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Hydrological Modelling with the Tank Model for Water Resource Management of Nilwala River Basin

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Abstract: Presently, hydrologic modelling is widely used for the quantitative and qualitative estimation of water resources. Such estimations are the baseline to develop strategies for sustainable water and environmental management. In this study, applicability of a daily lumped conceptual model was evaluated to quantify water resources of Nilwala River at Pitabeddara (291.4 km^2). A spreadsheet model developed using Sugawara's Tank Model concept was calibrated and verified by using a daily dataset from water year 2008/09 up to 2017/18. The performance of the model with a four-tank structure was evaluated by using an objective function to match daily hydrographs and the flow duration curves while observing the adequacy of annual water balance estimations. Model performed very satisfactorily with Mean Ratio of Absolute Error (MRAE) values of 0.31 and 0.43 during model calibration and validation, respectively. Most importantly, the best results were in the intermediate flow regime. Streamflow estimations at monthly scale had an average accuracy level of 78% with an average water quantity error of 6% per month. The present work by carrying out a systematic development of a four-tank lumped conceptual model, demonstrated the capability to successfully estimate daily and monthly streamflow at the selected watershed. Hence, the model and its parameters can be confidently used to sustainably manage water resources of the selected watershed and similar watersheds.

Keywords: Tank model, Water resources management, Daily, Flow duration curve

1. Introduction

Demand for freshwater, both for consumptive and non-consumptive use, is increasing with the growth of population and expansion of economic activities thereby leading to a severe stress on limited water resources [1]. This influences social, economic, environmental and political concerns at local and national level which in turn creates a challenge for water managers to follow systematic, careful and integrated management practices for sustainable management of precious water resources [2].

Even though an accurate assessment of the quantity and quality of available water resources is the baseline to develop such management practices [3], [4], there are only a limited range of streamflow measurements and measuring techniques, both in space and time [5]. Thus, mathematical hydrologic models based on historical observations are developed and used as a popular tool to reproduce catchment streamflow [6]. In the field of hydrologic modelling, there are different types of models based on model concept, model structure, and their functionality depending on temporal and spatial resolutions. Empirical models, conceptual models and physical process-based models differentiate models based on their structure [7], [8]. The empirical models are the simplest while physical process-based models have the most complexities [9].

The empirical models such as Rational method, Unit Hydrograph etc. are observation oriented models capable of estimating streamflow easily without considering process of hydrological system [8], [9]. The conceptual models conceptualize the behaviours of catchments with series of reservoir storages and simplified equations of hydrologic system to estimate streamflow in the catchment. GR4J model, MAC-HBV model, NAM model, IHACRES, Tank model are few popular conceptual models [10]–[14]. Based on the hydrological processes and related physics, the physical process-based models such as SWAT, HEC-HMS, TOPMO are developed [15]–[18]. Since these models consist

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large number of mathematical equations and parameters, they are capable of providing vast range of information in the catchment, but require more inputs and greater efforts for model calibration [4], [8], [9].

Due to complexities of water movement in saturated and unsaturated zones which is yet to fully understand, and challenges in the watershed heterogeneity, hydrologic modellers prefer models with simple yet refined methods, having less number of parameters to illustrate hydrological processes, yet satisfactorily performing under low input requirements [19]. Under such circumstances, the conceptual models with their ease of use, less time requirement for model development and modelling, limited data demand and acceptable accuracy, are widely used for mathematical modelling of hydrologic systems [4], [9].

Most Sri Lankan watersheds are faced with the challenge of data availability. Only a limited number of Sri Lankan watersheds are gauged. Hence, there is a significant challenge when developing hydrological models. Therefore, this study focused on the assessment of the applicability of a conceptual model for the reproduction of daily streamflow of a watershed for water resources management applications. The conceptual Tank model of Sugawara [20]–[22] was selected for this study because of its simplicity, and successful application in several Sri Lankan watersheds and in many regional watersheds [12], [13], [23]–[25].

2. Study Area and Data

Study area is the Pitabeddara sub-watershed of Nilwala River basin in the Wet Zone of Sri Lanka. The Nilwala River basin, one of the largest river basins in Sri Lanka, receives rainfall from both South-West monsoon and North-East monsoon with an annual average rainfall around 4,000 mm. Nearly 40% of total annual rainfall reaches the sea draining over 1,073 km^2 of land area [26].

In the sub-watershed at Pitabeddara river gauging station has a drainage area of 291 km^2. A summary of watershed characteristics is shown in Table 1.

2.1 Data

In the current study, 10 years of daily rainfall data from 2008/09 to 2017/18 water years were collected at five gauging stations, namely, Aninkanda, Dampahala tea factory, Urawa Rotumba, Deranagala Hill and Hulandawa tea factory from Department of Meteorology (Figure 1). Daily pan evaporation data was collected at Kottawa station since it is the closest station with evaporation data and a pan coefficient of 0.8 was considered to determine evapotranspiration [22], [27], [28]. The streamflow data was collected from the Department of Irrigation.

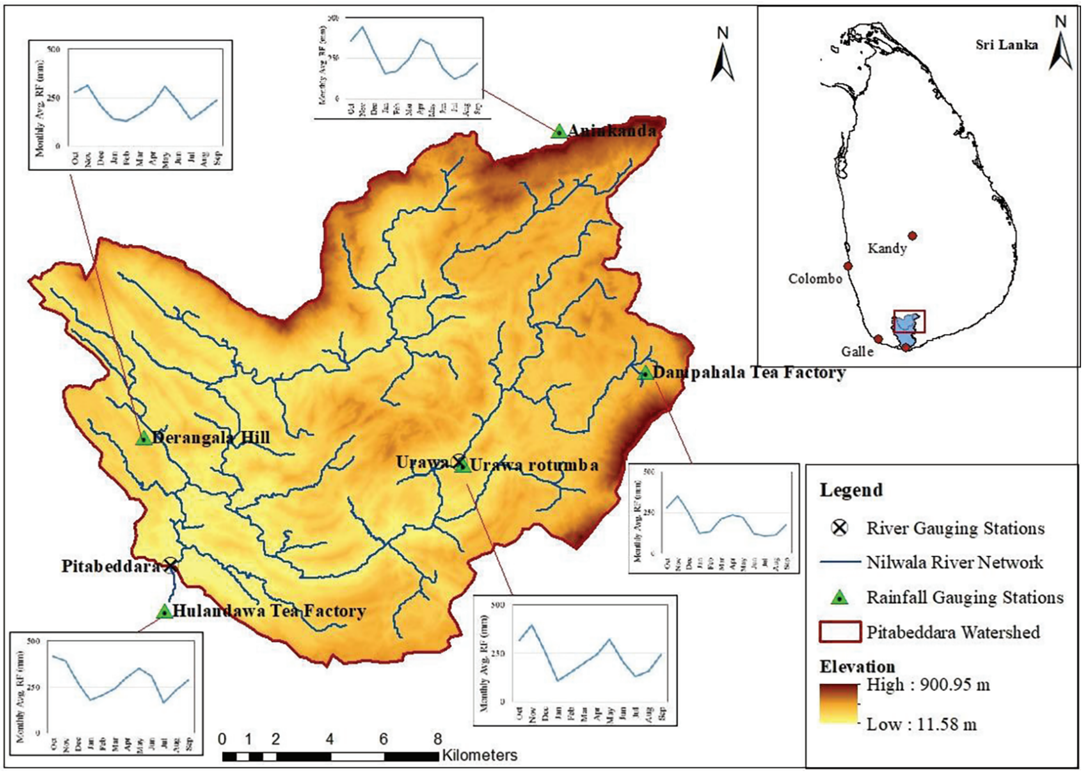

Figure 1 - Pitabeddara Watershed and nearby Rainfall Stations

The data were checked by computing annual water balance, plotting double mass curves and visual checking of streamflow hydrographs with Thiessen rainfall in order to identify any outliers and inconsistencies in the data series. The checks revealed that the dataset can be used for modelling.

Table 1 - Characteristics of the Study Watershed at Pitabeddara

General	
Drainage Area	291 km^2
Topography	Rolling (-11m to 901m)
Soil	Red-yellow podzollic
Land use	
Agriculture	29%
Forest	38%
Homestead	23%
Paddy	8%
Other	2%
Rainfall, Evaporation and Streamflow (2008/09 to 2017/18)	
Annual Avg. Thiessen Rainfall	3002.7 mm
Annual Avg. Evaporation	971.0 mm
Annual Avg. Streamflow	1878.7 mm
Annual Avg. Runoff Coefficient	0.62

3. Methodology

3.1 Tank Model

The Tank model is a conceptual rainfall-runoff model developed by Sugawara in 1961 [20], [28]. It consists of a series of storage tanks with outlets arranged vertically and horizontally to represent both vertical and lateral flows of water in the watershed [29]. Rainfall and evapotranspiration are the main inputs to the model.

Successive developments had been done to the original model by Sugawara in 1967, 1974, 1984 and 1995 for better estimation of runoff from rainfall. In order to achieve better predictions from the model, the number of storage tanks can be varied based on land-use of the area and purpose of modelling [30]–[32]. A Tank model with four linear storage tanks as shown in Figure 2, which is common and recommended for daily flow simulation, was used to model the selected watershed.

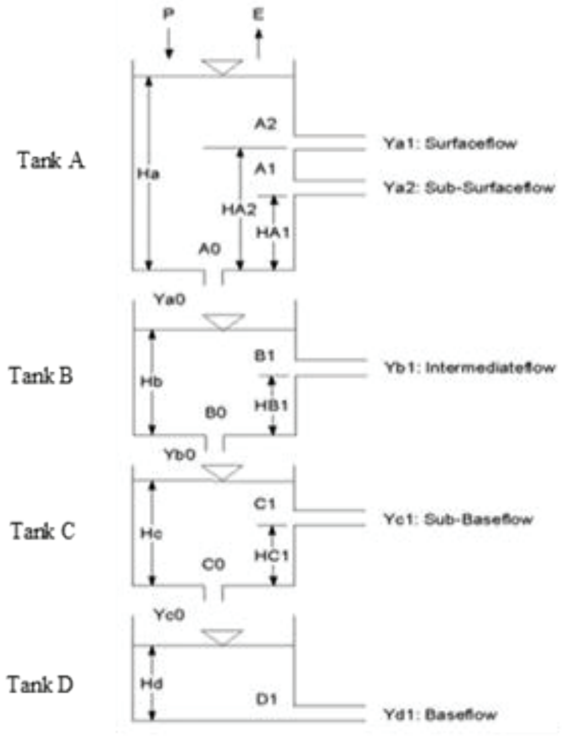

Figure 2 - Simple Tank Model Structure

A0, A1, A2, B0, B1, C0, C1, and *D1* (See Figure 2) are side and bottom outlet coefficients of storage tanks, which enable control of runoff and infiltration. HA1, HA2, HB1 and HC1 are heights of outlets from the bottom of respective storages [12], [21], [28]. Ha, Hb, Hc and Hd represent moisture levels of each tank at each time step. The model considers the storage, available moisture and external inputs to each tank moisture loss from evaporation and drainage through tank openings, for its computations using continuity equations.

Based on the water balance or the mass balance theory as in (Eq. 1), output from side outlets of each tank were determined and, the total output volume from all side outlets was computed as the total runoff from the watershed.

$$\frac{dH}{dt} = P(t) - ET(t) - Y(t) \qquad \text{... (1)}$$

where, H is storage of tank (mm), $P(t)$ is daily rainfall (mm/day), $ET(t)$ is daily evapo-transpiration (mm/day) and $Y(t)$ is daily outflow (mm/day).

3.2 Model Development

This study used the Microsoft Excel spreadsheet, its functionalities and optimisation tools, to develop the daily hydrologic model based on the Tank model. In order to eliminate any error propagation due to unstable initial conditions in the model because of the soil moisture in the four tanks, the model requires a warm-up session [33], [34]. Accordingly, the model was warmed up using a five water year cycle, which enabled achieving stable initial soil moisture levels for continuous streamflow estimation. Available literature related to tank model development in Sri Lanka and in the region along with the guidance given by Sugawara (1984) [20] were used to select the initial model parameters.

3.3 Model Calibration and Validation

The Tank model developed for Pitabeddara watershed was calibrated for five water years from 2008/09 to 2012/13 and then validated by using the remaining five water year data from 2013/14 to 2017/18.

3.3.1 Parameter Optimization

Optimization algorithms enable the most acceptable matching of estimated and observed hydrographs [35]. The model developed in MS Excel software, incorporated the inbuilt GRG non-linear optimization algorithm in Solver Add-in for model parameter optimization.

A semi-automatic calibration was followed during parameter optimization where the parameter values obtained for minimum value in objective function through the Solver tool were adjusted further by a manual trial and error procedure which considered the order of magnitude of parameters, matching of hydrograph features and the stability of soil moisture in each tank.

3.3.2 Model Performance Evaluation

The goodness of fit in model predictions was quantitatively evaluated using Mean Ratio of Absolute Error (MRAE) as the objective function [24], [36], [37]. MRAE is defined as,

$$MRAE = \frac{1}{N}\sum_{i=1}^{N}\frac{|Q_C - Q_O|}{Q_O} \quad \ldots. (2)$$

where N is the number of observations in the data series, Q_O is the observed streamflow and Q_C is the calculated streamflow from the model.

Phien & Pradhan (1983) [28] recommend that the matching of annual discharge and hydrograph shall be checked during optimization of parameters in Tank model. Matching of flow duration curves is considered as important because flow duration curve assists in the identification of the capability of a model to reproduce the frequency of measured flows [38]. Therefore, in addition to the comparison of daily streamflow using the objective function, the performance of the

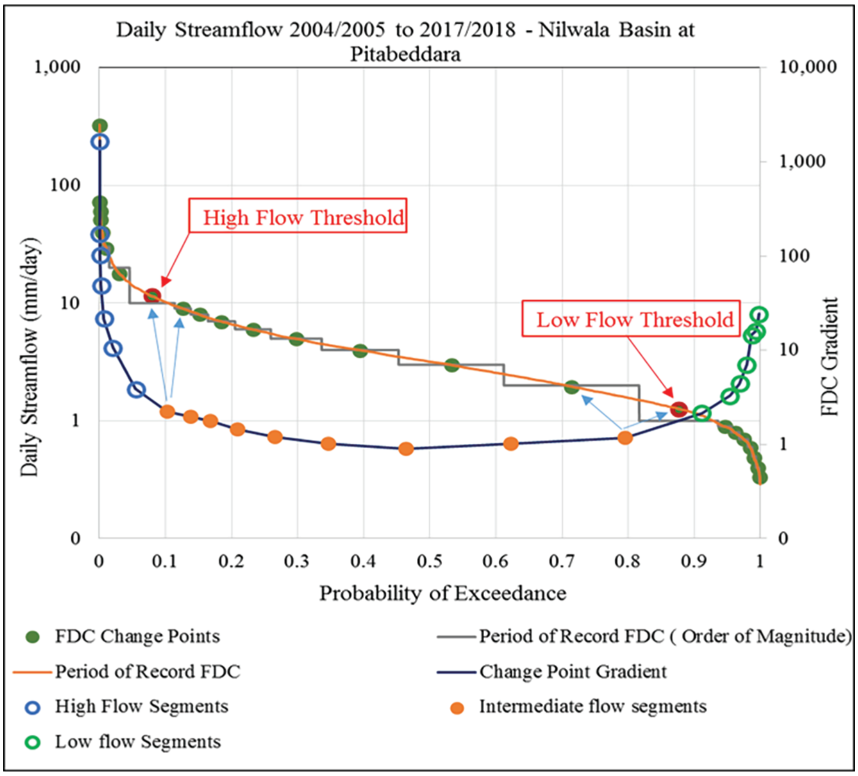

Figure 3 – Streamflow Threshold Determination (Pitabeddara Watershed)

model was evaluated graphically and numerically by observing annual water balance error, and matching of high, intermediate, and low flows in the flow duration curve.

3.4 Flow Classification

In order to compare the matching of each flow regime in the model estimations, identification of high, medium and low flow thresholds of the watershed runoff is vital. Wijesekera (2020) [39] described a methodology to scientifically and rationally identify the flow thresholds specific to a set of streamflow estimations pertaining to a particular watershed. The method considers change in the gradient of flow duration curve and captures the streamflow thresholds, which enable identification of the Probability of Exceedance (PoE) corresponding to high flow (HF), Intermediate flow (IF) and low flow (LF) regions. Figure 3 illustrates the flow classification of Pitabeddara watershed based on Wijesekeara (2020) [39] methodology. Accordingly, 8% and 87%, which are the respective PoE values of high and low flow thresholds, depict the streamflow regime of Pitabeddara watershed.

4. Results

4.1 Model Performance

Performance of the developed Tank model during calibration and validation periods are given in Table 2. The optimized parameters of Tank model for the Pitabeddara watershed are shown in Table 5.

Table 2 - Model Performance during Calibration & Validation

Evaluation Indicator		Calibration Period	Validation Period
MRAE	Overall	0.31	0.43
	HF	0.34	0.35
	IF	0.29	0.43
	LF	0.36	0.53

Overall matching of observed and calculated streamflow during calibration and validation periods are excellent with highly acceptable MRAE values. The MRAE values in Table 2 for each flow regime also demonstrate very good matching in high, intermediate and low flow regimes during both calibration and validation periods.

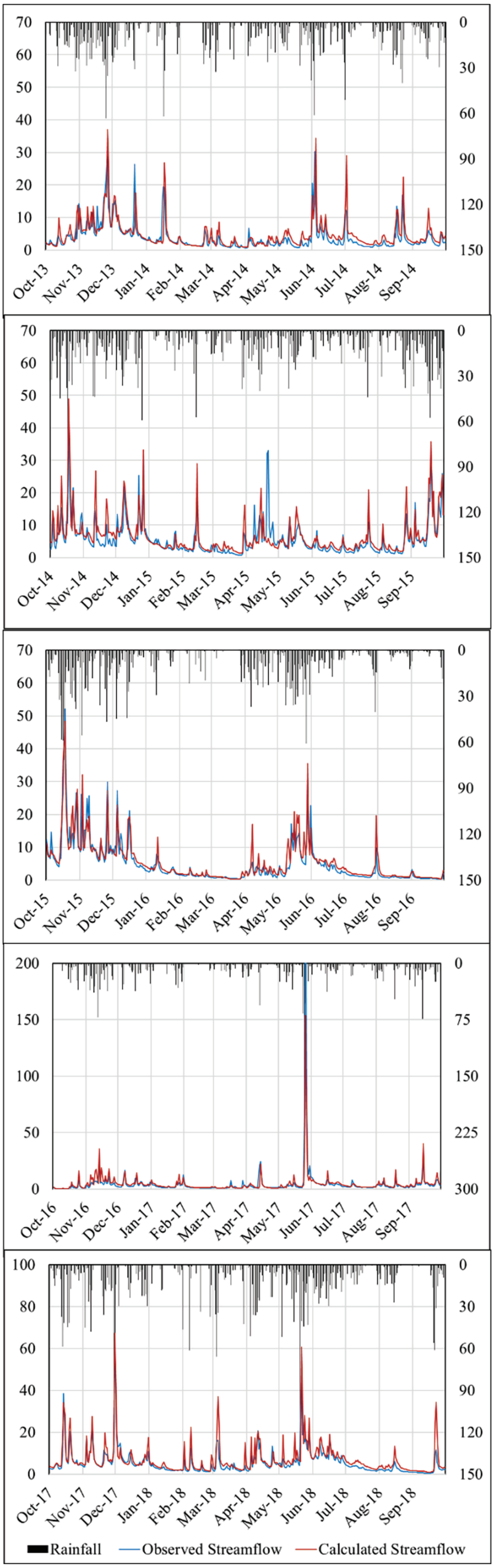

Figure 4 - Comparison of Observed and Calculated Streamflow (Model Calibration)

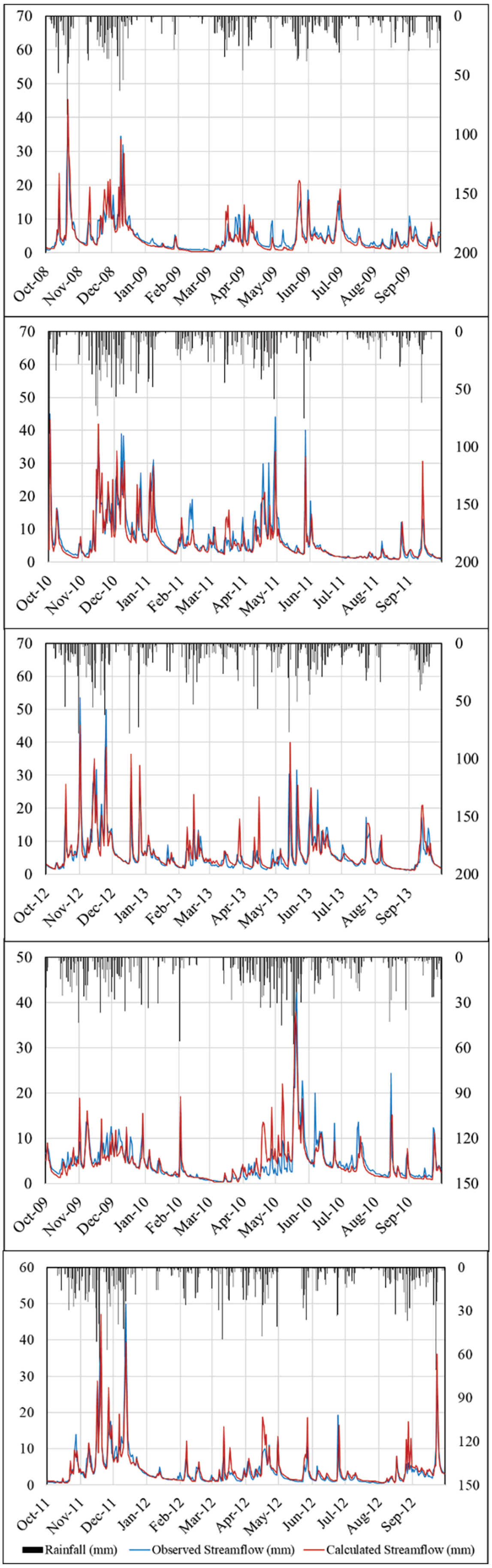

Figure 5 - Comparison of Observed and Calculated Streamflow (Model Validation)

Comparison of calibration and validation hydrographs are shown in Figure 4 & Figure 5, respectively. Annual water balance comparison during model calibration and validation are given in Table 3 & Table 4.

During calibration, the model reflected a minor underestimation of streamflow values. The annual average water balance error was -6.7%. In case of validation, the model overestimated streamflow to an annual average water balance error that reflected the overestimation as 23%.

The comparison of flow duration curves is shown in Figure 6 and Figure 7. Matching of high and intermediate flows during calibration and validation is very good but low flow estimation by the model during validation was relatively poor.

Table 3 - Comparison of Annual Water Balance during Model Calibration

Water Year	Rainfall (mm)	Evapotranspiration (mm)	Observed Streamflow (mm)	Calculated Streamflow (mm)	Observed Water Balance	Calculated Water Balance
2008/09	2750	897	1818	1615	933	1135
2009/10	2654	824	1706	1639	948	1015
2010/11	3367	852	2534	2289	832	1078
2011/12	2692	832	1461	1578	1231	1113
2012/13	3357	798	2268	2328	1089	1030
Average	**2964**	**841**	**1957**	**1890**	**1007**	**1074**

Table 4 - Comparison of Annual Water Balance during Model Validation

Water Year	Rainfall (mm)	Evapotranspiration (mm)	Observed Streamflow (mm)	Calculated Streamflow (mm)	Observed Water Balance	Calculated Water Balance
2013/14	2776	775	1421	1722	1355	1054
2014/15	3454	653	2095	2392	1359	1062
2015/16	2718	707	1803	2013	916	706
2016/17	2762	741	1646	1686	1115	1076
2017/18	3482	666	2017	2571	1465	911
Average	**3038**	**708**	**1796**	**2077**	**1242**	**962**

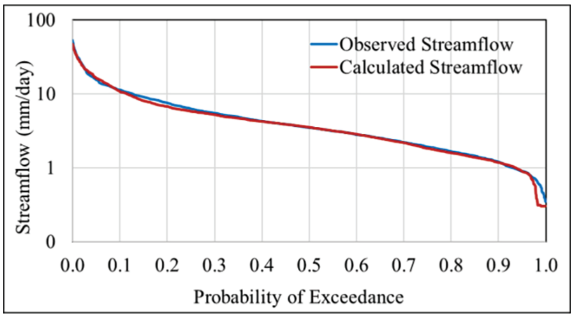

Figure 6 - Flow Duration Curves during Model Calibration

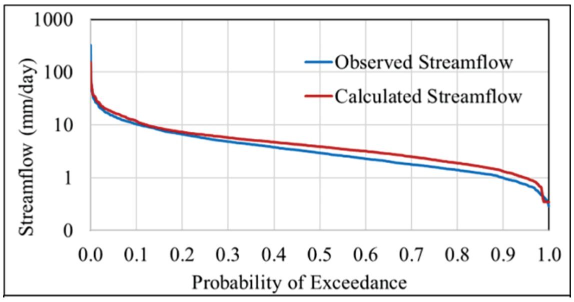

Figure 7 - Flow Duration Curves during Model Validation

Table 5 - Optimized Model Parameters

Parameter	Optimized Value
A0 (1/day)	0.2618
A1 (1/day)	0.1190
A2 (1/day)	0.4153
B0 (1/day)	0.03134
B1 (1/day)	0.0335
C0 (1/day)	0.00693
C1 (1/day)	0.0200
D1 (1/day)	0.000041
HA1 (mm)	3.10
HA2 (mm)	28.45
HB1 (mm)	42.62
HC1 (mm)	81.00

5. Discussion

5.1 Model Performance

The study considered several statistical and graphical indicators to evaluate the model performance. This enabled to capture most of the aspects of the hydrologic time series i.e. rising and recession limbs, and peaks, as emphasized by Kumarasamy & Belmont (2018) [17].

During model calibration, a good agreement between estimated streamflow values and observed values were observed according to flow hydrographs and flow duration curves where the MRAE value confirmed the same while the accuracy was approximately 70%.

According to Figure 6 and Figure 7, on average, 40% of high flows of the watershed had been underestimated by 20%. This hinted a non-perfect matching of peaks by the model which was stated by Phien & Pradhan (1983) [28]. Nepal et al. [40] have explained that underestimation of peaks might also occur due to underestimation of rainfall, failure of model concept in flood processes, the nonlinearity of watershed, and especially uncertainty in discharge rating curves during the high flows. Hence, these have to be further investigated prior to concluding on the model capability. The high flow prediction of the developed model was with an average accuracy of 66%.

A very good matching of intermediate flows were observed during calibration period with an average accuracy of 71%. However, during validation period, the intermediate flow predictions of the model were less accurate. The flow duration curve (Figure 5) and the hydrographs (Figure 7) highlighted overestimation of intermediate flows, providing the opportunity to better understand the streamflow behaviour.

On average, 60% of low flows in the watershed was overestimated by 20% or more (Figure 6 and Figure 7). This had led to slightly higher MRAE for low flows compared to other flow regions. Since the modelling was done as a lumped catchment, it was assumed that the heterogeneity of soils and land uses in the entire watershed could be lumped to a single set of parameters in a single vertical tank structure. However, as in Basri (2013) [30], such diversity has an impact on infiltration rates over the watershed. Since low flows are dominated by sub-base flows and base flows created from infiltrated water, lumping of heterogeneity would have caused the observed overestimation of low flows and this has to be further investigated.

Nevertheless, annual water balance comparisons (Table 3 and Table 4) indicate a great performance of the Tank model for the simulation period where the aggregated annual streamflow was predicted with an average accuracy of 90%.

In general, the model developed for Pitabeddara watershed enabled the prediction of high, intermediate and low flows of the watershed with acceptable level of accuracy. This confirmed that, though there is a lack of physical representativeness in a distributed manner, the lumped conceptual models are sufficient to predict watershed outflows which had also been stated by Xu and Singh (2006) [41].

5.2 Applicability for Water Resource Management

In the Sri Lankan context, monthly or seasonal water yield are vital for planning in water management. Thus, the model results were aggregated to monthly and seasonal scale to evaluate the performance of the model for reliable water resource planning and management applications.

The monthly flow comparisons are shown in Figure 8 and Figure 9.

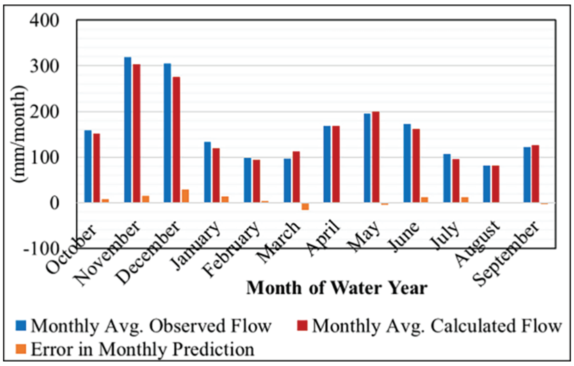

Figure 8 - Monthly Flow Comparison during Model Calibration

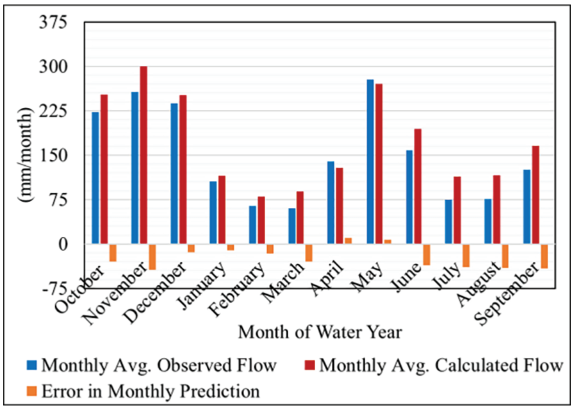

Figure 9 – Monthly Flow Comparison during Model Validation

Accordingly, monthly averaged predictions and observed flows were having a very high degree of matching during the calibration period in which the predictions were having accuracy more than 90% for all months except for March where the error was 16.7%.

As expected, the accuracy of monthly averaged predictions was with lesser accuracy during model validation. This was due to overestimation of daily streamflow, although the accuracy of monthly averaged predictions were more than 75% for 8 months. In March, July, August and September, the error values were around 50%. The monthly rainfall variation in the basin, during February – April and July – September, demonstrates a transition from dry to a wet season. As a result, soil moisture movement in these periods changes from unsaturated to saturated media flow. This creates a variation of behaviour when water starts moving through the soil mass which may not be well represented by an unchanged set of outlets and outlet parameters in the tank model. Such issues also lead to the differences in the estimation of streamflow during these transition periods. Such flows often belong to the low flow region.

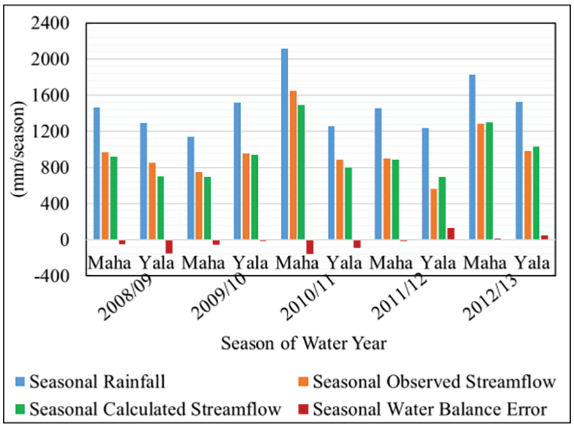

Figure 10 - Seasonal Flow Comparison during Model Calibration

The streamflow matching based on seasons indicated a higher accuracy (Figure 10 and Figure 11). However, the seasonal comparison showed that the streamflow estimations in three Yala seasons (2013/14, 2015/16 & 2017/18) during the simulation period had an accuracy less than 70%. Yala seasons are dominated by low flows and the model performance during such periods is not very accurate. Hence, the low value of accuracy.

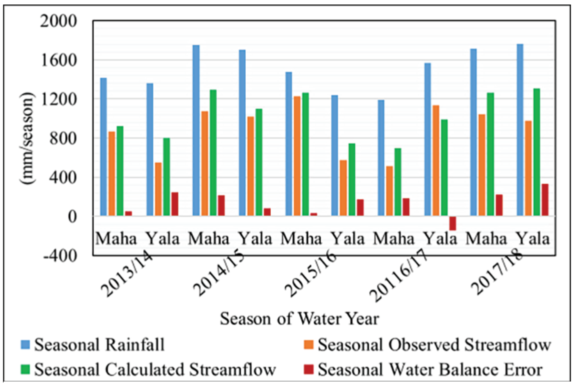

Figure 11 - Seasonal Flow Comparison during Model Validation

The water yield error during Maha and Yala seasons were approximately 9.6% and 16.7%, respectively. The monthly and seasonal scaled predictions also reflect that the developed Tank model can be used with a high level of confidence for sustainable water resource management.

6. Conclusions

Major conclusions of the present study are as follows:

1. Conceptual lumped Tank model was calibrated and validated with a MRAE value of 0.31 during calibration while the same was 0.43 during validation.
2. Monthly scaled streamflow from 2008/09 to 2017/18 water years in the Pitabeddara watershed can be estimated up to an average accuracy of 78%, and average error in water quantity was 6% per month.
3. The daily simulation of the Tank model during 2008/09 to 2017/18 water years demonstrated the best matching in the intermediate flow regime with an accuracy range between 57% to 71%.
4. Higher accuracy in the estimation of streamflow in daily, monthly and seasonal time scales achieved with the developed model confirmed that a lumped Tank model can be satisfactorily utilized for water resources management in the Pitabeddara watershed and other similar watersheds.
5. The flow duration curve separation carried out in this study enabled the identification of watershed thresholds of high and low flows 8%and 87% probability of exceedance values, respectively.

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