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MODELLING OF STREAM FLOWS OF A FORESTED CATCHMENT IN THE TROPICS USING HEC-HMS

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ABSTRACT

Singharaja and adjacent forested areas drains into two major rivers in Sri Lanka and they are crucial sources of drinking water downstream and contributes to frequent floods. This study was done to model stream flows and evaluate the applicability of the model for a dense tropical forest catchment. Hydrological model HEC-HMS was calibrated (2009-2014) and validated (2015-2019) for river flow simulation and evaluated using the residual method. R2 values of the best calibration and validation were 0.7070 and 0.7797, respectively. In the best calibration, 73.7% and 92.3% of residuals fell within +1SD and +2SD, and in the best validation, 74.3% and 93.6% of residuals fell within +1SD and +2SD, respectively. The results indicated that HEC-HMS can be used to simulate flows of a catchment covered with tropical forests reliably, especially during high rainfall and flow conditions. The model could be used to model rainfall and flow events leading to floods with greater accuracy than previous applications in other Sri Lankan catchments. It further confirms that the HEC-HMS model is a good tool to predict flows from a catchment covered with dense natural evergreen forests and planted forests in the tropics. HEC-HMS can reliably be used as a tool in biodiversity conservation in the tropical forest and streams fed by the catchment as these streams are the habitat for many endemic and endangered life.

Keywords: HEC-HMS, Forested Catchment, Flows, Simulation, Flood, Calibration, Validation

INTRODUCTION

Since the beginning when humans began to inhabit earth, river systems played a major role in the water cycle while sustaining the flow of water and the entire web of life. People rely on rivers for domestic consumption, waste removal, decomposition, commerce, transportation, recreation and agriculture (Karr and Chu, 2000). With the increase of global human population, alteration of land use and vegetation patterns and the surface water and groundwater management systems have led to drastic changes in the earth's surface (Wada et al., 2017). Degradation of rivers due to these factors have gained the attention of policy makers to take steps towards conservation of rivers. However, these water sources are continuously being subjected to degradation. A debate prevails whether the momentum between rate at which mitigation strategies are carried out and rate of degradation will be sufficient to reverse the harm that has been done (Karr and Chu, 2000).

Sri Lanka is a country that is heavily sustained by rivers. Sri Lanka consists of 103 district river basins with a total length of 4,500 km, covering 90 percent of the island (UNESCO and MoAIMD, 2006). The knowledge of the potential global water shortages led to the first global water resource assessment. It compared water availability with water use based on normal statistics and observed climate information in the late 19th century. The first generation of hydrological models in large scales could solve local water balance and quantify the river discharge. These water models considered the relationship between groundwater flows and very small-scale human activity and did not distinguish water usage from groundwater and surface water supplies. It is therefore evident that hydrological simulation cannot be avoided any more at the current pace of human activities (Wada et al., 2017).

Hydrological models are the best and simplest tools to forecast flow variation. The modelling results from these models are very important environmental impact evaluation components and can provide the environmental management agencies with the basis and technical support they need to make correct decisions. Precise and comprehensive water information are critical to engineers, planners and decision makers at all levels. Despite the accuracy of the model it can impact the reasonability and technicality of the projects and the availability of pollution control measures. HEC-HMS is a hydrologic modeling software that includes many well-known and well-applicable hydrologic methods to simulate rainfall-runoff process in river basins (Nandalal and Ratnayake, 2010). It consists of several models for calculation of losses and runoff due to a single rainfall event or a continuous rainfall (Nandalal and Ratnayake, 2010).

This study is based on Gin river which is a crucial source of drinking water in the Galle district (Wickramaarachchi et al., 2014). Gin river watershed is vulnerable to intermittent floods and droughts (Dias, 2006). This situation has aggravated mainly with the land use change, rapid urbanization and climate change impacts which have affected adversely on the water supply schemes, mini hydropower plants and agriculture (Gunasekara, 2018). The storm that resulted in a flood that amounted 1400 m^3 in May 1940 was the maximum flood stagnation (IDGauging, 1940) which was widespread in the wet zone (Senewiratne, 1983). These floods lasted for more than a week and disrupted transport services. Areas such as Mapalagama, Halpathota, Gonapinuwala, Baddegama and Keembi-ela are known to face frequent floods even in the present days. Floods and water shortages are restricting domestic economic growth and can contribute to detrimental conditions of health and living. This study would be a step towards anticipating potential problems, detecting them early, allowing cities to prevent environmental incidents and mitigate their potential impact. Flood basins of Gin river are used as paddy cultivation but fertilizer is not added due to the risk of flood (Senewiratne, 1983). This shows that there is an indirect impact of floods on paddy crop yield. Therefore, it is a timely need to manage the Gin river watershed in an efficient manner without leading to any water deficits for crucial water requirements. Decision making on Gin river watershed can effectively be done if water flows can be predicted at particular locations with sufficient accuracy. Flow modeling of Gin river watershed is not reported and hence, it is very important to explore the possibility of using a modeling approach for this watershed. Hence, a study was done with the objectives to calibrate and validate HEC-HMS model to simulate water flow in the Gin river and model certain high rainfall events from 2009-2019.

METHODOLOGY

Study Area

Gin river originates from the Gongala mountains (1,300 m) in Deniyaya and joins the Indian Ocean at Ginthota, Galle. Gin river has a catchment area of about 932 km^2 (Rangana et al., 2015). The basin is mainly located within the Galle (83%), Matara (9%), Rathnapura (7%) and Kalutara (1%) districts. Gin river's annual discharge is about 1,268 million cubic meters (Rangana et al., 2015). The catchment is highly humid with an average temperature from 24 to 32 degrees Celsius (Wickramaarachchi et al., 2014)**.** The estimated average annual rainfall received by the basin is around 3,290 mm. The location of the study catchment is shown in Figure 1. The Gin river is 115.9 km long (Balasooriya et al., 2005). The study catchment lies between latitudes 6°5'47.66"N to 6°22'31.43"N and longitudes 80°7'33.56"E to 80°37'36.12"E. The study catchment covered nearly 99% of the Gin river basin. The sub catchments; Baddegama and Tawalama were chosen based on the two flow measuring points along the river (Baddegama: 80°10'38.293"E 6°10'26.903"N, Tawalama: 80°19'57.049"E 6°20'31.935"N). The largest sub catchment is Tawalama (518.3 km^2). Baddegama, the other catchment spreads over 454.6 km^2.

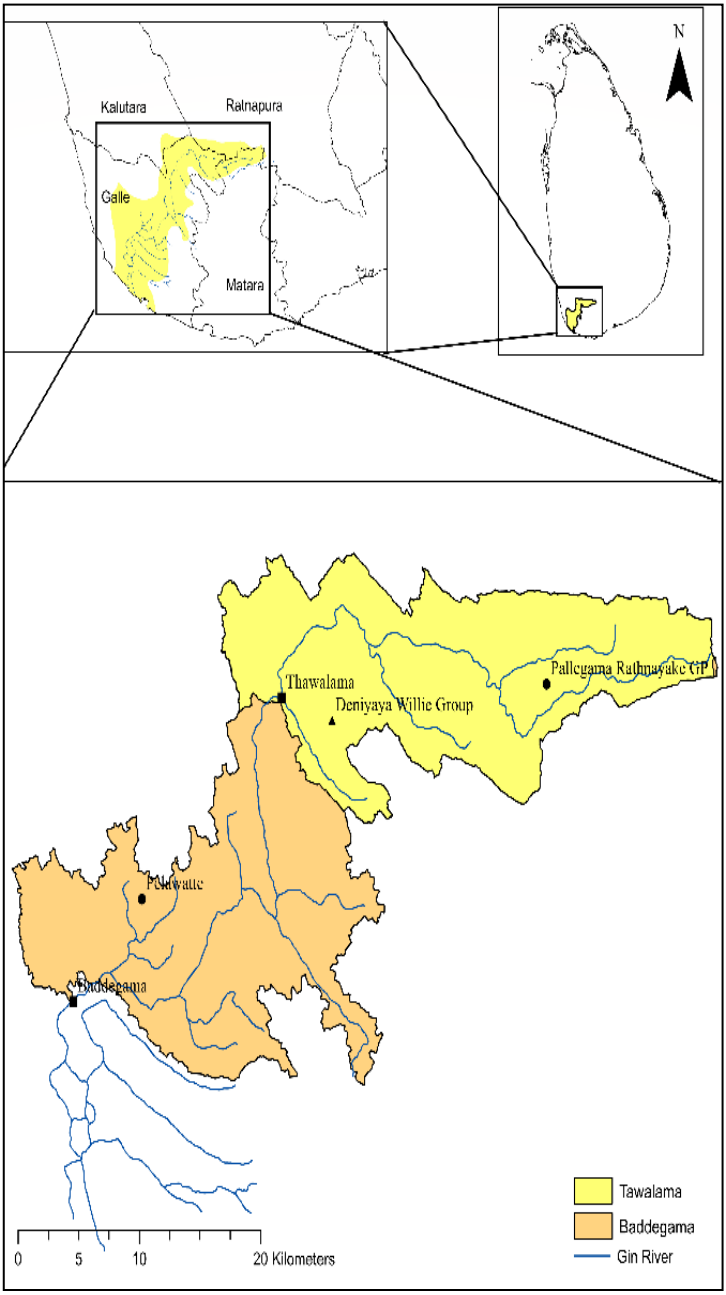


Figure 1: Study catchment, Gin river and Data collection points

DATA COLLECTION

Hydrometeorological data

Flow Data

Daily river flow data for ten years (2009-2019) was obtained from the Irrigation Department of Sri Lanka in the stations, Baddegama (80°10'38.293"E 6°10'26.903"N) and Tawalama (80°19'57.049"E 6°20'31.935"N).

Rainfall Data

Rainfall and other meteorological data (evaporation data) for the period 2009-2019 was collected from the Department of Meteorology (DOM), Sri Lanka using their facility to disseminate data using a pricing policy. The rainfall data was obtained from two stations; Pallegama (6°20'60.00"N 80°31'48.00"E) and Pelawatte (6°25'12.00"N 80°13'12.00"E) Average monthly evaporation was obtained from the agrometeorology station, Deniyaya (6°19'48.00"N 80°22'12.00"E). The data gaps in the rainfall stations were replaced by the closest station's data.

Topographic, soil and land use data

ArcGIS 10.2.2 software package was used for spatial data preparation such as maps of sub watersheds, catchment boundary and land use. The topographic maps with 1:50,000 scale was first registered according to the SL_grid_99 projection system (Datum_Kandawala). Data maps required for the preparation of land use maps and contour maps in digital format was obtained from the Department of Survey. GIS data were used to classify river pathways, catchments, natural waterways, patterns of land use, geological conditions and types of soil in the basin. Data maps needed as input for flow estimation were prepared in different layers.

HEC-HMS Model Conceptualization

After preparation of maps Hydro-meteorological data were input to compute the flow using HEC-HMS 4.5. Calibration and Validation of the HEC-HMS model was done using the model parameters; initial constant loss method, Snyder unit hydrograph transform method and constant monthly baseflow method.

Calibration process for Hydrological parameters

The model calibration was done for the six years from 2009-2014 by feeding daily rainfall data, monthly baseflow, monthly evaporation and area of the study catchment. Ten different calibrations were made after assigning values to the model parameters.

Loss

To calculate loss, initial and constant model was selected, as it is very simple but still appropriate for watersheds that lack detailed soil information. It includes one parameter (the constant rate) and one initial condition (the initial loss). The initial loss specifies the amount of incoming precipitation that will be infiltrated or stored in the watershed before surface runoff begins. There is no recovery of the initial loss during periods without precipitation. The constant rate defines the infiltration rate when the soil layer is saturated.

The area of the sub-basin which is impervious (%) needs to be specified. No loss calculations are carried out on the impervious areas where all the precipitation on such portions become excess precipitation and subjected to direct runoff.

Transform

The Snyder unit hydrograph computes peak flow as a result of unit of precipitation. It estimates the time base of hydrograph and width at 50% peak flow. The standard lag is defined as the length of time between the centroid of precipitation mass and the peak flow of the resulting hydrograph. The peaking coefficient measures the steepness of the hydrograph that results from a unit of precipitation. For different peaking coefficients, the model simulation was performed in order to find the most suitable peaking coefficient for the simulated flow.

Validation process for Hydrological Parameters

After calibration, the same model parameters were used in the validation process with another set of rainfall data for the next five years (2015-2019). The ten calibrations were applied in the validation process and the results were compared statistically.

Statistical Evaluation

The model was evaluated by residual method (Pauly, 1980). A graphical plot was used to represent the difference between observed and modelled data points. Over estimations or under estimations can be clearly observed using this method. The ideal value would be zero. R^2 values and percentage residuals within ±1SD and ±2SD ranges were calculated. Model parameters were modified until the R^2 value and the results of the statistical assessment were the maximum between ±1SD and ±2SD. This method was used in Sri Lanka to evaluate a water flow model of a sub-catchment in the Upper Mahaweli catchment area (Gunawardena and Najim, 2017).

RESULTS AND DISCUSSION

Study Catchment

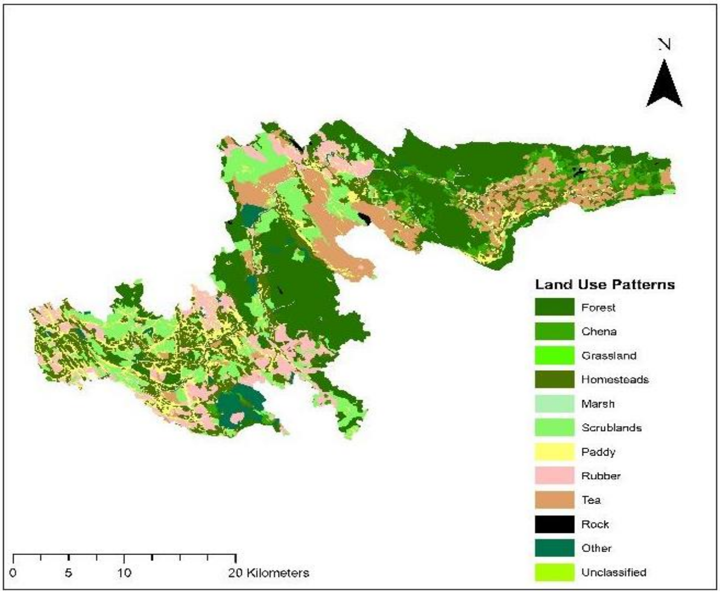
The study area is 923.5 m^2, which is 99.08% of the total Gin river catchment's area ($932m^3$). Only the area below 30m of the basin does not belong to the study catchment. Therefore, the study can be considered as a fair representation of the whole catchment. The Gin river originates from the Rakwana Hills (a separated component of the central highlands) that consists of several peaks over 1,400 m. It flows through the southern forests of Singharaja, Hiniduma and the Kanneliya extending to the Hikkaduwa marine sanctuary (Gunathilake et al., 2005). This rich ecosystem of the Gin basin is recommended as a model river basin landscape-seascape conservation area in Sri Lanka. Therefore, the conservation of this catchment is of high priority.

Land use map (Figure 2a) prepared for the catchment area was used to measure land use type, total area of catchment and land use percentages (Table 1). The main agricultural crop of the catchment is rubber, which covers about 8.79% of the land area. Home gardens occupy nearly 11.67% of the area. Majority of the catchment's area (40.12%) is covered with undisturbed dense tropical rainforests. The elevation of the uppermost catchment area varies between 500 m - 1320 m while the lower parts of the catchment is 30-500m in elevation (Figure 2b). The elevation up to 300m belongs to the Low country, the elevation up to 500m belongs to the mid country and that the elevation above that to the up country. The catchment belongs to the wet and intermediate zones of Sri Lanka. The rainfall received by the agroecological regions in which the catchment is located ranges from >1100mm to >3300mm per annum.

The study catchment is significant due to its land use patterns comprising mainly of planted and natural forests. Sinharaja and Kanneliya are two major rain forests in the catchment. Sinharaja is designated as a Man and Biosphere Reserve and World Heritage Site by UNESCO. Kanneliya forest is an important source for Gin river, which flows west to the forest. The remaining populated areas of the catchment are also highly vegetated. These land use patterns are different to other forested catchments in Sri Lanka such as Attanagalu Basin (Halwatura and Najim, 2013) and Nilambe basin (Gunawardena and Najim, 2017). The upper catchment of Attanagalu basin mainly consists of rubber plantations. In the Nilambe basin the major agricultural crop is tea, which occupies about 58.9 per cent of the catchment area. Vegetables, other export crops and home gardens account for almost 10.9 per cent of the region. Land patches consisting of unclassified woodland, pine and eucalyptus plantation forests and scrubland cover around 21.2 per cent of the catchment area. In contrast the Gin study catchment, there is only 8.79% rubber and 40.13% forest. The remaining populated areas also consists of various agricultural crops such as coconut, paddy and tea.

Table 1: Land use patterns of the catchment

Name	Total Area (Km^2)	Percentage
Unclassified	0.01	0.00
Marsh	0.07	0.01
Water holes boundaries	0.25	0.03
Grassland	0.50	0.05
Stream (LINE/AREA)	1.51	0.16
Rock	2.31	0.25
Coconut	4.88	0.53
Other cultivations	22.87	2.48
Chena	32.98	3.57
Paddy	67.29	7.29
Rubber	81.18	8.79
Scrub land	107.49	11.64
Homesteads/Garden	107.80	11.67
Tea	123.80	13.41
Forest - Unclassified	370.57	40.13
Total Catchment Area	**923.51**	



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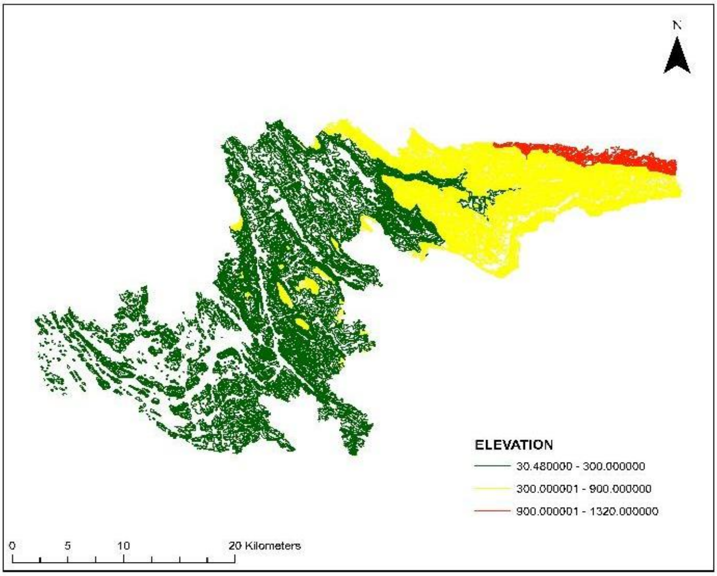


b)

Figure 2: a) Land use patterns of the Study Catchment, b) Topography of the Study Catchment

Flow simulation using HEC-HMS 4.5

The model parameters for simulation were chosen based on results of previous studies (Viessmann et al., 1997; Horton, 1935; Skaggs and Khaleel, 1982). Initial constant loss method along with Snyder Unit hydrograph transform method was used successfully in modelling water flow in Nillambe Oya, Sri Lanka (Gunawardena and Najim, 2017). Initial constant loss method requires values for initial loss (in), constant rate (in/h) and imperviousness (%) while Snyder unit hydrograph transform method required values for standard lag (h) and peaking coefficient. Initial and constant rate loss method was used to determine the hydrologic losses from the study area. This method has been known to successfully model flooding (Zema et al., 2017). Also, as the study area lacks detailed soil information, this method is more appropriate. Initial loss is the maximum precipitation depth that can fall on the watershed with no runoff and it depends on watershed terrain, land use, soil types, and soil treatment. As the catchment is majorly covered with forest areas, the initial loss ranged between 12.7-38.1 mm (0.5-1.5 inches)(Viessmann et al., 1997; Horton, 1935). The constant rate is ultimate infiltration capacity of the soils and it depends on the type of soil group in the catchment. The three soil types in the catchment: Red yellow podzolic, alluvial and bog and half bog soils belong to soil groups ranging between 1.27-7.62 mm/h (0.05-0.3 in/h). Therefore, the constant rate varied mainly between 3.81-7.62 mm/h (0.15-0.30 in/h) (Skaggs and

Khaleel, 1982). Rocky and constructed areas were considered to be impervious. Therefore, only a very small portion of the catchment is impervious (Tawalama-0.391%, Baddegama-0.062%).

In Snyder Unit hydrograph, Standard lag and peaking coefficient was adjusted to simulate flow. Standard lag was adjusted between 25-44 h indicating higher difference in the time of the hydrograph peak and time related with the centroid of the excess rainfall hydrograph. Higher standard lag values could be observed in other catchments of Sri Lanka (Gunawardena and Najim, 2017). The coefficient varied between 0.4 and 0.8. The Snyder unit hydrograph has been known to simulate flows more reliably than the Clark unit hydrograph method while applying HEC-HMS to Attanagalu Oya, Sri Lanka (Halwatura and Najim, 2013).

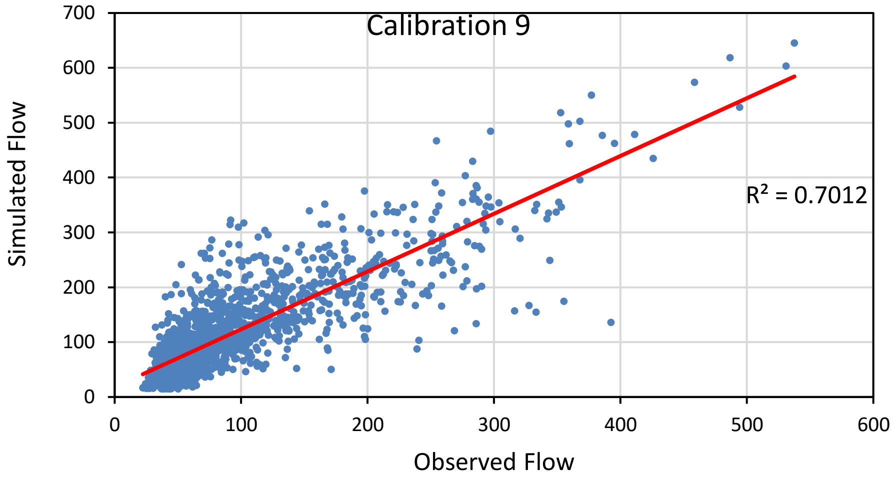
Significant differences in R^2 value could not be observed by changing the initial loss, constant rate or peaking coefficient values. Increasing the standard lag value increased the R^2 in a significant amount. Obtained residual plots and calculated residual percentages for the six years (2009-2014) of ten calibrations and five years (2015-2019) of ten validations is shown in Table 6. All the simulations produced results with high percentage residuals within ±1SD and ±2SD. According to the statistical analysis, R^2 values of 0.7010 and 0.7797 for model calibration and validation respectively reflected satisfactory overall model performance. Estimation of low and medium streamflow demonstrates a slight over prediction and the flow at high flow scenarios demonstrates a slight under prediction. However, the model has a very good matching in terms of the shape of hydrograph and the long-term pattern of hydrographs. Overall, the flow simulation was satisfactory giving more than 70% residuals within ±1SD and more than 90% residuals within ±2SD.

Table 2: R^2 and Standard Deviation values

	Calibration			**Validation**		
	R^2	**Standard Deviation**		**R^2**	**Standard Deviation**	
		±1	**±2**		**±1**	**±2**
1	0.6269	77.46	92.62	0.6973	79.93	94.98
2	0.6258	74.03	91.23	0.7001	77.39	94.06
3	0.6265	71.33	90.44	0.7132	73.88	93.02
4	0.6465	73.63	91.43	0.7244	75.89	94.23
5	0.6490	69.74	90.05	0.7393	71.45	92.56
6	0.6592	69.15	89.65	0.7501	70.30	92.73
7	0.6916	41.79	79.63	0.7715	41.41	79.35
8	0.7030	61.11	89.32	0.7751	60.15	89.97
9	0.7012	73.76	92.35	0.7797	74.39	93.66
10	0.7070	59.99	89.45	0.7786	60.09	89.45

The percentage residuals within ±1SD and ±2SD for Calibration 9 and Validation 9 is much better than the values for the other processes. The calibration 9 produced results with R^2 value greater than 0.7 and high percentage residuals within ±1SD (73.76%) and ±2SD (92.35%). Therefore, this calibration was used for further analysis of the model.

In contrast to the models developed for other river catchments of Sri Lanka using HEC-HMS; such as Attanagalu (Halwatura and Najim, 2013) and Nilambe (Gunawardena and Najim, 2017) the model developed for the study catchment gives a satisfactory simulation for flood events. In the model developed for Attanagalu River, over predictions were observed during sudden heavy rainfalls after a dry period and during high continuous rainfall events. Under predictions were observed during the occurrence of a high rainfall event within a long dry spell (Halwatura and Najim, 2013). Meanwhile the model developed for Nilambe River over-predicted the flow very slightly in few calibration processes and under-predicted the flow in very minor quantities (Gunawardena and Najim, 2017). The simulations that were observed for the Gin study catchment shows that low rainfall events are slightly overpredicted and rainfall events are rarely underpredicted. Continuous high rainfalls are well predicted along with the peaks and hydrograph shape. This shows that this model could be used to model rainfall and flow events leading to floods with greater accuracy than previous applications of the model in other catchments in Sri Lanka.



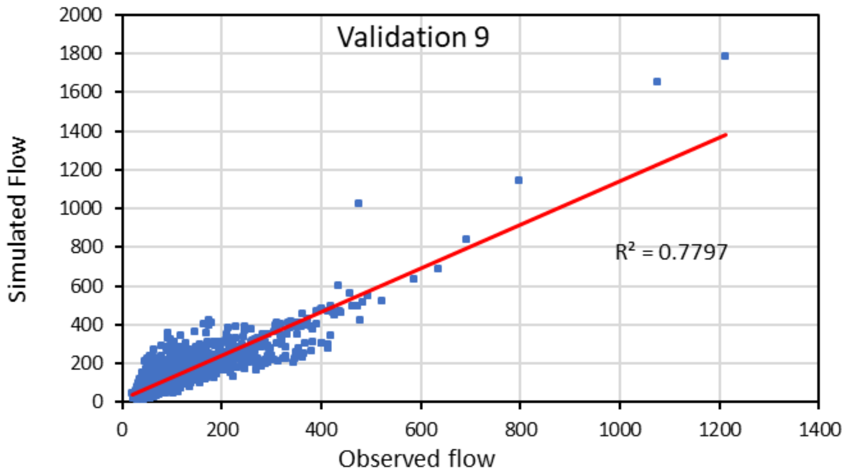
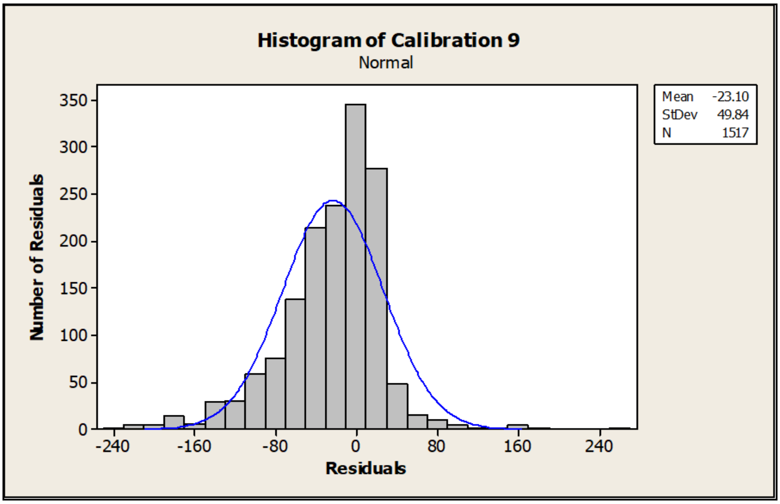


Figure 3: Graphical plots of Calibration and Validation 9



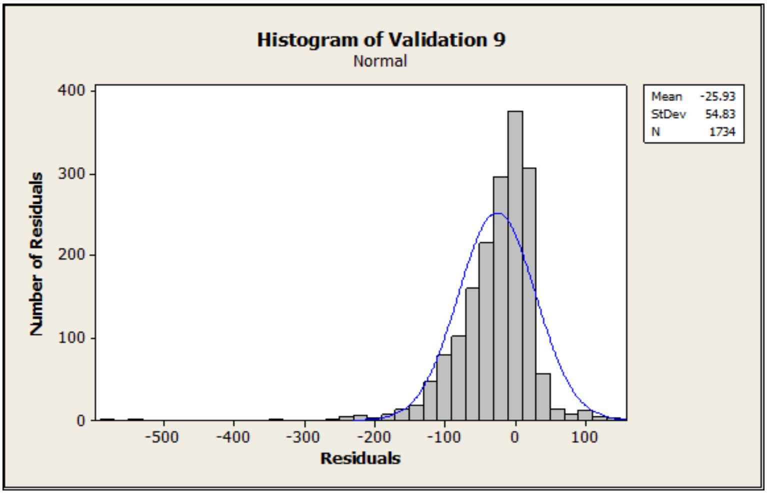


Figure 4: Histograms of Calibration and Validation 9

Event Modeling

To evaluate the accuracy of the model in various flow and rainfall conditions, the model was applied to certain random events during the study period (2009-2019) (Table 3). The model parameters from the best calibrations were used for this purpose.

Table 3: R^2 values and standard deviations- Event Modeling

Date Range	R^2	SD values		Condition	
		1	2	Rainfall	Flow
3.8.2009-4.20.2009	0.2729	43.1	70.4	Moderate	Moderate
8.1.2012-9.30.2012	0.4893	50.8	86.8	Moderate	Moderate
10.12.2009-12.31.2009	0.4976	61.7	87.6	Moderate	Moderate
1.1.2009-2.28.2009	0.5191	76.2	89.8	Low	Moderate
4.1.2015-5.31.2015	0.5367	37.7	72.1	Moderate	Moderate
1.1.2019-9.30.2019	0.7796	70.3	93.7	Moderate	Lowest recorded
5.25.2014-6.30.2014	0.8754	54	81	Sudden spike	Moderate
4.1.2011-6.31.2011	0.9250	74.7	92.3	Moderate	Moderate
5.24.2011-6.30.2011	0.9511	76.2	92.07	Sudden Spike	Moderate
5.1.2017-6.30.2017	0.9521	91.8	93.4	Highest recorded	Highest recorded

Rainfall- Low (0-60mm); Moderate (60-120mm); High (above 120mm)
Flow- Low (0-200 m^3s^{-1}); Moderate (200-400 m^3s^{-1}); High (above 400 m^3s^{-1})

According to the statistical evaluation, most of the moderate events are not modeled accurately. The best R^2 value and percentage residuals within ±1SD and ±2SD were recorded during the date range consisting the highest flow and rainfall of the study period. This would be an advantage of applying the model to the study catchment as it is frequently prone to floods. In conclusion, this model can be used to catchments with dense natural undisturbed forest areas such as the Gin basin. The model could also be further developed for flood predictions by increasing the accuracy further.

The unique biodiversity in Sri Lanka is considered to be confined to the South Western wet zone. The natural ecosystem along the Gin River across the southern forests of the Singharaja forest cluster with the Hiniduma and Kanneliya cluster extending to the Hikkaduwa marine sanctuary in confluence with the Indian Ocean is proposed as a model river basin landscape-seascape protection area (Gunathilake et al., 2005). This landscape-seascape conservation area is a key conservation priority in this biodiversity hotspot. The primary land use practices in the upper catchment area of Gin river are forest management activities, while agriculture and other land use related functions are more prevalent in the lower catchment region. These natural forest areas and agricultural areas are home to a vast biodiversity.

The Gin River Wetland Marsh in the southern lowland has been identified as one of the most dynamic ecosystems in Sri Lanka. It is composed of many different habitats, including abandoned agricultural lands, undisturbed forest lands and agriculture areas with varying levels of biodiversity. A highly endangered species *Nypa fruiticans* and an endemic species *Argyreia populifolia* (Girithilla) were observed in this ecosystem. Although the undisturbed area of the wetland marsh is rich in biodiversity, the biodiversity in the disturbed area is in a state where it's difficult to recover (Amarathunga et al., 2016).

As compared to the Gin river basin's middle and lower catchments, the upper catchment produces less suspended sediment. As a result, high suspended sediment concentrations in the Gin river basin have had a negative impact on aquatic invertebrate diversity (Amarathunga and Fernando, 2016).

It is clear that monitoring of hydrodynamic process play a major role in environment conservation. The biodiversity in river catchments such as the study catchment that are highly prone to floods is at high risk. Floods may result in loss of wildlife and biodiversity as a result of habitat destruction, reduction of food sources and imbalance of ecosystems. There is a correlation between the magnitude of flood and the quantity of biodiversity of the area (Schindler et al., 2016). Therefore, it is of utmost importance to monitor and manage this biodiversity rich study catchment.

CONCLUSION

The HEC-HMS 4.5 computer model can be reliably used to simulate Gin river flows with proper calibration and validation. As the transformation method, Snyder unit hydrograph method simulates flows reliably in the study catchment, along with initial loss method. Results from this study shows that HEC-HMS model can be applied with considerable accuracy to tropical catchments with undisturbed evergreen forests and planted forests to predict stream flows. The model is most accurate in high rainfall and flow conditions which could be used in flood prediction compared to studies done in other catchments. Also, the Gin river basin is a high priority area for biodiversity conservation and management and meeting socioeconomic needs of the local community of the region. Therefore, it is necessary to preserve the rich biodiversity of the region.

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