ENGINEER - Vol. LV, No. 03, pp. [29-41], 2022

DOI: http://doi.org/10.4038/engineer.v55i3.7519

Hydrological Modelling for Reservoir Operation: Application of SWAT Model for Kalu Ganga Catchment, Sri Lanka

G.A.T. Madushanka, K.D.W. Nandalal and L.P. Muthuwatta

Abstract: Kalu Ganga, a major tributary of Amban Ganga, is one of the perennial rivers of Sri Lanka. Also, Amban Ganga is a major tributary of Mahaweli Ganga. The Kalu Ganga starts from Knuckles mountains, and about 90% of the catchment is covered with forests. The Government of Sri Lanka constructed Kalu Ganga and Moragahakanda Reservoirs in 2014 to increase the water availability in Mahaweli Basin to improve the agricultural and drinking water benefits in several provinces. This study used the Soil Water Assessment Tool (SWAT) to simulate the hydrology of the Kalu Ganga catchment and estimate the daily streamflow series of the Kalu Ganga. The long-term mean annual flow of the Kalu Ganga at the dam site would be 196 MCM (equivalent to 6.24 m^3/s) with a standard deviation of 57.5 MCM and coefficient of variation of 0.29. The mean annual catchment rainfall is 2763 mm, streamflow is 59%, and evapotranspiration is 33% of the rainfall. The Kalu Ganga catchment hydrology is dominated by the wet season rainfall, which governs the Kalu Ganga flow, where 89% of the annual flow volume is produced. Further, 67% of the flow volume is produced from November to January. The model results show that 89% of the annual average of streamflow is generated as baseflow, a feature of a perennial river. The high baseflow fraction is hydrologically favourable for the water availability of the catchment as this shows the utilizable quantity of water is high.

Keywords: Water availability, Kalu Ganga, SWAT

1. Introduction

1.1. General

Water is an indispensable resource needed in all aspects of human activities and plays a crucial role in all physiological processes of both animals and plants. The shortage of water would negatively affect human and animal habitats, economic prosperity, food supply, human migration, and domestic and international relations [1, 2]. Also, the water surpluses during wet periods would damage agricultural areas, properties, and lives. The increasing demand for fresh water due to rapid population growth, industrial development, and changes in land-use patterns and land management procedures would aggravate the seasonal disparity of the natural water supply [3, 4]. The most suitable way of handling seasonal water availability due to variability in rainfall is the construction of storage reservoirs [5] and thereby ensuring the supply of water throughout the year. Therefore, a well-established water management system consisting of physical infrastructure and operational practices is required to effectively manage available water resources for the well-being of society and the environment.

Sri Lanka is an agriculture-based country with a long history of water resources development. Paddy cultivation is mainly conducted in the Dry Zone of the country despite the shortage of water. All other conditions in the dry zone (flat terrain, fertile soil and sunshine) are favorable for paddy cultivation [6]. The cultivation is conducted in two agricultural seasons called 'Maha' (from October to March) and 'Yala' (from April to September).

Eng. ***G.A.T. Madushanka****, BSc(Eng)Hons, CIMA, Adv Dip MA, Research Student, Department of Civil Engineering, University of Peradeniya*
Email:thilina.guru.mwsip@gmail.com
http://orcid.org/0000-0003-1315-0334
Eng. (Prof.) K.D.W. Nandalal*, IntPE(SL), FIE(SL), CEng, BSc(Eng)Hons., MEng, PhD, Senior Professor, Department of Civil Engineering, University of Peradeniya*
Email:kdwn@pdn.ac.lk
http://orcid.org/0000-0002-8799-7952
Dr. L.P. Muthuwatta*, BSc, MSc, MPhil, PhD, Senior Regional Researcher, International Water Management Institute, Battaramulla.*
Email:L.MUTUWATTE@cgiar.org
http://orcid.org/0000-0002-5030-6003

The mean annual rainfall of Sri Lanka is around 1850 mm, and it varies spatially from about 900 mm to 5000 mm. The rainfall of the country has considerable spatial and intra-annual variations [7] as well as a high year-to-year variability. The rains are seasonal, extremely variable, and evaporation losses are generally high [8]. The dry zone receives substantially high rainfall during the Maha season and low rainfall in the Yala season. However, lower rainfall and higher variability are noticed in the dry zone than in the wet zone [8] and thus droughts are much more severe and prevalent in the dry zone.

Long durational hydrometric information collected over a basin such as measured river flow records constitute the fundamental inputs for the design of various water resources projects and the study of climate change impact on water resources [9]. Further, when the inter-annual variability in rainfall and river flow is high, the importance of having a longer flow duration is high [10, 11].

However, the availability of river flow gauging stations is limited in the country. Thus, the common practice adopted to overcome this issue is to convert the available rainfall records in catchments to river flows based on hydrological models [12]. These have been mainly conducted using computer models which offer advantages for economic savings in terms of time efficiency and resource utilization since they are capable of representing processes that occur in the real world in space and time [12]. The success of such models heavily depends on the extent to which the available rainfall data can represent actual rainfall over the catchment. This indicates the importance of having rainfall data at an evenly distributed dense grid within a catchment [13].

Three types of hydrological models exist: lumped, semi-distributed, and fully distributed. These are differentiated based on the spatial representation of the model domain. Lumped models are designed to simulate the total runoff at the catchment outlet point, considering the entire catchment as homogeneous ignoring spatial variability of model parameters. The lump modelling process is efficient in terms of computational time, however, may not accurately represent large catchments since such models are developed based on many assumptions and averaged conditions [14, 15]. However, in contrast, semi-distributed and fully distributed models are significantly different compared to lumped models with features of distributed models. Semi distributed models could consist of a series of lumped parameters applied quasi-spatially distributed. The model process divides the catchment into smaller areas (e.g., Sub basins and Hydrological Response Units), with different parameters for each area [16]. The division into sub-areas is carried out in a logical order based on drainage network, slope, soil group, vegetation zones, etc. Different combinations of these characteristics are called Hydraulic Response Units (HRUs), in which the region within the HRU responds to rainfall the same way, based on overlaying maps of land cover, soil, and elevation [17]. The benefits of a semi-distributed model are fast computational time and the ability to use fewer data and fewer parameters than a distributed model [18].

Distributed hydrological models are the most complex because they account for spatial heterogeneity of inputs and parameters and separate the model process by small elements or grid cells [19] where specific hydrological data are required. Nevertheless, in reality, the data are scarce and lead to reducing the effectiveness of the modelling exercise. Another weakness is the large computational time needed to run one simulation.

1.2. Mahaweli Development Programme

Mahaweli Development Programme (MDP) is the most extensive water resources development program ever implemented in Sri Lanka. The objectives of the MDP are to increase agricultural production in the dry zone areas, hydropower generation, drinking water supply, flood mitigation, inland fisheries and employment generation [20].

The MDP spreads over 12 river basins (including the Mahaweli Basin) to develop several large irrigation systems, conveyance systems and multipurpose reservoirs. Part of the infrastructure proposed under the MDP has already been constructed, and some are yet to be constructed. The study area of this research, i.e, Kalu Ganga catchment, lies within the Mahaweli System. The Kalu Ganga is a tributary of Amban Ganga while the Amban Ganga is a tributary of Mahaweli Ganga. A dam was constructed across the Kalu Ganga at Pallegama to create Kalu Ganga reservoir as a part of the MDP to supply the water requirement of Mahaweli System F and divert surplus water to Moragahakanda reservoir to improve the agricultural and drinking water benefits in several provinces (Figure 1)

The Kalu Ganga Reservoir and conveyance structures were designed per the hydrological assessments conducted on a monthly time step model in 2004. Also, only a single rainfall station (Pallegama) was located within the Kalu Ganga catchment during the study period, which was discontinued in 1968 [21].

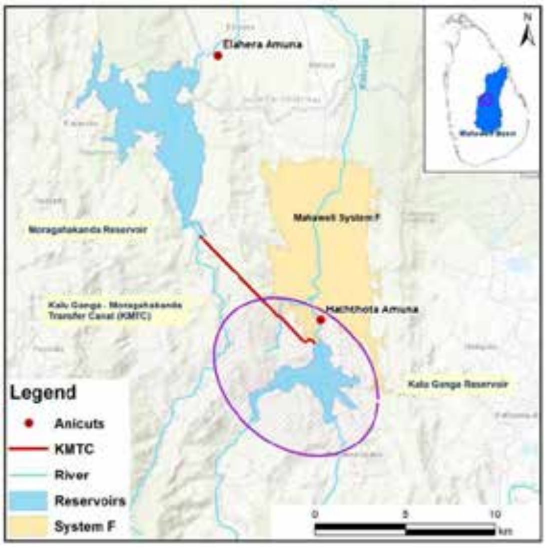

Figure 1 - Map of the Study Area

This study investigates the possible hydrological impacts on the Mahaweli System due to the construction of the Kalu Ganga Reservoir through modelling its catchment using Soil Water Assessment Tool SWAT, which adequately represents physical processes governing the catchment hydrology. Also, this would enable in the assessment of the water availability in the Kalu Ganga Reservoir to divert surplus water to the Moragahakanda Reservoir.

2. Study Area, Data and Methodology

2.1. Study Area

Kalu Ganga, a perennial river, has a total catchment area of 307 km^2 at its confluence with the Amban Ganga, while the catchment area of the Kalu Ganga Reservoir is 116 km^2. The river starts from Knuckles mountains, and about 90% of the catchment is covered with forests. The Kalu Ganga catchment consists primarily of a mountainous area with an elevation from more than 1860 m MSL (Mean Sea Level) to 145 m MSL at the location of Kalu Ganga Dam. 8% of the catchment area is in a slope range of 0-10%, 81% within 10-60%, and 11% of the area above the 60% slope range. The upper reaches of the catchment are located in the Matale district in the Central Province and the lower reaches are located in the Polonnaruwa district in the North Central Province. A weir structure called Haththota Amuna, constructed across the Kalu Ganga, has been used to divert water to an irrigation area since the ancient era [21]. The proposed Irrigation System F of area 3000 ha covering the lower valley area downstream of the dam would be supplied with irrigation water through Left Bank and Right Bank canals running through some restored and newly constructed set of regulatory reservoirs [22].

2.2. Soil and Water Assessment Tool (SWAT)

SWAT is a watershed scale model developed to predict the impact of land management practices on water, sediment, and agricultural chemical yields in large, complex watersheds with varying soils, land use, and management conditions over long periods. The model is conceptual and computationally efficient, uses readily available inputs and enables users to study long-term impacts [24]. The SWAT is internationally recognized as a solid interdisciplinary watershed-modelling tool with diverse applications [23, 25, 26, 27]. It can be used to simulate a single watershed or a system of multiple hydrologically connected watersheds. Each watershed is first divided into sub-watersheds and then into hydrologic response units (HRUs) based on the land use and soil distributions.

In the SWAT, the watershed delineation and generation of the river network are performed by an automatic delineation method using the Digital Elevation Model (DEM). It represents the local water balance through four storage volumes: snow, soil profile, shallow aquifer and deep aquifer. It facilitates an assortment of parameters defined at HRU, sub-catchment or catchment level. The SWAT simulates the various hydrological processes by the soil water balance equation.

$$SW_t = SW_o + \sum_{i=1}^{t} (R_{day} - Q_{Surf} - E_a - W_{seep} - Q_{gw}) \quad ...(1)$$

where,
SW_t - *final soil water content (mm),*
SW_o - *initial soil water content (mm),*
R_{day} - *amount of precipitation on day i (mm),*
Q_{Surf} - *amount of surface runoff on day i (mm),*
E_a - *amount of evapotranspiration on day i (mm),*
W_{seep} - *amount of water entering the vadose zone from soil profile on day i (mm),*
Q_{gw} - *amount of return flow on day i (mm)*

It provides the basis for modelling, and the simulated processes include surface runoff, infiltration, evaporation, plant water uptake, lateral flow and percolation to shallow and deep aquifers. The surface runoff volume is calculated by using the Soil Conservation Service (SCS) curve number equation. Potential evapotranspiration (PET) can be estimated by one of the following three methods: Penman-Monteith, Priestly and Taylor or Hargreaves. The actual evapotranspiration is estimated based on simulated plant growth and soil water availability. The model calculates percolation when the soil-water content exceeds the soil-field capacity and determines the amount of water moving from one soil layer to the next by using a storage routing method. In each sub-catchment, the SWAT model simulates two groundwater aquifers: a shallow aquifer that contributes to streamflow and a deeper aquifer that does not add to streamflow [23].

The SWAT model was used to simulate the hydrology of the Kalu Ganga catchment and estimate its daily streamflow series.

2.3. Preparation of Data

SWAT model requires a large number of input data such as the Digital Elevation Model (DEM), land use, soil, climate (rainfall and temperature) and streamflow. These data were obtained for the study from different sources given in Table 1.

The delineation of the catchment into sub-catchments and generation of the stream network was conducted using the SRTM DEM. The parameters such as basin area, sub-catchments, stream network, and confluence points were internally derived in the SWAT modelling process using the DEM. In the 1:50,000 scale land use map, eight land use types were identified in the catchment as presented in Figure 2. The land use features of the catchment have remained unchanged during the past decades except for the development carried out under the Kalu Ganga Reservoir Project.

The in-built land use database in the SWAT includes relevant hydrological properties under each land use type required for the hydrologic processes simulated by the SWAT. These processes include canopy storage, surface runoff, infiltration, evapotranspiration, lateral flow, tile drainage, redistribution of water within the soil profile, consumptive use through pumping (if any), return flow, and recharge by seepage from surface water bodies, ponds, and tributary channels [28]. Therefore, the land use types in the land use map were assigned with the equivalent land use types of the in-built SWAT database. The details of prevailing land use types in the catchment as per the map and the equivalent land use types in the SWAT database are given in Table 2.

The soil data used by the SWAT could be categorized into physical and chemical properties. The soil physical properties govern the movement of water and air through the profile and significantly impact the cycling of water within the HRU. The chemical properties are used to set initial levels of the different chemicals in the soil. The soil properties of the catchment were incorporated into the SWAT model similar to the procedure adopted in land use. Five soil types are identified in the catchment as shown in Figure 3. The details of soil types in the catchment as per the soil map are given in Table 3.

Table 1 - Details of Collected Data

Data Type	Data	Data source
Topography	Digital elevation model (DEM) (30 m × 30 m)	Shuttle Radar Topography Mission (SRTM) Downloaded from *https://www2.jpl.nasa.gov/srtm/*
Landuse	Landuse map (1:50,000)	Survey Department (developed in 2013/14)
Soil	Soil map (1:500,000)	Landuse Division of the Irrigation Department
Climate	Meteorological data: Rainfall and Temperature	Department of Meteorology
Hydrology	Measured streamflow data (Laggala Gauging Station)	Irrigation Department

Table 2 - Details of Land Use (LU) in Kalu Ganga Catchment

No	LU type as per LU map of Sri Lanka	SWAT LU type – Description	SWAT LU type	Land Area (km²)	Land Area %
1	Chena	Agricultural Lands - Generic	AGRL	0.72	0.62
2	Forest unclassified	Forest – Evergreen	FRSE	54.10	46.57
3	Homestead garden	Garden	PEAS	3.97	3.42
4	Paddy	Rice	RICE	2.96	2.55
5	Rock	Transportation	UTRN	3.37	2.90
6	Scrubland	Range brushes	RNGB	49.92	42.97
7	Reservoir, River	Water	WATR	1.12	0.96
8	Tank boundaries	Wetlands - Forested	WETF	0.01	0.01

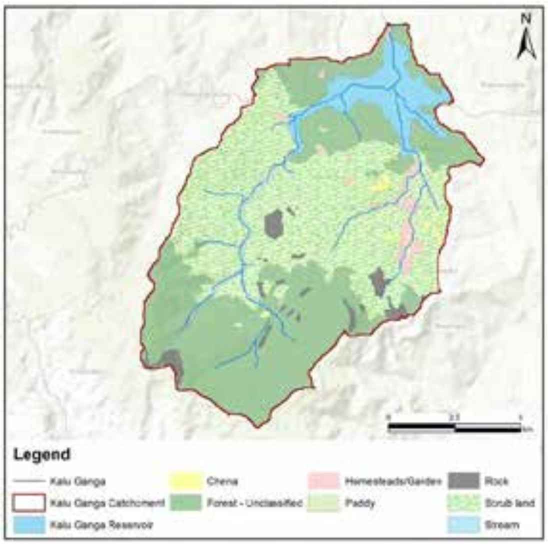

Figure 2 – Land Use Map of Kalu Ganga Catchment

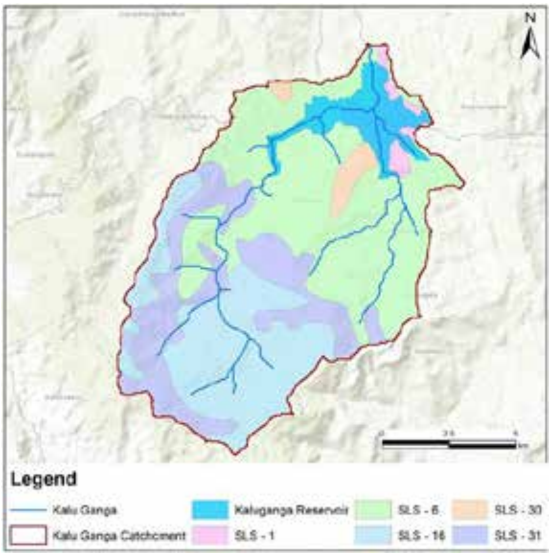

Figure 3 - Soil Map of Kalu Ganga Catchment

Table 3 - Details of Soil Types Prevalent in Kalu Ganga Catchment

No	Soil Type	Description	Land Area (km²)	Land Area %
1	SLS 01	Reddish-brown Earth and low humic gray soils undulating terrain	6.06	5.22
2	SLS 06	Reddish-brown Earth and Immature brown looms, rolling, hilly and steep terrain	53.73	46.25
3	SLS 16	Red-yellow podzolic soils and mountain regosoils mountainous terrain	29.89	25.73
4	SLS 30	Erosional Remnants	2.89	2.49
5	SLS 31	Steep Rockland and Lithosols	23.61	20.32

The relevant hydrological properties required for the internal calculations within the SWAT were calculated for the prevalent soil types in the catchment as given in Table 4. This was conducted by using the available data from the samples obtained in the catchment during the geotechnical tests carried out in the Kalu Ganga Reservoir project. These soil hydrological properties were input to the user soil database.

The SWAT selects the climate data for each sub-catchment from the station nearest to the centroid of each sub-catchment. The daily rainfall data of eight meteorological stations located adjacent to the basin (none available within the basin) from 1989 to 2018 were used. The minimum and maximum temperature data are not available for the entire period, and thus, average monthly data were used. The Hargreaves method [29] was used to estimate potential evapotranspiration.

Table 4 - Properties of Prevalent Soil Types in Kalu Ganga Catchment

Name of the Property	Description	Soil Type				
		SLS01	SLS06	SLS16	SLS30	SLS31
NLAYER (Nos)	Number of layers in the soil	1	1	1	1	1
HYDGRP	Soil Hydrologic Group	C	B	B	C	C
SOL_ZMX (mm)	Maximum rooting depth of soil profile	2000	1500	1500	2000	2000
ANION_EXCL (Fraction)	Fraction of porosity (void space) from which anions are excluded	0.12	0.12	0.1	0.1	0.1
SOL_CRK (Fraction)	Crack volume potential of soil	0.5	0.5	0.5	0.5	0.5
SOL_Z (mm)	Depth from the soil surface to the bottom of the layer	3000	2500	3500	3500	3500
SOL_BD (g / cm^3)	Moist bulk density	2.02	1.69	1.48	2.17	2.17
SOL_AWC [mm/mm]	Available water capacity of the soil layer	0.156	0.053	0.074	0.168	0.168
SOL_K [mm/hr]	Saturated hydraulic conductivity	1.25×10^{-7}	1.25×10^{-7}	2.88×10^{-7}	2.88×10^{-7}	2.88×10^{-7}
SOL_CBN	Organic carbon content	2	2.5	2.5	1.5	1.5
CLAY (%)	Clay content	32	14	18	20	20
SILT(%)	Silt content	16	29	22	32	32
SAND (%)	Sand content	51	49	44	47	47
ROCK (%)	Rock fragment content	1	8	16	1	1
SOL_ALB	Moist soil albedo	0.22	0.25	0.25	0.22	0.22

The daily streamflow data measured at the Laggala gauging station (located at 07° 33′ 59″, 80° 49′ 59″, elevation 158 m) is used to calibrate the model. The station was started in 1989 and functioned up to 2014 till its closure with the construction of the Kalu Ganga Reservoir. The measured runoff can be considered a natural flow during this period without any upstream interventions. The locations of rainfall gauging stations and Laggala stream gauge are shown in Figure 4.

2.4. Model Development

The SWAT model for the Kalu Ganga catchment is developed on an ArcSWAT interface. The catchment was delineated for 200 ha of area threshold, and the watershed was divided into 30 sub-catchments. The size of the largest sub-catchment is 10.97 km^2, and the smallest is 0.05 km^2, with a mean of 3.87 km^2. The delineated sub-catchments are shown in Figure 5.

2.5. Model Calibration and Validation

The calibration was performed with the measured flow series at the Laggala gauging station.

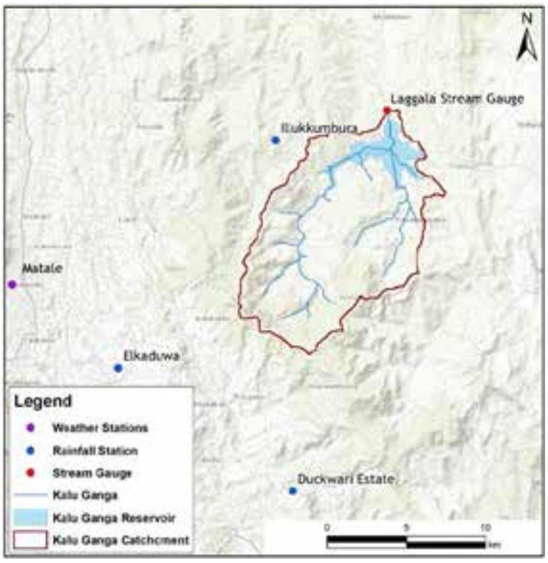

Figure 4 - Location Details of Meteorological and Stream Gauge Network

The period from 01/01/1990 to 31/12/1993 was selected for the calibration, and from 01/01/2010 to 31/12/2013 was selected for the validation. The indicators used to assess the performance of the model are described below.

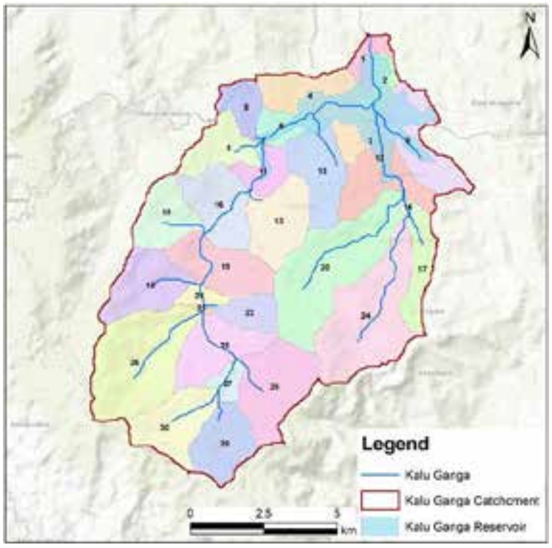

Figure 5 - Delineated Sub-Basin Map of Kalu Ganga Catchment

Pearson's Correlation Coefficient

The Correlation Coefficient is a scale to measure the strength and direction of linear association between variables. The perfect value of the Coefficient of Correlation is 1.0, which means the perfect positive relationship, and (-1) means the perfect negative relationship between compared parameters. If the coefficient is 0, there is no linear relationship between them.

$$r = \frac{n * \sum_{i=0}^{n}(Q_{obs} * Q_{Sim}) - (\sum_{i=0}^{n} Q_{obs}) * (\sum_{i=0}^{n} Q_{Sim})}{\sqrt{[n * \sum_{i=0}^{n} {Q_{obs}}^2 - (\sum_{i=0}^{n} Q_{obs})^2] * [n * \sum_{i=0}^{n} {Q_{Sim}}^2 - (\sum_{i=0}^{n} Q_{Sim})^2]}} \quad \text{....(2)}$$

where,

r - *Pearson's Correlation coefficient*

Q_{obs} - *Observed Discharge (Daily)*

Q_{Sim} - *Simulated Discharge (Daily)*

n - *No of months*

Coefficient of Determination (R^2)

The Coefficient of Determination, R^2, assesses the ability of a model to predict or explain an outcome in linear regression. R^2 indicates the proportion of the variance in the dependent variable (simulated flow) and the independent variable (measured flow). The range of R^2 is 0 to 1 and a high value of R^2 indicates a good fit between the two variables. In hydrological studies based on monthly time steps, $R^2 > 0.5$ is considered acceptable [31].

Nash-Sutcliffe Efficiency (*NSE*)

The Nash–Sutcliffe efficiency (*NSE*) indicates the match between observed and estimated values. The *NSE* has a range between -∞ to 1. *NSE* values between 0 to 1 are generally illustrated as acceptable performance, whereas 1 is the perfect match.

$$NSE = 1 - \frac{\sum_{i=0}^{n}(Q_{obs} - Q_{Sim})^2}{\sum_{i=0}^{n}(Q_{obs} - Q_{mean\ (obs)})^2} \quad \text{...(3)}$$

where,

NSE - *Nash-Sutcliffe Coefficient*

Other variables as defined before.

The Relative Percentage of Bias (*PBIAS*)

The Relative Percentage of Bias (*PBIAS*) indicates the average relative tendency of the estimated data to deviate from the observed data set (larger or smaller). The perfect value of *PBIAS* is 0.0. When the *PBIAS* has a lower magnitude of values (+ or -), that indicates an acceptable match compared to the observation. Positive values indicate that the estimated data set has an under-estimation bias, whereas negative values indicate over-estimation bias.

$$PBIAS = \frac{\sum_{i=0}^{n}(Q_{obs} - Q_{Sim})}{\sum_{i=0}^{n}(Q_{obs})} \quad \text{....(4)}$$

where,

PBIAS - *Relative Percentage of Bias*

Other variables as defined before.

3. Results and Discussion

3.1. Calibration and Validation of SWAT Model for Daily Time Steps

The SWAT model was calibrated using the Sequential Uncertainty Fitting (SUFI-2) algorithm integrated into SWAT-CUP. The SWAT-CUP would help to identify parameters that affect the streamflow and to identify the best performing parameter combination [30].

The SWAT model was calibrated to improve the statistical and graphical relationship between the measured and simulated streamflow series from 1990 to 1993. Previous studies [31, 32] have suggested ranges of best fit for different model performance indicators to evaluate the quality of the comparison. Subsequently, the calibrated model was validated using data from 2010 to 2013. The values of model performance indicators calculated between the observed and the simulated flow series are given in Table 5. As Table 5 reveals, the performance indicators show that the calibration of the model is successful. The comparison plots of the measured flow series and simulated flow series by SWAT during calibration period (1990-1993) are shown in Figure 6 while those during the validation period (2010-2013) are shown in Figure 7.

A strong graphical relationship between the observed flow series and the simulated flow series is observed. The model has very closely simulated the base flows, lag-time, and recession limbs of hydrographs but has failed to simulate the peaks, though the dates of peaks are overlapping. The accuracy of measuring the peak flows is doubtful in a terrain of shallow river sections and wide flood plain sections. The rating curve of the Laggala gauging station has been developed for low flows occurred within the river section and higher discharges with overbank flows have not been measured due to accessibility issues. Therefore, the peak flows are estimated by extrapolating the rating curve done for the river section. The river flow velocity over the flood plain is much lower than that of the river section, while the flow area is much higher than the river section and hence extrapolated rating curves may give rise to erroneous estimates [22].

3.2. Calibration Parameters

In the SWAT model, there is a large number of input parameters related to the land use (e.g., SCN curve no) and soil types (e.g., available water capacity of the soil, hydrologic group of soil). A set of model parameters based on the experience from previous studies [2, 27, 28, 32] were carefully selected for the calibration of the model and they are given in Table 6

Table 5 - Results of SWAT Model Calibration (1990-1993) and Validation (2010-2013)

Model performance indicator	Calibration				Validation			
	Daily		Monthly		Daily		Monthly	
	OBS	SIM	OBS	SIM	OBS	SIM	OBS	SIM
Annual flow volume (MCM/yr)	211.30	196.06	-	-	225.01	214.80	-	-
Pearson's Correlation Coefficient	0.81		0.95		0.71		0.92	
Coefficient of Determination (R^2)	0.65		0.91		0.51		0.85	
Nash-Sutcliffe Efficiency (*NSE*)	0.65		0.90		0.48		0.83	
Relative Percentage of Bias (*PBIAS*)	7.22		7.22		4.54		4.54	

* OBS - Observed streamflow, SIM - Simulated streamflow

Figure 6 - Comparison of Daily Flows in the Calibration Period (1990-1993)

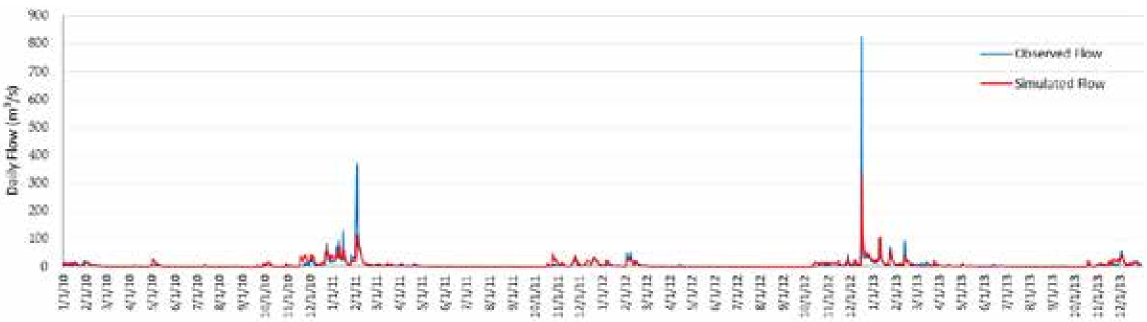

Figure 7 - Comparison of Daily Flows in the Validation Period (2010-2013)

3.3. Results of SWAT Modelling

The catchment level hydrology simulated using the calibrated and validated SWAT model is shown in Figure 8.

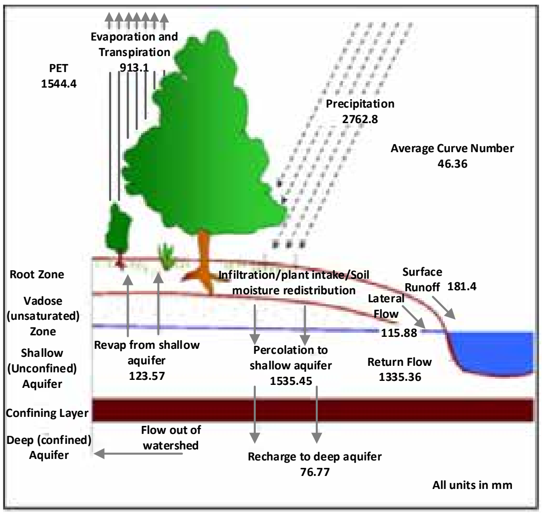

Figure 8 - Catchment Hydrology

The results of the hydrological assessment show that 59% of the rainfall (2763 mm) is converted to runoff (1633 mm) along the Kalu Ganga, and actual evaporation and transpiration is 33% (913 mm). The percentage of base flow (lateral flow + return flow) is 89% of the total flow, and surface runoff is only 11% which may be due to the 90% of the catchment being covered with forests which reduces the surface runoff. A low percentage of surface runoff indicates a low possibility of sediment transportation along the river.

The simulated flow series was developed from the calibrated SWAT model for the Kalu Ganga dam site for 30 years (1989 - 2018) on daily time steps. The statistical details of simulated monthly and annual cumulative flows (derived from daily flows) at the location of the Kalu Ganga Dam are given in Table 7.

Table 6 - Details of SWAT Model Calibration Parameters

Model Parameter	Acronym	Unit	Adjustment value / range
Soil evaporation compensation factor	ESCO		0.44
Groundwater delay	GW_DELAY	Days	0.11
Baseflow alpha factor	ALPHA_BF		0.96
Threshold depth of water in the shallow aquifer required for return flow to occur	GWQMN	mm	1333
Groundwater "revap" coefficient	GW_REVAP	mm	0.08
Threshold depth of water in the shallow aquifer for "revap" to occur	REVAPMN	mm	812
SCS runoff curve number	CN2	%	39.3 - 65.8
Manning's "n" value for the main channel	CH_N2	$m^{(-1/3)} \cdot S$	0.09
Baseflow alpha factor for bank storage	ALPHA_BNK		0.60
Manning's "n" value for the tributary channels	CH_N1	$m^{(-1/3)} \cdot S$	0.12
Available water capacity of the soil layer	SOL_AWC	%	0.0580 - 0.1838
Average slope length	SLSUBBSN	m	141.9

Table 7 - Statistical Details of Simulated Average Monthly Flow Volume

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Unit	(MCM/Month)												(MCM/ yr)
Min	1.2	0.8	2.0	1.9	1.3	0.8	0.7	0.6	0.4	0.8	5.9	10.8	87.5
20% Percentile	21.1	6.5	3.2	2.2	1.9	1.2	1.0	0.8	0.7	3.3	19.6	30.3	156.4
Average	40.7	22.0	9.4	7.6	7.6	2.3	1.5	1.3	1.5	11.4	35.5	56.1	196.8
80% Percentile	69.2	34.2	12.6	11.3	13.2	2.8	1.9	1.4	1.9	15.9	49.7	80.5	226.7
Max	91.5	61.4	32.9	23.4	27.0	12.6	3.2	5.7	4.3	36.3	83.3	130.0	340.1
STD (σ)	25.3	14.8	7.3	6.4	7.7	2.2	0.6	0.9	1.0	10.4	18.9	31.9	57.5
CV (σ/μ)	0.62	0.67	0.78	0.84	1.00	0.95	0.41	0.71	0.68	0.91	0.53	0.57	0.29

The highest average monthly flow volume produced in December is 56.1 MCM/month (28.5% of total flow) and the second-highest average monthly flow volume produced in January is 40.7 MCM/month (20.7% of total flow), whereas the lowest average monthly flow volume produced in August is 1.3 MCM/month (0.6% of total flow).

The simulated annual flow distribution at the Kalu Ganga Dam site is shown in Figure 9. The annual flow volume varies from 87.5 MCM/yr (1998) to 340.1 MCM/yr (2015), with a standard deviation of 57.5 and a coefficient of variation of 0.29.

The simulated seasonal flow distribution at the Kalu Ganga Dam site is shown in Figure 10. This graph clearly shows that a major portion of the average flow is generated during the Maha season (174 MCM/season - 89%), whereas only about 21.8 MCM/season (11%) is generated during the Yala season.

The Yala seasonal flow volume varies from 6.2 MCM/season (2012/13) to 64.3 MCM/season (2015/16) with a standard deviation of 13.3 and coefficient of variation of 0.61. Also, the Maha seasonal flow volume varies from 38.4 MCM/season (1996/97) to 310.7 MCM/season (2015/16) with a standard deviation of 65.2 and a coefficient of variation of 0.37. Thus, the Yala season's flow variability is higher than the Maha season’s. However, higher flow variation in the Yala season has a minor effect on the overall water availability because of the lower contribution to the total annual flow from the Yala season.

The monthly flow series at the Kalu Ganga Dam site for 30 year modelling period is shown in Figure 11. The highest monthly flow volume (130 MCM) was produced in December 2014 and the lowest flow volume (0.44 MCM) was in September 2012.

4. Conclusion and Recommendations

The SWAT was applied to simulate the hydrology of the Kalu Ganga catchment to estimate the daily Kalu Ganga discharge at basin and sub-basin levels. Despite the shortage of rainfall data within the catchment, the model shows promising results indicating that the considered rainfall stations are representative. The performance indicators at the model calibration and validation prove the applicability of the SWAT to the catchment.

This study estimates the long term mean annual flow at the dam site would be 196 MCM with a standard deviation of 57.5 MCM and a coefficient of variation of 0.29. The mean annual catchment rainfall is 2763 mm, and streamflow and evapotranspiration are 59% and 33% of the rainfall, respectively.

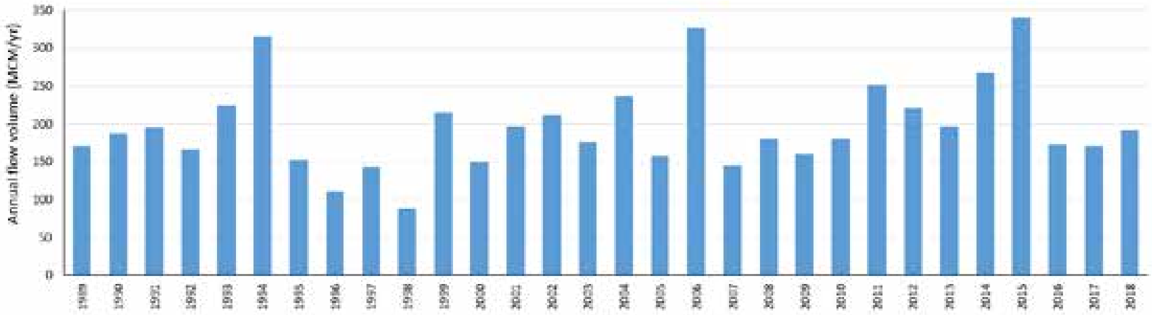

Figure 9 - Simulated Annual Flow at Kalu Ganga Dam Site (1989-2018)

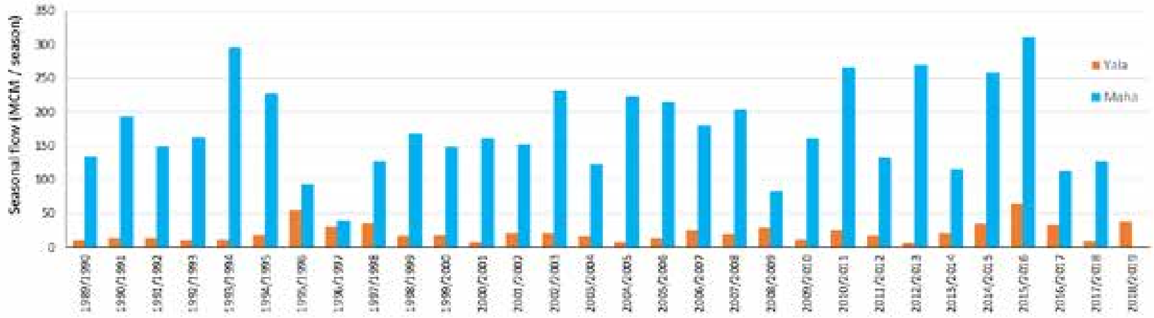

Figure 10 - Seasonal Flow at Kalu Ganga Dam Site (1989-2018)

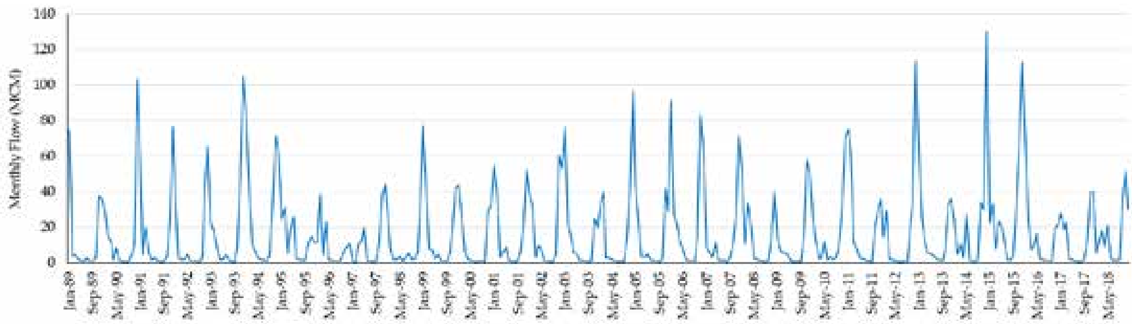

Figure 11 - Simulated Monthly Flow at Kalu Ganga Dam Site (1989-2018)

The catchment hydrology is dominated by the Maha seasonal rainfall (Second inter monsoon and North-East monsoon), which governs the Kalu Ganga flow, where 89% of the flow volume was produced. Further, 67% of the flow volume is produced from November to January. Therefore, the management of the reservoir shall mainly focus on the water quantity received during this period in developing measures for effective water management by reducing the spillages. The frequent reservoir spilling during December and January needs to be released in a controlled manner to protect the downstream lives and properties by developing effective and efficient spillway operation guidelines.

The primary commitment of the Kalu Ganga Reservoir is to supply the irrigation water to the Mahaweli System F and Haththota Amuna scheme. Only the surplus water in the reservoir is available to divert to the Moragahakanda Reservoir. The diversion could be increased if the irrigation water requirement of the System F is reduced by utilising the system rainfall effectively by scheduling the irrigation seasons with rainfall seasons (especially in the Maha season). The Maha season rainfall in the area starts in October and continues until January. Therefore, the irrigation water requirement in the Maha season could be curtailed if the cultivation is started in October with the start of the rainy season. This would reduce the water quantity released from the reservoir.

The model results show that 89% of the annual average of streamflow is generated as baseflow, which is a feature of a perennial river. The high baseflow fraction is hydrologically favourable for the water availability of the catchment as this shows the utilisable quantity of water is high. Therefore, this favourable condition of the catchment shall be maintained by preserving the forest cover in the catchment by implementing catchment protection programs.

References

1. Rodriguez-Iturbe, I., "Ecohydrology: A Hydrologic Perspective of Climate-Soil Vegetation Dyanamics", *Water Resources Research,* Vol. 36, No. 1, 2000, pp.3-9.

2. Guug, S. S., Abdul-Ganiyu, S., & Kasei, R. A., "Application of SWAT Model for Assessing Water Availability at the Sherigu Catchment of Ghana and Southern Burkina Faso", *HydroResearch*, 2020,.pp.124-133.

3. Pangare, G., Pangare, V., & Das, B., *Springs of Life: India's Water Resources.* New Delhi: India: Academic Foundation, 2006.

4. Okello, C., Tomasello, B., Greggio, N., & Wambiji, N., "Impact of Population Growth and Climate Change on the Freshwater Resources of Lamu Island, Kenya", *Water*, 2015, pp.1264-1290.

5. Jain, S. K., Agarwal, P. K., & Singh, A. V., *Hydrology and Water Resources of India*, Springer, The Netherlands, 2007.

6. Sivakumar, S., *Water Resources and Water Policy Initiatives in Sri Lanka*, Jaffna, 2021.

7. CC,. *National Adaptation Plan for Climate Change Impacts, Sri Lanka.* Climate Change Secretariat-Ministry of Mahaweli Development and Environment, 2016.

8. Rajendram, K., "Rainfall Variability and Drought in the Dry and Wet Zones of Sri Lanka", *World Sci. News*, 2021, pp.172-189.

9. Mishra, A. K., & Coulibaly, P., "Developments in Hydrometric Network Design: A Review", *Advancing Earth and Space Science*, 2009, pp.1-24.

10. Sene, K., & Farquharson, F., "Sampling Errors for Water Resources Design: The Need for

Improved Hydrometry in Developing Countries", *Water Resources Management*, 1998, pp.121-138.

11. Houghton-Carr, H., & Fry, M., "The Decline of Hydrological Data Collection for Development of IWRM Tools in Southern Africa", *Climate Variability and Change—Hydrological Impacts (Proc of the 5th FRIEND World Conference*. Havana: IAHS Publ. 308, 2006, pp.51-55.

12. Seizarwati, W., & Syahidah, M., "Rainfall-Runoff Simulation for Water Availability Estimation in Small Island using Distributed Hydrological Model WFLOW", *ICWRDEP 2021*, Malang, Indonesia, 2021, pp.1-12.

13. Paudel, S., & Benjankar, R., "Integrated Hydrological Modeling to Analyze Effects of Precipitation on Surface Water and Groundwater Hydrologic Processes in a Small Watershed", *Hydrology*, 2022, pp.1-18.

14. Moradkhani, H., and Sorooshian, S., "General Review of Rainfall-Runoff Modeling: Model Calibration, Data Assimilation and Uncertainty Analysis", in Sorooshian, S., Hsu, K.L., Coppola, E., Tomassetti, B., Verdecchia, G., and Visconti G. (Eds.), *Hydrological Modelling and the Water Cycle: Coupling the Atmospheric and Hydrologic Models*, Springer, Berlin, 2008.

15. Breinl, K., "Driving a Lumped Hydrological Model with Precipitation Output from Weather Generators of Different Complexity", *Hydrol. Science Journal*, 2016, pp.1395-1414.

16. Rinsema, J. G., *Comparison of Rainfall Runoff Models for the Florentine Catchment.* University of Tasmania 2014.

17. Beven, K., *Rainfall-Runoff Modelling - The Primer.* Oxford: John Wiley & Sons, 2012.

18. Pechlivanidis, I. G., Jackson, B. M., Mcintyre, N. R., & Wheater, H., "Catchment Scale Hydrological Modelling: A Review of Model Types, Calibration Approaches and Uncertainty Analysis Methods in the Context of Recent Developments in Technology and Applications", *Global NEST Journal*, 2011, pp.193-214.

19. Bouadi, T., Cordier, M. O., Moreau, P., Quiniou, R., Salmon-Monviola, J., & Gascuel-Odoux, C., "A Data Warehouse to Explore Multidimensional Simulated Data from a Spatially Distributed Agro-Hydrological Model to Improve Catchment Nitrogen Management", *Environ. Modelling & Software*, 2017, pp.229-242.

20. ADB, *Project Preparatory Technical Assistance/ TA-8633 - Sri Lanka: Water Resources Development Investment Program-47381.* Asian Development Bank, 2014.

21. Lahmeyer, CECB, & UCG, *Feasibility Study of Kalu Ganga Development Project.* Colombo: Mahaweli Authority/Sri Lanka, 2004.

22. PMDSC *Special Report No. 6 – Generation of inflow time series for Kalu Ganga basin using SWAT and HEC-HMS models.* Colombo: Ministry of Mahaweli Development and Environment, 2017.

23. Muthuwatta, L., Sood, A., & Sharma, B., "Model to Assess the Impacts of External Drivers on the Hydrology of the Ganges River Basin", *Evolving Water Resources Systems: Understanding, Predicting and Managing Water–Society Interactions Proceedings of ICWRS2014* Bologna, Italy: IAHS Publ. 364, 2014. pp.76-81.

24. Arnold, J., Kiniry, J., Srinivasan, R., Williams, J., Haney, E., & Neitsch., S., *Soil and Water Assessment Tool Input / Output and Theoretical Documentation, Version 2012.* Texas: Agricultural Research Service and the Texas Agricultural Exp. Station, 2012.

25. Sood, A., Muthuwatta, L., & McCartney, M., "A SWAT Evaluation of the Effect of Climate Change on the Hydrology of the Volta River Basin", *Water International*, 2013, pp.1-15.

26. Giri, S., Arbab, N. N., & Lathrop, R. G., "Water Security Assessment of Current and Future Scenarios through an Integrated Modeling Framework in the Neshanic River Watershed", *Journal of Hydrology*, 2018,.pp.1025-1041.

27. Marahatta, S., Devkota, L. P., & Aryal, D., "Application of SWAT in Hydrological Simulation of Complex Mountainous River Basin (Part I: Model Development)", *Water*, 2021, pp.1-19.

28. Arnold, J. G., Moriasi, D. N., Gassman, P. W., Abbaspour, K. C., White, M. J., Srinivasan, R., & Jha, M. K., "SWAT: Model Use, Calibration, and Validation", *Transactions of the ASABE*, 2012, pp.1491-1508.

29. Hargreaves, G., & Samani, Z., Reference Crop Evapotranspiration from Temperature. *Applied Engineering in Agriculture,* 1985.

30. Abbaspour, K., *User Manual for SWAT-CUP, SWAT Calibration and Uncertainty Analysis Programs.* Duebendorf, Switzerland: Swiss Federal Institute of Aquatic Science and Technology, 2007.

31. Moriasi, D. N., Arnold, J. G., Liew, M. W., Bingner, R. L., Harmel, R. D., & Veith, T. L., "Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations", *Transactions of the ASABE,* 2007.

32. Ayele, G. T., Teshale, E. Z., Yu, B., Rutherfurd, I. D., & Jeong, J., "Streamflow and Sediment Yield Prediction for Watershed Prioritization in the Upper Blue Nile River Basin, Ethiopia", *MDPI-Water*, 2017, pp.1-29.