	0 – 0.3	0 – 0.14	0.12
MSK_CO2	V_	Watershed level parameter	0 - 1	(-0.04) – 0.59	0.11
MSK_CO1	V_	Watershed level parameter	0 - 1	0.96 – 1.31	1.15
ALPHA_BF	V_	Groundwater parameter	0 - 1	(-0.17) – 0.23	0.22
SOL_K	R_	Soil parameter	(-1) - 1	(-1.21) – 0.06	(-1.09)
CH_K2	V_	Water routing parameter	0 – 10	4.27 – 6.73	4.59
CH_N1	V_	Sub-basin level parameter	0 – 1	(-0.13) – 0.20	0.02
CH_N2	V_	Water routing parameter	0 – 0.1	0.04 – 0.06	0.06
GW_DELAY	V_	Groundwater parameter	0 – 200	38.90 – 89.94	42.42
GW_REVAP	V_	Groundwater parameter	0.02 – 0.5	0.24 – 0.45	0.37
GWQMN	R_	Groundwater parameter	1 - 3	3.14 – 4.32	4.23

Table 31: Sensitive parameters & their ranges related to daily simulation at Maguru Oya sub-catchment

Parameter	**Type of change**	**Category**	**Ranges applied at 1st iteration**	**Ranges applied at 4th iteration (Parameter uncertainties)**	**Optimum value**
GWQMN	R_	Groundwater parameter	1 - 3	0.96 – 1.38	1.00
CN2	R_	HRU management level parameter	(-0.2) – 0.2	(-0.14) – (-0.03)	(-0.07)

CH_N2	V_	Water routing parameter	0 – 0.2	0.07 – 0.11	0.09
CH_N1	V_	Sub-basin level parameter	0 - 1	0.49 – 0.74	0.67
ALPHA_BNK	V_	Water routing parameter	0 - 1	(-0.02) – 0.31	0.09
CH_K2	V_	Water routing parameter	15 - 45	25.57 – 39.70	35.81
ESCO	V_	Soil parameter	0.3 - 1	0.41 – 0.64	0.46

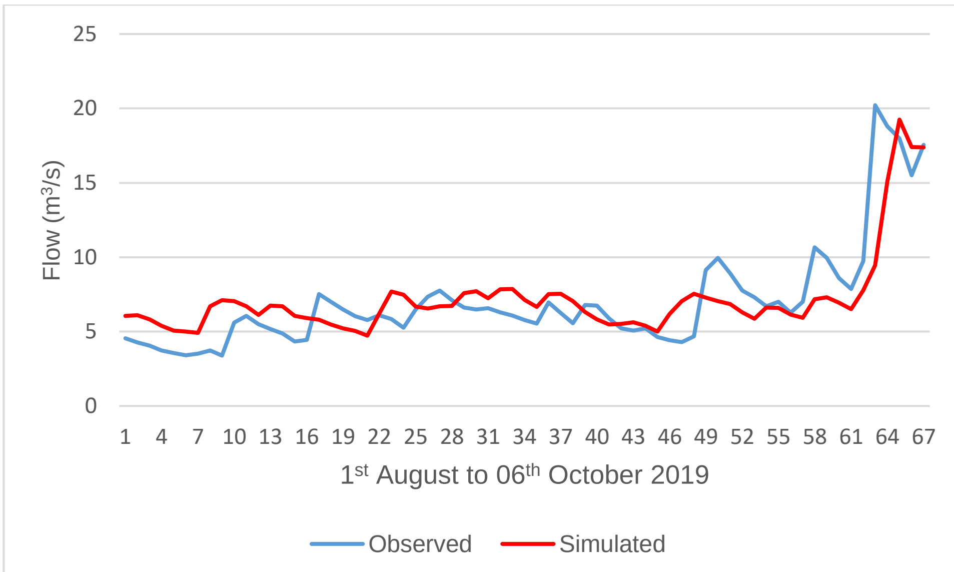


Figure 69: Observed and simulated daily flow for Deduru Oya sub-catchment during the period of 1st August to 06th October 2019

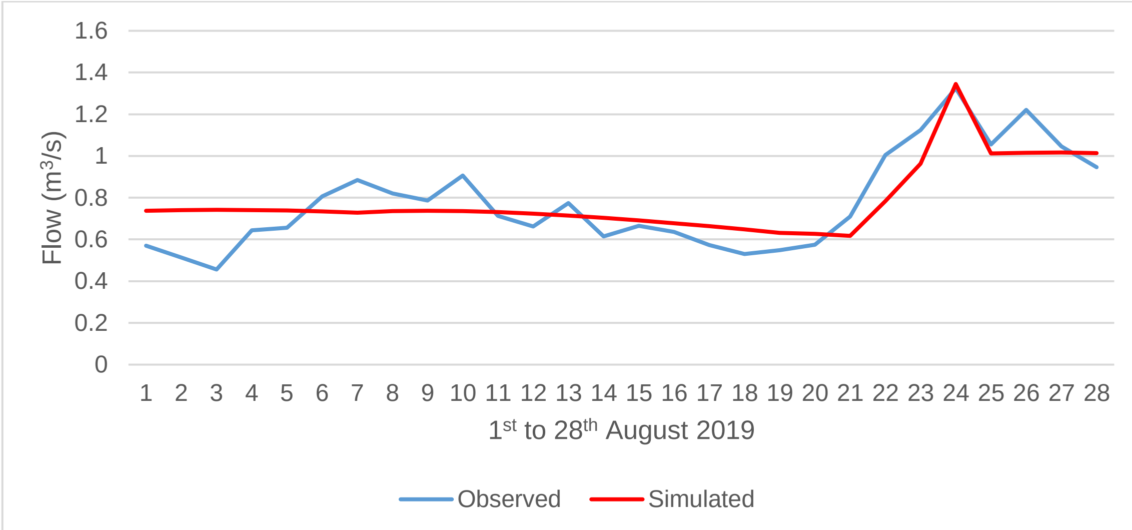


Figure 70: Observed and simulated daily flow for Maguru Oya sub-catchment during the period of 1st August to 28th August 2019

Table 32: Statistical results related to daily simulation

Sub-catchment	Period	P factor	R factor	R^2	NS
Deduru Oya Sub-catchment	1st August to 06th October 2019	0.87	0.98	0.69	0.69
Maguru Oya Sub-catchment	1st August to 28th August 2019	0.82	1.02	0.71	0.69

For both Deduru Oya and Maguru Oya sub-catchments, statistical results show better model performance at daily time-step. However, the model could not be further validated for daily time-step due to the unavailability of continuous dataset after the month of October.

5.4.3 Optimization of model parameters at hourly time step

The main intention of this research is to simulate the hourly stream flow of the Deduru Oya upper watershed. 4ONSE hourly weather data has been uploaded into the SWAT model and used the regionalized parameter values given in Table 29 to regionalize the model. For other parameters the default parameter values in the SWAT database have been applied. Next, the SWAT's hourly project files were uploaded to the SWAT-CUP for model parameterization and calibration. SWAT-CUP requires hourly stream flow / discharge to parameterize and calibrate the model. As explained in section 3.2.4, the MB7383 Ultrasonic Sensor which is used in the 4ONSE river gauges have shown downward trends in water level records in day time hours (around 07:00 to 16:00) due to solar heating. Therefore, to calibrate the hourly model, Irrigation Department's water level data obtained from Amunugama and Masptha river gauges have been used.

The sensitive parameters which identified for daily simulation may or may not be applicable for hourly simulation. Hence, OAT analysis was performed again to identify the dominant / sensitive parameters and their ranges related to hourly simulation. Table 33 and 34 shows the sensitive parameters and their ranges at hourly time step for Deduru Oya and Maguru Oya sub-catchments. The fourth column shows the approximate ranges applied at the first iteration and the fifth column shows the suggested ranges by the model to simulate the best result during the fourth iteration. When validating the model, the ranges of the fourth iteration have been applied. As the hydrological model developed in this research follows a stochastic modelling approach, the parameter values applied at different time periods are subjected to change. However, if those parameter values exist within the suggested range of the 4^{th} iteration, with acceptable model fitness, the model is considered as a validated model. Hence, the ranges suggested by the SWAT-CUP during the 4^{th} iteration were considered as the uncertainties of the parameters.

The model uses weather data of four stations (Paragahadeniya, Rambadagalla, Batalagoda and SB Herath) to simulate the river flows of Deduru Oya sub-catchment, while only one station's data (Lyceum) is used to simulate the river flows of Maguru Oya sub-catchment. The Figures 71 – 75 show the simulated result (hourly) for Deduru Oya sub-catchment, while the Figure 76 shows the simulated result (hourly) for Maguru Oya sub-catchment. As explained above, to calibrate the hourly simulation, Irrigation Department's water level data have been used. Out of the four upper streams, the reservoir receives the maximum flow from Deduru Oya stream. Hence, the Irrigation Department's automatic river gauges take continuous measurements only from the Deduru Oya stream via the river gauge located at Amunugama. The river gauge located at Maspotha does not have a continuous data set as Amunugama, due to low flows of Maguru Oya stream. Therefore, validation for Maguru Oya sub-catchment could not be performed.

Table 35 shows the statistical results related to model fitness. During the model calibration, the periods that the stations were unable to count the rainfall records were removed to obtain a better result. However, the performance of the model could not be tested for the rest of the months, due to missing data of Rambadagalla station. The rainfall data of Rambadagalla station was compared with a nearby station's rainfall data located at Bathalagoda during the months of September and October. As shown in Figure 77, the Rambadagalla station had continuous records of missing data for that period. The black colour and ash colour columns in Figure 77 show the Rambadagalla and Batalagoda stations' data respectively.

Table 33: Sensitive parameters of Deduru Oya sub-catchment with reference to hourly time step

Parameter	**Type of change**	**Category**	**Ranges applied at 1st iteration**	**Ranges applied at 4th iteration (Parameter uncertainties)**
CN2	R_	HRU management level parameter	(-0.2) – 0.2	(-0.3) – 0.1
SOL_BD	R_	Soil parameter	(-0.2) – 0.2	(-0.08) – 1.77
MSK_X	V_	Watershed level parameter	0 – 0.3	0 – 0.1
MSK_CO2	V_	Watershed level parameter	0 – 10	0 – 8.1

MSK_CO1	V_	Watershed level parameter	0 – 10	1.0 – 5.2
ALPHA_BF	V_	Groundwater parameter	0 – 0.3	0 – 0.2
SOL_K	R__	Soil parameter	(-1) - 1	(-0.47) – (-0.04)
SURLAG	V_	HRU level parameter	0 – 2	(-0.5) – 1.0
CH_K2	V_	Water routing parameter	1 – 50	1.1 – 27.3
CH_N1	V_	Sub-basin level parameter	0 – 1	(-0.3) – 0.7
CH_N2	V_	Water routing parameter	0 – 0.5	0 – 0.7
GW_REVAP	V_	Groundwater parameter	0.02 – 0.2	0.1 – 0.2
GWQMN	R_	Groundwater parameter	0.63032 - 1.35957	0.8 – 2.0

Table 34: Sensitive parameters of Maguru Oya sub-catchment with reference to hourly time step

Parameter	**Type of change**	**Category**	**Ranges applied at 1st iteration**	**Ranges applied at 4th iteration (Parameter uncertainties)**
CN2	R_	HRU management level parameter	(-0.2) – 0.2	(-0.12) – (-0.02)
SOL_BD	R_	Soil parameter	(-0.2) – 0.2	0.10 – 0.19
ESCO	V_	HRU level parameter	0.3 - 1	0.2 – 0.4
GW_DELAY	V_	Groundwater parameter	0 - 200	67 - 140

ALPHA_BF	V_	Groundwater parameter	0 – 0.25	0.03 – 0.11
SOL_K	R_	Soil parameter	(-1) - 0	(-0.6) – (-0.22)
GWQMN	R_	Groundwater parameter	(-0.8) – (-0.3)	(-0.17) - 0
GW_REVAP	V_	Groundwater parameter	0.02 – 0.2	0.08 – 0.13
CH_N2	V_	Water routing parameter	0 – 0.4	0.25 – 0.34
SURLAG	V_	HRU level parameter	0 – 0.25	0.02 – 0.06

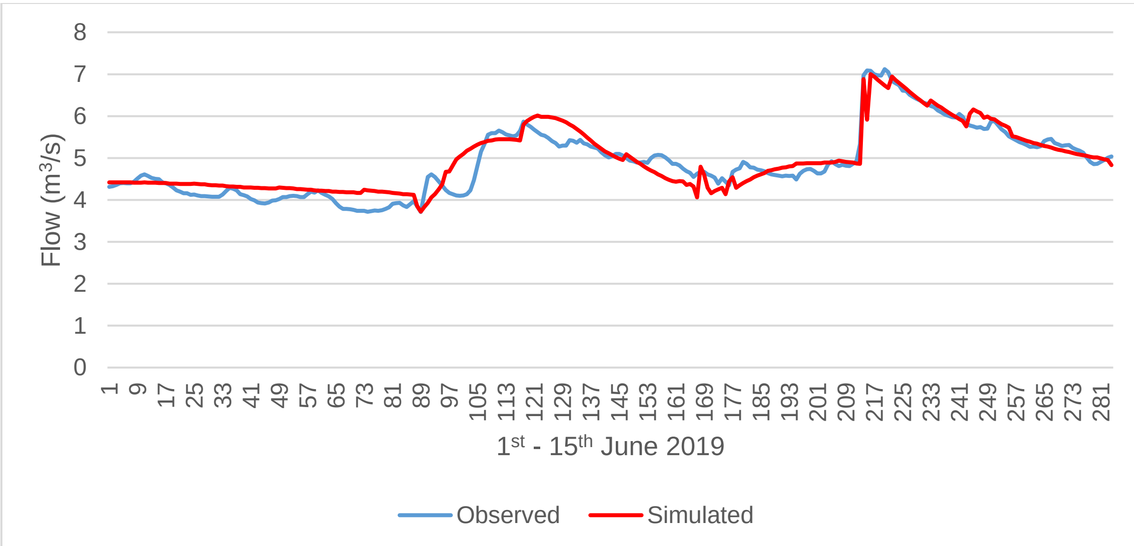


Figure 71: Observed and simulated hourly flow of Deduru Oya sub-catchment during the period of 1st June – 15th June 2019

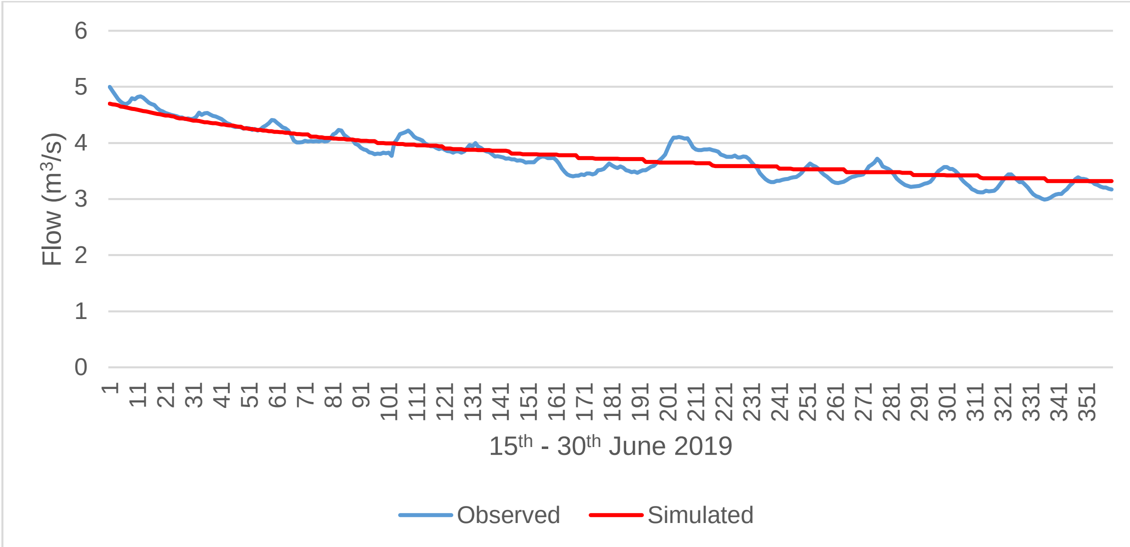


Figure 72: Observed and simulated hourly flow of Deduru Oya sub-catchment during the period of 15th June – 30th June 2019

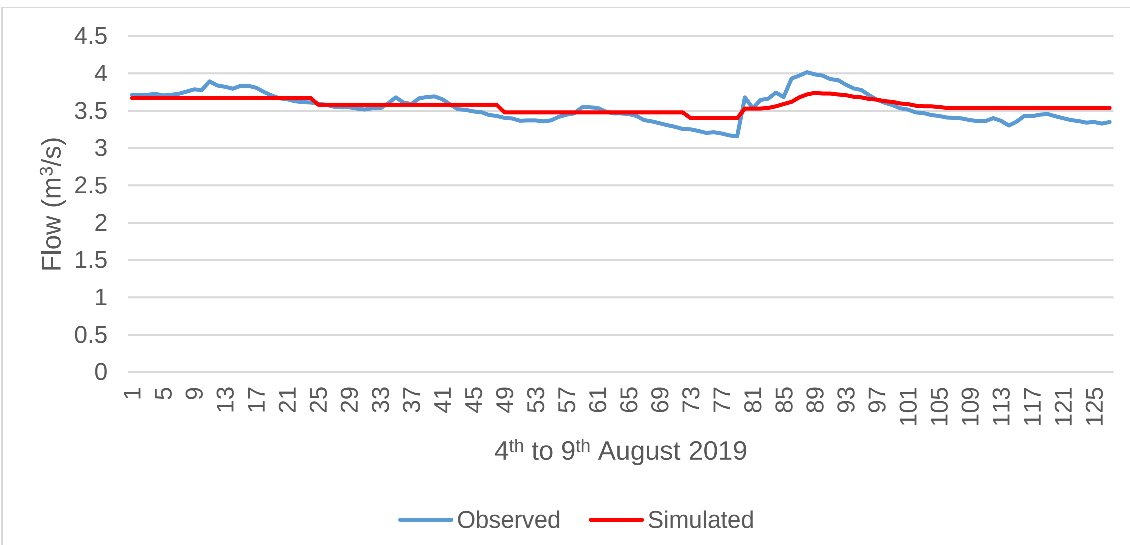


Figure 73: Observed and Simulated hourly flow for Deduru Oya sub-catchment during the period of 4th August to 9th August 2019

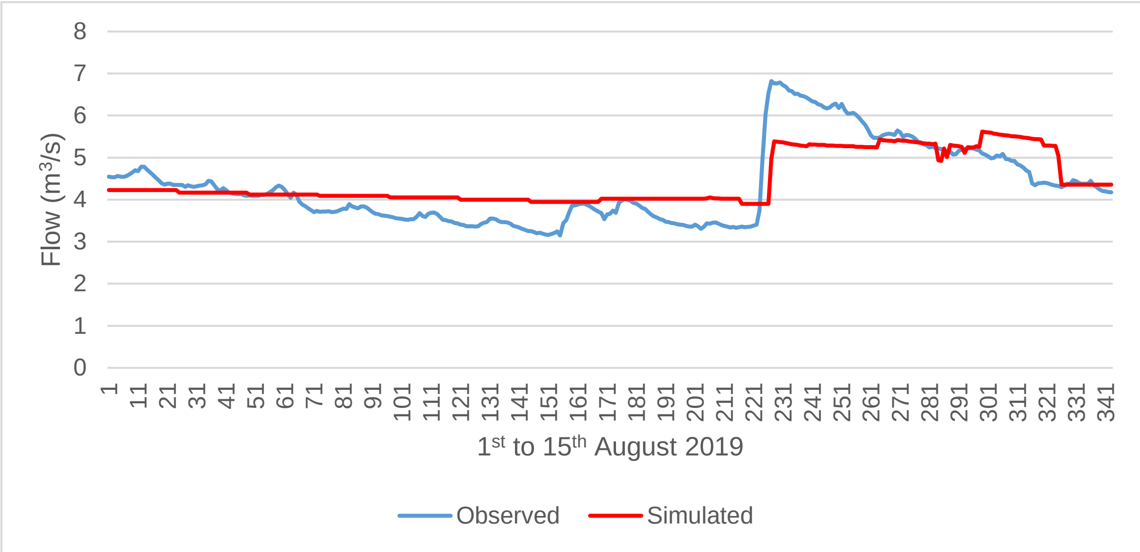


Figure 74: Observed and Simulated hourly flow for Deduru Oya sub-catchment during the period of 1st August to 15th August 2019

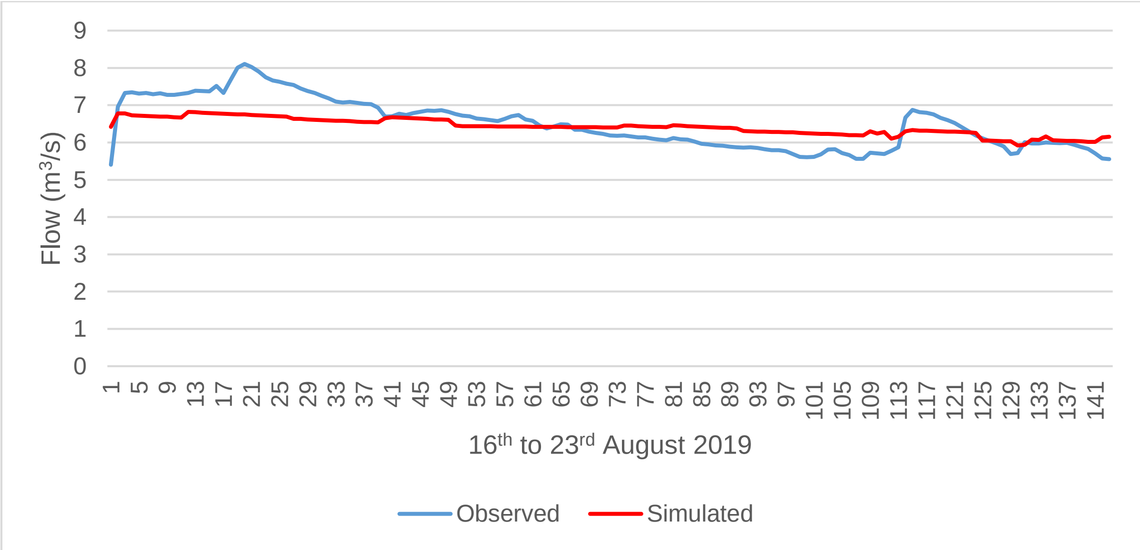


Figure 75: Observed and Simulated hourly flow for Deduru Oya sub-catchment during the period of 16th August to 23rd August 2019

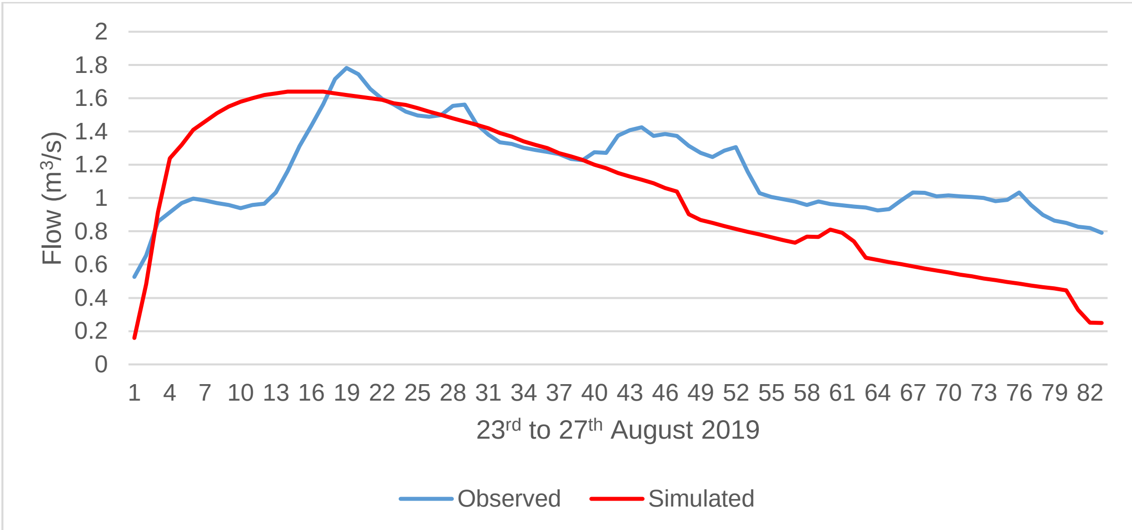


Figure 76: Observed and Simulated hourly flow for Maguru Oya sub-catchment during the period of 23rd August to 27th August 2019

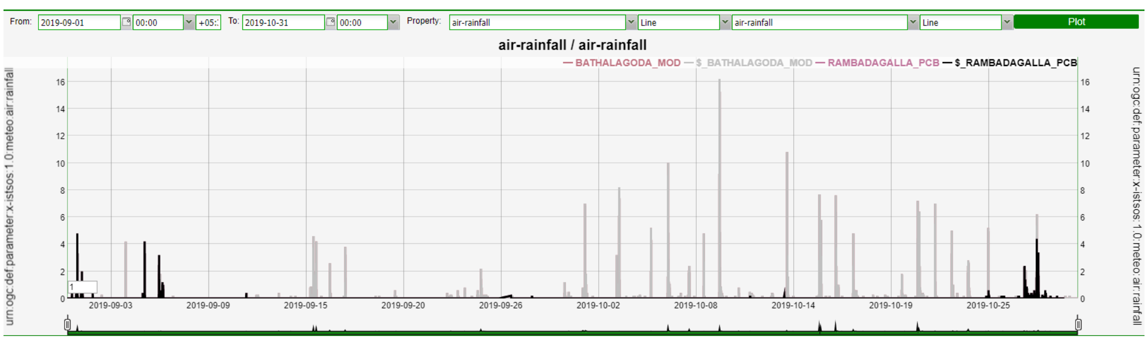


Figure 77: istSOS view of rainfall data in Rambadagalla and Batalagoda stations during the months of September and October in 2019

Table 35: Statistical results related to hourly simulation

Sub-catchment	**Period**	**P factor**	**R factor**	**R^2**	**NS**	**Dry / Wet**
Deduru Oya Sub-catchment	1st to 15th June 2019	0.96	0.76	0.76	0.75	Dry
	15th to 30th June 2019	0.96	0.89	0.89	0.88	

	4th to 9th August 2019	1.0	0.53	0.77	0.55	Wet
	1st to 15th August 2019	0.74	0.54	0.67	0.63	
	16th to 23rd August 2019	0.83	0.00	0.67	0.43	
Maguru Oya Sub-catchment	23rd to 27th August 2019	0.70	0.56	0.59	0.42	Wet

As per the statistical results given in Table 35, the performance of the model in simulating the hydrological processes at hourly time step is satisfactory. The Davis rain gauge used in the 4ONSE weather stations usually have an error percentage of ±4% for rain rates up to 50mm/hour and ±5% for rain rates within the range of 50mm/hr to 100mm/hr. This is the main causative factor for some of the peaks that the model was unable to reach to its level. Since the model operates in hourly basis, the continuity of the data in the 4ONSE stations is also significantly affect for the model's performance. For an example, Figure 78 shows the hourly simulated and observed flow of Deduru Oya sub-catchment during the period of 1st June to 15th June 2019. Within that period, underestimation of stream flow can be seen within 5th June to 7th June 2019 period. Deduru Oya sub-catchment use weather data of 4 stations (Paragahadeniya, Rambadagalla, Batalagoda & SB Herath) to run the model. Out of these 4 stations, Paragahadeniya station had missing data during 4th June to 8th June 2019 (Figure 79). Usually stream flow starts to rise after the occurrence of rainfall. Accordingly, missing data in the Paragahadeniya station has caused to underestimate the simulated flow of Deduru Oya sub-catchment. Hence, availability of continuous rainfall data in 4ONSE stations is essential to produce better model result and the SWAT weather generator could not be used to compensate such missing data.

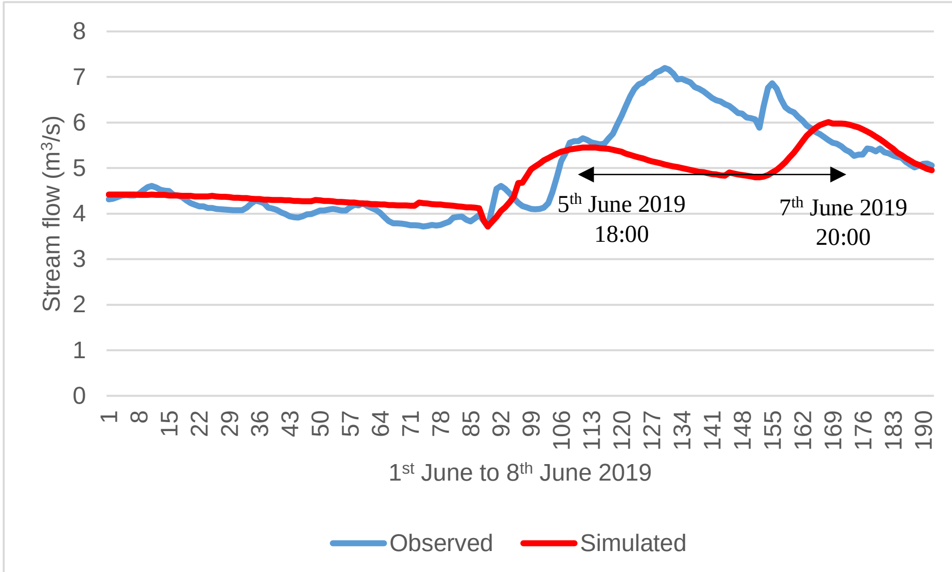


Figure 78: Simulated and observed flow of Deduru Oya sub-catchment during 1st June to 8th June 2019

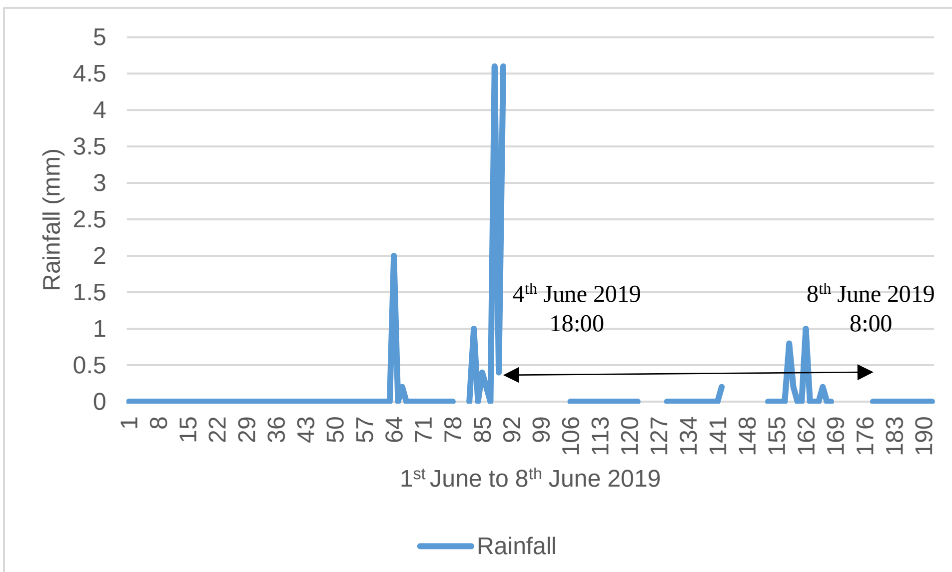


Figure 79: Rainfall of Paragahadeniya weather station during 1st June to 8th June 2019

5.4.4 Parameter comparison between daily and hourly models

This section elaborates the sensitive / dominant parameter comparison of Deduru Oya sub-catchment with reference to daily and hourly simulation. Except the SOL_AWC, ESCO, GW_DELAY and SURLAG parameters, all the other parameters were received as sensitive for both daily and hourly time interval for Deduru Oya sub-catchment. As the time narrows down to hours, the contribution of SOL_AWC, ESCO and GW_DELAY parameters have become insignificant and the SURLAG parameter has become significant to simulate the hourly flows. The model suggests both Muskingum coefficients should be greater than 1, for simulating the hourly flows. Due to the left shift of the simulated stream flow shown at the beginning of the model, the CH_N2 parameter was regionalized first by increasing the value. However, during the daily simulation it was stabilized again into a lower value which is about 0.06, and the model has recommended again to go for a higher CH_N2 value (greater than 0.1) for hourly simulation.

5.4.4 Parameter comparison between wet and dry periods

Figure 80 shows the variation of parameter values during the dry and wet periods which were taken for calibration and validation. Since the SUFI2 algorithm used in the SWAT-CUP calibration assessment tool follows a stochastic modelling approach, the model cannot be run using a single parameter set. Hydrological parameters cause for changes, due to the continuous changes in the climatic and geographic processes. As per the Figure 80 and Table 36, the parameters such as MSK_X, MSK_CO1, ALPHA_BF, CN2 and GW_REVAP have shown very slight variation, while the remaining parameters have shown significant variations during the dry and wet periods.

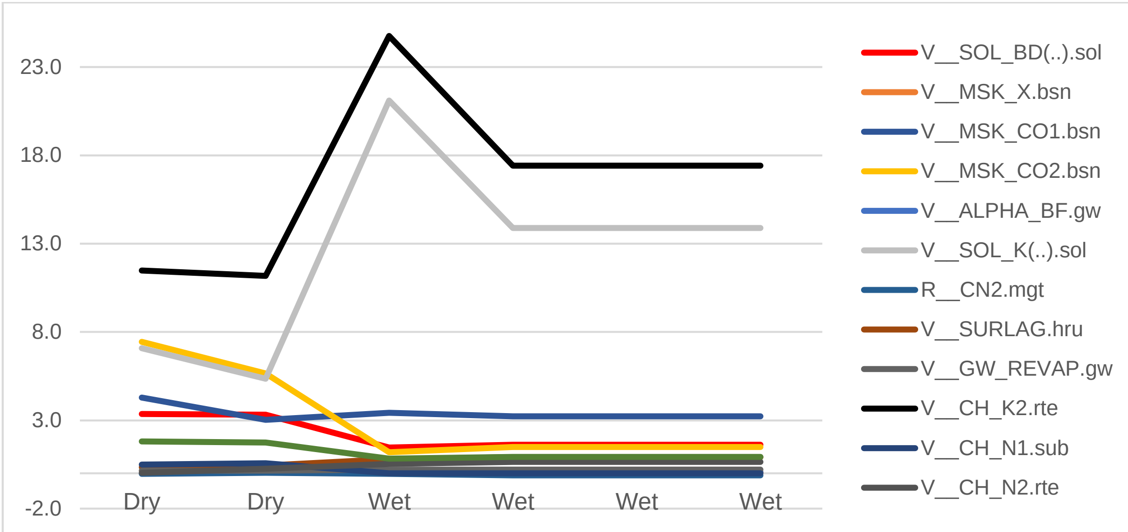


Figure 80: Variation of parameter values during the dry and wet periods in Deduru Oya sub-catchment

Table 36: Parameter values received for dry and wet periods

Parameter	**Dry period**		**Wet period**				
V__SOL_BD(..).sol	3.4	3.3	1.5	1.6	1.6	1.6	1.6
V__MSK_X.bsn	0.1	0.1	0.1	0.1	0.1	0.1	0.1
V__MSK_CO1.bsn	4.3	3.0	3.4	3.2	3.2	3.2	1.8
V__MSK_CO2.bsn	7.4	5.7	1.2	1.5	1.5	1.5	0.4
V__ALPHA_BF.gw	0.0	0.1	0.1	0.1	0.1	0.1	0.1
V__SOL_K(..).sol	7.1	5.4	21.1	13.9	13.9	13.9	21.1
R__CN2.mgt	0.0	0.0	0.0	-0.1	-0.1	-0.1	-0.3
V__SURLAG.hru	0.3	0.4	0.8	0.9	0.9	0.9	0.2
V__GW_REVAP.gw	0.1	0.2	0.2	0.2	0.2	0.2	0.2
V__CH_K2.rte	11.5	11.2	24.8	17.4	17.4	17.4	26.1
V__CH_N1.sub	0.5	0.6	0.0	0.0	0.0	0.0	0.0

V__CH_N2.rte	0.0	0.3	0.5	0.6	0.6	0.6	0.6
R__GWQMN.gw	1.8	1.7	0.8	0.9	0.9	0.9	0.9

5.5 Application of tank management model

The model which has been developed in this research using SWAT open-source software, cannot be directly used for flood modelling. It only helps to simulate the incoming flow to the reservoirs/ tanks which subsequently supports for mitigating downstream flash floods which occur as a result of opening reservoir gates.

However, the simulated inflows by the model can be applied in the SWAT's reservoir management tool to build scenarios to assess the reservoir capacity and the outflow of the reservoir. Such results can be coupled with open-source hydraulic modelling software like HEC-RAS to develop flood models and to prepare flood inundation maps. Though, the current SRTM DEM layer used in the SWAT model does not adequate to HEC-RAS, as it requires high resolution DEMs to identify the flood depths.

5.5.1 Application of 4ONSE data in the hydrological model for water pre-release decisions at Deduru Oya reservoir

With reference to fifth sub-objective, this section demonstrates two applications with reference to Deduru Oya reservoir:

1. application of sample of 4ONSE weather dataset and optimized parameters in the hydrological model to obtain outputs
2. application of outputs of the hydrological model to estimate the amount of water that should be pre-released and to estimate the opening heights of the reservoir gates

Table 37, shows the sample of dataset which has been used to run the hydrological model. The third column of Table 38 output of the hydrological model with reference to the dataset shown in Table 37. As per the experience of the reservoir operators of Deduru Oya reservoir, usually it takes nearly 6 hours to reach water to the reservoir after the occurrence of rainfall in the Deduru Oya upper sub-catchment. According to the data given in Table 25, the water level of the reservoir starts to rise at 5pm.

Table 37: 4ONSE weather data at 4 stations in Dedruru Oya sub-catchment

Parameter	**Date & Time**		**Location of the 4ONSE station**			
			Paragahadeniya National College	**Rambadagalla Central College**	**Batalagoda Rice Research Institute**	**SB Herath National School**
Hourly rainfall (mm)	4^{th} June 2019	10am	1	0	0	0.2
		11am	0	2.6	0.6	1.2
		12noon	0.4	0.6	5.8	7.2
		1pm	0.2	0	0	0
		2pm	0	0	0	0
		3pm	4.6	25.2	2.8	3.6
		4pm	0.4	0	0.8	11.2
		5pm	4.6	0	0	19.2
Daily average maximum temperature (^{0}C)	4^{th} June 2019		-99	32.29	30.01	31.81
Daily average minimum temperature (^{0}C)	4^{th} June 2019		-99	23.44	23.93	24.27
Daily relative	4^{th} June 2019		-99	81.92	90.64	77.74

humidity (%)					
Daily wind speed (ms^{-1})	4th June 2019	-99	0.26	1.02	0.32

Table 38: Results of the scenario generation

Day	**Time**	**[a]Flow of Deduru Oya sub-catchment(m^3/s)**	**[b]Flow of other sub-catchments (m^3/s)**	**[c]Total flow to the reservoir (m^3/s)**	**[d]Height of the radial gate opening (m)**
04th June 2019 (Day 1)	t=5pm	4.14	2.76	6.90	0.5
	t=6pm	4.55	3.03	7.58	0.5
	t=7pm	4.61	3.07	7.69	0.5
	t=8pm	4.55	3.03	7.58	0.5
	t=9pm	4.44	2.96	7.41	0.5
	t=10pm	4.34	2.90	7.24	0.5
	t=11pm	4.23	2.82	7.06	0.5
5th June 2019 (Day 2)	t=0am	4.17	2.78	6.95	0.5
	t=1am	4.14	2.76	6.90	0.5
	t=2am	4.10	2.74	6.84	0.4
	t=3am	4.10	2.73	6.83	0.4
	t=4am	4.10	2.74	6.84	0.4
	t=5am	4.13	2.76	6.89	0.5
	t=6am	4.23	2.82	7.04	0.5
	t=7am	4.47	2.98	7.46	0.5
	t=8am	4.81	3.21	8.02	0.5
	t=9am	5.15	3.43	8.58	0.6

	t=10am	5.33	3.56	8.89	0.6
	t=11am	5.56	3.70	9.26	0.6
	t=12noon	5.59	3.73	9.32	0.6

[a] – This column represents the output generated by the model

[b] – As per the Figure 27, the flow of the other sub-catchments (Maguru Oya and combined flow of Kimbulwana and Hakwatuna Oya) was assumed as 2/3rd of the Deduru Oya sub-catchment's flow

[C] – This column represents the total flow of 3rd and 4th columns

[d] – The Equation 25 was applied when calculating the height of the radial gate opening

$$h_t = \frac{Q_t}{n \times w \times v} \quad \text{Equation 25}$$

Where h_t is the height of the redial gate opening at t^{th} hour, Q_t is the discharge at t^{th} hour, n is the number of radial gates decided to open (Deduru Oya reservoir has 8 radial gates. For this example, the number of radial gates decided to open was thought as 3), w is the width of each radial gate (8.5m), v is the average velocity of water discharged at radial gates (it was assumed v as 0.6m/s).

As per the resultant data shown in Table 38, the reservoir managers can decide the opening height of the reservoir gates at each hour, in order to accommodate the new flow. Accordingly, by knowing the incoming flow to the reservoir few hours before, helps the reservoir operators to take water pre-release decisions.

5.5.2 Application of tank management model to a different river basin

The tank management model developed in this research can be applied to any other river basin in the country. For that, the approach demonstrated in Figure 51, can be followed to develop the hydrological model. The watershed and the sub-basins boundaries should be delineated first. The data such as DEM, soil, CFSR weather data can be downloaded from the links mentioned in the Table 19. The stream network of the relevant river basin needs to digitize using QGIS or any other GIS software. In addition, the model requires land use of the selected river basin. Land use data can be freely downloaded from SWAT website, or else need to purchase from the Survey Department. Prior to run the model, all the land use and soil classes need to classify as per the FAO’s classification scheme and need to produce a database including monthly weather statistics of the relevant basin. These monthly statistics can be calculated from the CFSR data. The required daily and sub-daily weather data has to be obtained from weather stations from the upper basin area. In absence of weather data, satellite retrieved weather data and as well as estimated / forecasted weather data of numerical weather prediction models can also apply in the model.

The approach presented in Figure 54, can be used to calibrate the model through SWAT-CUP. This requires daily and sub-daily water level data from river gauge/s which locate at the basin outlet. If the river basin has several stream networks, it is better to divide the basin into several sub-catchments based on them and need to create several sub-models to calibrate each sub-catchment.

However, the model presented in this research is more applicable to simulate the incoming flow to the tank / reservoir. If there’s any series of tanks / cascade system in the basin, the daily and sub-daily discharge flow of the tanks in the upper basin need to be taken into consideration when developing the model.

The simulation time interval applied in the model can be changed as per the requirement of the decision makers who make the decisions pertaining to water pre-release. Customizing the weather data and optimizing the parameters have to be performed according to the selected time interval. Moreover, application of near-real time weather data in the model is more valid when the time required for decision making is greater than the time taken to concentrate water to the tank/reservoir from the upper basin. Therefore, forecasted data of numerical weather prediction models have to apply if the decision making needs to perform at very limited time. The following section demonstrates an approach of obtaining ERA5-land data portal climate data which have been derived from numerical weather prediction models.

5.5.3 A demonstration of obtaining ERA5 data derived from numerical weather prediction models

ERA5-land data portal which is maintained at Copernicus geographic data service allied with European space agency can be considered as one of the free and open, accurate climatic data store that allows temporal data extraction over last few decades. It contains Modeled data series which is processed accordance with the laws of physics. ERA5-land Data Set is generally called as reanalysis data set due to its levels of processing and modeling. Reanalysis produces data that goes several decades back in time, providing an accurate description of the climate of the past. It uses several atmospheric variables to estimate and interpolate climatic data with high consistency. Air temperature and humidity parameters are used to correct the modeling errors of other climatic parameters at Reanalysis. The following is the link to extract ERA5 data:

https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land

The climate data categories available in the above link are:

1. ERA5-Land monthly averaged data from 2001 to present
2. ERA5-Land hourly data from 2001 to present
3. ERA5 monthly averaged data on pressure levels from 1979 to present
4. ERA5 hourly data on pressure levels from 1979 to present
5. ERA5 monthly averaged data on single levels from 1979 to present
6. ERA5 hourly data on single levels from 1979 to present

The above data sets are used to develop time series analysis in Climatic data modelling and predicting. However, climatic observations are not directly mapped as raw observations but modifies accordance with other atmospheric conditions. This is called as atmospheric forcing on climatic data estimating. In addition to that, based on the air pressure and the laps rates, climatic data estimation is reshaped.

Table 39 shows the available key data parameters available for hourly data estimation.

Table 39: Key data parameters available in the ERA5 dataset for hourly data estimation

Temperature	**Radiation and heat**	**Wind, Pressure and Precipitation**
2m dew point temperature	Forecast albedo	10m u-component of wind
2m temperature	Surface latent heat flux	10m v-component of wind
Skin temperature	Surface net solar radiation	Surface pressure
Soil temperature level 1	Surface net thermal radiation	Total precipitation
Soil temperature level 2		Surface sensible heat flux
Soil temperature level 3		Surface solar radiation downwards
Soil temperature level 4		

Temporal resolution and the spatial resolution of the data set highly support for the regional level data analysis. Specially these data can be integrated towards the flood and drought modelling. Key advantage of the data service is, it allows to download global data free of charge and support bulky downloads. Data can be downloaded through web api that compatible with python environment. Since it includes temporal data, multidimensional data supportive formats are used to process them. Figure 81 demonstrates the steps of extracting the data.

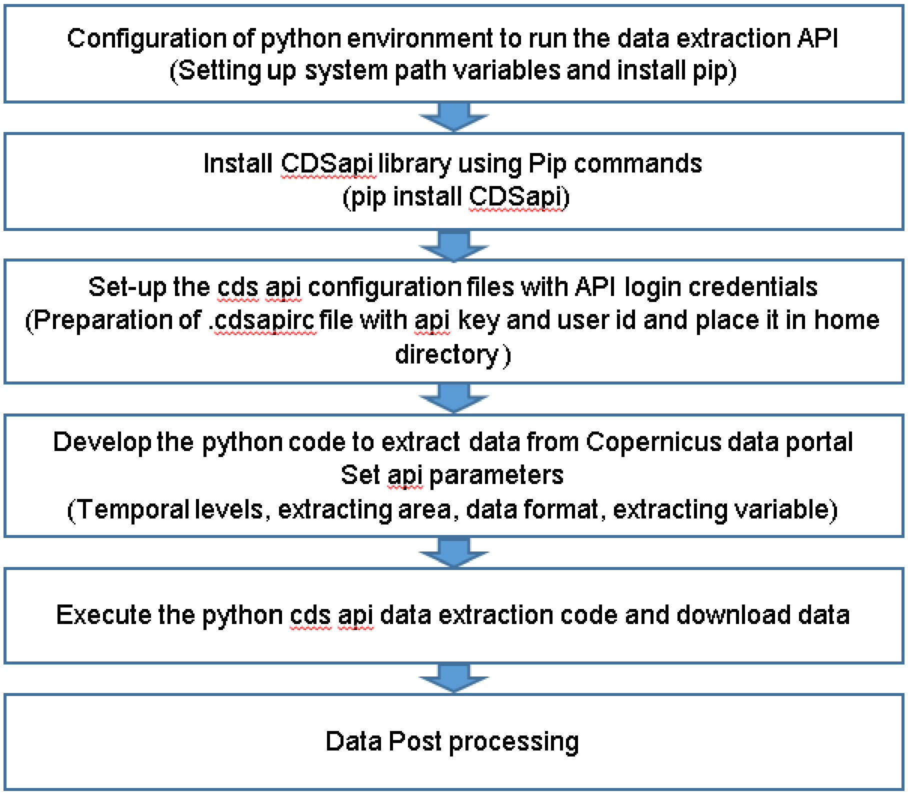


Figure 81: Steps of extracting data from ERA5

Data can be downloaded in grib and netcdf formats. These formats support multi-dimensional data storing for tempo-spatial data handling. Extracted data need to be converted in to other formats which can be analyze under spatial analytics. The example code for extracting data is given in Annexure 7. The data post processing approach is demonstrated in Figure 82.

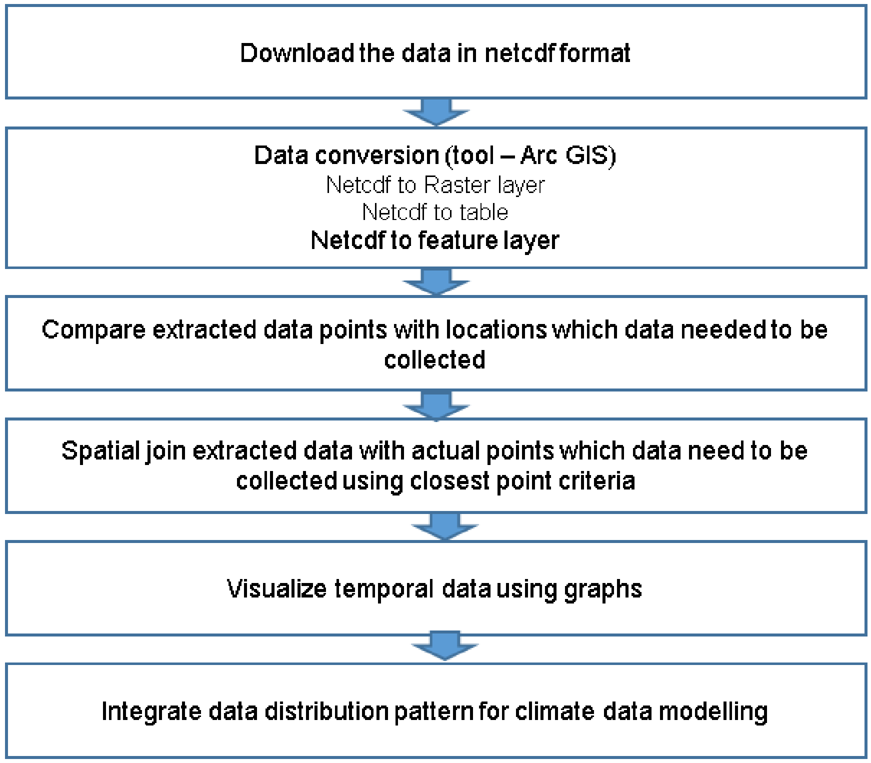


Figure 82: Post processing of data

CHAPTER 6
CONCLUSION

This chapter contains two sections. The section one summarizes the contribution of the research with respect to the main research objective and sub-objectives. The section two elaborates the limitations of the research and discusses the directions for future research.

6.1 Contributions of the Research

The main objective of this research is to develop open technologies-based tank management model for reservoir flood control. In this context, five research questions have been inquired through the literature review and five sub-objectives have been formulated with respect to state-owned hydro-meteorological data, hydro-meteorological network, hydrological modelling software, modelling parameters and application of hydrological models for reservoir pre-release decision making.

The first sub-objective of this research is to develop a hydrological model operated by combined open-source technologies for reservoir flood control and the second objective is to identify a suitable open-source hydrological modelling tool for this purpose. The tank management model, presented in this research operated as a hydrological model to simulate the hourly inflow to the Deduru Oya reservoir. Five types of open-source tools (QGIS Brighton version, QSWAT, SWAT Editor, SWAT-CUP, istSOS) have been used to develop the hydrological model and the data feed into the model was obtained from weather station network developed from three open-source technologies (Open hardware – Arduino, Open software – istSOS, Open standards – OGS-SOS). After comparing several open-source water resources management tools, SWAT tool has been selected to develop the hydrological model. Although more than 1500 research papers were published based on SWAT hydrological modelling tool, sub-daily applications remain limited. Moreover, over the last few decades, different researchers, practitioners and hobbyists have developed open hardware and software-based stations for environmental monitoring. However, application of combined open-source platforms to collect, store, sort, process and analyze data to support tank water release decision making have not been found in the literature as yet. Therefore, with respect to the first and second sub-objectives, this is the initial tank management model which has been developed using combined open-source technologies, to simulate the hourly inflow to the Deduru Oya reservoir. Further, this study introduces a new approach for making hazard warning in more remote environments where the environmental processes cannot be realistically monitored nor studied due to inaccessibility and lack of facilities.

The third sub-objective is to identify optimum locations for open-source weather station network for hydrological modelling. The research starts with determining the required number of stations and suitable locations to deploy them. Although World Meteorological Organization (WMO) recommends minimum station densities for different physiographic areas with some detailed standards on siting and calibrating the instruments used in the stations, they don't provide any guideline to decide number and optimum locations to deploy the stations. Since some of the most widely used parameters in hydrological modelling, such as precipitation can vary greatly with small distances, in reality, the required density is higher than the recommended density by the WMO. In previous works, the locations were selected primarily based on accessibility and network coverage. Hence, in this research a new approach has been presented to find the optimum locations for 4ONSE weather stations network to get maximum results from the hydrological models. Usually, when there are limited number of stations in and around the basin, the analysts need to estimate the input weather data uploaded into the hydrological model through different areal averaging methods, to get the optimum result. In this study, the converse has been applied; that is to get the optimum results from the hydrological models, the weather stations were deployed primarily based on the uncertainties of rainfall distribution, distance to sub-basins' centroids and some other factors such as accessibility, security, availability of open spaces and distance to water bodies.

The fourth sub-objective is to identify the dominant parameters and their values based on sub-catchment level and different temporal scales. The hydrological model presented in this research belongs to physically based semi-distributed modelling category and follows the stochastic modelling approach during the model parameterization. Therefore, the same set of parameters cannot be applied for the model for every occasion. Estimation of variation of parameter values with reference to different time periods (i.e. rainfall seasons, months) is tiresome, time consuming and labor and capital intensive. However, the hydrological modelling approach presented in this research avoids the necessity of pre-determined parameter values and allows users to determine them at any time, by following the procedure demonstrated in this study. The dominant or sensitive parameters and their values have been identified in this research at sub-catchment level for both hourly and daily time intervals and as well as for dry and wet periods. Further, hydrological models commonly divide into two types based on the available options to decide the initial condition of the catchment. Type one has an option to add initial river discharge, while type two allows to assign model warm-up period to estimate the initial river discharge. SWAT model belongs to type two category and requires at least a warm up period of one year to stabilize the model until the beginning date of the model simulation. The previous applications of SWAT have used historical weather data of at least one year for warm-up period. As 4ONSE is a newly deployed weather station network, the available data is inadequate to consider for the warm up period. Therefore, this is the first application, where a novel approach has been presented to utilize SWAT-weather generator to estimate the historical data required for the warm-up period. This approach prevents the underutilization of 4ONSE data for warm-up period while optimizes the application of 4ONSE data for the simulation period.

The fifth sub-objective is to apply outputs of the hydrological model to estimate the amount of pre-release water and opening heights of reservoir gates. Considering the existing literature, it appears that the ultimate outcome of most of the hydrological modelling approaches is to estimate the runoff based on the meteorological observations. Since runoff is part of the hydrological cycle, it cannot be modelled alone with precipitation data. Other meteorological inputs such as air temperature, humidity, solar radiation and wind speed are essential to compute components of the hydrological cycle and thereby to estimate the runoff. Further, flood management applications require generating modelling results with short lead time using near-real-time meteorological data as input data. Owing to the limitations of this existing setup, incorporating near-real-time and quality hydro- (Azharuddin & Jana, 2016)meteorological inputs in producing an accurate hydrological estimate to manage the flood risk in the river basin areas, has never been practiced in Sri Lanka. In this context, this research aiming at introducing a cost effective, open technologies-based decision support system to reservoir flood control.

6.2 Directions for Future Research

The selected locations for 4ONSE weather stations have shown adequate enough to simulate the sub-basin level runoff generated in the catchment. However, further researches need to execute to assess the suitability of the 27 locations in collecting weather observations from the 4ONSE stations. For an instance, one approach is to collect long-term data on precipitation and application of Shannon's entropy index to find how the uncertainty has spatially distributed with respect to the existing 4ONSE network arrangement. Accordingly, some stations can be shifted to places with higher rainfall uncertainties. The hydrological model's outputs can be also compared for different network arrangements to identify the best arrangement for simulating the hydrological processes in the catchment.

As the deterministic modelling approach has now been considered as outdated, the stochastic hydrological modelling approach presented in this research can be used to estimate the parameter values suitable for different time periods and different rainfall intensities. Therefore, further studies and 4ONSE weather data are needed to develop such parameter sets for different occasions. Further, the dense weather station network arrangement at Deduru Oya basin, lets users to obtain required input data from nearby station/s, when one or few stations become malfunctioned. As the parameter values are subjected to change based on the locations of the input data, different parameter sets can be developed through parameterization for different weather station collections. For an example, in this study, the required input data for Deduru Oya sub-catchment has been obtained from 4ONSE stations located at Paragahadeniya National School (PGD), Rambadagalla Central College (RBG), Batalagoda Rice Research Institute (RRI) and SB Herath National School (SBH). Accordingly, in this research parameterization of the Deduru Oya sub-catchment has been performed for the model run with PGD-RBG-RRI-SBH weather station collection. Presence of different parameter sets for different weather station collection lets model to be operated without any hassle, if there's any missing data in any weather station collection.

The major aim of implementing the 4ONSE project in Sri Lanka is to introduce a low cost and non-conventional weather station network for environmental monitoring. Hence, low cost sensors were selected to develop the stations. Out of these sensors, a low cost BH1750 light sensor module has been used to measure the light intensity due to the high cost of solar radiation sensors. In this study, SWAT's weather generator has been used to estimate the solar radiation (measured in W/m^2), since the 4ONSE stations measure the light intensity (measured in Lux) instead of solar radiation. There is no direct formula or a conversion factor to convert light intensity to solar radiation. Therefore, by way of developing conversion guide for light intensity, the measurements of the low cost BH1750 light sensor module can be also used as input data to run the model.

The 4ONSE weather stations are equipped with 0.2mm resolution 6465 Davis AeroCone rain gauge to measure the precipitation. This tipping bucket type rain gauge has not been proven better performance during the heavy rainfall events, as the small bucket inside the rain collector make rainwater to tipping off during the heavy rains. As a result of this rainfall underestimation, the model has not been capable enough to simulate some peaks during certain rainfall events. However, the manual of the Davis rain gauge has not provided any guide for percentage of measuring error for different rainfall intensities. If there's any error guide, the performance of the model can be further improved by customizing the rainfall data as per the error percentages given in the guide.

In this study, Irrigation Department's river gauge data has been used to calibrate and parameterize the model for hourly basis, owing to the solar heating problem in MB7383 ultrasonic sensor. This issue can be minimized by shielding the sensor and facilitating the air to flow around it. If not, an equation needs to be developed to use the temperature readings of the station to estimate the actual water levels based on them.

In this study, stage-discharge relationship equations developed by Irrigation Department has been used to convert the water level into a flow. They produced the equations only for river gauges in Deduru Oya basin (Maspotha bridge, Amunugama bridge and Ethiliyagala bridge), using their current meters. Most of the equations have been developed several years back and some of them are not suitable to estimate the stream flow, due to the change of stream morphology. A rating curve is a graph which represents stream water volume per unit time versus water level, for a given location on the stream. This rating curve is used to calculate the water volume based on water level. A rating curve / equation can be developed by obtaining stream velocities at selected points through a river cross section. To update the existing equations and to develop few more equations for newly identified locations of the stream, a low-cost mobile device based on open hardware can be developed to measure the stream velocities.

The hydrological model in this study has been developed using the SWAT (Soil and Water Assessment Tool) open source application. Over the past 20 years, the SWAT has become widely used across the globe for water resources modelling. However, the users must have certain knowledge on hydrological modelling and Geographical Information System (GIS) to use the SWAT tool for tank / reservoir management. The entire approach of getting data from the istSOS, preparing weather data files, uploading weather data files into the model, writing the input files, running the model and getting the SWAT outputs can be automated and simplified by way of developing a web application. Hence, if the entire approach of tank management can be customized to run as a web application, even a layman can get the final outputs from the model for decision making.

The Deduru Oya reservoir receives water from 14 sub-basins which are located in the upper watershed. A notification system, most probably as a SMS system can be developed to alert the reservoir managers to run the model when the upper sub-basins receive rainfall greater than a certain amount (i.e. 30mm). Through such a system, they can decide the time that the model should be run to determine the incoming flow to the reservoir.

The approach presented in this research can be easily applied to any other river basin in Sri Lanka to simulate the incoming flow to the reservoirs/tanks. However, application of near-real-time data to operate the model is more valid, if the time required for water pre-release decision making is greater than the time of concentration of that particular sub-basin. Conversely, the model can be also operated using the forecasted data of numerical weather prediction models. Though, the parameters have to optimize again with regard to the forecasted data and new river basin, prior to use the model for estimation of reservoir / tank inflow.

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Annexure 1 – Comparison of QSWAT, WEAP and HEC-HMS hydrological modeling tools

Aspect	**Selected hydrological modeling tools**		
	SWAT	**WEAP**	**HEC-HMS**
Developer	SWAT (Soil and Water Assessment Tool) was developed by Dr Jeff Arnold for the USDA (United States Department of Agriculture).	WEAP (Water Evaluation And Planning system) was created in 1988, and continues to be developed and supported by the U.S. Center of the Stockholm Environment Institute, a non-profit research institute based at Tufts University in Somerville, Massachusetts	HEC-HMS (Hydrologic Engineering Center - Hydrologic Modeling System) is a product of the Hydrologic Engineering Center within the U.S. Army Corps of Engineers.
Model Type	SWAT is a physically based semi-distributed continuous model. The physical processes associated with water movement, sediment movement, crop growth, nutrient cycling, etc. are directly modeled by SWAT using the input data of weather, soil properties, topography, vegetation, etc. SWAT is deterministic in nature, SWAT produces the same output every time. However, using the SWAT-CUP calibration and uncertainty program, the model outputs can be generated stochastically.	WEAP is a physically based model that which consider physical processes such as water supply, water demand, water routing, evaporation, runoff, soil moisture, etc.	HEC-HMS is a lumped model. Many of the models in the HEC-HMS contain parameters with a physical basis and may be estimated from measurable properties of the watershed to measure the properties such as evapotranspiration, movement of water, overland runoff of excess precipitation, melting of accumulated snowpack and solar radiation. HEC-HMS program is

			deterministic where all parameter values are taken as constant in time, even for long simulations.
Access to software	SWAT's Graphical User Interface (GUI) is embedded in the popular and widely used open source GIS environments – ArcGIS (ArcSWAT), QGIS (QSWAT) and MapWindow (MWSWAT).	WEAP evaluation version is only available to those who have joined the WEAP Forum. To fully activate your copy of WEAP, a valid License is required. WEAP issues a free license for non-profit, governmental or academic organization based in a developing country.	HEC-HMS is an open source software.
Applications	SWAT tool is applied in river basin scale hydrologic and water quality modeling.	WEAP can function as a database, a forecasting tool and a policy analysis tool. As a database, WEAP provides a system for maintaining water supply and demand information. As a forecasting tool, WEAP simulates water demand, supply, flows, storage, pollution generation, treatment and discharge. As a policy analysis tool, WEAP evaluates a full range of water development and management options and takes account of multiple and competing uses of water systems.	HEC-HMS is applied in the studies related to floods, reservoir design and environment.

Simulation of hydrology	The hydrologic cycle as simulated by QSWAT is based on the water balance equation. Simulation of the hydrology of the watershed was divided into two major divisions: 1. Land phase of the hydrologic cycle – this controls the amount of water, sediment, nutrient and pesticide loadings to the main channel in each sub-basin. 2. Water or routing phase of the hydrologic cycle – movement of water, sediments, etc. through the channel network of the watershed to the outlet.	WEAP is a water demand and supply accounting model (water balance accounting). Hence it places the demand side of the water balance equation[2] on a par with the supply side.	HEC-HMS was designed to simulate the precipitation-runoff processes of dendritic watershed systems. Basically it includes all of the different components of the hydrologic cycle: (a) It includes components for representing atmospheric conditions over a watershed (precipitation, evapotranspiration and snowmelt), (b) water flow over the land surface (infiltration, surface runoff, base flow), (c) water flow below the (stream flow with possible percolation losses)
Discretization schemes	The three most commonly used discretization schemes are grid cell, representative hillslope and sub-watershed. SWAT uses the sub-watershed configuration as the primary discretization scheme for a watershed. However, because of the routing command language utilized in SWAT it is possible to use any of these three, alone or in combination to model a watershed.	WEAP doesn't have any specific discretization scheme, since the components of the watershed are schematically represented.	WEAP doesn't have any specific discretization scheme, since the components of the watershed are graphically represented as nodes and lines.
Main Components	Includes 4 main components: (1) Delineate watershed - Use data on	Includes 5 main components: (1) Schematic view –	Includes 3 main components: (1) Basin model - gives the

	terrain, stream network, inlets and outlets to delineate watershed area and sub-basin boundaries (2) Create HRUs - Use land use and soil data to group the watershed area into different HRUs. (3) Edit Inputs and Run SWAT - Allows for running the SWAT Editor by connecting the model weather database (4) Visualize - Helps to visualize the outputs with reference to HRUs, Reaches, Sub-basins and Sediment loads	Components of the watershed are schematically represented in this view as nodes and lines. In addition, vector and raster files can be added as background layers. (2) Data view – Allows to create variables and relationships. Further, assumptions and projections can be created using mathematical expressions. (3) Results view – Allows to display all model outputs as charts and tables. (4) Scenario explorer – for viewing the scenarios (5) Notes – to document data and assumptions	physical description of the watershed. (2) Meteorological model - describes atmospheric conditions over the watershed land surface with respect to precipitation, evapotranspiration and snowmelt (3) Control specifications - time control during a simulation run.
Pixel based modeling	QSWAT allows for pixel-based modeling using raster data. The values related to input variables such as land use, soil and DEM should be in raster format prior to use them for modeling.	WEAP doesn't allow for pixel-based modeling. Hydrologic elements such as rivers, diversions, reservoirs, groundwater sources, supply sites, demand sites, catchments, flows, transmission links and gauges are represented schematically. However, when the built-in	Hydrologic elements such as subbasins, reaches, junctions, sources, sinks, reservoirs and diversions are represented schematically in HEC-HMS. However, it has the ability of performing Gridded simulation. The gridded capability was originally designed to take advantage of radar rainfall

		WEAP groundwater model is not sufficient for complex analysis, WEAP has a specific option called MODFLOW which allows for cell-based analysis.	estimates that became available in the early 1990s. Basically, it is the same as normal calculation at the subbasin scale, except that calculations are performed separately for each grid cell instead of the whole subbasin. Cells may be from 30 meters to 2 kilometers in size. Results may not be improved if subbasins are small and the storm is large or relatively uniform. However, gridded simulation can dramatically improve results in cases where the storm is heterogeneous. Precipitation, evapotranspiration and snowmelt are defined on a grid cell basis. Infiltration and excess precipitation is computed separately for each cell. ModClark transform method is used to process excess precipitation into runoff at the subbasin outlet.
Delineating catchment areas and sub-basins	Can delineate the catchment boundaries and the sub-basins. It uses TauDEM (Terrain Analysis Using Digital Elevation Models,	Cannot delineate the catchment boundaries nor sub-basins. Catchment locations need to mark as points for modeling runoffs	Cannot delineate catchment boundaries in HEC-HMS. Locations of the sub-basins need to mark as points for modeling.

	http://hydrology.usu.edu/ taudem/taudem5) for catchment delineation. The catchment areas can be further subdivided into sub-basins and then into homogeneous areas called Hydrological Response Units (HRUs). An HRU has a particular sub-basin it belongs to and has a particular combination of land use, soil, and slope range.	and irrigation demands. If going for a smaller unit like sub-basin level, users need to create manually each sub-basin as points.	HEC-GeoHMS can be used to delineated catchment and sub-basin boundaries using terrain data. However, HEC-GeoHMS is an extension which has been designed to use with ArcGIS software.
Editing/Entering data	Available vector and raster data can be used directly without digitizing them again. The following formats are used to input data of the QSWAT: Stream – vector (need to break the stream lines from the intersecting points) DEM – raster Land use – raster Soil – raster Weather data – txt format and access database	Both vector & rater data can be added, but they can be used only to view the locations. All the spatial locations (streams, demand sites, links, reservoirs, etc.) need to digitize again on the schematic view, prior to entering data in the data view. Other than that, weather data, population data can be entered using the options given below: 1. Expression builder 2. Time series wizard 3. Read from file wizard 4. Look up function wizard	Shape files, DXF files and Aerial Photos representing the catchment area can be added to the display as background maps. All the hydrologic elements need to draw schematically inside this catchment boundary. Data on precipitation, discharge at water outlet, can be entered in HEC-DSSVue and these DSS format data can then be used in HEC-HMS. Other than that, HEC-HMS also allows for entering data manually.
Input data – Land use / Land cover	All the land uses / covers should be reclassified to the classification method provided in the SWAT manual. Use the raster converted land use layer for	For modeling values of different land use classes need to enter as a share of the land area	Land use / Land cover data are not directly used in the model. However, category of the land uses are examined to derive the

	modeling		values on certain model parameters. Ex: Curve Numbers used in the model are primarily based on the land cover types HEC-GeoHMS can be used to estimate parameters using the land use data in an automated way.
Input data - Soil	All the soil types should be reclassified as per the FAO soil classification method. Use the raster converted soil layer for modeling	When using the "Rainfall Runoff (soil moisture method)" method for modeling need to insert values pertaining to water holding capacity of upper soil layer and deep soil layer and conductivity rate of the deep soil layer When using "MABIA" method for modeling need to insert values on soil water capacity, thickness of soil layer, maximum infiltration rate into soil and maximum percolation rate from soil to groundwater	Soil data are not directly used in the model. However, category of the soils are examined to derive the values on certain model parameters. Ex: When computing loss using the Initial/Constant Loss method, the constant loss rate can be viewed as the infiltration capacity of the soil. Different scholars have identified loss rates for different soil types. HEC-GeoHMS can be used to estimate parameters using the soil data in an automated way.
Input data - weather	QSWAT requires daily weather data on the parameters of precipitation, relative humidity, temperature, solar radiation and wind speed, stored in the txt format. In addition, SWAT reference data base	The weather data in Excel and Comma Separated Values (CSV) files can import/export data to WEAP. Average temperature, precipitation, humidity and	Weather data can be entered manually in HEC-HMS and also DSS format weather data can be directly used.

	in mdb format requires weather data on the following parameters: 1. Mean daily maximum & minimum temperature 2. Standard deviation for daily maximum & minimum temperature 3. Mean total monthly precipitation 4. Standard deviation for daily precipitation 5. Skew coefficient for daily precipitation 6. Probability of a wet day following a dry day 7. Probability of a wet day following a wet day 8. Average number of days of precipitation in month 9. Maximum 0.5hour rainfall in entire period of record 10. Mean daily solar radiation 11. Mean daily wind speed The above weather parameters are used for all HRUs, the main channel and any ponds or wetlands located within the sub-basin. The precipitation, solar radiation, wind speed, temperature and humidity files	average wind speed are the climatic data required for WEAP model.	

	may be used up to 18 files in each simulation and each file can hold data for up to 300 stations except the temperature file. The temperature input files which contains daily measured maximum and minimum temperatures can hold data for up to 150 stations.		
Weather generation	The model generates a set of weather data for each sub-basin. Daily values for weather are generated from average monthly values. ▪ Generated precipitation – Uses a model developed by Nicks (1974) ▪ Generated air temperature and solar radiation – generated from a normal distribution ▪ Generated wind speed – A modified exponential equation is used ▪ Generated relative humidity – Uses a triangular distribution		Meteorological data analysis is performed by the meteorological model and includes precipitation, evapotranspiration and snowmelt. There are four methods for analyzing the historical precipitation: Gage weights, Inverse distance, User specified hyetograph and Gridded precipitation. There are four methods for producing synthetic precipitation: Frequency storm, HMR52 storm, SCS storm and Standard project storm. The inverse distance method addresses dynamic data problems. An unlimited number of recording and non-recording gages can be used to automatically proceed when missing data is encountered.
Calculating sub-	The direction of the runoff is generated	After marking the location of the	Runoff directions need to mark

basin runoffs	automatically during process of QSWAT modeling.	new catchment, the runoff path need to mark as an arrow, starting from the catchment into water body.	from the subbasins to the junction/outlet using the "Connect downstream" icon. The transform method in the subbasin converts excess precipitation into runoff at the subbasin outlet using the unit hydrograph methods (Clark, SCS, S-graph, Snyder and User-specified) and other methods such as Kinetic Wave and ModClark distributed.
Visualizing the results	Compared to other SWAT interfaces (Ex:ArcSWAT) QSWAT has an enhanced feature of visualizing the outputs. There are 3 types of visualization in QSWAT: 1. Static visualization – summarized results will be displayed on the map classifying them under Jenks Natural Breaks Algorithm 2. Dynamic visualization - the outputs are displayed for each time step over a period of time via animation. 3. Plot function – shows graphs of the outputs. This helps to comparisons between different sub-basins, model simulations, or simulated and observed results.	The output results cannot be visualized spatially in a map. Therefore, compared to QSWAT, static visualization is not available in WEAP. Dynamic visualization is available to certain extent, when using the MODFLOW model in WEAP. It allows for animating the results in chronological order. WEAP allows for representing results by means of databases, tables and charts. Therefore, Plot function option is available in WEAP.	The model can visualize only the schematic diagram of hydrologic elements. The final results of the model are displayed as follows: 1. Global summary table - shows the drainage area, peak discharge, time of peak discharge, and total volume for each element 2. Element graph - shows flows and precipitation for each sub-basin 3. Element summary table - shows the peak inflow, peak outflow, total inflow and total outflow of each hydrologic element 4. Element time series table - This

			table shows the same data as the element graph which includes the observed and computed inflows and outflows as well as their residuals. This table supports copy/paste so data can be easily transferred to a spreadsheet or math program.
Return flow	SWAT considers the return flow, which is the volume of streamflow originating from groundwater. SWAT partitions groundwater into 2 aquifer systems: a shallow, unconfined aquifer which contributes return flow to streams within the watershed and a deep, confined aquifer which contributes return flow to streams outside the watershed.	In the modeling process WEAP can consider the Return Flow. For that, specific point(s) where the return flow is connected to the river is needed to mark. However, practically, in some areas this won't work when the return flow is coming to the river from infinite number of point sources.	HEC-HMS is designed for Dendritic stream systems. It is not designed to work with looped or braided systems. Other than that, all computations are carried out from the headwaters to the outlet. It is not possible for upstream calculations to have any knowledge of downstream conditions so the effects of backwater cannot generally be included.
Minimum flow requirement	In QSWAT there is no such an option to consider minimum flow. However, researches has done on adding a seasonally calibrated scheme to avoid the problem of poor performance in dry periods which occurs with SWAT (Zhang & Chen, 2015).	WEAP can considers the minimum flow requirement which is the minimum monthly flow required along a river to meet water quality, fish & wildlife, navigation, recreation, downstream or other requirements.	-

Working with scenarios	SWATGraph can display and compare different scenarios. It can also compare observed data with simulated outputs. Time period of the weather data is the main determinant of visualizing and generating QSWAT outputs. For an example, if we included daily weather data for the period of 1990 – 2010, the outputs of the QSWAT can be generated for the entire 1990-2010 period or for a selected period between 1990 &2010. If someone wants to generate outputs for the future, it is required to include predicted daily weather data (Ex: using the weather prediction models like WRF) for the future period.	Can easily develop and compare scenarios & sub-scenarios (Ex: Scenarios with reference to population growth, constant climate, variable climate, different time periods, etc.) within a single project file When modeling the supply side scenarios, WEAP uses the "Water Year Method". This method needs values for define Very Dry, Dry, Normal, Wet, Very Wet to predict the condition of the climate in upcoming years. This method is good when modeling the scenario under variable climatic condition, but it is hard to decide what weather will be there in the future and it is unjustifiable to assign only one class to describe the climatic condition of an entire year, since it varies seasonally.	HEC-HMS model includes a basin model, meteorological model and control specifications. Hence, different scenarios can be generated by changing the above 3 models separately. The precipitation/outflow ration option can be used to, for example, increase the computed precipitation in the meteorology model by 25% without actually changing the meteorology data.
Working with demanding nodes and its sub-levels	Within the QSWAT model, it considers biological demands such as Biological Oxygen Demand (BOD), Evaporative demand, Nitrogen Demand, etc. rather than demand of activities within the	WEAP has facilities to work with demanding nodes such as cities, industrial areas, agricultural areas, etc. by deciding their activity levels, water use rates,	

	boundary.	monthly variation and water lost from the system. Further, WEAP also allows for define the priority levels of the demanding nodes considering their level of importance.	
Checking errors	"SWAT-Check" tool is there to summarize the results from SWAT simulation. It gives a quick summary of the different parameters. Users can, therefore, compare these values with published literature values or measured estimates and get an idea on how to improve the model performance in subsequent model calibration processes.	WEAP doesn't have such an option to check the errors in the model. Users need to find their own ways to compare the observed and the computed values.	HEC-HMS doesn't have such an option to check the errors in the model. Users need to find their own ways to compare the observed and the computed values. However, the residual values in the Element time series tables can be used to validate the model to a certain extent.

Annexure 2 – SWAT land use database

Parameter values of the different plants

CPNM	BIO_E	HVSTI	BLAI	FRGRW1	LAIMX1	FRGRW2	LAIMX2	DLAI	CHTMX	RDMX	T_OPT	T_BASE	CNYLD	CPYLD	BN1	BN2	BN3	BP1	BP2	BP3	WSYF	USLE_C	GSI	VPDFR
AGRL	33.5	0.45	3	0.15	0.05	0.5	0.95	0.64	1	2	30	11	0.0199	0.0032	0.044	0.0164	0.0128	0.006	0.0022	0.0018	0.25	0.2	0.005	4
FRST	15	0.76	5	0.05	0.05	0.4	0.95	0.99	6	3.5	30	10	0.0015	0.0003	0.006	0.002	0.0015	0.0007	0.0004	0.0003	0.01	0.001	0.002	4
WETL	47	0.9	6	0.1	0.2	0.2	0.95	0.7	2.5	2.2	25	12	0.016	0.0022	0.035	0.015	0.0038	0.0014	0.001	0.0007	0.9	0.003	0.005	4
WETN	47	0.9	6	0.1	0.2	0.2	0.95	0.7	2.5	2.2	25	12	0.016	0.0022	0.035	0.015	0.0038	0.0014	0.001	0.0007	0.9	0.003	0.005	4
PAST	35	0.9	4	0.05	0.05	0.49	0.95	0.99	0.5	2	25	12	0.0234	0.0033	0.06	0.0231	0.0134	0.0084	0.0032	0.0019	0.9	0.003	0.005	4
RNGE	34	0.9	2.5	0.05	0.1	0.25	0.7	0.35	1	2	25	12	0.016	0.0022	0.02	0.012	0.005	0.0014	0.001	0.0007	0.9	0.003	0.005	4
SWRN	34	0.9	1.5	0.05	0.1	0.25	0.7	0.35	1	2	25	12	0.016	0.0022	0.02	0.012	0.005	0.0014	0.001	0.0007	0.9	0.003	0.005	4
WATR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
RICE	22	0.5	5	0.3	0.01	0.7	0.95	0.8	0.8	0.9	25	10	0.0136	0.0013	0.05	0.02	0.01	0.006	0.003	0.0018	0.25	0.03	0.008	4
RUBR	5.6	0.9	2.6	0.1	0.15	0.5	0.75	0.99	3.5	2	20	7	0.0019	0.0004	0.006	0.002	0.0015	0.0007	0.0004	0.0003	0.05	0.001	0.0071	4
COCO	24	0.56	5	0.15	0.7	0.25	0.99	0.99	10	3.5	30	0	0.0015	0.0003	0.006	0.002	0.0015	0.0007	0.0004	0.0003	0.6	0.001	0.0019	4
BARR	0.01	0.01	0.01	0.05	0.05	0.49	0.95	0.99	0.01	0.1	25	12	0.0234	0.0033	0.06	0.0231	0.0134	0.0084	0.0032	0	0.9	0.2	0.005	4

CPNM	FRGMAX	WAVP	CO2HI	BIOEHI	RSDCO_PL	OV_N	CN2A	CN2B	CN2C	CN2D	FERTFIELD	ALAI_MIN	BIO_LEAF	MAT_YRS	BMX_TREES	EXT_COEF	BM_DIEOFF
AGRL	0.75	8.5	660	36	0.05	0.14	67	77	83	87	1	0	0	0	0	0.65	0.1
FRST	0.75	8	660	16	0.05	0.1	36	60	73	79	0	0.75	0.3	50	1000	0.65	0.1
WETL	0.75	8.5	660	54	0.05	0.05	49	69	79	84	0	0	0	0	0	0.65	0.1
WETN	0.75	8.5	660	54	0.05	0.05	49	69	79	84	0	0	0	0	0	0.65	0.1
PAST	0.75	10	660	36	0.05	0.15	49	69	79	84	0	0	0	0	0	0.65	0.1
RNGE	0.75	10	660	39	0.05	0.15	49	69	79	84	0	0	0	0	0	0.33	0.1
SWRN	0.75	10	660	39	0.05	0.15	39	61	74	80	0	0	0	0	0	0.33	0.1
WATR	0	0	0	0	0	0.01	92	92	92	92	0	0	0	0	0	0	0.1
RICE	0.75	5	660	31	0.05	0.14	62	73	81	84	1	0	0	0	0	0.35	0.1
RUBR	0.75	3	660	20	0.05	0.14	45	66	77	83	0	0.75	0.3	10	500	0.65	0.1
COCO	0.75	8	660	16	0.05	0.14	45	66	77	83	1	0.75	0.3	30	1000	0.65	0.1
BARR	0.75	10	660	0.01	0.5	0.14	77	86	91	94	0	0	0	0	0	1	0.1

BIO_E – Radiation-use efficiency or biomass-energy ratio ((kg/ha)/(MJ/m^2))
HVSTI – Harvest index for optimal growing conditions
BLAI – Maximum potential leaf area index
FRGRW1 – Fraction of the plant growing season or fraction of total potential heat units corresponding to the 1st point on the optimal leaf area development curve
LAIMX1 – Fraction of the maximum leaf area index corresponding to the 1st point on the optimal leaf area development curve
FRGRW2 – Fraction of the plant growing season or fraction of total potential heat units corresponding to the 2nd point on the optimal leaf area development curve
LAIMX2 – Fraction of the maximum leaf area index corresponding to the 2nd point on the optimal leaf area development curve
DLAI – Fraction of growing season when leaf area begins to decline
CHTMX – Maximum canopy height
RDMX – Maximum root depth
T_OPT – Optimal temperature for plant growth
T_BASE – Minimum temperature for plant growth
CNYLD – Normal fraction of nitrogen in yield
CPYLD – Normal fraction of phosphorus in yield

BN(1) – Nitrogen uptake parameter #1: normal fraction of nitrogen in plant biomass at emergence (kg N/kg biomass)
BN(2) – Nitrogen uptake parameter #2: normal fraction of nitrogen in plant biomass at 50% maturity (kg N/kg biomass)
BN(3) – Nitrogen uptake parameter #3: normal fraction of nitrogen in plant biomass at maturity (kg N/kg biomass)
BP(1) – Phosphorus uptake parameter #1: normal fraction of phosphorus in plant biomass at emergence (kg P/kg biomass)
BP(2) – Phosphorus uptake parameter #2: normal fraction of phosphorus in plant biomass at 50% maturity (kg P/kg biomass)
BP(3) – Phosphorus uptake parameter #3: normal fraction of phosphorus in plant biomass at maturity (kg P/kg biomass)
WSYF – Lower limit of harvest index
USLE_C – Minimum value of USLE C factor for water erosion applicable to the land cover / plant
GSI – Maximum stomatal conductance at high solar radiation and low vapor pressure deficit (ms-1)
VPDFR – Vapor pressure deficit (kPa) corresponding to the second point on the stomatal conductance curve
FRGMAX – Fraction of maximum stomatal conductance corresponding to the second point on the stomatal conductance curve
WAVP – Rate of decline in radiation use efficiency per unit increase in vapor pressure deficit
CO2HI – Elevated CO2 atmospheric concentration (μL CO_2/L air) corresponding the 2nd point on the radiation use efficiency curve
BIOEHI – Biomass-energy ratio corresponding to the 2nd point on the radiation use efficiency curve
RSDCO_PL – Plant residue decomposition coefficient
OV_N – Manning's "n" value for overland flow
CN2A – SCS runoff curve number for moisture condition II – For hydrologic soil group A
CN2B - SCS runoff curve number for moisture condition II – For hydrologic soil group B
CN2C - SCS runoff curve number for moisture condition II – For hydrologic soil group C
CN2D - SCS runoff curve number for moisture condition II – For hydrologic soil group D
FERTFIELD – Fertilizer identification number from fertilizer database
ALAI_MIN – Minimum leaf area index for plant during dormant period (m^2/m^2)
BIO_LEAF – Fraction of tree biomass accumulated each year that is converted to residue during dormancy
MAT_YRS – Number of years required for tree species to reach full development (years)
BMX_TREES – Maximum biomass for a forest (metric tons / ha)
EXT_COEF – Light extinction coefficient
BM_DIEOFF – Biomass dieoff fraction

Parameter values of the different land uses

URBNAME	FIMP	FCIMP	CURBDEN	URBCOEF	DIRTMX	THALF	TNCONC	TPCONC	TNO3CONC	OV_N	CN2A	CN2B	CN2C	CN2D	URBCN2
URMD	0.38	0.3	0.24	0.18	225	0.75	550	223	7.2	0.1	31	59	72	79	98
URLD	0.12	0.1	0.24	0.18	225	0.75	460	196	6	0.1	31	59	72	79	98

FIMP – Fraction total impervious area in urban land type. This includes directly and indirectly connected impervious areas
FCIMP – Fraction directly connected impervious area in urban land type
CURBDEN – Curb length density in urban land type (km / ha)
URBCOEF – Wash-off coefficient for removal of constituents from impervious area (mm^{-1})
DIRTMX – Maximum amount of solids allowed to build up on impervious areas (kg/curb km)
THALF – Number of days for amount of solids on impervious areas to build up from 0 kg/curb km to half the maximum allowed
TNCONC – Concentration of total nitrogen suspended solid load from impervious areas
TPCONC – Concentration of total phosphorous in suspended solid load from impervious areas
TNO3CONC – Concentration of nitrate in suspended solid load from impervious areas
OV_N – Manning's "n" value for overland flow
CN2A – SCS runoff curve number for moisture condition II – For hydrologic soil group A
CN2B - SCS runoff curve number for moisture condition II – For hydrologic soil group B
CN2C - SCS runoff curve number for moisture condition II – For hydrologic soil group C
CN2D - SCS runoff curve number for moisture condition II – For hydrologic soil group D
URBCN2 – Curve number for moisture condition II in impervious areas of urban land type

Annexure 3– SWAT soil database

Parameter values of the soil properties

SNAM	NLAYERS	HYDGRP	SOL_ZMX	ANION_EXCL	SOL_CRK	TEXTURE	SOL_Z1	SOL_BD1	SOL_AWC1	SOL_K1	SOL_CBN1	CLAY1	SILT1	SAND1	ROCK1	SOL_ALB1	USLE_K1	SOL_EC1
Af45-2b	2	C	910	0.5	0.5	SANDY_CLAY_LOAM	300	1.3	0.158	11.02	1.6	24	27	49	0	0.0224	0.2576	0
Ao73-2bc	2	C	890	0.5	0.5	LOAM	300	1.3	0.156	12.07	1.8	22	28	50	0	0.0152	0.2568	0
Ap19-2b	2	C	1000	0.5	0.5	LOAM	300	1.3	0.175	9.01	6.3	24	31	45	0	0	0.2258	0
Bf12-3bc	2	C	970	0.5	0.5	CLAY_LOAM	300	1.1	0.147	22.04	2.4	36	26	37	0	0.0048	0.248	0
Jd5-2-3a	2	D	1000	0.5	0.5	CLAY_LOAM	300	1.4	0.175	4.07	2.6	30	40	30	0	0.0032	0.2814	0
Lc71-2b	2	C	960	0.5	0.5	SANDY_CLAY_LOAM	300	1.3	0.167	14.49	0.7	24	22	54	0	0.1269	0.2735	0
Lc72-2a	2	C	810	0.5	0.5	SANDY_CLAY_LOAM	300	1.3	0.109	12.47	0.8	23	26	51	0	0.1047	0.2759	0
Lc73-2bc	2	C	890	0.5	0.5	LOAM	300	1.3	0.156	9.64	1.1	23	31	46	0	0.0587	0.2608	0
Qc50-1a	2	C	1000	0.5	0.5	SANDY_LOAM	300	1.3	0.131	50.89	5.3	10	16	74	0	0	0.186	0
Re66-1a	2	C	1000	0.5	0.5	SANDY_LOAM	300	1.6	0.14	10.45	0.5	14	19	67	0	0.1867	0.3124	0

SNAM	SOL_Z2	SOL_BD2	SOL_AWC2	SOL_K2	SOL_CBN2	CLAY2	SILT2	SAND2	ROCK2	SOL_ALB2	USLE_K2
Af45-2b	1000	1.3	0.158	8.34	0.4	37	25	38	0	0.2265	0.2576
Ao73-2bc	1000	1.4	0.156	5.15	0.7	32	26	42	0	0.1269	0.2568
Ap19-2b	1000	1.3	0.175	7.65	5.4	36	29	36	0	0	0.2258
Bf12-3bc	1000	1.2	0.147	14.87	0.6	46	21	33	0	0.154	0.248
Jd5-2-3a	1000	1.5	0.175	2.39	0.9	37	35	27	0	0.0863	0.2814
Lc71-2b	1000	1.5	0.167	3.33	0.3	35	24	42	0	0.2747	0.2735
Lc72-2a	1000	1.5	0.109	3.15	0.4	34	25	41	0	0.2265	0.2759
Lc73-2bc	1000	1.4	0.156	4.56	0.5	30	31	40	0	0.1867	0.2608
Qc50-1a	1000	1.3	0.131	49.04	5.3	11	15	74	0	0	0.186
Re66-1a	1000	1.5	0.14	17.48	0.2	15	15	70	0	0.3331	0.3124

SNAM – Soil nam
NLAYERS – Number of layers
HYDGRP – Soil hydrologic group (A, B, C or D)
SOL_ZMX – Maximum rooting depth of soil profile (mm)
ANION_EXCL – Fraction of porosity (void space) from which anions are excluded
SOL_CRK – Potential or maximum crack volume of the soil profile expressed as a fraction of the total soil volume
TEXTURE – Texture of soil layer
SOL_Z (layer #) – Depth from soil surface to bottom of layer (mm)
SOL_BD (layer #) – Moist bulk density (Mg/m^3 or g/cm^3)
SOL_AWC (layer #) – Available water capacity of the soil layer (mm H_2O / mm soil)
SOL_K (layer #) – Saturated hydraulic conductivity (mm/hr)
SOL_CBN ((layer #) – Organic carbon content (% soil weight)
CLAY (layer #) – Clay content (% soil weight)
SILT (layer #) – Silt content (% soil weight)

SAND (layer #) – Sand content (% soil weight)
ROCK (layer #) – Rock fragment content (% total weight)
SOL_ALB(layer #) – Moist soil albedo
USLE_K (layer #) – USLE equation soil erodibility (K) factor
SOL_EC(layer #) – Electrical conductivity (dS/m)

Annexure 4 – Definitions of the variables and the statistical values required for SWAT weather generator and the calculated values for the Deduru Oya river basin

Variables and Statistics used in SWAT weather generator

Variable name	Definition
WLATITUDE	Latitude of the weather station (decimal degrees)
WLONGITUDE	Longitude of the weather station (decimal degrees
WELEV	Elevation of the weather station
RAIN_YRS	The number of years of maximum monthly 0.5 rainfall data used to define values for RAIN_HHMX(1) – RAIN_HHMX(12).
$TMPMX_{(mon)}$	Mean daily maximum air temperature for month (^{0}C) $$\mu mx_{mon} = \frac{\sum_{d=1}^{N} T_{mx,mon}}{N}$$ Where μmx_{mon} is the mean daily maximum temperature for the month, $T_{mx,mon}$ is the daily maximum temperature on record d in month mon (^{0}C). N is the total number of daily maximum temperature records for month mon.
$TMPMN_{(mon)}$	Mean daily minimum air temperature for month (^{0}C). $$\mu mn_{mon} = \frac{\sum_{d=1}^{N} T_{mn,mon}}{N}$$ Where μmn_{mon} is the mean daily minimum temperature for the month, $T_{mn,mon}$ is the daily minimum temperature on record d in month mon (^{0}C). N is the total number of daily maximum temperature records for month mon.
$TMPSTDMX_{(mon)}$	Standard deviation for daily maximum air temperature in month (^{0}C). This parameter quantifies the variability in maximum temperature for each month. The standard deviation is calculated: $$\sigma mx_{mon} = \sqrt{\left[\frac{\sum_{d=1}^{N}(T_{mx,mon} - \mu mx_{mon})^2}{N-1}\right]}$$ Where $\sigma mx_{mon}$is the standard deviation for daily maximum temperature in month mon (^{0}C), $T_{mx,mon}$ is the daily maximum temperature on record d on month mon (^{0}C), μmx_{mon} is the average daily maximum temperature for the month (^{0}C), and N is the total number of daily maximum temperature records for month mon.
$TMPSTDMN_{(mon)}$	Standard deviation for daily minimum air temperature in month (^{0}C). $$\sigma mn_{mon} = \sqrt{\left[\frac{\sum_{d=1}^{N}(T_{mn,mon} - \mu mn_{mon})^2}{N-1}\right]}$$ Where $\sigma mn_{mon}$is the standard deviation for daily minimum temperature in month mon (^{0}C), $T_{mn,mon}$ is the daily minimum temperature on record d on month mon (^{0}C), μmn_{mon} is the average daily minimum temperature for the month (^{0}C), and N is the total number of daily minimum temperature records for month mon.
$PCPMM_{(mon)}$	Mean total monthly precipitation (mm H_2O) $$\overline{R_{mon}} = \frac{\sum_{d=1}^{N} R_{day,mon}}{yrs}$$ Where $\overline{R_{mon}}$ is the mean monthly precipitation (mm), $R_{day,mon}$ is the daily precipitation for record *d* in month *mon*, *N* is the total number of records in the month mon used to calculate the average, and *yrs* is the number of years of daily precipitation records used in calculation.
$PCPSTD_{(mon)}$	Standard deviation for daily precipitation in month (mm/day). This parameter quantifies the variability in precipitation for each month. The standard deviation is calculated: $$\sigma_{mon} = \sqrt{\left[\frac{\sum_{d=1}^{N}(R_{day,mon} - \bar{R}_{mon})^2}{N-1}\right]}$$ Where σ_{mon} is the standard deviation for daily precipitation in month *mon*(mm), $R_{day,mon}$is the amount of precipitation for record *d* in month *mon* (mm), $\bar{R}_{mon}$ is the average precipitation for the month (mm), and *N* is the total number of daily precipitation records for month *mon*.
$PCPSKW_{(mon)}$	Skew coefficient for daily precipitation in month. This parameter quantifies the symmetry of the precipitation distribution about the monthly mean. The skew coefficient is calculated:

	$$g_{mon} = \frac{N.\sum_{d=1}^{N}(R_{day,mon} - \bar{R}_{mon}{}^{3})}{(N-1)(n-2)(\sigma_{mon}{}^{3})}$$ Where g_{mon} is the skew coefficient for precipitation in the month, *N* is the total number of daily precipitation records for month *mon*, $R_{day,mon}$ is the amount of precipitation for record d in month *mon* (mm), and σ_{mon} is the standard deviation for daily precipitation in month *mon* (mm).
PR_W$_{(1,mon)}$	Probability of a wet day following a dry day in the month. This probability is calculated: $$P_i\left(\frac{W}{D}\right) = \frac{days_{\frac{W}{D},i}}{days_{dry,i}}$$ Where $P_i\left(\frac{W}{D}\right)$ is the probability of a wet day following a dry day in month *i*, $days_{\frac{W}{D},i}$ is the number of times a wet day followed a dry day in month *i* for the entire period of record, and $days_{dry,i}$ is the number of dry days in month i during the entire period of record. A dry day is a day with 0 mm of precipitation. A wet day is a day with > 0mm precipitation.
PR_W$_{(2,mon)}$	Probability of a wet day following a wet day in the month. This probability is calculated: $$P_i\left(\frac{W}{W}\right) = \frac{days_{\frac{W}{W},i}}{days_{wet,i}}$$ Where $P_i\left(\frac{W}{W}\right)$ is the probability of a wet day following a wet day in month *i*, $days_{\frac{W}{W},i}$ is the number of times a wet day followed a wet day in month *i* for the entire period of record, and $days_{wet,i}$ is the number of wet days in month I during the entire period of record. A dry day is a day with 0 mm of precipitation. A wet day is a day with > 0mm precipitation.
PCPD$_{(mon)}$	Average number of days of precipitation in month. This parameter is calculated: $$\overline{d_{wet,\iota}} = \frac{days_{wet,i}}{yrs}$$ Where $\overline{d_{wet,\iota}}$ is the average number of days of precipitation in month *i*, $days_{wet,i}$ is the number of wet days in month *i* during the entire period of record, and *yrs* is the number of years of record.
RAINHHMX$_{(mon)}$	Maximum 0.5 hour rainfall in entire period of record for month (mm). This value represents the most extreme 30-minute rainfall intensity recorded in the entire period of record.
SOLARAV$_{(mon)}$	Average daily solar radiation for month (MJ/m^2/day). This value is calculated by summing the total solar radiation for every day in the month for all years of record and dividing by the number of days summed: $$\mu rad_{mon} = \frac{\sum_{d=1}^{N} H_{day,mon}}{N}$$ Where μrad_{mon} is the mean daily solar radiation for the month (MJ/m^2/day), $H_{day,mon}$ is the total solar radiation reaching the earth's surface for day *d* in month month *mon* (MJ/m^2/day), and *N* is the total number of daily solar radiation records for month *mon*.
DEWPT$_{(mon)}$	Average daily dew point temperature for each month (^{0}C) or relative humidity (fraction) can be input. If all twelve months are less than one, the model assumes relative humidity is input. If any month has a value greater than 1.0, the model assumes dew point temperature is input. Dew point temperature is the temperature at which the actual vapor pressure present in the atmosphere is equal to the saturation vapor pressure. This value is calculated by summing the dew point temperature for every day in the month for all years of record and dividing by the number of days summed: $$\mu dew_{mon} = \frac{\sum_{d=1}^{N} T_{dew,mon}}{N}$$ Where μdew_{mon} is the mean daily dew point temperature for the month (^{0}C), $T_{dew,mon}$ is the dew point temperature for day d in month *mon* (^{0}C), and *N* is the total number of daily dew point records for month *mon*.
WNDAV$_{(mon)}$	Average daily wind speed in month (m/s). This value is calculated by summing the average or mean wind speed values for every day in the month for all years of record and dividing by the number of days summed: $$\mu wnd_{mon} = \frac{\sum_{d=1}^{N} \mu_{wnd,mon}}{N}$$ Where μwnd_{mon} is the mean daily wind speed for the month (m/s), $\mu_{wnd,mon}$ is the average wind speed for day d in month mon (m/s), and N is the total number of daily wind speed records for month mon.

Calculated values and statistics for Deduru Oya basin

					Max Temp (TMPMX)												Min Temp (TMPMN)											
STATION	WLATITUDE	WLONGITUDE	WELEV	Rain_YRS	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
73797	7.33738	79.6875	-9999	32	28.84	29.26	29.74	29.79	29.32	28.33	27.81	27.68	27.99	28.17	28.4	28.54	24.63	25.11	26.36	27.29	27.52	27.01	26.61	26.47	26.6	26.39	25.86	25.11
73800	7.33738	80	26	32	32.55	34.55	35.23	33.6	31.54	29.55	29.15	29.36	30.06	30.37	30.82	31.28	21.84	21.66	22.98	24.68	25.32	24.69	24.29	24.28	24.44	23.91	22.87	22.25
73803	7.33738	80.3125	135	32	30.55	33.09	34.46	32.84	30.16	27.88	27.5	27.88	28.68	28.86	28.96	29.33	19.58	19.24	20.32	22.19	23.12	22.58	22.2	22.18	22.28	21.78	20.76	20.03
73806	7.33738	80.625	460	32	27.12	30.03	32.18	31.72	29.07	26.79	26.59	27.03	27.6	27.35	26.56	26.22	17.6	16.6	17.46	19.88	21.23	20.97	20.58	20.54	20.5	19.96	19.02	18.28
76797	7.64961	79.6875	-9999	32	28.52	29.08	29.63	29.75	29.36	28.32	27.76	27.61	27.92	28.07	28.22	28.23	24.4	24.86	26.23	27.32	27.6	27.04	26.61	26.45	26.59	26.34	25.75	24.96
76800	7.64961	80	46	32	32.17	34.22	35.22	33.99	32.27	30.28	29.95	30.16	30.77	30.67	30.67	30.96	21.52	21.39	22.84	24.8	25.56	25	24.64	24.63	24.76	24.1	22.94	22.14
76803	7.64961	80.3125	113	32	31.45	34.12	35.77	34.74	32.66	30.41	30.13	30.54	31.2	30.99	30.47	30.33	19.8	19.55	20.9	23.01	24.1	23.76	23.39	23.41	23.44	22.7	21.44	20.49
76806	7.64961	80.625	364	32	29.45	32.61	35.27	35.45	33.15	30.8	30.6	31.09	31.67	31.25	29.79	28.74	18.89	18.26	19.25	21.54	23.04	23.11	22.72	22.7	22.55	21.66	20.41	19.58
80797	7.96184	79.6875	-9999	32	28.25	28.93	29.55	29.69	29.42	28.38	27.8	27.62	27.91	28.04	28.09	27.95	24.29	24.66	26.16	27.46	27.85	27.25	26.79	26.6	26.73	26.44	25.76	24.93
80800	7.96184	80	41	32	31.54	33.85	35.03	33.78	32.2	30.47	30.27	30.47	30.88	30.49	30.2	30.31	21.3	21.18	22.65	24.75	25.76	25.25	24.94	24.93	25	24.12	22.84	22.03
80803	7.96184	80.3125	103	32	31.24	34.23	36.32	35.33	33.25	31.32	31.17	31.57	31.99	31.38	30.47	30.1	19.75	19.41	20.78	23.12	24.49	24.36	24.02	24.04	24	22.93	21.48	20.58
80806	7.96184	80.625	152	32	30.12	33.37	36.5	36.87	34.68	32.56	32.44	32.92	33.29	32.52	30.65	29.37	18.96	18.4	19.49	22.03	23.83	24.17	23.81	23.8	23.56	22.32	20.85	19.93

STATION	SD for daily maximum temp (TMPSTDMX)												Standard deviation for daily minimum temp (TMPSTDMN)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
73797	0.857	0.855	0.759	0.762	0.724	0.747	0.666	0.652	0.672	0.785	0.934	0.933	0.861	0.921	0.893	0.677	0.644	0.628	0.607	0.584	0.632	0.682	0.727	0.811
73800	2.185	2.157	2.177	2.215	1.853	1.998	1.923	1.93	1.911	2.367	2.443	2.235	1.31	1.489	1.416	0.859	0.653	0.679	0.598	0.593	0.625	0.827	1.04	1.086
73803	2.367	2.393	2.479	2.925	2.274	2.439	2.423	2.45	2.411	2.713	2.569	2.359	1.503	1.644	1.464	0.888	0.609	0.616	0.511	0.516	0.509	0.8	1.235	1.332
73806	2.522	2.664	2.916	3.43	2.625	2.455	2.463	2.486	2.507	2.805	2.513	2.35	1.957	2.478	2.172	1.17	0.708	0.578	0.53	0.527	0.536	0.964	1.533	1.732
76797	0.875	0.873	0.78	0.716	0.695	0.717	0.642	0.604	0.633	0.741	0.902	0.904	0.872	0.988	0.97	0.689	0.649	0.632	0.603	0.558	0.624	0.693	0.731	0.807
76800	2.084	2.061	1.952	2.108	1.827	1.983	1.851	1.863	1.872	2.143	2.2	2.096	1.422	1.628	1.539	0.885	0.704	0.701	0.63	0.617	0.666	0.845	1.078	1.14
76803	2.466	2.397	2.348	2.676	2.154	2.385	2.275	2.3	2.288	2.593	2.519	2.362	1.629	1.806	1.612	0.908	0.717	0.654	0.573	0.572	0.597	0.863	1.252	1.393
76806	2.655	2.715	2.787	3.244	2.515	2.35	2.273	2.345	2.402	2.813	2.718	2.512	1.888	2.156	1.886	1.071	0.869	0.612	0.585	0.581	0.647	1.009	1.433	1.652
80797	0.899	0.903	0.814	0.694	0.656	0.679	0.612	0.557	0.586	0.687	0.858	0.895	0.891	1.077	1.099	0.725	0.661	0.635	0.594	0.532	0.6	0.714	0.752	0.804
80800	2.23	2.282	2.118	2.201	1.756	1.883	1.735	1.76	1.786	2.094	2.162	2.135	1.407	1.657	1.64	0.989	0.804	0.754	0.674	0.629	0.707	0.943	1.147	1.141
80803	2.665	2.749	2.679	2.884	2.207	2.256	2.153	2.195	2.217	2.653	2.563	2.498	1.725	2.014	1.838	1.033	0.897	0.703	0.644	0.614	0.696	1.017	1.381	1.456
80806	2.745	2.992	3.138	3.44	2.523	2.237	2.187	2.243	2.32	2.88	2.836	2.641	2.18	2.458	2.145	1.21	1.127	0.669	0.677	0.662	0.8	1.171	1.532	1.803

STATION	Mean total monthly precipitation (PCPMM)												Standard deviation for daily precipitation (PCPSTD)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
73797	87.87	64.68	77.015	215.3	438	770.6	571.5	499.9	465.7	573.2	415.9	224.9	7.493	8.023	5.742	14.27	18.97	24.05	19.07	18.95	18.04	24.46	19.99	14.16
73800	55.31	47.44	61.275	177.8	221.2	381.2	386.4	337.4	244.1	340	293.1	141.8	6.136	6.585	4.85	11.5	12.43	16.71	14.2	14.68	12.67	17.38	15.8	11.36
73803	80.16	72.76	97.729	268.6	213.6	253	301.4	259.2	222.5	415.4	441.6	213.3	8.768	8.51	6.987	13.47	11.01	12.7	11.84	12.58	11.6	18.63	18.97	15.53
73806	137.9	107.2	130.67	323.6	199.3	87.95	109.6	108.4	166.5	427.8	544.2	316.6	13.08	10.56	8.673	14.4	9.696	6.919	6.668	7.71	9.941	19.16	21.12	18.25
76797	98.55	73.46	88.692	251	503.9	764.5	539.1	493.1	522.1	659.9	499.8	260.9	7.968	9.67	6.019	14.76	19.35	23.12	19.13	18.62	19.72	25.53	21.71	14.24
76800	52.93	47.8	63.449	173.1	227	391.7	386.5	340.9	267.2	345.4	286.4	137.9	5.54	6.745	4.674	11.07	12.56	15.85	13.83	14.79	12.57	16.14	14.87	9.996
76803	54.87	48.6	64.055	173.8	108.3	119.3	141.9	123.6	111.7	254.3	293.5	142.9	6.725	6.607	4.901	10.37	7.181	8.569	7.59	9.348	7.251	13.86	14.53	11.49
76806	78.91	54.91	62.911	162.6	81.67	23.31	32.19	34.26	71.07	227.8	312.2	174	9.444	6.858	5.627	10.03	6.027	3.94	3.72	5.654	6.23	13.43	15.48	13.11

80797	115.7	79.15	91.721	218.2	389.8	542.2	338.1	323.9	389.1	583.7	526.4	294.2	9.306	9.377	6.113	12.22	16.56	19.79	15.34	14.83	16.96	23.23	23.05	14.87
80800	78.17	60.37	82.805	209	249.7	402.3	380.4	357.2	313.6	428.3	354.6	184.9	6.831	6.66	5.185	10.43	12.37	15.14	13.68	15.04	12.8	16.25	16.28	10.59
80803	71.31	51.71	71.005	186.9	131.5	111.5	140	126.3	136.4	279.3	313.7	168	6.879	5.831	4.77	9.822	7.532	7.407	6.979	9.039	7.449	12.57	13.75	10.8
80806	84.38	48.48	58.261	142.6	79.29	22.34	37.88	41.16	82.73	206.8	278.1	170.8	7.973	5.306	4.565	8.727	5.327	3.091	3.497	6.188	6.278	10.66	13.74	11.49

STATION	Skew coefficient precipitation (PCPSKW)												Probability of a wet day following a dry day in the month (PR_W(1))											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
73797	4.368	8.399	4.584	5.283	2.407	1.143	1.492	1.773	1.84	3.279	2.832	4.23	0.192	0.174	0.243	0.567	0.688	0.632	0.67	0.645	0.586	0.534	0.443	0.332
73800	6.628	9.081	5.871	5.117	3.406	2.105	1.504	2.62	3.056	3.792	3.152	5.84	0.148	0.147	0.254	0.475	0.432	0.539	0.567	0.575	0.522	0.495	0.405	0.276
73803	6.542	6.048	4.837	3.457	5.246	3.209	2.044	3.938	4.308	2.972	2.335	5.42	0.18	0.164	0.271	0.49	0.455	0.531	0.512	0.504	0.426	0.476	0.422	0.311
73806	6.727	5.087	4.039	2.835	5.287	7.006	4.678	7.203	4.704	2.841	2.111	4.58	0.283	0.206	0.241	0.407	0.448	0.421	0.444	0.447	0.393	0.467	0.594	0.487
76797	4.499	9.986	4.074	4.55	1.792	0.952	1.481	1.593	1.497	3.179	2.88	3.754	0.21	0.175	0.247	0.673	0.693	0.589	0.6	0.568	0.5	0.507	0.463	0.362
76800	7.419	10.76	6.435	6.018	3.419	1.862	1.536	3.127	2.151	4.007	3.846	5.843	0.158	0.153	0.256	0.47	0.473	0.511	0.57	0.557	0.482	0.559	0.444	0.293
76803	7.698	7.899	5.216	4.443	4.816	4.516	3.146	8.962	4.063	4.306	3.577	7.019	0.139	0.128	0.235	0.44	0.355	0.375	0.412	0.376	0.322	0.442	0.405	0.276
76806	7.498	5.916	5.371	4.138	5.393	11.22	7.58	16.6	5.636	4.637	3.59	6.699	0.195	0.132	0.178	0.342	0.241	0.15	0.181	0.183	0.205	0.325	0.454	0.304
80797	5.07	8.552	3.453	4.101	2.128	1.327	2.105	2.166	1.686	3.013	3.659	2.874	0.224	0.168	0.261	0.59	0.587	0.56	0.447	0.51	0.461	0.509	0.496	0.41
80800	6.18	7.763	3.464	4.672	3.003	1.7	1.367	3.06	1.627	2.96	4.932	4.2	0.207	0.15	0.25	0.577	0.432	0.56	0.572	0.511	0.532	0.573	0.535	0.373
80803	6.88	6.597	3.24	4.861	4.389	4.746	2.787	9.729	2.787	3.742	4.308	5.146	0.18	0.144	0.217	0.48	0.4	0.417	0.465	0.406	0.361	0.498	0.482	0.311
80806	6.235	5.449	3.783	5.604	4.831	9.469	5.214	16.44	5.048	4.478	4.933	6.325	0.207	0.121	0.16	0.393	0.24	0.159	0.195	0.185	0.234	0.399	0.465	0.322

STATION	Probability of a wet day following a wet day in the month (PR_W(2))												Average no of days of precipitation in month (PCPD)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
73797	0.366	0.379	0.405	0.45	0.465	0.486	0.472	0.474	0.469	0.48	0.468	0.434	10.16	8.656	13.03	23	26.47	27.63	27.41	26.59	25.25	26.84	24.28	18.34
73800	0.362	0.368	0.396	0.451	0.446	0.46	0.468	0.458	0.454	0.465	0.469	0.415	8.125	7.563	13.41	21.91	21.56	24.38	25.66	24.97	22.88	24.94	23.06	15.5
73803	0.382	0.37	0.411	0.446	0.459	0.447	0.461	0.447	0.446	0.47	0.468	0.438	9.969	8.281	15.06	23.56	21.97	22.94	24.59	23.56	21.78	25.22	24.59	17.91
73806	0.424	0.385	0.411	0.474	0.455	0.419	0.421	0.428	0.452	0.467	0.478	0.447	15.69	11.13	14.69	23.47	23.44	18.28	19.75	20.16	21.09	25.38	26.69	22.5
76797	0.366	0.376	0.407	0.447	0.466	0.483	0.468	0.465	0.479	0.474	0.476	0.441	10.84	8.813	13.66	23.69	26.69	26.66	26	25.28	24.38	26.81	25.41	19.91
76800	0.355	0.361	0.393	0.451	0.438	0.471	0.472	0.455	0.462	0.465	0.466	0.425	8.531	7.625	13.53	22.09	21.59	24.5	25.84	24.44	22.88	25.97	24.09	16.91
76803	0.364	0.361	0.379	0.447	0.402	0.383	0.419	0.411	0.42	0.454	0.46	0.436	8.25	6.844	12.69	21.13	16.88	15.59	18.56	17.19	16.59	22.66	23.28	16.06
76806	0.371	0.351	0.367	0.434	0.4	0.27	0.332	0.299	0.388	0.454	0.45	0.435	10.03	7.125	9.875	17.94	14.13	6.25	8.188	7.625	11.44	20.44	23.25	17.31
80797	0.386	0.377	0.401	0.455	0.458	0.453	0.435	0.439	0.44	0.471	0.474	0.44	12.22	8.875	13.88	23.44	24.47	24.03	21.06	21.69	21.19	25.53	25.78	20.66
80800	0.39	0.389	0.392	0.459	0.445	0.468	0.447	0.456	0.45	0.482	0.469	0.436	11.38	8.438	13.72	23.88	22.28	24.31	24.06	23.97	23.66	27.13	25.5	19.63
80803	0.394	0.37	0.384	0.458	0.422	0.39	0.414	0.419	0.426	0.456	0.474	0.437	10.31	7.688	12.28	22.84	19.09	16.81	19.25	18.06	18.13	24.28	24.88	18.31
80806	0.38	0.375	0.403	0.425	0.403	0.256	0.345	0.315	0.392	0.44	0.462	0.441	11.34	7	10.16	19.03	14.97	6.469	9.063	8.344	12.34	21.53	23.81	18.34

STATION	Maximum 0.5 hour rainfall in entire period of record for month (RAINHHMX)												Average solar radiation for month (SOLARAV)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
73797	25.75	39.52	21.19	55.66	59.92	44.54	37.56	40.09	43.8	87.43	62.02	48.06	20.3	22.9	24.29	23.62	22.92	21.29	21.46	22.28	22.87	21.21	18.97	18.83
73800	26.8	38.69	24.41	50.63	36.35	43.43	33.45	54.78	42.22	56.74	43.23	57.46	19.31	21.76	22.73	22.26	22.17	19.6	19.71	20.64	21.71	20.1	18.25	17.92
73803	39.49	39.18	28.85	49.2	58.53	41.61	33.9	57.36	46.35	53.4	46.43	76.03	18.02	20.08	19.91	18.97	20	16.27	16.06	17.37	19	17.19	16.11	16.3
73806	56.83	39.46	35.43	45.39	52.46	33.11	26.17	42.98	43.81	61.59	48.74	81.7	16.08	18.91	18.41	16.54	18.71	15.85	15.78	17.01	17.49	14.92	13.57	14.01
76797	30.49	54.71	23.56	51.81	35.83	40.81	38.82	39.77	41.4	105.9	72.94	49.47	19.8	22.6	24.04	23.6	22.89	21.23	21.47	22.19	22.64	21.03	18.68	18.31

76800	29.66	42.77	26.12	56.57	39.25	35.32	33.43	65.92	27.35	66.14	51.06	48.98	18.79	21.7	22.82	22.32	22.48	20.28	20.78	21.49	22.01	20.17	18.02	17.36
76803	31.85	33.52	20.08	37.57	27.13	32.23	27.19	64.37	28.82	51.78	48.64	58.29	18.48	21.33	21.77	20.61	22.07	19.41	19.75	20.63	21.27	19.15	17.36	16.89
76806	40.61	26.3	24.71	35.52	28.51	25.48	17.4	48.18	26.42	56.93	55.69	66.62	17.91	21.31	21.71	19.76	21.71	19.98	20.1	20.9	20.84	18.43	16.57	16.2
80797	39.43	48.21	17.67	38.39	36.34	36.16	35.56	41.63	31.71	87.8	91.78	43.94	19.3	22.21	23.73	23.54	23.01	21.32	21.56	22.18	22.56	20.97	18.48	17.72
80800	30.63	33.52	18.74	42.12	36.83	37.55	29.76	67.6	25.92	58.42	70.47	39.91	17.5	20.68	21.61	21.31	22.24	20.2	20.89	21.4	21.74	19.55	17.26	16.05
80803	30.3	27.03	13.92	45.8	25.57	34.58	24.38	65.49	21.36	51.16	57.07	43.51	17.09	20.47	20.84	19.59	21.72	19.72	20.36	20.87	21.06	18.5	16.69	15.56
80806	34.76	21.15	12.86	44.52	21.3	18.93	13.66	52.89	29.88	49.42	62.18	55.21	17.29	21.13	21.73	19.68	21.42	20.43	20.73	21.05	20.53	18.27	16.67	15.73

STATION	Average daily dew point temp for each month / Relative humidity (DEWPT)												Average daily wind speed (WNDAV)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
73797	0.725	0.711	0.74	0.767	0.789	0.796	0.803	0.808	0.802	0.792	0.774	0.755	6.004	4.63	3.975	4.291	6.128	7.216	6.695	6.537	6.089	4.767	4.1	5.438
73800	0.672	0.636	0.673	0.736	0.763	0.796	0.803	0.797	0.778	0.794	0.797	0.748	3.567	2.928	2.692	2.945	4.186	4.675	4.336	4.286	4.099	3.108	2.468	3.157
73803	0.731	0.661	0.68	0.769	0.802	0.833	0.839	0.829	0.81	0.832	0.841	0.803	2.891	2.46	2.19	2.369	3.712	4.362	4.096	4.025	3.768	2.759	2.054	2.507
73806	0.818	0.725	0.711	0.795	0.826	0.833	0.833	0.824	0.819	0.854	0.882	0.869	2.504	2.188	1.848	1.894	3.415	4.396	4.153	4.043	3.619	2.576	1.835	2.181
76797	0.737	0.715	0.742	0.772	0.79	0.796	0.804	0.809	0.804	0.797	0.781	0.765	6.484	5.213	4.433	4.807	7.076	8.356	7.788	7.537	6.989	5.353	4.498	5.905
76800	0.692	0.64	0.668	0.732	0.748	0.776	0.78	0.772	0.757	0.786	0.798	0.76	4.274	3.523	3.164	3.625	5.512	6.332	5.929	5.719	5.351	3.91	2.953	3.797
76803	0.729	0.648	0.647	0.725	0.74	0.762	0.765	0.753	0.739	0.78	0.813	0.791	3.471	2.97	2.595	2.983	5.069	6.098	5.774	5.539	5.075	3.576	2.472	3.012
76806	0.782	0.683	0.648	0.714	0.724	0.723	0.724	0.712	0.711	0.769	0.828	0.828	2.802	2.615	2.242	2.332	4.374	5.654	5.374	5.155	4.566	3.156	2.093	2.428
80797	0.747	0.72	0.741	0.776	0.79	0.792	0.799	0.805	0.802	0.798	0.785	0.774	6.585	5.576	4.792	5.146	7.751	9.187	8.554	8.235	7.608	5.735	4.741	6.076
80800	0.722	0.657	0.673	0.746	0.749	0.766	0.765	0.756	0.749	0.792	0.815	0.783	4.397	3.778	3.362	3.875	6.158	7.224	6.785	6.474	5.964	4.243	3.123	3.962
80803	0.756	0.67	0.652	0.729	0.732	0.738	0.737	0.722	0.718	0.78	0.827	0.811	3.528	3.139	2.69	3.168	5.709	6.986	6.621	6.284	5.674	3.862	2.556	3.087
80806	0.791	0.699	0.651	0.704	0.698	0.683	0.682	0.67	0.676	0.753	0.828	0.832	2.837	2.763	2.369	2.499	5.01	6.565	6.229	5.905	5.164	3.449	2.165	2.467

Annexure 5 – SWAT's input parameters, their levels and definitions

Process	Parameter & the ranges given in SWAT database	Level	Description
Potential and Actual Evapotranspiration	ESCO (Soil evapotranspiration compensation factor) Range: 0 – 1 Units: NA	.bsn, .hru	Generally, the upper soil layer contributes more for the evaporation and deep soil layers contribute less or none for the evaporation. When the upper layer cannot satisfy the evaporative demand, SWAT allows lower layers to compensate it by introducing a coefficient known as $esco$ which ranges 0.01 to 1.00. Accordingly, evaporative demand of a soil layer ($E_{soil,ly}$) can be calculated as: $E_{soil,ly} = E_{soil,zl} - E_{soil,zu}.esco$ Where; $E_{soil,zl}$ = evaporative demand at the lower boundary of the soil layer (mm H_2O), $E_{soil,zu}$ = evaporative demand at the upper boundary of the soil layer (mm H_2O) and $esco$ = soil evaporation compensation coefficient. When ESCO is reduced, the model is able to extract more of the evaporation demand from the lower levels.
	CANMX (Maximum canopy storage) Range: 0 – 100 Units: mm	.hru	CANMX is the maximum amount of water that can be trapped in the canopy when the canopy is fully developed. This value is important to calculate the daily canopy storage as a function of the leaf area index.
	EPCO (Plant uptake compensation factor) Range: 0 – 1 Units: NA	.bsn, .hru	If upper layers in the soil profile do not contain enough water to meet the potential water uptake required for plants, users may allow lower layers to compensate it, by introducing the coefficient$epco$, which ranges 0.01 to 1.00. Accordingly, the model calculates the potential water uptake from any soil layer as ($w_{up,ly}$): $w_{up,ly} = w_{up,zl} - w_{up,zu} + w_{demand}.epco$ Where $w_{up,zl}$ is the potential water uptake for the profile to the lower boundary of the

			soil layer (mm H_2O), $w_{up,zu}$ is the potential water uptake for the profile to the upper boundary of the soil layer (mm H_2O) and w_{demand} is the water uptake demand not met by overlying soil layers (mm H_2O) and $epco$ is the plant uptake compensation factor. As $epco$ approaches 1.00, the model allows more of the water uptake demand to be met by lower layers in the soil.
	SOL_ALB (Moist soil albedo) Range: 0 – 0.25 Units: NA	.sol	Moist soil albedo is the fraction of the incident solar radiation reflected from the surface. This depends on the solar elevation angle, soil moisture, soil texture, vegetation cover, mineral composition of the soil, etc.
	REVAPMN (Threshold depth of water in the shallow aquifer for percolation to the deep aquifer to occur) Range: 0 – 1000 Units: mm	.hru	Movement of water from the shallow aquifer to the unsaturated zone is allowed only if the volume of water in the shallow aquifer is equal or greater than REVAPMN
	GW_REVAP (Groundwater "revap" coefficient) Range: 0.02 – 0.2 Units: NA	.hru	To avoid confusion with soil evaporation and transpiration, SWAT uses a special coefficient called "revap" to differentiate the process of movement of water into the overlying unsaturated layer as a function of water demand for evaporation. Water can be removed from the aquifer by deep rooted plants which are able to uptake water directly from the aquifer. The revap is determined by the land use. When GW_REVAP is 0, movement of water from the shallow aquifer is restricted. When GW_REVAP is 1, the rate of moving water from the shallow aquifer to the root zone approaches the rate of PET.

Surface Runoff	CNCOEF (Plant evapotranspiration curve number coefficient) Range: 0.5 – 2 Units: NA	.bsn	This evapotranspiration weighting coefficient is needed if the daily CN value is calculated as a function of plant evapotranspiration.
	CN2 (Initial SCS runoff curve number for moisture condition II) Range: 35 – 98 Units: NA	.mgt	SCS curve number is a function of the soil's permeability, land use and antecedent soil water conditions.
	SURLAG (Surface runoff lag coefficient) Range: 1 – 24 Units: days	.bsn	SURLAG controls the fraction of the total available water that will be allowed to enter the reach on any one day. SURLAG value decreases when more water is held in storage rather than in surface runoff.
Time of concentration	CH_L(1) (Longest tributary channel length in sub-basin) Range: 0.05 – 200 Units: km	.sub	The channel length is the distance along the channel from the sub-basin outlet to the most distant point in the basin
	CH_N(1) (Manning's "n" value for the tributary channels) Range:	.sub	Manning's roughness coefficient for channel flow

	0.01 - 30 Units: NA		
	OV_N (Manning's "n" value for overland flow) Range: 0.01 - 30 Units: NA	.hru	Manning's roughness coefficient for overland flow
	CH_S(1) (Average slope of tributary channels) Range: 0.0001 - 10 Units: m/m	.sub	The average channel slope is computed by taking the difference in elevation between the sub-basin outlet and the most distant point in the sub-basin and dividing by CH_L
	SLSUBBSN (Average slope length) Range: 10 – 150 Units: m	.hru	Slope length should be measured to the point that flow begins to concentrate
Crack Flow	SOL_CRK (Potential or maximum crack volume of the soil profile expressed as a fraction of the total soil volume) Range: 0 – 1 Units: fraction	.sol	This value is used when the model considers crack flow in soil, especially the areas dominated by Vertisols.
Transmission losses from	CH_L(1) (Longest tributary channel	.sub	The channel length is the distance along the channel from the sub-basin outlet to the most distant point in the basin.

surface runoff	length in sub-basin) Range: 0.05 – 200 Units: km		
	CH_K(1) (Effective hydraulic conductivity in tributary channel alluvium) Range: 0 – 300 Units: mm/hr	.sub	This parameter controls transmission losses from surface runoff as it flows to the main channel in the sub-basin.
	CH_W(1) (Average width of tributary channels) Range: 1 – 1000 Units: m	.sub	Average width of tributary channels
Soil water	FFCB (Initial soil water storage) Range: 0 – 1 Units: fraction	.bsn	Initial soil water storage is expressed as a fraction of field capacity water content. If the FFCB is set to 0.0, the model will calculate it as a function of average annual precipitation.
	SOL_K (Saturated hydraulic conductivity) Range: 0 – 2000 Units: mm/hr	.sol	This is a measure of the ease of water movement through the soil. This value is the reciprocal of the resistance of the soil matrix to water flow.
	SOL_BD (Moist bulk density)	.sol	The soil bulk density expresses the ratio of the mass of solid particles to the total volume of the soil.

	Range: 0.9 – 2.5 Units: g/cm^3		
	SOL_Z (Depth from soil surface to bottom of layer) Range: 0 – 3500 Units: mm	.sol	Depth from soil surface to bottom of layer
	SOL_AWC (Available water capacity of the soil layer) Range: 0 – 1 Units: mm/mm	.sol	This is the water available for plants. This is calculated by subtracting the fraction of water present at permanent wilting point from that at field capacity.
Lateral flow	HRU_SLP (Average slope steepness) Range: 0 – 0.6 Units: m/m	.hru	SWAT assigns same value for all HRUs within a subbasin. However, it can be changed by soil type and land cover.
	SLSOIL (Slope length for lateral subsurface flow) Range: 0 – 150 Units: m	.hru	If no value is entered, the model sets SLSOIL = SLSUBBSN. SWAT assigns same SLSOIL value for all HRUs within a subbasin. However, it can be changed by soil type and land cover.
	LAT_TTIME (Lateral flow travel time) Range: 0 – 180 Units: days	.hru	If the LAT_TTIME is set to 0, the model will calculate the travel time based on hydraulic properties.

Groundwater	SHALLST (Initial depth of water in the shallow aquifer) Range: 0 – 5000 Units: mm	.gw	If at least 1-year warm-up period is used during the model, SHALLST is not that much important.
	ALPHA_BF (Baseflow alpha factor) Range: 0 – 1 Units: days	.gw	This is a direct index of groundwater flow response to changes in recharge.
	DEEPST (Initial depth of water in the deep aquifer) Range: 0 – 10000 Units: mm	.gw	If at least 1-year warm-up period is used during the model, DEEPST is not that much important.
	GWQMN (Threshold depth of water in the shallow aquifer required for return flow to occur) Range: 0 – 5000 Units: mm	.gw	Groundwater flow to the reach is allowed only if the depth of water in the shallow aquifer is equal to or greater than GWQMN.
	GW_DELAY (Ground water delay time) Range: 0 – 500 Units: days	.gw	The lag between the time that water exits the soil profile and enters the shallow aquifer.
	GW_REVAP (Groundwater	.gw	This is a coefficient which controls the movement of water from the shallow aquifer

	“revap” coefficient) Range: 0.02 – 0.2 Units: NA		into the overlying unsaturated zone. The removed water due to evaporation is replaced by the underlying aquifer and at the same time deep-rooted plants also uptake water directly from the aquifer. If GW_REVAP is 0, movement of water from the shallow aquifer to the root zone is restricted. If GW_REVAP is 1, the rate of transfer from the shallow aquifer to the root zone approaches to the rate of potential evapotranspiration.
	RCHRG_DP (Deep aquifer percolation factor) Range: 0 – 1 Units: fraction	.gw	The fraction of percolation from the root zone which recharges the deep aquifer.
	REVAPMN (Threshold depth of water in the shallow aquifer for “revap” or percolation to the deep aquifer to occur) Range: 0 – 1000 Units: mm	.gw	This controls the movement of water from the shallow aquifer based on its volume. Water is only moved if the volume of water in the shallow aquifer is equal to or greater than REVAPMN.
	WUDEEP Range: 0 – 10000 Units: 10^4 m3/day	.wus	Mean daily water removal from the deep aquifer
	WUSHAL Range: 0 – 10000 Units: 10^4 m3/day	.wus	Mean daily water removal from the shallow aquifer

Channel water routing	TRNSRCH Range: 0 – 1 Units: NA	.bsn	Fraction of transmission losses from the channel network
	MSK_CO1 (Muskingum coefficient for normal flow) Range: 0 – 10 Units: NA	.bsn	This coefficient is used when the channel flow is modelled through Muskingum method. This is used to control the impact of the storage time constant for normal flow (when river is at bankfull depth)
	MSK_CO2 (Muskingum coefficient for low flow) Range: 0 – 10 Units: NA	.bsn	This coefficient is used when the channel flow is modelled through Muskingum method. This is used to control the impact of the storage time constant for low flow (when river is at 0.1 bankfull depth)
	MSK_X (Weighting factor for wedge storage) Range: 0 – 0.3 Units: NA	.bsn	This coefficient is used when the channel flow is modelled through Muskingum method. This is a weighting factor that controls the relative importance of inflow and outflow in determining the storage in a reach.
	EVRCH Range: 0.5 – 1 Units: NA	.bsn	The evaporation coefficient to represent reach evaporation
	CH_W(2) Range: 0 – 1000 Units: m	.rte	Average width of main channel at top of bank (m)
	ALPHA_BNK	.rte	Baseflow alpha factor for bank storage (days)

	Range: 0 – 1 Units: NA		
	CH_D Range: 0 – 30 Units: m	.rte	Depth of main channel from top of bank to bottom (m)
	CH_N(2) Range: -0.01 – 1 Units: NA	.rte	Manning’s “n” value for main channel
	CH_S(2) Range: -0.001 – 10 Units: m/m	.rte	Average slope of main channel along the channel length
	CH_K(2) Range: -0.01 – 500 Units: mm/hr	.rte	Effective hydraulic conductivity in main channel alluvium
	CH_L(2) Range: -0.05 – 500 Units: km	.rte	Length of main channel (km)

Annexure 6

Number of the day in the year (J)

Day	January	February	March*	April*	May*	June*	July*	August*	September*	October*	November*	December*
1	1	32	60	91	121	152	182	213	244	274	305	335
2	2	33	61	92	122	153	183	214	245	275	306	336
3	3	34	62	93	123	154	184	215	246	276	307	337
4	4	35	63	94	124	155	185	216	247	277	308	338
5	5	36	64	95	125	156	186	217	248	278	309	339
6	6	37	65	96	126	157	187	218	249	279	310	340
7	7	38	66	97	127	158	188	219	250	280	311	341
8	8	39	67	98	128	159	189	220	251	281	312	342
9	9	40	68	99	129	160	190	221	252	282	313	343
10	10	41	69	100	130	161	191	222	253	283	314	344
11	11	42	70	101	131	162	192	223	254	284	315	345
12	12	43	71	102	132	163	193	224	255	285	316	346
13	13	44	72	103	133	164	194	225	256	286	317	347
14	14	45	73	104	134	165	195	226	257	287	318	348
15	15	46	74	105	135	166	196	227	258	288	319	349
16	16	47	75	106	136	167	197	228	259	289	320	350
17	17	48	76	107	137	168	198	229	260	290	321	351
18	18	49	77	108	138	169	199	230	261	291	322	352
19	19	50	78	109	139	170	200	231	262	292	323	353
20	20	51	79	110	140	171	201	232	263	293	324	354
21	21	52	80	111	141	172	202	233	264	294	325	355
22	22	53	81	112	142	173	203	234	265	295	326	356
23	23	54	82	113	143	174	204	235	266	296	327	357
24	24	55	83	114	144	175	205	236	267	297	328	358
25	25	56	84	115	145	176	206	237	268	298	329	359
26	26	57	85	116	146	177,	207	238	269	299	330	360
27	27	58	86	117	147	178	208	239	270	300	331	361
28	28	59	87	118	148	179	209	240	271	301	332	362
29	29	(60)	88	119	149	180	210	241	272	302	333	363
30	30	-	89	120	150	181	211	242	273	303	334	364
31	31	-	90	-	151	-	212	243	-	304	-	365

* add 1 if leap year

Annexure 7

Example code for extracting data from ERA5.

```
import cdsapi                          // calling the cdsapi library

c = cdsapi.Client()                    // access Copernicus data portal using api
credentials

c.retrieve(
  'reanalysis-era5-land',                        // Specify    extracting data
category
    {
      'format':'netcdf',                         // specify the dta format
      'variable':'surface_net_solar_radiation',  // Specify data variable
      'area':  '7.3298/79.83806/7.96406/ 80.56865',  //Specify extracting area

      'year':[
        '2017','2018','2019'                 //Specify temporal parameters
      ],
      'month':[
        '01','02','03',
        '04','05','06',
        '07','08','09',
        '10','11','12'
      ],
      'day':[
        '01','02','03',
        '04','05','06',
        '07','08','09',
        '10','11','12',
        '13','14','15',
        '16','17','18',
        '19','20','21',
        '22','23','24',
        '25','26','27',
        '28','29','30',
        '31'
      ],
      'time':[
        '00:00','01:00','02:00',
        '03:00','04:00','05:00',
        '06:00','07:00','08:00',
        '09:00','10:00','11:00',
        '12:00','13:00','14:00',
        '15:00','16:00','17:00',
        '18:00','19:00','20:00',
        '21:00','22:00','23:00'
```

```
    ]
  },
  'downloadsolarrad.nc')                    //name and the format of the download
```