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Sustainable Water Management in Kalu River Basin of Sri Lanka: Comparison of Watershed Yield Computations for Water Security

S.T. Siriwardana and N.T.S. Wijesekera

Abstract: Irrigation reservoir design associated with ungauged watersheds requires reliable watershed streamflow estimations. In practice, designs are either based on the empirical model of Irrigation Department guideline or based on recent conceptual mathematical models. Use of empirical models require appropriate design levels for the calculation of design streamflow. Popular mathematical models require adequate guidance for the application of safety factors to the model outputs. The two aspects that need attention are, the reliability of streamflow estimations by models and the incorporation of safety factors when converting model outputs as design streamflow. The main gap in the literature is a critical evaluation of the importance of these two factors with real-life applications. The authors, in a review paper, identified that best available method for yield estimation is the Irrigation Department Guideline Method (IGM) but pointed to the necessity of verification with field observations. Accordingly, the present study compared the most commonly used IGM, HEC HMS and the Unit Hydrograph method (UH) models by carrying out an evaluation of yield estimation in Kalu Ganga watershed at Ellagawa. This study, while focusing on the availability of model parameters for streamflow assessments in ungauged watersheds, aimed at the demonstration of a comparison in a watershed which has data and established model parameters. It is expected that this model demonstration would facilitate the selection of an appropriate yield estimation model not only in wet zone but also the dry zone of Sri Lanka. Spreadsheet models were developed for each method while using literature reported model parameters and incorporating best engineering judgment. Comparison of model estimations with observed data was done for annual and seasonal water balance, and for flow duration curves, while using Mean Ratio of Absolute Error (MRAE) as the numerical indicator. Evaluation of outputs from the three methods showed that the IGM estimates of monthly yield estimations closely matched with the observed data. MRAE for Overall Hydrograph, in-case of IGM, HEC HMS, UH methods were 0.35, 0.58 and 0.4, respectively. The necessity of incorporating yield thresholds for modern hydrological models and updating of available guidelines were highlighted. The study revealed the necessity of establishing design guides for selection of model parameters when computing streamflow in ungauged watersheds.
IGM with guidance for parameters was recognized as the best model amongst the selected for monthly yield estimation. HEC and UH results create significant ambiguities when compared with IGM because of the unreliability associated with the selection of processes and parameters. This study pointed to the necessity of considering safety factors, as clearly pointed out in Irrigation Department guidelines. This is vital when using modern mathematical models.

Keywords: Water Security, Hydrology, Mathematical modelling, Streamflow, Ungauged, Design, Safety

1. Introduction

The world over, most of reservoir planning, water management and all new infrastructure design works are associated with ungauged watersheds. Even in gauged watersheds, lack of sufficient records and poor monitoring systems [1] affects the reliability of streamflow estimations. All over the world, streamflow gauging is a rarity and accurate estimation of streamflow is the challenge presently faced by the water sector[2]. Reliable streamflow estimation to an adequate accuracy is the main challenge faced by ungauged watershed managers and engineers due to the natural scarcity of good quality water, higher demand due to population increase, huge investment costs for irrigation infrastructure projects and time spans considered for designs. Accurate streamflow estimations by using correct safety factors to account for rainfall and watershed uncertainties, enable the right use of water

Eng.S.T.Siriwardana, AMIE(SL),B.Sc.Eng.Hons(Moratuwa) MSc(Moratuwa),Irrigation Engineer, Department of Irrigation, Sri Lanka. Email:sasiri.tharasara@gmail.com
https://orcid.org/0000-0002-9379-2814
Eng. (Prof.) N.T.S. Wijesekera, C.Eng., FIE(SL), MICE(UK), B.Sc.Eng.Hons.(Sri Lanka),P.G.Dip.(Moratuwa), M.Eng.(Tokyo), Ph.D.(Tokyo), Emeritus Professor (Moratuwa), Chairman Construction Industry Development Authority (CIDA), Sri Lanka. Email:sohanw2@gmail.com
https://orcid.org/0000-0003-0964-4331

without overusing. Hence, correct design of irrigation infrastructure using accurate models and suitable safety factors ensures water security.

In case of watershed streamflow estimations, on one hand, there are "Time Tested Empirical Models (TTEM) generally with a coarse resolution. On the other hand, there are most recent Generalized Process-based Hydrologic Models (GPHM) which can provide distributed outputs at finer temporal and spatial resolutions, enabling a model to conceptualize with awareness of the known physics. Available guidelines depict a clear necessity to provide adequate details for comparative evaluations of these models for use in the design of water infrastructure. The increasing desire of practising engineers and managers to use recent hydrologic modelling advances for their designs, makes this comparative evaluation an urgent need. Such evaluations must be embedded in design guidelines for the assurance of water security.

The objective of the study is a comparative evaluation of commonly used streamflow calculation methods with observed streamflow to evaluate the accuracy of estimating the watershed streamflow for water management and infrastructure design. This evaluation would enable the accuracy of yield estimation of ungauged watersheds by many practising engineers who often use either IGM, HEC HMS or UH models for such computations. In order to carry out a comparative evaluation, it is necessary to have observed data, model and model parameters for the particular watershed. In Sri Lanka, there is a scarcity of watersheds having both observations and parameters for all three models. In Kalu river watershed, there have been many HEC HMS model applications and the IDG [3] provide parameters for other two models. Hence the Kalu river watershed was utilized for this study. This study demonstrates the applicability and weaknesses of each model, thereby guiding practising engineers to select the best models for the yield computation in any watershed in Sri Lanka.

2. Literature Review

Empirical approach for design catchment inflow estimation in ungauged catchments is recommended with careful engineering judgment [4], [5]. Binnie's percentages and Inglis and DeSouza formula for estimation of annual runoff, Barlow's tables for seasonal runoff, Strange's tables for daily runoff, Khosla's formula for monthly & annual runoff, are some common TTEM used for the estimation of watershed streamflow in India and Pakistan [5],[6],[7]. Parkers formulae to compute annual runoff associated with Britain, Germany and East USA are other common TTEMs [8].

TTEMs are mostly rainfall streamflow correlations while there are several with relationships using rainfall and other climatic or watershed characteristics [5],[8],[9]. Considering irrigation guidelines in South Asian region, many guidelines provide empirical methods and simple conceptual models [6], [10], [11] which are associated with rainfall and coefficients based on catchment characteristics.

There are many GPHMs such as Rational method [4], Unit hydrograph [4], [12], Explicit Soil Moisture Accounting Model (ESMA) [13], HEC-HMS [14]–[16], IHACRES [17], monthly water balance models [18], SWAT [19]–[21], SWMM [22]–[24] etc. for estimation of streamflow in ungauged catchments.

UH is a popular recommendation among the guidance materials on watershed runoff estimation. Snyder's Synthetic Unit Hydrograph [25], the Soil Conservation Service (SCS) Unit Hydrograph [26] are some recommended UH models. The Hydrologic Modelling System (HEC-HMS) and its River Analysis System (HEC-RAS) developed by the Hydrologic Engineering Center (HEC), which is capable of handling any watershed and a river system [27] and recommended after many research [14]–[16], [28]–[30], are examples of GPHMs. There are several studies that have been done for Sri Lankan watersheds by using HEC-HMS and UH models.

A GPHM for a particular watershed is developed embedding hydrological functions and used after calibration of parameters and then verification of outputs. Many point out the need for design streamflow computations to carefully examine the dependability of the simplifications in GPHMs with respect to reliability of streamflow estimations [4], [31 - 36],because such models do not provide a clear guidance with respect to the application safety factors when computing design streamflows.

Troin, Arsenault, Martel, & Brissette [37] in their work, stating that GPHM structure contributes most to uncertainty on the projected streamflow, indicate the importance to determine appropriate safety factors when determining design watershed streamflow. Bourdin & Stull [38], Olsson and Lindström [39], Mays [40], highlighting the uncertainty of meteorological input and also of the GPHM, discuss the importance of an appropriate final value for the hydrological forecast. Hence, whether it is a TTEM or a popular GPHM, there is a need to clearly express the reliability of streamflow estimates and associated safety factors for a sustainable water management.

Irrigation Department Guideline (IDG) of Sri Lanka [12] facilitates a direct TTEM for monthly watershed streamflow estimation based on seasonal iso- yield curves. According to the IDG, the net catchment area multiplied by the specific seasonal yields, provides the seasonal yield for Yala and Maha seasons, and specific seasonal yields are obtained by iso- yield curves. There are two safety considerations in the method as: (1) using 75% probable value for rainfall, and (2) using seasonal yield limits for yield value determination [12]. A comprehensive literature review on yield comparison options for planning irrigation reservoirs that was carried out by referring 110 available text books, guidelines and other literature considering runoff estimation methods, revealed the need to incorporate threshold considerations for hydrologic estimations [3]. This study has revealed the necessity to verify design watershed yield estimation methods by using observed data while explicitly incorporating safety factors. The review also showed that the available guidelines require updating with recent data and knowledge.

Literature reveals that the determination of design flows is faced with the dilemma of selecting either the trendy GPHMs or to continue with TTEMs. Hence it is important to perform a comparative evaluation using observed data to fill the gap. Accordingly, the present study carried out a comparative study by calibrating and verification of three commonly used models using observed streamflow values of Kalu river watershed at Ellagawa.

3. Methodology

The present study, considering the availability of data, carried out the comparison for Ellagawa sub watershed of Kalu river watershed which has an extent of 1446 km^2 (Figure 2). The study methodology is presented in (Figure 1). Design data were collected from IDG and published literature. Rainfall and evaporation data were collected from the Department of Meteorology and streamflow data from the Department of Irrigation (Table 1). Station density, visual screening, annual water balance, double mass curve were main data checking methods utilized. Missing data were estimated using normal ratio method, regression analysis, and slope proportional analysis. Thiessen polygon method was used for computation of average rainfall of the watershed. In case of streamflow estimation, three (3) mostly used models as options are the IGM, UH and HEC-HMS [3]. In these three (3) models, the computations incorporate a variety of output estimations, namely, direct runoff, baseflow, effective rainfall, total rainfall, etc. However, as the present study is carrying out a comparative study, the yield computations use the same output of the hydrological cycle. Therefore, each model computation involves the inclusion of process models to generate the final output from that particular model. Spreadsheets based on Microsoft Excel were developed.

3.1 IGM

Model parameters for IGM were obtained from Iso-yield maps of Sri Lanka available in IDG. Ellagawa watershed falls into six (6) agro-ecological regions as WL1, WL2, WM1, WM3, IL1 and WU1, hence monthly rainfall of iso-yield maps were weighted using the coverage of agro-ecological regions. Model outputs with and without upper (35%) and lower (7.5%) seasonal runoff thresholds given in IDG were computed for comparative purposes.

3.2 HEC-HMS Model

HEC-HMS model was developed by selecting the commonly used deficit and constant method as loss method [41]–[43], SCS UH method was chosen as transform method [41], [44] while the selected recession method based on wider usage was base flow method [41], [42],[44],[45]; HEC process models were selected by considering literature recommendations (Table 3) and model application studies for Sri Lankan catchments. Considering the catchment, data period and the availability of a calibrated and verified model, the parameter set of Jayadheera [41] was selected for the model developed for the present study.

3.3 UH Model

Cp and Ct are main regional parameters for Snyder's UH method. Cp value ranges in literature are, 0.56-0.69 [46], 0.23-0.67 [47], while Ct value ranges in literature are 1.8-2.2[46], 1.01-4.33 [47]. Sri Lankan values for regional parameters are presented in Table 2. Annual baseflow index method, defined as the long-term ratio of baseflow to total streamflow[48],[49], [50]was used for baseflow estimation and Φ index method was applied for effective rainfall estimation in UH.

In the absence of BFI studies for Sri Lanka, different values for BFI which could be captured from literature elsewhere (Table 4) were utilized for calculation of baseflow.

Effective rainfall calculation with Φ index method requires loss rates. Manchanayake [51] had published event based loss rates for nine (9) Sri Lankan watersheds while Thapa [52] had published that calibrated and validated loss rate for the nearby Karasnagala watershed in Attanagalu is 1.2 mm/hr.

Watershed geometric parameters for UH were extracted with the use of ArcGIS software. Cp, Ct regional parameters were selected from Irrigation guideline. The best available parameters and engineering judgment were used to select the best parameters for computations of Φ index and baseflow index methods. Selected model parameters and references are shown in Table 5.

3.4 Analysis Step 1- Qualitative Ranking

Analysis was done based on two main steps. Analysis step 1 was done with the purpose of identifying and analysing the issues and difficulties in ungauged watershed modelling that a practising water engineer would encounter. Other than the above, this step was intended to provide a method to make decisions when selecting a watershed model for irrigation planning and design. The GPHMs require an input rainfall and it is usually measured rainfall data. The IDG gives guidance for its inputs. Considering both, in order to perform the Analysis step 1, design rainfall in IDG was applied to all three models considering the non-availability of rainfall data when designs are to be carried out for ungauged watersheds.

Modeled streamflow order of magnitude and the computed runoff coefficients were compared for the cases of with and without design thresholds for yield.

A qualitative assessment coupled with a ranking system was considered sufficient for the comparison because of the computational uncertainties. This was weighted in five categories as (1) Lowest uncertainty, (2) Uncertainty between lowest and moderate, (3) Moderate uncertainty, (4) Uncertainty between moderate and highest, (5) Highest uncertainty (Table 7). Eleven uncertainty factors were considered for the qualitative analysis as (1) Rainfall input conversion, (2) Process selection, (3) Parameter selection, (4) Yield threshold selection, (5) Example application cases, (6) Guideline availability, (7) Time tested practise, (8) Order of magnitude of computed yield, (9) Comparison with physical runoff coefficient, (10) Comparison with water balance and (11) Computation after threshold applications (Table 8). The decisions were taken considering normalized average method.

3.5 Analysis Step 2 – Verification with Observed Streamflow

Although there are no observations for ungauged watersheds, in this study, the watershed streamflow measurements were available. Hence the streamflow computed in Step 1 can be verified as a check for the adequacy of outputs generated by designers who perform computations for ungauged watersheds. The Analysis step 2 performed the verification by comparing watershed streamflow model results with observed streamflow in the selected time period. In this assessment, streamflow from GHPM models were from the observed rainfall because, in case of actual practice, even for watersheds without gauged streamflow, design engineers often find observed rainfall.

Output comparisons were carried out by using average annual water balance, period of record flow duration curves, runoff coefficients and streamflow. The numerical indicators used for the comparison utilizing MRAE [41],[53]–[56],[57],[58] were (1) Average annual water balance error (AAWBE), (2)Average Maha seasonal water balance error (AMSWBE), (3) average Yala seasonal water balance error (AYSWBE), (4) Percentage error of annual average runoff coefficient, (5) MRAE overall hydrograph, (6) MRAE for period of record FDC and (7) MRAE for annual FDC.

$$MRAE = \frac{1}{n}\sum\frac{|Qobs-Qmodel|}{Qobs} \qquad \ldots(1)$$

where, Q_{obs} is the observed streamflow, Q_{model} is the calculated streamflow from the model and n is the number of observations in the data series.

4. Analysis and Results

4.1 Analysis Step 1- Qualitative Ranking

The summary of the results for Analysis step 1 given in Figure 3, Figure 4 and Table 6 reveals that IGM overestimates the streamflow without thresholds, and thresholds have not affected HEC-HMS model outputs.

The physical runoff coefficient calculated for Ellagawa watershed was 0.54 using the method described in [4]. HEC HMS and UH models estimated streamflow with an average annual runoff coefficient of 0.10, 0.41, respectively, indicate that such estimated streamflow values are approximately 18% and 76% of the expected values from physical runoff coefficients.

Incorporation of yield thresholds indicated the overestimated seasonal streamflow reaching a limit of 35% of rainfall. The IGM and UH model outputs that had shown abnormally high runoff coefficients were reduced by restricting the runoff coefficient to the upper threshold of 35%(Figure 3 and Figure 4). Estimations of both these models for Maha and Yala seasons indicated yield values above the upper boundary of estimates. HEC HMS model outputs revealed that the yield values in both seasons and for both watersheds were between the lower and upper bounds of yield limitations in Ponrajah 1984 [12]. Therefore the HEC HMS values remained unadjusted for modelling uncertainties (Table 6) that had been noted during computations.

Streamflow estimations of IGM model were higher than the input rainfall and seasonal yield limitations were used as the threshold. HEC-HMS showed results closer to lower bounds. Due to number of parameters, assumptions and the complexity of the process selection, UH model results were noted an uncertain behavior.

Table 7 and Table 8 show the results of the qualitative assessment that was carried out by assigned ranks for uncertainties associated with design streamflow computations by engineering judgment [3],[59]. The normalized ranking indicated that the IGM shows a moderate uncertainty while UH shows highest uncertainty and the HEC-HMS show uncertainty between highest and moderate. Overall evaluation shows that the most valuable factor for a practising engineer is availability of a guideline for calculation of the yield.

4.2 Analysis Step 2 – Verification with Observed Streamflow

All model verification with observed streamflow in analysis step 2 were carried out using quantitative indices for both design and observed rainfall generated streamflow outputs. Model streamflow variation with the observed rainfall is presented in Figure 5. Figure 6 presents that high flows are underestimated by IGM, while UH underestimates the low flows.

Comparison with the input of observed rainfall data for 8 years demonstrated the following: IGM with thresholds underestimate the average seasonal (11%-Maha, 29%-Yala) and annual (22%) streamflow (Table 9), UH underestimates the average seasonal (8%-Maha, 13%-Yala) (Table 9) and annual (11%) streamflows, while HEC-HMS model over estimates seasonal (37%-Maha, 19%-Yala) and annual (26%) streamflows (Table 9) for observed rainfall application for the models. Table 9 shows the model results.

In terms of MRAE values for streamflow outputs with design rainfall as input (Table 10) the following could be summarized. IGM with thresholds shows better results of overall hydrograph (0.38), low flows (0.33) while UH model shows better results for overall FDC (0.35), Annual FDC (0.35) and high flows (0.31). HEC –HMS model shows higher MRAE values (0.81-0.83) for all indices. For validation data, observed rainfall application shows IGM with thresholds has best values of overall hydrograph (0.35), overall FDC (0.35), Annual FDC (0.27) and low flows (0.11) while UH model shows moderate results and HEC-HMS shows higher MRAE results.

Numerical indicator comparison for all three models are presented in Table 11 and shows that UH model shows lowest water balance error (162.97 mm) while IGM with yield thresholds shows second lowest (322.73 mm). IGM without yield thresholds shows highest water balance error for annual (-1179.21mm) and seasonal (-664.95 mm for Maha and -514.26 mm for Yala). Lowest MRAE values from all models for overall hydrograph (0.35), FDC for period of record (0.35) and annual FDC (0.27) were shown by IGM with thresholds and second lowest values were shown by UH model. IGM without yield thresholds demonstrated the highest MRAE values.

By comparing of model results (Table 6, Table 9, Table 10, Table 11) and other qualitative criteria (Table 7 and 8) considering parameter availability, easiness of applicability, number of parameters etc.[3], the rankings for IGM, HEC-HMS and UH get 1, 2 and 3.

5. Discussion

Comparing models suitable for engineering designs poses few difficulties with respect to the identification and incorporation of uncertainties. One is related to rainfall uncertainties; the other is with uncertainties in model structure and parameters, and then finally the need of safety factors for design flows for the determination of infrastructure dimensions. The assigning of safety factors for strength arises subsequently. Though this is the responsibility of associated design guidelines and user training, there is a significant gap that threatens sustainable infrastructure development.

The following issues were the main reason for the approach described in the present study. First is the absence of a guide to use design return periods for daily resolution rainfall series when generating streamflow from GPHMs. Second is availability of yield thresholds in the IGM which were treated as implicit safety factors for generated streamflow. However, there was no guide for safety factors when working with GPHMs. Third is the lack of a guide for a design engineer to convert a time series of modelled streamflow as design data. The design data period of the IGM is one year covering both Yala and Maha seasons.

During estimations, the IGM thresholds demonstrated the ability to focus on overestimations (Table 6). However, the HEC HMS outputs for the selected data series showed unaffected by thresholds (Table 6) and this may be the suitability of model component and parameter selections using engineering judgment. World over, runoff coefficients provide a reasonable indication of the acceptability of generated streamflow[4],[27]. However, in the present study, the HEC model showed a very low value while UH generated streamflows were less than 50% of a reasonable value based on the method recommended in Chow et al. (1988) (Table 6). This shows the need of guidance for parameters, processes and thresholds.

According to the state of the art review, IGM was identified as the best available watershed yield estimation model among other yield estimation models [3]. Availability of a guideline for calculation of yield is a better option for a practising engineer who works in ungauged watersheds. However, the study of systematic comparison of three mostly used streamflow estimation model options demonstrated the problems faced by design engineers when selecting a model for the yield computation in ungauged watersheds. The study demonstrates that the lack of data and parameters for ungauged watersheds need to be addressed using the available literature and data and then incorporating engineering judgment.

Streamflow estimations of IGM with design rainfall application and observed rainfall application showed slightly underestimation compared to observed streamflow (Table 9).

In the verification of results, though IGM underestimates high flows and UH underestimates low flows, when considering monthly, seasonally and annually, IGM and HEC-HMS models show a wider variation of observed and modelled streamflow (Figure 5, Figure 6).

Comparison of three models revealed that IGM is the closest monthly yield estimation model with 0.35 MRAE for overall hydrograph. HEC-HMS shows 0.58 MRAE value for overall hydrograph, while UH model shows 0.4 (Table 10). The use of HEC and UH model results create significant ambiguities when compared with the IGM because of the unreliability associated with the process and parameters. Further research needs to be done for selected case study applications.

Considering the percentages of overestimations, it is clear that correction factors need to be applied for both UH and HEC models. In the absence of guides, the practising engineers have to make judgments based on engineering knowledge and available reviewed literature. Such action requires careful supervision as a measure of verification.

The most valuable factor of the IGM model is the availability of an application guideline which is a time tested model for irrigation infrastructure construction throughout, Sri Lanka [3]. However, the key issue is the lack of references used for the determination of methods and parameters.

Available guidelines for HEC-HMS model are by the tool developers and the coverage is general. In the present work, rainfall uncertainty was considered similar to the IGM. There are no yield thresholds or guidelines especially for HEC-HMS model and the results showed that design rainfall application to the HEC_HMS model were closer to the lower boundary.

Model application guidelines for the event based UH model are mostly from text books which provide concepts in general and available in common hydrological text books [4],[13]. UH application with a time series requires assumptions for a sequence of events.

Incorporation of baseflow for UH applications to generate long-term streamflow is also a challenge that was overcome in the present study. There were several assumptions needed to convert monthly design rainfall to daily inputs, selection of baseflow model, and rational loss model to calculate effective rainfall. Those create significant uncertainties when modelling streamflow by using UH theory.

Data used in the study were relatively consistent but showed deviations when responding to models. This may be either due to areal averaging of rainfall or due to non-responsiveness of hydrology in models, or due to errors in measurements. The study noted that design data in guidelines given for Sri Lankan applications require updating to consider climate changes that have been captured in recent research.

The present study demonstrated that design of sustainable irrigation infrastructure can be achieved through an appropriate estimation of yield and by incorporating appropriate safety factors. Such action will prevent over or under use of water and contribute to water security.

6. Conclusions

1. The study, through a systematic comparison of one empirical and two conceptual models, demonstrated the problems faced by the design engineers when selecting a model for the determination of design streamflows for water infrastructure development in ungauged watersheds.
2. The study demonstrated the importance of guidelines for the clear identification of observed rainfall and design rainfall for selection of model inputs, and a clear identification of modelled and design streamflow for the use of designing water infrastructure in ungauged watersheds.
3. The study demonstrated the option of using the best engineering judgment and capable supervision, for the selection of model parameters from reviewed literature when resorting to such options due to lack of guidelines for ungauged watersheds.
4. The study demonstrated difficulties faced by design engineers due to the non-availability of guidance for the incorporation of safety factors to incorporate uncertainties associated with inflows, model parameters, processes and other associated factors.
5. The study with observed data showed that the IGM when compared with the HEC and UH is the relatively better model for monthly yield estimations in ungauged watersheds because when compared with IGM, HEC and UH results create significant ambiguities as a result of the reliability associated with process and best available parameters.
6. The study recognized the need of guidelines that use recent data and research backed with evidence of using recent knowledge.

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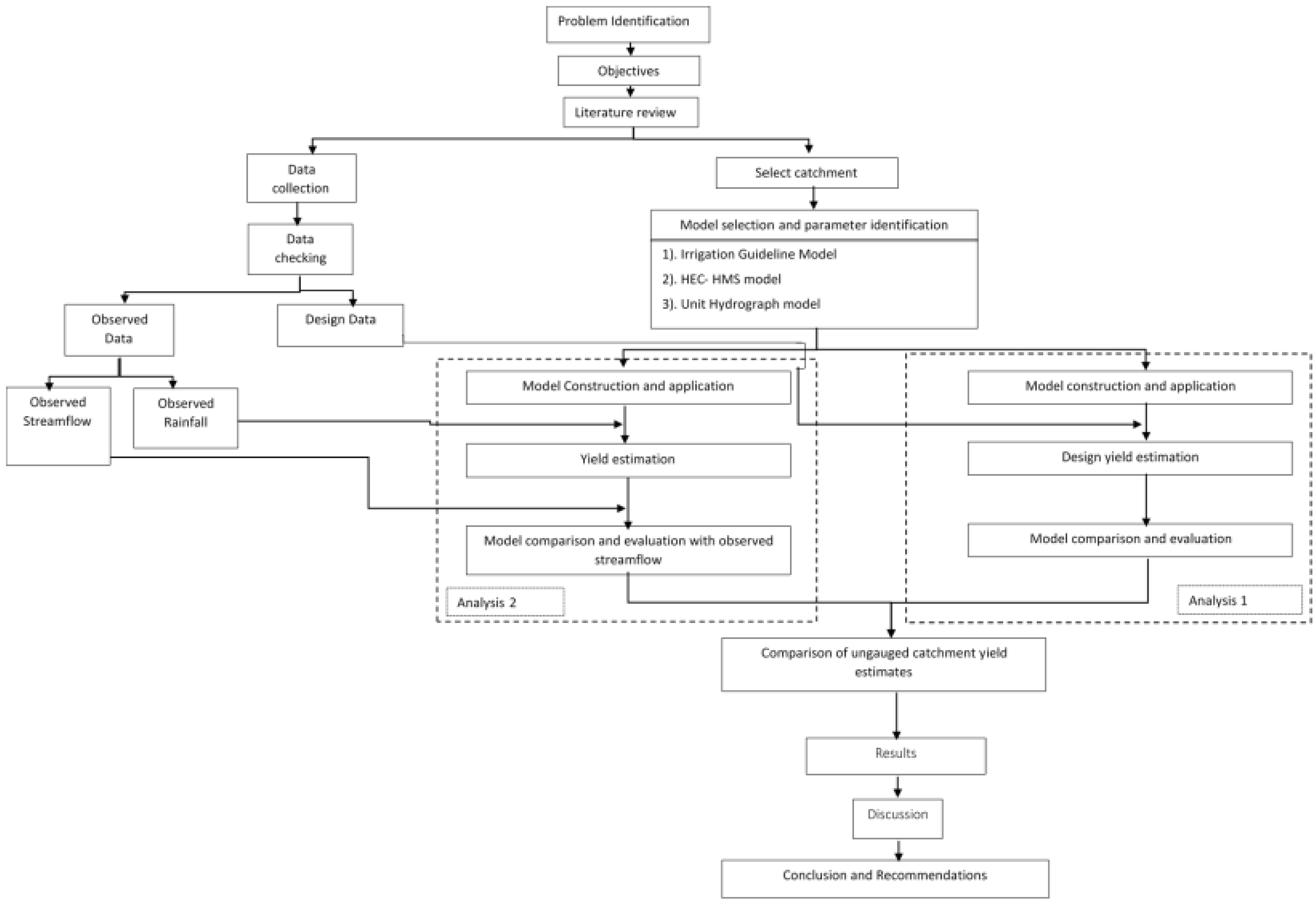

Figure 1 - Methodology Flow Chart

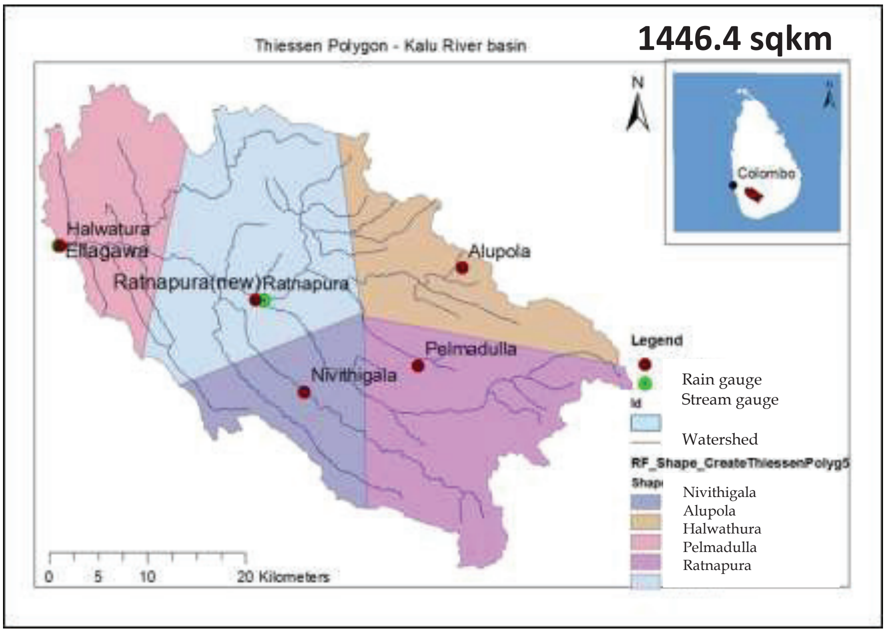

Figure 2 - Study Area Map

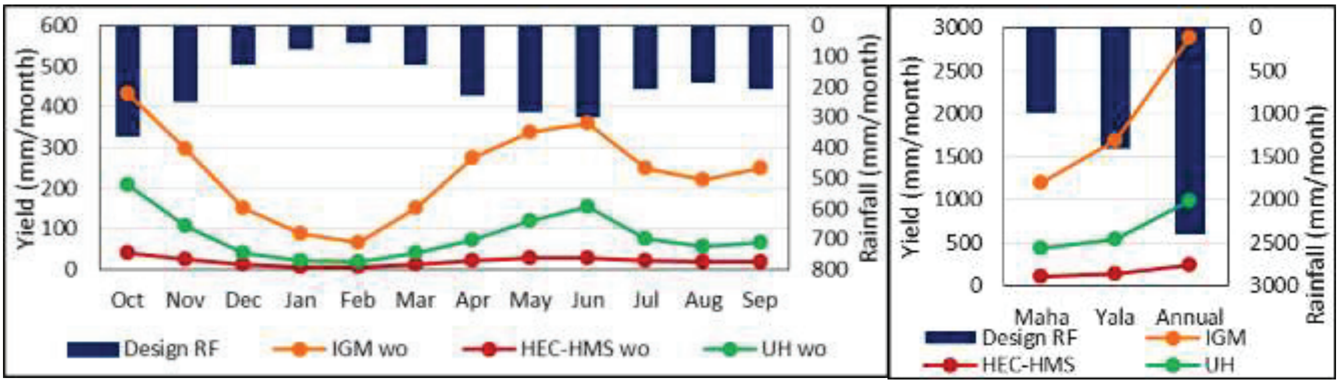

Figure 3 - Monthly, Seasonal and Annual Yield Comparison without Yield Thresholds

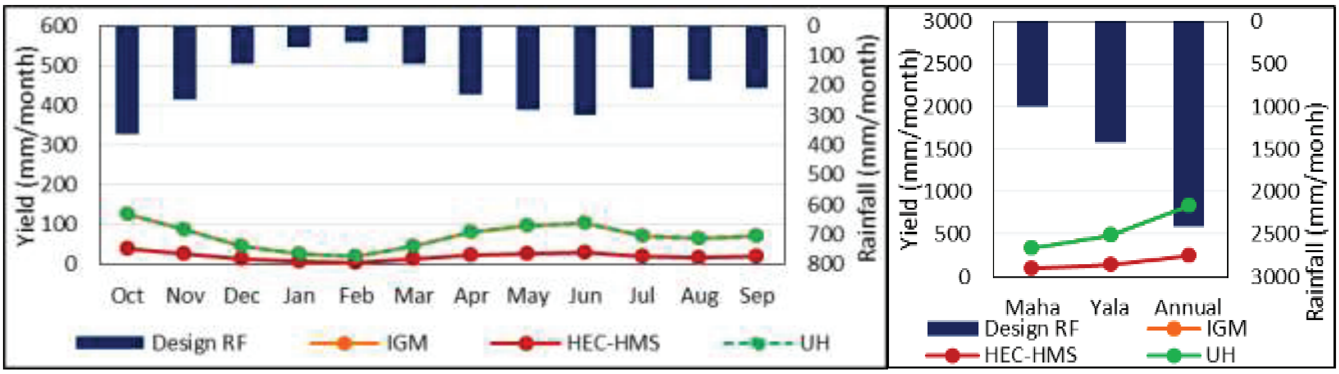

Figure 4 - Monthly Seasonal and Annual Yield Comparison with Yield Thresholds

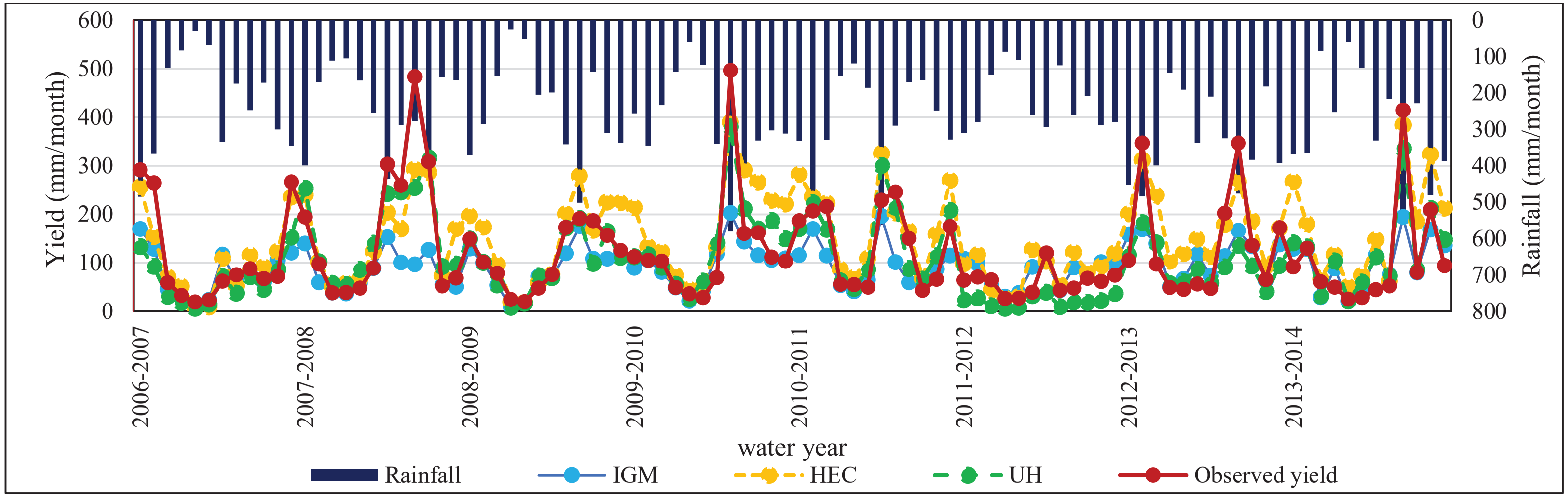

Figure 5 - Monthly Yield Comparison for Observed Data

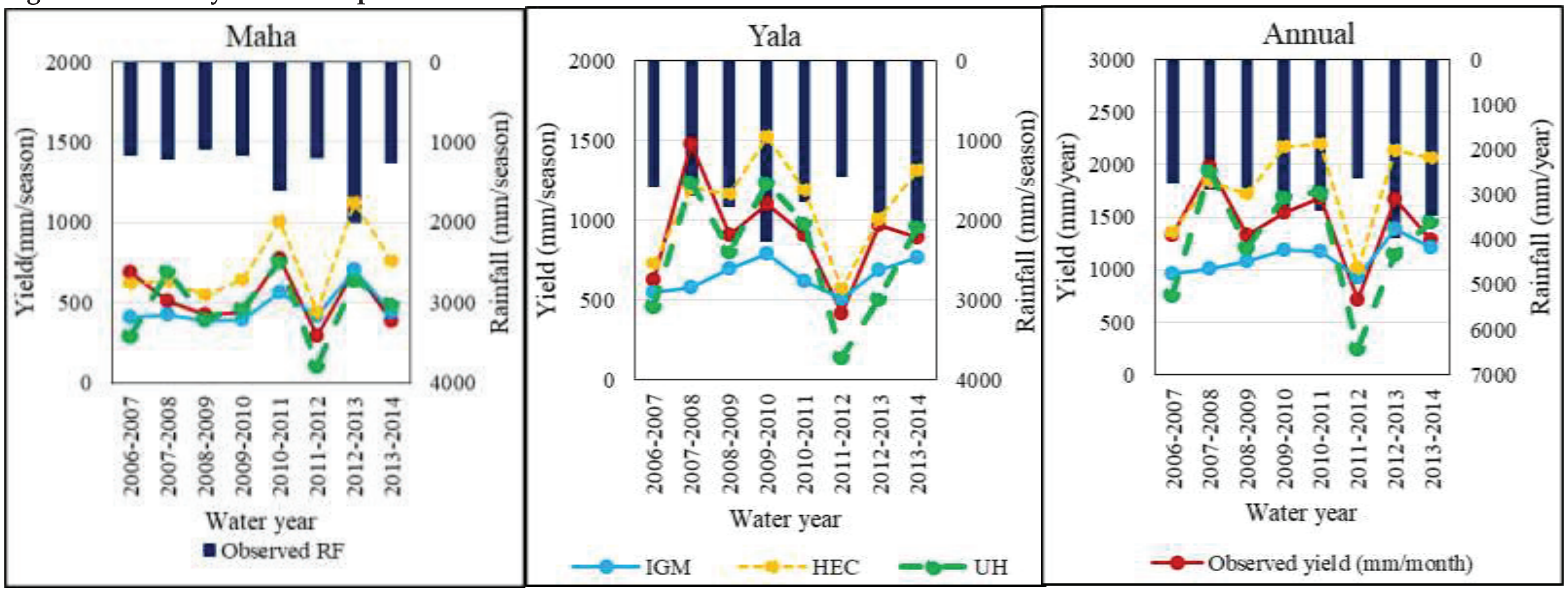

Figure 6 - Seasonal and Annual Yield Comparison for Observed Data

Table 1 - Data Collection Details

Data	Location	Resolution	Period	Source
Rainfall	Halwathura, Alupola, Pelmadulla, Nivithigala, Ratnapura	Daily	2006-2014	Department of Meteorology
Stream flow	Ellagawa	Daily	2006-2014	Department of Irrigation
Evaporation	Ratnapura	Daily	2006-2014	Department of Meteorology

Table 2 - Regional Parameters for UH Model for Sri Lankan Watersheds

Reference	Basin	Cp	Ct
[52]	Karasnagala	0.38	3.75
[60]	Kalu basin	0.47	8.7
	MahaOya	0.9	1.67
	Kelani Ganga	0.55	3.76
[12]	Putupaula	0.47	8.7
	Holumbuwa	1.0	2.52

Table 3 - Applications of HEC-HMS Model for Sri Lankan Watersheds

Basin	Reference	Data period	Calibration and Validation	Loss method	Transform method	Base flow method
Kalu	[41]	2006-2014	C- 2006-2010, V- 2010-2014	Deficit & constant	SCS UH	Recession
Kalu	[42]	1986-1995	C-1986-1990, V- 1991-1995	Deficit & constant	Snyder's UH	Recession
DeduruOya	[45]	1986-1989	C -3 months V– 3 years	Five layer moisture accounting	Clark UH	Recession
Kelani	[61]	4 extreme events, (2005-2010)	C-extreme event Nov 2005 V- other events	Green &Ampt	Clark UH	Recession
Nilwala	[62]	5 Extreme events (1974-1984)	C-3 extreme events V-3 extreme events	Green &Ampt	Clark, Snyder, SCS UH methods	Recession
Attanagalu	[43]	2005-2010	C- 2005-2007 V-2008-2010	SCS curve no, Deficit & constant	Clark, Snyder UH methods	Not mentioned

Table 4 - Literature Results for BFI Values

Study Area	BFI value	Reference
River Thames (44 small catchments)	0.65	[63]
Agricultural catchments, Ohio, USA (28 catchments)	0.4-0.7	[64]
114 Catchments, Victoria, Australia (0.05 km² to 192 km² area)	0.49	[65]
14 Volcanic catchments, Japan	0.533-0.85	[66]
Zimbabwe	0.05-0.3 - Cristalline rocks 0.5-0.7 – Well watered eastern highlands	[67]
World	tropical, rainforest -0.77 tropical, monsoon -0.74 tropical, savannah -0.71 arid, desert -0.49 arid, steppe -0.57 temperate, dry summer -0.65 temperate, dry winter -0.67 temperate, no dry season -0.63 cold, dry summer -0.77 cold, dry winter -0.74 cold, no dry season -0.74 polar, tundra -0.64 polar, frost 0.70	[68]

Table 5 - Model Parameters and References

Model	Parameter	Magnitude	Reference
IGM	Agro ecological regions	WL1, WL2, WM1, WM3, WU1, IL1	[12]
	Iso yield value - Maha	2500 Ac.ft/ sq.mile	
	Iso yield value -Yala	3000 Ac.ft/ sq.mile	
HEC- HMS	Constant loss	0.487 mm/hr	[41]
	Initial deficit	3.384 mm	
	Lag time	2677 min	
	Recession constant	0.907	
	Threshold ratio	0.151	
UH	Catchment area (A)	1446.4 sqkm	Arc- GIS software
	Length of the longest river (L)	74.03 km	
	Length of the river from centroid/ near centroid (Lc)	29.23 km	
	Cp	0.47	[12]
	Ct	8.7	
	Φ index	1.2 mm/hr	[52]
	BFI	0.77	[68]

Table 6 - Comparison of Models with and without Yield Thresholds for Design Rainfall

	without yield thresholds				with yield thresholds		
	Design Rainfall (mm)	IGM wo (mm)	HEC wo (mm)	UH wo (mm)	IGM w(mm)	HEC w(mm)	UH w(mm)
October	362.1	433.6	42.9	209.5	126.73	42.90	126.73
November	247.2	295.9	25.8	108.6	86.51	25.80	86.51
December	127.2	152.3	13.6	42	44.50	13.60	44.50
January	74.0	88.6	7.8	23.3	25.90	7.80	25.90
February	56.5	67.6	5.6	17.7	19.77	5.60	19.77
March	127.5	152.6	12.3	40.2	44.61	12.30	44.61
April	229.3	274.5	22.0	72.4	80.25	22.00	80.25
May	282.7	338.5	27.9	120.3	98.93	27.90	98.93
June	300.3	359.5	29.8	153.3	105.09	29.80	105.09
July	207.5	248.5	21.4	76.8	72.64	21.40	72.64
August	184.3	220.7	18.5	58.7	64.50	18.50	64.50
September	207.3	248.2	20.4	65.9	72.54	20.40	72.54
Maha	994.3	1190.6	108.0	441.3	348.02	108.00	348.02
Yala	1411.3	1689.9	140.0	547.4	493.95	140.00	493.95
Annual	2405.6	2880.5	248.0	988.7	841.97	248.00	841.97

Table 7 - Rank for Qualitative Assessment of Models

Rank	Description
1	Lowest Uncertainty
2	Uncertainty between Lowest and Moderate
3	Moderate Uncertainty
4	Uncertainty between Moderate and Highest
5	Highest Uncertainty

Table 8 - Qualitative Ranking of Models Based on Case Study Applications[3]

#	Uncertainty Factor associated with Yield Computation	Qualitative Ranking based on Case Study Applications – Kalu river Watersheds			
		ID model	**HEC HMS Model**	**UH Model**	**Remarks/Rationalisation**
1	Rainfall Input Conversion	1	3	5	ID model needs no conversion, UH model conversion has more assumptions than HEC HMS Conversion requirements
2	Process Selection	1	3	5	ID method is direct, HEC HMS with continuous capability is less uncertain than with Event based UH for Continuous modelling
3	Parameter Selection	2	4	5	ID model has to deal with low resolution seasonal iso yield maps, HEC model has reasonable nearby watershed applications, UH model has many sub model parameters to select
4	Yield Threshold Selection	1	3	3	ID model has specific guidance, Use of same thresholds for HEC HMS and UH models can be justified
5	Example Application Cases	4	3	5	Based on reviewed publications and priority for Sri Lankan case studies
6	Guideline Availability	1	3	3	ID models has a clear guideline, other two models with general and textbook guides
7	Time Tested Practice	1	4	4	Absence of literature evidence of using HEC HMS and UH models in official practice, ID model in Sri Lankan official practice since 1984
8	Order of Magnitude of Computed Yield	5	4	5	Based on relative reliability or acceptability of computed yield values without Thresholds
9	Comparison with Physical Runoff Coefficient	5	4	5	Based on relative reliability or acceptability of computed yield values without Thresholds
10	Comparison with Water Balance	5	4	5	Based on relative reliability or acceptability of computed yield values without Thresholds
11	Computations after Threshold Applications	3	4	5	ID model have specific thresholds but they are seasonal and needs updating, the others do not have any specific attachment, HEC HMS values are within the lower and upper bounds
Normalised Uncertainty Ranking		**3**	**4**	**5**	

Table 9 - Comparison of Models with and without Yield Thresholds for Observed Rainfall Application Compared with Observed Streamflow

	Observed rainfall(mm)	without yield thresholds			with yield thresholds	Observed streamflow (mm)
		IGM wo(mm)	HEC wo(mm)	UH wo(mm)	IGM w(mm)	
October	520.40	342.36	225.84	137.15	130.08	149.35
November	414.41	305.98	176.04	122.05	119.84	165.52
December	207.10	171.15	114.21	73.16	69.57	89.81
January	87.49	111.31	67.03	45.73	43.36	40.95
February	110.78	85.20	50.81	33.91	34.40	34.54
March	225.39	174.60	87.24	69.36	68.46	45.48
April	398.85	269.51	151.04	129.15	118.25	119.15
May	326.97	221.10	163.69	152.76	102.28	193.69
June	290.31	276.41	239.55	163.25	126.78	235.35
July	184.11	193.55	166.44	111.60	94.41	131.58
August	205.49	221.22	164.60	114.70	99.33	99.49
September	270.00	246.95	204.33	124.33	110.61	135.21
Maha	1,565.57	1,190.61	721.16	481.36	465.72	525.66
Yala	1,675.74	1,428.73	1,089.64	795.79	651.68	914.47
Annual	3,241.31	2,619.33	1,810.80	1277.15	1,117.40	1440.12

Table 10 - MRAE for Design and Observed Rainfall

MRAE	Flow type	Ellagawa design RF	Ellagawa observed RF
IGM with thresholds	Overall hydrograph	0.38	0.35
	Overall FDC	0.39	0.35
	Annual FDC	0.39	0.27
	High flow	0.43	0.22
	Low flow	0.33	0.11
HEC-HMS model	Overall hydrograph	0.82	0.58
	Overall FDC	0.82	0.57
	Annual FDC	0.82	0.51
	High flow	0.83	0.31
	Low flow	0.81	0.51
UH model	Overall hydrograph	0.4	0.4
	Overall FDC	0.35	0.39
	Annual FDC	0.35	0.32
	High flow	0.31	0.11
	Low flow	0.40	0.12

Table 11 - Numerical Indicators for Model Estimations

Numerical indicators	IGM wo	IGM w	HEC-HMS	UH model
AAWBE (mm)	-1179.21	322.73	-370.68	162.97
AMSWBE (mm)	-664.95	59.94	-195.51	44.29
AYSWBE (mm)	-514.26	262.79	-175.17	118.68
Percentage error of annual average runoff coefficient	-81.88	22.41	-25.74	11.32
MRAE overall hydrograph	1.47	0.35	0.58	0.4
MRAE PoR FDC	1.47	0.35	0.57	0.39
MRAE Annual FDC	1.34	0.27	0.51	0.32