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Evaluating the Options for Streamflow Modelling in Ungauged Watersheds for Sustainable Engineering Designs - A Case Study at Attanagalu River Basin, SriLanka

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Abstract: Water management and infrastructure designs all over the world are mostly associated with ungauged watersheds. The critical task is to estimate the streamflow at a desired location and then to convert the streamflow as design streamflow by incorporating safety factors. In the current setting, practicing engineers find a deficiency in guidelines to select a model and also find out ways to incorporate safety factors ensuring sustainable design of water infrastructure. The guideline of Irrigation Department, Sri Lanka, provides guidance on the use of an empirical model while the Snyder's synthetic unit hydrograph method and HEC-HMS model are two other popular process-based models opted by most recent modelers to estimate watershed streamflow. The authors carried out a critical literature review and a case study in the Kalu river basin to investigate the issue of model selection faced by ungauged watershed modelers. A streamflow modeler of ungauged watersheds requires to responsibly select a streamflow model, model parameters and safety factors. In this context, the major challenge in the Sri Lankan practice is the unavailability of catchment studies with comparative evaluations of model studies with observed streamflow. The objective of the present work was to first determine the rationale for a design engineer to select a watershed model and parameters when computing design streamflow from an ungauged watershed and then to verify the selection using observed streamflow. Accordingly, the Irrigation Department Empirical Model (IDEM), Snyder's UH Model (SUHM) and HEC-HMS model were selected and developed for Dunamale watershed of the Attanagalu river basin using methods and parameters from responsible publications. Then the model estimates were critically evaluated by comparing the observed streamflow. IDEM estimates of monthly yield estimations closely matched with the observed data. In the case of overall hydrographs, the IDEM indicated a MRAE value of 0.43 for design rainfall estimation, while the same for HEC-HMS model and SUHM method were 0.63 and 0.61, respectively. The qualitative review based on the uncertainties associated with the computations using IDEM, HEC-HMS and SUHM models classified them into three, as Moderately uncertain, Uncertainty between moderate and high, and Highly uncertain, respectively. The study concluded that, amongst the three selected models, the IDEM is still the best option available for an ungauged watershed modeler to compute design streamflow but pointed to the urgent need for upgrading the ID guidelines with focused research. The study pointed to the importance of identifying appropriate models and parameters for each watershed for meaningful use of process based streamflow models for design of water infrastructure. It was identified that explicit safety factors should be established to incorporate the uncertainties associated with the models and their parameters.

Keywords: Mathematical modelling, Streamflow estimation, Ungauged watershed, Safety factor, Parameter, Engineering design

1. Introduction and Literature Review

Reliable streamflow estimation in ungauged watersheds is a challenge for a practicing engineer for sustainable water management and water infrastructure designs. In case of watershed streamflow estimations, there are two reasonable options for an ungauged catchment modeler. One is to use a Time Tested Coarse Resolution Empirical Model (TTEM) and the other is to select from modern Generalized Process-based Hydrological Models (GPHM) which are capable of providing distributed outputs at finer temporal and spatial resolutions [1], [2]. Many streamflow calculation options in guidelines and textbooks are either direct,

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empirical, or simple conceptual models ([3] to [11]) which are mainly based on empirical methods. Most of these are time tested methods and do not provide evidence on the selection of safety factors. Unless there is evidence and a guide to determine the reliability of using the model and its parameters for Sri Lankan context, a streamflow modeler encounters the difficulty of rationalization of designs using such estimates. Watershed streamflow calculation methods have developed from the use of regression type [4], [12], [13] to sophisticated process based hydrological models such as Hydrologic Engineering Centre – Hydrologic Modelling System (HEC-HMS), Soil Water Assessment Tool (SWAT), Storm Water Management Model (SWMM). These methods, which vary between empirical and mathematical, are either available as guidelines [4] to [8], [10], [14] to [18] or can be found as research publications [19] to [26]. Data limitation for calibration and validation is the main problem in hydrological modelling for ungauged catchments [27], [28]. A review done by the authors points to the fact that, though the literature points to several applications of popular hydrological models for watershed streamflow estimations, there is a shortfall of comparative evaluation of models for their applicability in irrigation planning and infrastructure designs thereby ensuring sustainable water resources management [1]. A subsequent case study incorporating a watershed in the Kalu river basin of Sri Lanka and selecting three popular models, the authors demonstrated the challenges faced by the ungauged watershed modelers, and the urgent need to establish guidelines for selection of models, parameters and safety factors [2]. The recent technological advances in the use of remotely sensed distributed land use, soil and terrain data, GIS technologies, the inclination to use the available physics-based understanding on the watershed hydrological processes, and the availability of a wide variety of free and propriety hydrological models, provide the opportunity to uplift the prevailing practice and compute distributed outputs for easy management of watersheds. Though the theme of utilizing theoretical advances and technological developments presents a great attraction, the major issue that engulfs is the dependability on the outputs. These advanced and recent hydrological models must be appropriately selected, calibrated with reliable parameters and sufficiently verified prior to use for water infrastructure designs for public use. In case of Sri Lanka, the Irrigation Department uses an empirical model with flow thresholds [5]. Although this model has been in practice for nearly four decades, there is a shortfall in literature other than a study by the authors [2] to evaluate the suitability of the model and the reliability of model parameters. In case of recent models, though there are a few modelling studies that have been carried out for several Sri Lankan watersheds, the absence of a guideline poses problems when selecting model components and parameters for watershed applications. The above issues have been identified and discussed in detail in Siriwardana and Wijesekera [1], [2]. In the recent study by authors which was quoted above, the major issue is the observation that there is a wide variation of watershed streamflow quantity estimated with the IDEM, HEC-HMS and SUHM used for the application in the Kalu river basin. In this backdrop, there is a dilemma when a design engineer is embarking upon the task of estimating streamflow of an ungauged watershed. On one hand there is the desire to update with recent developments to use a process based mathematical model that requires established parameters, and on the other hand there is a guideline that had been in use over a long period of time and recommends the use of an empirical model but without sufficient evidence to support its capability to deliver reliable streamflow estimates. Hence, as the prime objective, there is an urgent need to study the streamflow estimation from a few models, compared with the observations and then establish the rationale for a design engineer to select a watershed model and parameters to determine streamflow from an ungauged watershed. Accordingly, the irrigation Department Empirical Model (IDEM), Snyder's Unit Hydrograph Model (SUHM) and HEC-HMS model were selected for a critical evaluation of streamflow estimations for the Dunamale watershed of the Attanagalu river basin by using the available guidelines and model parameters for a practicing designer. The selection of the same models as in the authors' previous study enabled verification of findings.

2. Methodology and Analysis

The Dunamale sub-watershed (157.5 km^2) in Attanagalu river watershed was selected for the study considering the data availability (Figure 1). Design data were collected from Irrigation guideline [5] and available literature [4]. Topographic data were obtained from Survey Department maps and were calculated using Arc-GIS 10.3 software. Rainfall data were collected from Department of Meteorology and streamflow data were collected from Irrigation Department

(Table 1). In this study, data from year 2005 to 2015 were used while computations were based on the water-year of Sri Lanka which is from October to September of the following year.

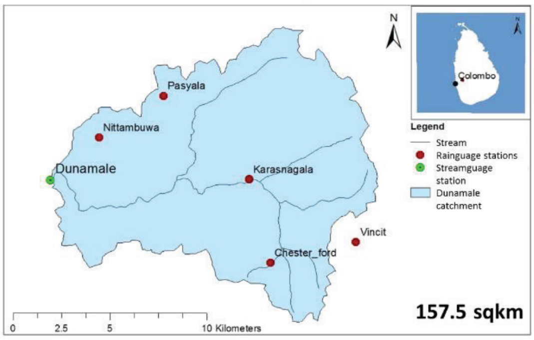

Figure 1 - Study Area Map

Thiessen polygon method was used to compute average rainfall. Similar to the previous study by authors [2], in order to fulfill the purpose of demonstrating the case of an ungauged watershed, the model components and parameters were selected using the available literature and the best engineering judgment (Table 2). The finer details of computations pertaining to all three models with assumptions made during this study are in the thesis by Siriwardana [29].

Computations for each model was initially done for design rainfall input to compare the options available and mentioned in [1] for an ungauged watershed modeler. This was followed by comparing the modelled streamflow by each model for the observed rainfall, with observed streamflow. The computational method and incorporation of hydrological processes in each model was subjected to a careful study and thereafter the generated streamflow for Dunamale watershed was compared with the measured streamflow. The process followed for the analysis is outlined in Figure 2.

IDEM is a model based on Irrigation guideline of Sri Lanka and is an empirical time tested model. In this model, there are two planning requirements (1) 75% probable rainfall and (2) Application of yield thresholds. IDEM model followed the watershed yield estimation method in Irrigation guideline, Sri Lanka [5]. The 75% probable rainfall, calculated according to the agro ecological region, was estimated according to the method in Irrigation guideline, Department of Irrigation, Sri Lanka [5] and taken as the design rainfall for computations. As Dunamale watershed is a combination of three agro ecological regions, namely, WL1, WL2 and WL3, area weighted method was used for obtaining the design rainfall. The Irrigation Department guideline uses an upper and lower threshold for water yield as 35% and 7.5%, respectively, for the percentage runoff computed by its empirical model [5]. These values were used for the comparisons carried out in the present study.

In HEC-HMS model application, parameters and processes selection were done based on

1) Literature based calibrated and verified parameters and recommended processes, for Attanagalu Oya watershed
2) Considering the watershed similarity when there are no literature available parameters for the watershed
3) By the best engineering judgments.

An analysis of process and parameter selection from available literature based on HEC-HMS, done by authors is presented in reviewed publications [2], [29]. Comparing the loss methods, Jayadheera [30] says that Deficit and constant method is the suitableloss method, and it was selected as the loss method for the model. Snyder's UH method was selected as the transform method [31] and recession method was selected as the baseflow method [30], [32]. In the analysis, the computed daily streamflow values were summed up to obtain monthly, seasonal and annual streamflows. The computational procedure was similar to the application for Kalu river basin by the authors [2].

For SUHM model, unit hydrograph parameters, 0.38(C_p), 3.78(C_t) were selected for regional parameters for the model by considering various literature available parameter ranges and the applications for the watershed [29], [33]. Annual baseflow index (BFI), defined as the long-term ratio of baseflow to total streamflow [34]–[36] used for baseflow estimation, and Φ index method were used for effective rainfall estimation in SUHM. Considering literature and the topography of the selected watershed as the Table provided in [1], [29] the base flow index (BFI) was taken as 0.77. Watershed geometric parameters for SUHM model were extracted from Arc-GIS 10.3 software. Selected model parameters and references are shown in Table 2.

Table 1- Data Collection Details

Data	Location	Resolution	Period	Source
Rainfall	Nittambuwa Pasyala, Karasnagala, Chesterford, Vincit	Daily	2005-2015	Department of Meteorology & Department of Irrigation
Stream flow	Dunamale	Daily	2005-2015	Department of Irrigation

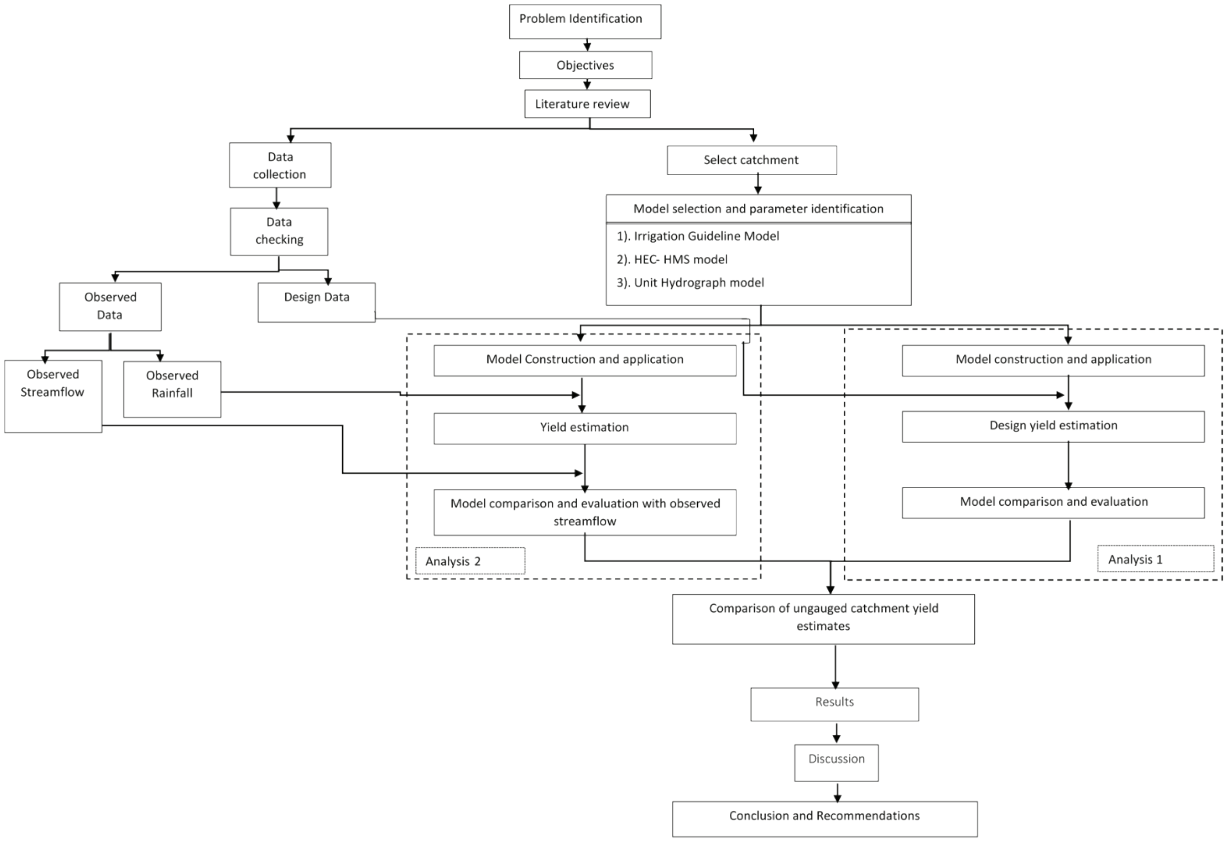

Figure 2 - Methodology Flow Chart

Table 2 - Model Parameters and References

Model	Parameter	Magnitude	Reference	Remarks
IDEM	Agro ecological regions	WL1, WL2, WL3	[5]	Agro ecological regions for Dunamale watershed
	Iso yield value - Maha	1750 Ac.ft/ sq.mile		Available iso-yield value in Irrigation Guideline
	Iso yield value -Yala	2000 Ac.ft/ sq.mile		
HEC- HMS	Constant loss	0.487 mm/hr	[30]	Assumed hydrologically similar watersheds
	Initial deficit	3.384 mm		
	Lag time	2466 min	[31]	Parameters available for the watershed
	Recession constant	0.907	[30]	Assumed hydrologically similar watersheds
	Threshold ratio	0.151		
SUHM	Catchment area (A)	157.5 sqkm	Arc-GIS software	Software calculated parameters
	Length of the longest river (L)	22.55 km		
	Length of the river from centroid/ near centroid (Lc)	12.67 km		
	C_p	0.38	[33]	Parameters available for the watershed
	C_t	3.78		
	Φ index	1.2 mm/hr	[37]	Parameters available for the watershed
	BFI	0.77	[39]	Parameters selected considering the suitability of the region

The study followed three stages of analysis. Firstly, the design data were used for streamflow estimation. Secondly, a qualitative assessment of the models was carried out. This assessment, while capturing the uncertainties associated with the design streamflow computations, used the same ranking method described by the authors [29]. In this assessment, weights for each model were assigned to reflect, 1) lowest uncertainty, 2) Uncertainty between lowest and moderate, 3) Moderate uncertainty, 4) Uncertainty between moderate and highest, 5) Highest uncertainty by engineering judgment [2], [29]. Thirdly the model computations with observed rainfall data were used as a verification of estimation potential of each model [2].

In the evaluations, the graphical outputs of observed, design and modelled streamflow and same of Flow Duration Curves (FDC) were compared. The FDC is recognized as a good indicator to demonstrate the behavior of streamflow estimates that fall into high, intermediate and low flows [40]–[43]. Mean Ratio of Absolute Error (MRAE) in Equation 1, which provides an indicator capable of reflecting the error of estimations relative to the observation at a particular time point, was used as the primary numerical indicator [44]–[49].

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

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. Since the watershed runoff coefficient provides a guidance for a modeler to evaluate the acceptability of the modelled streamflows, the present study guided by Chow et al. [4] computed the watershed runoff using land use and slope information of the study area.

3. Results and Discussion

3.1 Present Streamflow Estimation Options for Ungauged Watersheds

The evaluation of modelled streamflow for design rainfall input is vital to carryout sustainable design of water infrastructure for ungauged watersheds. The Irrigation Department guideline uses upper and lower thresholds to determine the design streamflow from its empirical model. However, in case of the other two models, there is no such practice of applying thresholds. In this study, in order to perform a critical evaluation, the streamflow from each of the models was subjected to the Irrigation Department thresholds.

The computed streamflow with and without thresholds are in Table 3 and Figure 3, respectively. The values show that computed streamflow from both IDEM and SUHM were curtailed by the thresholds while the HEC-HMS estimated streamflows were within the lower and upper thresholds. In both IDEM and SUHM models, the estimations were well above the upper threshold and hence the thresholds reduced the design streamflow to approximately 60% of modelled streamflow. The results also show that without the yield thresholds, the respective average annual runoff coefficients for IDEM, SUHM and HEC-HMS models were 0.89, 0.20 and 0.88, respectively, while the application of thresholds changed the same to 0.35, 0.20 and 0.35, respectively. However, from these results, the design engineer for ungauged watersheds would not be able to determine the appropriateness of a model or a method. The watershed average runoff coefficient provides an indication of the realistic nature of watershed streamflow estimates. The physical runoff coefficient value obtained by following the guidance of Chow et.al. [4] is 0.5 for Dunamale watershed. This shows that HEC-HMS indicates comparatively lower runoff coefficient of 0.2, demonstrating that streamflow values from this model are significantly underestimated and hence cannot be accepted as realistic. Although, the HEC-HMS model can be applied for ungauged watersheds, by making many assumptions when selecting the process and associated parameters are [50]–[52], the results lead to a general idea of streamflow, peak flow and the velocity of the peak flow [52] and some peaks can be over estimated [50]. Therefore, the necessity of further research for HEC-HMS applications for ungauged watersheds is recommended. Accordingly, the rational option for the ungauged modeler would be to select either the IDEM or SUHM by considering other factors such as model characteristics, the data used to develop the model and the factors considered when selecting the model parameters. In this study, the model structures and parameters were based on reported literature. Therefore, the natural selection of an ungauged watershed modeler would be to use the time tested IDEM until the three models and parameters are subjected to thorough research. IDEM model, being still the better option for Attanagalu river, shows a similar behaviour to the Kalu river basin [2].

The main reason for the approach taken by the present study highlights three key factors associated with the performing designs using mathematical models. One is the addressing of the uncertainty of input rainfall to the model, the next is addressing the uncertainties associated with the model and the model structure and finally it is the need to address the uncertainties associated with the model parameters.

Hence the present study, firstly addressed the absence of guidance to use design return periods for daily rainfall when generating streamflow using modern hydrological models by considering 75% probable rainfall as recommended by the Irrigation Department Guideline. Secondly, the incorporation of yield thresholds in the IDEM were identified and treated as implicit safety factors for generated streamflow and the absence of a guideline for safety factors when performing water resources designs utilizing modern hydrological models. These results were critically compared and discussed to identify the acceptability of modelled streamflow. Thirdly, the results of with and without thresholds for each model, demonstrate the importance of a design guideline that specifically states on the methodology to apply safety factors to responsibly convert a time series of modelled streamflow as input for engineering design.

Table 3 - Comparison of Streamflow for Design Rainfall: With and Without Yield Thresholds

	Without(wo) Yield Thresholds				**With(w)Yeld Thresholds**		
	Design Rainfall (mm)	**IDEM wo (mm)**	**HEC wo (mm)**	**SUHM wo (mm)**	**IDEM w (mm)**	**HEC w (mm)**	**SUHM w (mm)**
October	334.6	304.3	53.7	377.7	117.10	53.70	117.10
November	233.1	212	51.6	176.3	81.57	51.60	81.57
December	104.6	95.2	27.8	83.6	36.62	27.80	36.62
January	65.1	59.2	15.1	46.5	22.79	15.10	22.79
February	55.5	50.5	11	39.6	19.42	11.00	19.42
March	123.6	112.4	21.6	88.2	43.24	21.60	43.24
April	218.8	191.3	38.5	195.9	76.59	38.50	76.59
May	276.2	241.5	52.6	287.6	96.68	52.60	96.68
June	218.8	191.3	46.4	200.9	76.59	46.40	76.59
July	126.8	110.9	30.4	92.9	44.38	30.40	44.38
August	106.2	92.8	22.4	75.8	37.16	22.40	37.16
September	142.6	124.7	26.4	101.9	49.92	26.40	49.92
Maha	916.4	833.6	180.8	811.9	320.74	180.80	320.74
Yala	1089.5	952.5	216.7	955.1	381.31	216.70	381.31
Annual	2005.86	1786.1	397.5	1766.9	702.05	397.50	702.05
Annual Runoff Coefficient		0.89	0.20	0.88	0.35	0.20	0.35

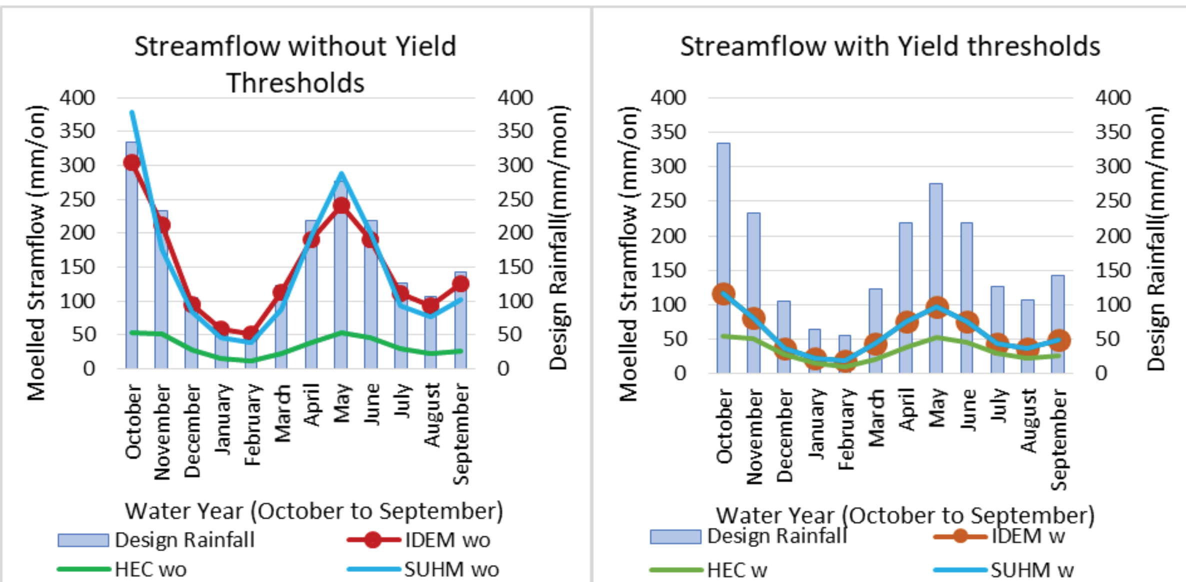

Figure 3 - Comparison of Modelled Streamflow for Design Rainfall: With and Without Yield Thresholds

Due to these issues, as at present, the only option of an ungauged watershed modeler to perform responsible designs is finding a data set and parameters of a similar catchment in same hydrological, meteorological conditions and then use available literature. Thereafter, the necessity of best engineering judgment and careful supervision is critical to select the most suitable parameters and data set for the watershed. Several papers on these vital issues, written by authors strengthen the idea [1], [2]. The decision-making method of yield estimation options from a practicing engineer's point of view shows the necessity of engineering judgment and capable supervision for selection of model parameters for ungauged watersheds to ensure sustainable water infrastructure designs.

3.2 Critical Evaluation of Streamflow Estimation Models

Table 4 shows the assigned ranks from the qualitative assessment. The normalized ranking indicated the IDEM having a moderate uncertainty, SUHM demonstrating the highest uncertainty and the HEC-HMS having an uncertainty between highest and moderate. The uncertainties that were pointed out highlight that the most valuable contributory factor for a responsible practicing engineer is the availability of a guideline for calculation of the design yield from a watershed.

The key model components identified during the present study as relatively uncertain were (1) the extraction of values from spatially coarse iso-yield curves, and then (2) using an assumption to apportion to get monthly yield values. During the series of studies by the authors conducted to identify the issues faced by a practicing engineer, it could be noted that although IDEM had been used for over four decades as a model for irrigation infrastructure construction, there is a lack of experimental or research references that had been utilized to determine the recommended methods, model parameters and safety factors.

In literature, the HEC-HMS and SUHM model applications are associated with computations using daily or finer temporal resolutions. It is widely accepted that these process based models at a daily temporal resolution would reflect better hydrological behavior when finer resolution outputs are aggregated to coarser resolution information for designs. In these process models, the uncertainty faced by the modeler when selecting sub models often lead to errors in model estimations.

In this study it was noted that, due to the process level incorporation of hydrological behavior in a watershed, the HEC-HMS model provides a confidence in the reasoning out the physical characteristics. However, the model contains limitations as model cannot predict flow accurately to the variations of land use [31], higher sensitive parameters as imperviousness, soil percolation [21] are difficult to accurately obtain in ungauged watersheds, prediction accuracy can change spatially [53] and model will over predict the rainfall for heavy rains after 2-3 week dry period [31]. Many researchers stated the necessity of calibrating the parameters for accurate flow generation [21], [31], [32]. Therefore, for real life application in ungauged watersheds, it creates ambiguities due to many reasons. Especially in Sri Lanka, there are many issues because of the lack of applications for same or similar watersheds. The reasons can be summarized as, 1) Availability of multiple models for one process and the availability of a limited number of applications for Sri Lankan watersheds cause problems to practicing engineers when selecting a representative process, 2) Even if a practicing engineer selects a process, often there are no representative parameters for Sri Lanka in the already published papers or in guidelines, 3) Higher number of parameters in the process models is another major drawback because in case of ungauged and uncalibrated watersheds, the practicing engineer needs to make many judgments to ensure the reliability of the results, 4) Very often due to the lack of field data in ungauged watersheds, a practicing engineer is unable to rationally select the appropriate processes and parameter values, 5) Errors that arise due to use without model calibration gives rise to issues with confidence when results are generated and hence need to find other methods for verification.

This is especially so when there is lack of research on the applicability of various concepts to a selected watershed or to similar watersheds. However, an ungauged watershed modeler requires to keep in focus that, even with a poor conceptualization, the present-day models would produce a streamflow time series and that the responsibility of determining its validity for an application lies on the modeler. Hence utmost care should be taken when selecting a model and model output for applications in ungauged watershed designs. There are two factors highlighted in the current study and the study by the authors for the Kalu river watershed [2] as 1) unrealistic nature of streamflow computed by all three models prior to application of thresholds, 2) the lack of guidelines for the recent models to incorporate safety factors to convert model outputs as design flow. This critical factor is very important for watershed managers who target to develop sustainable water management practices for both the humans and the environment.

Table 4 - Qualitative Ranking of Models Based on Case Study Applications

	Uncertainty Factor Associated with Yield Computation	Qualitative Ranking based on Case Study Applications - Dunamale Watershed			
		IDEM model	HEC HMS Model	SUHM Model	Remarks/Rationalisation
1	Rainfall Input Conversion	1	3	5	ID model does not require a conversion of input, UH model conversion required a conversion with assumptions. HEC HMS required lesser assumptions than the UH model when the input is determined.
2	Process Selection	1	3	5	ID method is clear and direct during application, HEC HMS with continuous estimation capability creates ambiguities. The UH application which requires fewer uncertainties compared to HEC HMS and are with the application of event based model for continuous modelling
3	Parameter Selection	2	4	5	ID model has to deal with low resolution seasonal iso-yield maps, In the absence of prior model results, HEC model requires reasonable nearby watershed applications, UH model requires dealing with many sub model parameters to select
4	Yield Threshold Selection	1	3	3	ID model with an application guidance creates no ambiguities. A practicing engineer with the awareness of ID guidance can rationalise and use same thresholds for HEC HMS and UH models and hence can be justified
5	Example Application Cases	4	3	5	Based on reviewed publications and assigning priority for Sri Lankan case studies
6	Guideline Availability	1	3	3	ID models has a clear guideline for Sri Lanka, other two models are only with general descriptions and textbooks as guidance material.
7	Time Tested Practice	1	4	4	Absence of literature evidence for using HEC HMS and UH models and the lack of responsible guidelines sanctioned by authorities for official practice of these two models. ID model has been sanctioned by Irrigation Department for Sri Lankan official practice since 1984.
8	Order of Magnitude of Computed Yield	5	4	5	Comparisons based on relative reliability or acceptability of computed yield values without the Thresholds for engineering designs. Used as a verification of model outputs.
9	Comparison with Physical Runoff Coefficient	5	4	5	Comparisons based on relative reliability or acceptability of computed yield values without the Thresholds for engineering designs. Used as a verification of model outputs.
10	Comparison with Water Balance	5	4	5	Comparisons based on relative reliability or acceptability of computed yield values without the Thresholds for engineering designs. Used as a verification of model outputs.
11	Computations after Threshold Applications	3	4	5	ID model has specific thresholds but they are seasonal and require updating. UH and HEC HMS do not have any specific indication for conversion of model estimations for designs. HEC HMS estimations appeared within the lower and upper bounds.
Normalised Uncertainty Ranking		**3**	**4**	**5**	

Though the SUHM model is based on many assumptions, time tested practice in Sri Lanka provides significant confidence when model selection is carried out. This model deals with effective rainfall, direct runoff and the model is event based. Therefore, in this case when using SUHM, many assumptions were made in relation to the continuous streamflow estimations, conversion of direct runoff to total runoff, and then estimating the baseflow values for a continuous time series. Apart from the above, an ungauged designer using these models has to estimate C_t and C_p values to ensure that the unit hydrograph generation process is reasonable. Use of these parameter values are currently based on literature. A previous study by [33], [37] has shown the need to identify these parameters suitable for Sri Lanka for use of typical watersheds. Similar to the study by authors for the Kalu river [2], in the present study, it demonstrates that the stated factors create significant uncertainties when modelling streamflow using SUHM theory.

3.3 Comparison with Observed Streamflow Data

In this study, there are two important considerations. One is the identification of the appropriate model in relation to a practical application for an ungauged catchment. Then the other is a typical research which compares the application of three models for their capability to reproduce watershed streamflow.

The modelled streamflow from all three models corresponding to observed rainfall and the flow duration curves is in Figure 4 and Figure 5. The overestimation of streamflow by all models is clearly visible from the results of all models. The flow duration curve shows that all models have made poor estimations during the very low flows. The poor estimations by the models reflect that the models that were available for a design engineer are not representative of the watershed and also that the modelled outputs cannot be considered as reliable streamflow estimates for responsible designs. The key numerical indicators given in Table 5 also show that the matching of hydrographs and flow duration curves are extremely poor. Annual water balance error without considering the streamflow thresholds also reflects poor reproduction of streamflow in the annual time scale. Even though all three models were incapable of acceptable quantifications, the graphical outputs in Figure 4 and Figure 5 show that all models were capable of reproducing the streamflow pattern. The modeled streamflow quantities aggregated to monthly, seasonal and annual temporal scales in Table 6 provide a clearer picture of the modelled streamflow. In case of IDEM, the case results for with and without thresholds are presented while the outputs of other two models are shown without considering the thresholds. Results without incorporating the threshold demonstrates that all three models overestimate the streamflow in the Attanagalu river watershed. IDEM demonstrated the lowest average over estimation value of 39% whereas the HEC and SUHM reflected high overestimations reaching 53% and 101%, respectively. Relative complexities in process and parameter selection, insufficient number of applications for Sri Lankan watersheds for better parameter selection, higher number of assumptions in model application, ambiguities in data, higher sensitivity of some parameters for the watershed are the causes described previously, which lead to errors of this magnitude. These errors are often attributed to parameter uncertainty selections and, especially when using for a different watershed, such action can lead to the overestimations especially in the case of HEC-HMS and SUHM models that lack case studies or guidelines for Sri Lanka. These uncertainties associated with HEC-HMS and SUHM models have been critically evaluated and addressed by the authors in their earlier publications [1], [2], [29].

Table 5 - Numerical Indicators Computed for Streamflow Estimation with Observed Rainfall

	IDEM with Threshold	Streamflow Without Thresholds		
		IDEM	HEC-HMS	SUHM
MRAE Overall hydrograph	1.09	2.21	1.90	2.52
MRAE Annual FDC	0.88	1.92	1.72	2.33
Average Annual Water Balance Error (AAWBE-mm)	160	160	-1854	-1299

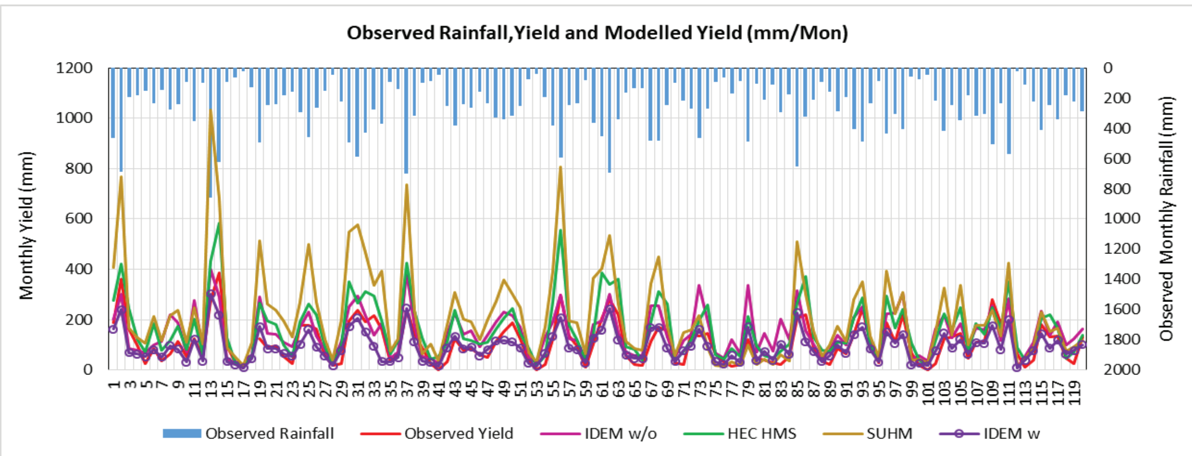

Figure 4 - Modelled Streamflow from All models with Observed Rainfall as the Input

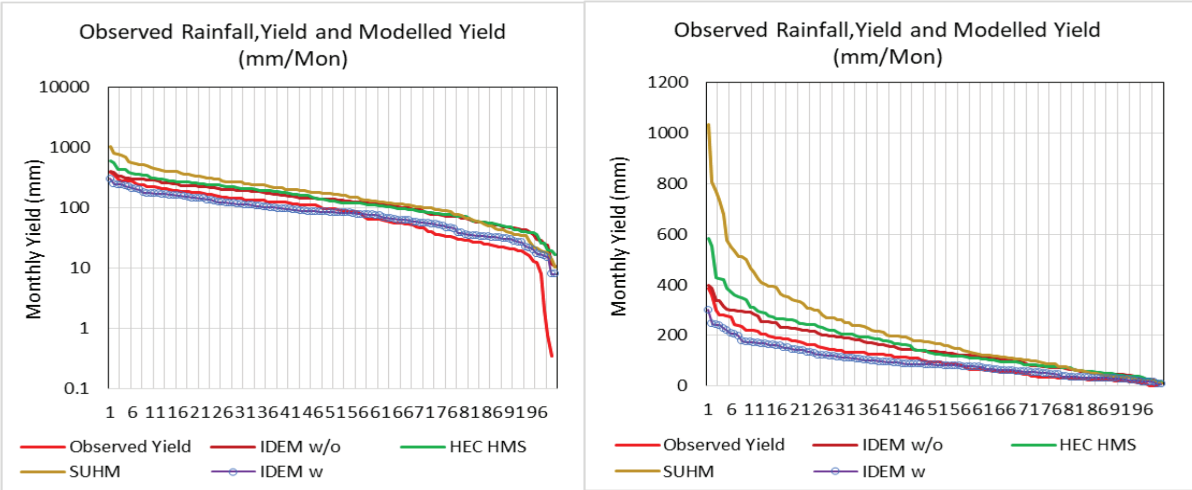

Figure 5 - Flow Duration Curves of Modelled Streamflow with Observed Rainfall as the Input

Table 6 - Comparison of Models for Observed Rainfall Application Compared with Observed Streamflow

	Averaged Variation of Estimates Relative to Observed Stramflow					Averaged % Variation of Estimates Relative to Observed Stramflow			
	IDEM w (mm)	IDEM wo (mm)	HEC wo (mm)	SUHM wo (mm)	Observed streamflow (mm)	IDEM w (mm)	IDEM wo (mm)	HEC wo (mm)	SUHM wo (mm)
October	182	278	286	463	197	-7	41	45	135
November	145	219	308	362	229	-37	-4	34	58
December	73	108	175	160	125	-42	-13	40	28
January	31	46	65	62	41	-26	13	57	51
February	39	59	56	69	14	183	333	309	403
March	79	122	116	174	58	35	109	98	198
April	140	226	207	302	125	12	81	65	142
May	114	182	230	300	135	-15	35	70	122
June	102	165	197	227	137	-26	21	43	66
July	55	102	90	140	69	-21	48	30	102
August	72	125	94	124	46	57	173	104	170
September	95	151	147	202	115	-18	32	28	76
Monthly Average	94	149	164	215	108	-13	38	53	100
Maha Season	548	833	1005	1290	658	-17	27	53	96
Yala Season	577	953	964	1295	627	-8	52	54	107
Annual	1125	1786	1969	2585	1285	-12	39	53	101
Average % variation (monthly, seasonal and annual)						-13	39	53	101

The results in Table 6 show that if an ungauged modeler uses either HEC-HMS or the SUHM then the infrastructure would be over designed and hence would lead to uneconomical designs.

According to the ID guidelines, the application of the IDEM model and thresholds is for the entire island of Sri Lanka. Hence it is prudent to notice that there is a tendency to behave similarly in all applicable watersheds. However, the readers and researchers are urged to perform similar studies in other watersheds to ensure the exact values of overestimations. The authors have noted that there are no guidelines for application of widely used mathematical models, recommend the preparation of guidelines to use appropriate thresholds when water infrastructure designs are carried out. Hence, sensitivity analysis for threshold limitations for all models and parameters of HEC-HMS and SUHM models is recommended for the usage of ungauged watershed applications.

Results in Table 6 show that incorporation of the threshold values reducing the streamflow estimate of the IDEM to a value 13% has to be discussed by critically evaluating the effectiveness of the structures that had been designed during the long period that the ID guidelines have served. Therefore the comparison of modelled streamflow with observed streamflow brings two key factors to light. One is that unless an ungauged modeler is provided with a responsible guideline for the selection of appropriate watershed models and model parameters, the water infrastructure designs of Sri Lanka cannot be considered as sustainable. The other is that the results of comparisons with and without threshold values lead to the conclusion that urgent initiation of focused research is necessary to guide the water infrastructure designers to incorporate appropriate safety factors to convert the watershed streamflow to design streamflow.

4. Conclusions

1. In the case of Dunamale watershed of Attanagalu river basin, the IDEM, HEC-HMS and SUHM models reflected the pattern of rainfall received, but demonstrated that the model outputs significantly overestimated the actual streamflow by respective values of 39% 53% and 101%. The application of Irrigation Department thresholds to the IDEM reduced the computed streamflow values by 13% from the observed streamflow. The present study cautions the ungauged watershed modelers on the non-reliability of using watershed models without acceptable model calibration and verifications.
2. The comparison of models for use of water infrastructure designs demonstrated that the HEC-HMS model with literature reported models and model parameters, estimated watershed streamflow which consisted an unacceptably low runoff coefficient, thereby indicating the need for ungauged modelers to use carefully selected, simplified processes and parameters prior to using a model for streamflow estimation.
3. The evaluation of model outputs, associated uncertainties and availability of guidelines revealed that, out of the three compared models, IDEM is the best option available for an ungauged watershed modeler to compute design streamflow.
4. Modelled streamflow with both design and observed input rainfall revealed that there is an urgent need to initiate studies to guide the selection of watershed hydrological models and model parameters for the estimation of streamflow from ungauged watersheds.
5. The present study established that it is vital to commence focused research to establish explicit safety factors to convert either observed or modelled streamflow to design streamflow for sustainable water infrastructure design.
6. The comparison of modern mathematical models and time tested empirical models for yield estimation of the Attanagalu river watershed on a single platform revealed that the availability of a recommended guideline supported by research based evidence is the most necessary factor for ungauged watershed modellers.

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