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A Critical Evaluation of Streamflow Estimation of an Ungauged Watershed using a Gauged Watershed of Same River Basin – Case of Nilwala River Basin

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Abstract: Transferring hydrological model parameters of a nearby gauged watershed to an ungauged watershed is being widely practiced to predict streamflow in the ungauged watershed. However, proper conclusions on transferring data from the main to sub-watershed and vice versa need to be established, then only watershed managers can plan where to locate or ensure optimum use of resources when establishing gauging stations. Therefore, the present study aimed to evaluate the performance of spatial transferability by using the Tank Model, which was initially calibrated to daily streamflow from water year 2008/09 to 2017/18 observed at two gauged watersheds in Nilwala River Basin, and then transferred from main to sub-watershed and vice versa. The efficiency of predictions under two parameter transferability scenarios was highly acceptable where the Mean Ratio of Absolute Error (MRAE) values were 0.35-0.39 and, the accuracy of annual water balance was 91.8%-93.3%. Most importantly, the best results were in the intermediate flow regime with an accuracy of 61%-70%. The monthly-scaled streamflow indicated an accuracy of 83%-92%. The present study demonstrated the liability of the Tank Model for successful estimation of daily streamflow with an average accuracy of 63% under spatial parameter transferability thereby with only a single well-managed streamflow gauging station, Tank Model can be applied for sustainable water resources management in similar ungauged watersheds of the basin.

Keywords: Parameter transferability, Tank model, Ungauged catchment, Water resources management, Daily data

1. Introduction

Water is one of the cornerstones of human and environmental persistence. However, fresh and safe water resources are being progressively depleted due to high exploitation and pollution with the expansion of industries and population growth which discharge tonnes of toxic elements, chemicals, and other emerging contaminants to water bodies [1], [2]. Therefore, sustainable water resources management practices are necessarily required for the persistence of humans and the environment where continuous series of data on the quantity and quality of water resources would be fundamental for developing management strategies [3]–[5].

Since the installation and maintenance of streamflow gauging stations are costly, locating a gauge in each point of interest for developing continuous data series is not worthwhile. Thus, the availability of streamflow data, both spatially and temporally, is limited.

Therefore, the hydrological models are widely used as a tool to quantify the streamflow in watersheds and to develop important information during decision-making for managing water [5]–[7]. These hydrological models have a number of parameters that are to be calibrated based on observed data until model predictions satisfactorily match the catchment's response. In poorly gauged or ungauged watersheds, the use of hydrologic models to understand the hydrologic regime is limited and difficult due to lack of observed time series data for calibrating the model [7]–[10]. In that context, parameter transferability is one of the commonly used methods in predicting the hydrologic regime of ungauged watersheds. This approach uses calibrated hydrologic model parameters of a gauged watershed to develop a hydrologic model for an ungauged watershed in the same homogeneous region and subsequently predicts its streamflow time series [8], [11]–[13].

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There is a wide range of transferability techniques developed by researchers, and numerous studies have been carried out globally for a large number of watersheds with different climatic and topographic characteristics to evaluate their applicability, especially after the initiative of Predictions in Ungauged Basins (PUB) in 2003 [7], [13], [14]. Comprehensive reviews on the different methods of parameter transferability have been done by Guo et al. (2020) [4], He et al. (2011) [11], Parajka et al. (2013) [15] and Razavi & Coulibaly (2013) [16]. Accordingly, similarity–based approach, regression-based approach, and spatial proximity approach were widely used by the researchers in transferring of model parameters. Although, there is no well-established approach to follow during parameter transferability and it needs site-specific evaluation. This might be due to the variability of climate, and heterogeneity of physical characteristics of watershed [7], [13], [14], [16].

In Sri Lanka, most of the rivers and tributaries are ungauged or with limited reliable data because of the financial limitations in installing and managing gauging stations incorporating the latest technologies [4], [6]. However, it is vital to have an understanding of the hydrologic regime of the watersheds for both water resources planning & management, and development. Therefore, watershed managers need to be more careful in planning where to locate or to ensure the optimum use of resources when establishing gauging stations. In that context, the performance of parameter transferability approaches in main-to-sub watershed and vice versa will be beneficial for making decisions on the requirement of gauging stations and their locations in a river basin in order to gather data and develop hydrologic models.

However, only a limited number of studies were done on this resolution in Sri Lanka, especially towards concluding the best approach for transferring data from main-to-sub watershed and vice versa. Thus, this study aims to critically evaluate the accuracy of daily streamflow predictions of a hydrologic model with spatial transferred parameters.

When predicting streamflow in ungauged watersheds, conceptual models are preferred over physical-based models by the researchers/hydrologists. The conceptual models are equally reliable for predicting streamflow with minimum input data and less computational effort with compared to physical-based hydrologic models. Further, the conceptual models have simple structure to represent hydrologic processes of watershed. On the other hand, physical based models require more input data and human effort for modelling a watershed which constrain their application for watersheds with no or limited data [14], [16]. Therefore, one of the best-performing conceptual models, lumped Tank Model, was used as a mathematical model in this study by considering its simple structure and performance in similar applications in different climatic conditions in many countries such as Japan, Korea, Iran, Germany, and Sri Lanka [5], [6], [8], [17].

2. Materials and Methods

2.1 Study Area

The study has focused on two sub-watersheds of Nilwala River Basin in Wet Zone of Sri Lanka. The Nilwala River originates at Paninkanda and traverses about 70 km covering a catchment area of 1,073 km^2 prior to falling into the sea at Matara. The Nilwala River Basin has an annual average rainfall of around 3,040 mm received from both South-West and North-East monsoons. Nearly 40% of total annual rainfall is drained to the sea annually [18], [19].

The concerned sub-watersheds are the catchment at Pitabeddara (291 km^2) and the catchment at Urawa (52 km^2) with an area ratio of 5.6:1 between them. Urawa is a sub-watershed of Pitabeddara main watershed as shown in Figure 1. A summary of characteristics for the concerned watersheds is shown in Table 1.

Table 1 – Characteristics of the Study Area

	Pitabeddara	**Urawa**
Area (km^2)	291	52
Elevation (MASL)		
Maximum (m)	901	789
Minimum (m)	11	145
Land cover (%)		
Agriculture	29	24
Forest	38	22
Homestead	23	41
Paddy	8	11
Other	2	2
Dominant Soil	Red- Yellow Podzolic	
Precipitation and Runoff (2008/09 to 2017/18)		
Annual Avg. Thiessen Rainfall (mm)	3002.7	2480.9
Annual Avg. Streamflow (mm)	1878.7	1419.8
Annual Avg. Runoff Coefficient	0.62	0.57

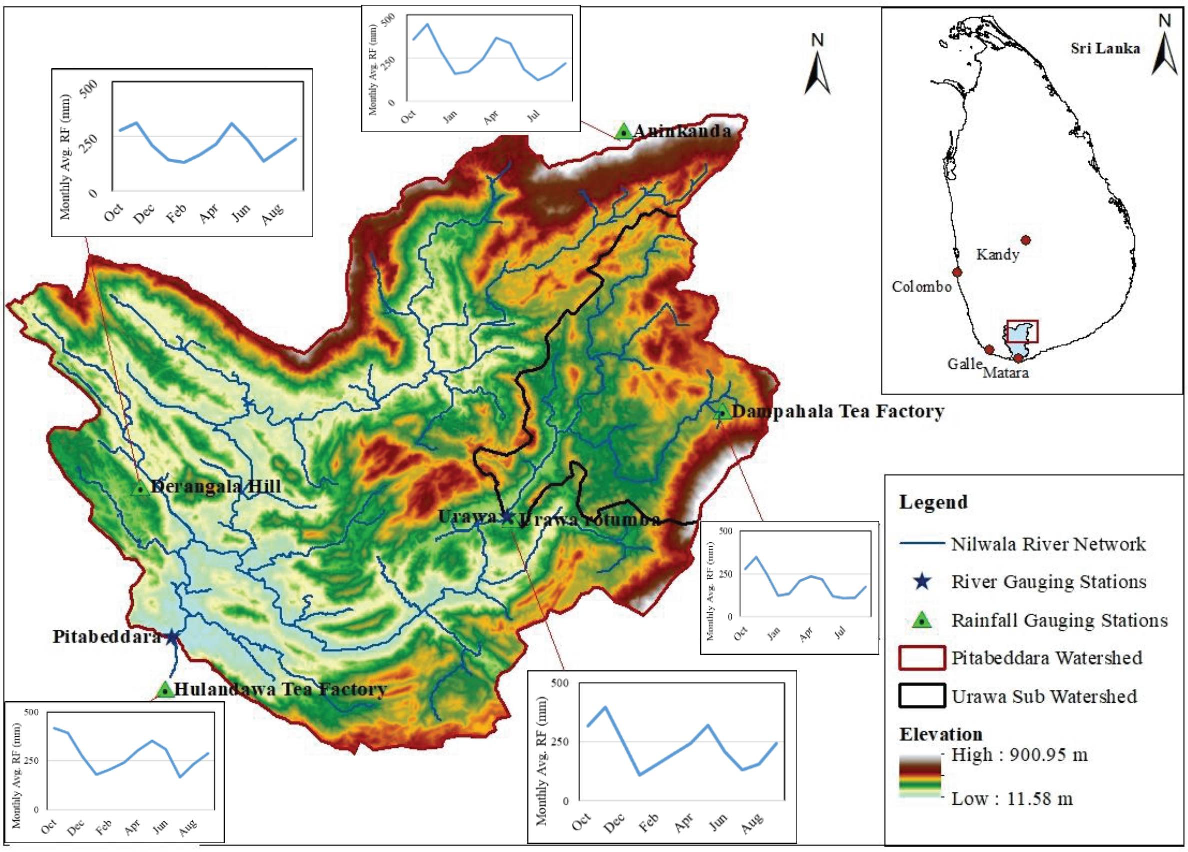

Figure 1 - Study Area

2.2 Data

A representative dataset with a sufficiently long period should be used for accurate estimation of catchment responses [6]. Therefore, by referring to past studies, we have used 10 years length of observed daily streamflow data from the water year 2008 to 2018 (i.e. 1st October 2008 to 30th September 2018), obtained from the Department of Irrigation, Sri Lanka. Daily rainfall data at five gauging stations and daily pan evaporation data at one gauging station were also collected for the same 10-year period from the Department of Meteorology, Sri Lanka. The areal average rainfall was determined by using the Thiessen polygon method.

In order to verify the homogeneity and consistency of the data, the datasets were comprehensively investigated by visual examination, computing annual water balance, and plotting double mass curves for streamflow and Thiessen rainfall. These investigations confirmed that the datasets are consistent and, with minor errors have an insignificant impact on the accuracy of model predictions.

2.3 Tank Model

The Tank Model is a conceptual rainfall-runoff model that simply estimates the runoff of a watershed from rainfall and evapotranspiration based on the Water Balance theory [20], [21]. Originally, the concept was developed by Sugawara for hydrological modelling of watersheds in Japan, in which, a series of storage tanks with side and bottom outlets were laid to represent the lateral and vertical flow of water in the surface and underground of the watershed [6], [21], [22], respectively.

Numerous studies have been carried out over the past years for different configurations in model structure with a varied number of storage tanks between one to five, and for data in different temporal scales, in order to assess the applicability and to improve the concept of Tank Model [8], [20], [22]–[30].

A typical Tank Model with four linear storage structures which was used in this study is schematically shown in Figure 2. The model is capable of illustrating surface runoff, intermediate runoff, sub-base runoff, and base flow by the water flowing through side outlets of the first tank (Tank A), second tank, third tank, and bottom tank (Tank D), respectively [23], [24]. Infiltration and percolation processes are demonstrated by flow through the bottom outlets of tanks [8].

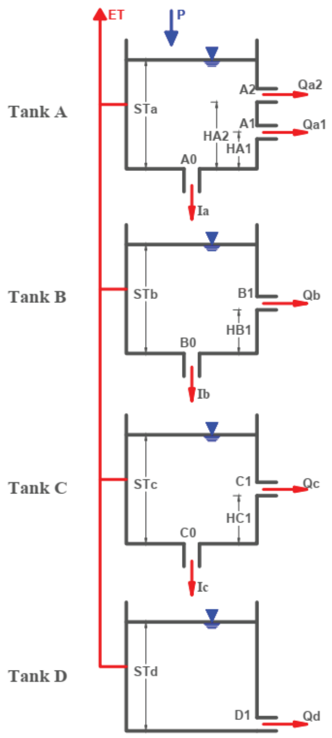

Figure 2 - Tank Model Structure

A0, A1, A2, B0, B1, C0, C1, and *D1* are side and bottom outlet coefficients of each tank that control the discharge through the outlet, and*HA1, HA2, HB1,* and *HC1* are heights of side outlets in each tank where these twelve parameters should be calibrated according to observed streamflow. STa, STb, STc & STd represent the moisture level of a tank at each time step.

The total runoff of the watershed is determined as a summation of discharge amounts from each side outlet of four tanks as follows where it is assumed that the amount of discharge through an outlet (runoff or infiltration) is linearly proportionate to the storage of the respective tank (Equations (1) and (2)) [21], [24].

$$Q_t = Q_{a1} + Q_{a2} + Q_b + Q_c + Q_d$$

$$Q_t = \sum_{i}^{a-d} \sum_{j}^{1,2} a_{ij} \times \left(ST_{i,t} - H_{ij}\right) \quad \dots (1)$$

$$I_i = ST_{i,t} \times b_i \quad \dots (2)$$

where Q_t is the total runoff of the watershed (mm), *i* is the tank order, *j* is the side outlet number, a_{ij} is the side outlet coefficient, $ST_{i,t}$ is the storage of *i*th tank at a time (mm), H_{ij} is the height of the side outlet in *i*th tank (mm), I_i is the amount of infiltration in *i*th tank (mm), and b_i is the bottom outlet coefficient in *i*th tank.

According to Water Balance Theory, the storage of each tank at each time step can be determined as follows.

$$\frac{d\,ST}{dt} = P_{i,t} - ET_{i,t} - I_{i,t} - Q_{i,t} \quad \dots (3)$$

where $P_{i,t}$ is daily rainfall (mm), $ET_{i,t}$ is daily evapotranspiration (mm). Based on the model concept, Tank Models for two watersheds were developed using a Microsoft Excel (MS Excel) spreadsheet.

2.4 Model Calibration and Validation

Prior to the calibration of parameters, models were warmed up using a five-water-year cycle in order to avoid any errors relevant to the initial conditions of the model parameters and to achieve a stable initial soil moisture level in each tank [31], [32]. The initial values for other model parameters were selected by referring to the guidance provided by Sugawara (1984) [20] and available literature relevant to Tank Model development in Sri Lankan watersheds.

The Tank Models were calibrated for five water years from 2008/09 to 2012/13 using a combination of automatic and manual (trial and error) approaches. First, in the automatic calibration approach, instructions and constraints were given to Solver Add-in in MS Excel for finding a combination of parameter values, which provide minimum or maximum value for the objective function. Secondly, in manual calibration approach, the parameter values were slightly adjusted by observing the matching of hydrograph. The models were validated for the following five water years from 2013/14 to 2017/18 for concerned catchments.

2.4.1 Objective Function

The selection of an objective function to evaluate the goodness-of-fit of model predictions is dependent on the purpose of the modelling and the time scale of the modelling. As this study aims to evaluate the accuracy of predicting the overall flow regime, scale-independent measures are more suitable. Measures based on relative error are one of the popular types of scale-independent measures [32], [33]. The Mean Ratio of Absolute Error (MRAE) is an indicator that measures the estimation error of each data point along the time series relative to each observation [26], [34], [35]. Thus, the objective function defined as in Equation (4) was used in this study.

$$MRAE = \frac{1}{N}\sum_{i=1}^{N} \frac{|Q_C - Q_O|}{Q_O} \quad \dots (4)$$

where Qo and Qc are observed and simulated streamflow at a time and N is the number of observations in the data set. The optimum value of MRAE is zero.

2.4.2 Parameter Optimization Algorithm

Achieving the global optimum set of parameters is vital for accurate predictions. In that context, the optimization algorithm enables to surf through the response surface to find the parameter values where the objective function is at its global minimum or maximum [36], [37]. Since, in this study, the model was developed in MS Excel software, the inbuilt GRG non-linear optimization algorithm in Solver Add-in was utilized for parameter optimization.

2.4.3 Model Performance Evaluation

The models were evaluated based on both quantitative and qualitative measures. MRAE was used as a quantitative evaluation indicator. Matching of annual water balance (AWB), total hydrograph and, high (HF), intermediate (IF), and low flows (LF) in the flow duration curve (FDC) were also performed as cross-validation of the results [40]. Matching the flow duration curve allows for verifying that the model is capable of reproducing the frequency of observed flows [22], [41]. Comparison of AWB allows to confirm that the model has interpreted the annual water cycle correctly. Annual water balance and error percentage in AWB were determined according to the following (Equations (5) and (6)):

$$\text{Annual Water Balance (mm)} = \text{Annual Thiessen Rainfall (mm)} - \text{Annual Streamflow (mm)} \quad \ldots(5)$$

$$\text{Error \% in AWB} = \frac{\text{AWB Observed (mm)} - \text{AWB Simulated (mm)}}{\text{AWB Observed (mm)}} \times 100\% \quad \ldots(6)$$

2.5 Transferability of Model Parameters

Many researchers have used the Tank Model to estimate the streamflow of ungauged watersheds in Japan, Korea, Germany, and Iran [5], [8], [9], [12], [38], [39] (Table 2) where transferability of model parameters were mostly based on regression approach, i.e., a relationship between model parameters and characteristics of the watershed [8], [42].

However, based on the studies on streamflow predictions in ungauged watersheds, Razavi & Coulibaly (2013) [16] and Karki et al. (2023) [40] recommended, the spatial proximity approach over the regression-based approach for warm temperate climate areas to transfer model parameters.

In Sri Lankan context, accurate estimation of the physical characteristics of a watershed is challenging especially for an ungauged watershed thereby the application of the regression approach for parameter transferability will be difficult. Further, without a sufficient number of watershed characteristics, proper parameter transferability cannot be achieved under the regression approach [43]. Therefore, the present study considered a simple spatial transferability approach to predict streamflow in ungauged watersheds where all the calibrated parameters are directly transferred.

The rationale considered in the spatial transferability approach is that the donor and target watersheds that are located closely, are assumed to be hydrologically similar since the climate and physical characteristics are likely to vary smoothly within the closest watersheds [10], [44], [45]. In the spatial transferability approach, two options were considered;

i. *Option 1*:Transfer the calibrated parameter set of the sub-watershed (Urawa) to the main watershed (Pitabeddara) for simulating the water year 2008/09 – 2012/13 [sub-to-main]
ii. *Option 2*:Transfer the calibrated parameter set of the main watershed (Pitabeddara) to the sub-watershed (Urawa) for simulating the water years 2008/09 – 2012/13 [main-to-sub].

Table 2 - An Overview of Previous Studies on Parameter Transferability of Tank Model

Reference	Country	Model Structure	No. of watersheds	Basin Area (km²)	Regionalization Method
Yokoo et al. (2001)[9]	Japan	4-tank	12	100 - 805	1. Arithmetic mean approach 2. Regression-based approach
Kang, Lee, Park(2013) [38]	Korea	3-tank	4	2 - 2060	Regression-based approach
An et al. (2015) [39]	Korea	3-tank	15	59 - 6661	Regression-based approach
Amiri et al.(2016) [12]	Germany	4-tank	30	53 - 737	Multiple linear regression approach
Song et al. (2019) [8]	Korea	3-tank	49	3 - 2990	Multiple linear regression approach

3. Results

3.1 Hydrological Modelling for the Two Watersheds

Several calibration trials were conducted until the improvement in evaluation indicators were insignificant within two trials. Accordingly, the performance of the models for both watersheds during calibration and validation is given in Table 3.

The models for the main and sub-watersheds were well calibrated with MRAE values of 0.32 and 0.31, respectively. Both models performed satisfactorily during the validation period also as MRAE values were 0.48 and 0.54 for the main and sub-watershed, respectively.

Comparison of hydrographs during a typical year of calibration and validation periods are shown in Figure 3 and Figure 4 for main and sub watershed, respectively.

Table 3 - Model Performance in Calibration & Validation

Evaluation Indicator		Main watershed (Pitabeddara)		Sub-watershed (Urawa)	
		Calibration	Validation	Calibration	Validation
MRAE	Overall	0.32	0.48	0.31	0.54
Error in FDC (MRAE)	HF	0.07	0.21	0.03	0.14
	IF	0.04	0.29	0.05	0.26
	LF	0.13	0.56	0.05	0.62
	Overall	0.05	0.32	0.05	0.32
Ave. annual water balance error		6.6%	18.7%	7.0%	25.1%

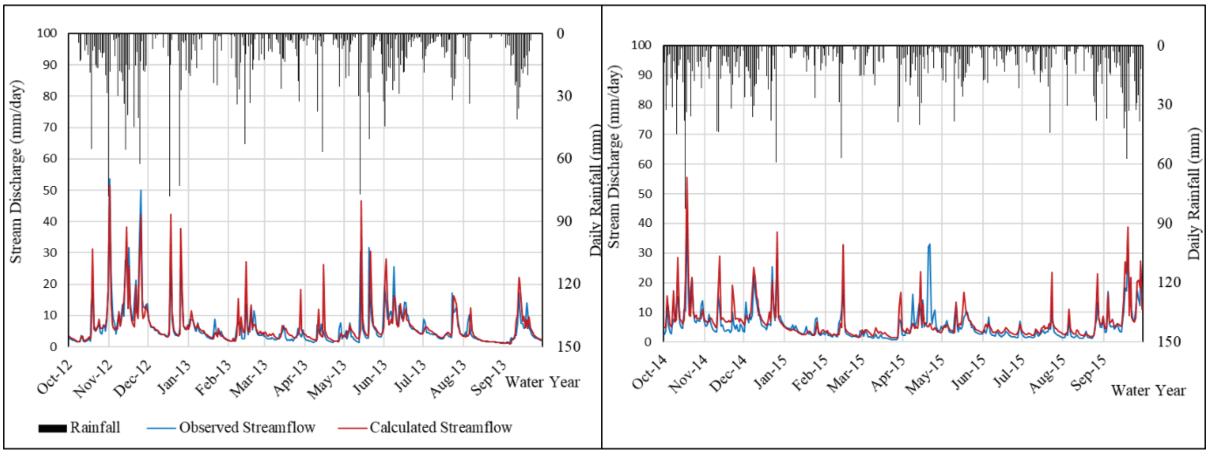

Figure 3 - Comparison of Observed and Calculated Streamflow of Pitabeddara Main-Watershed during Calibration (left) & Validation (right)

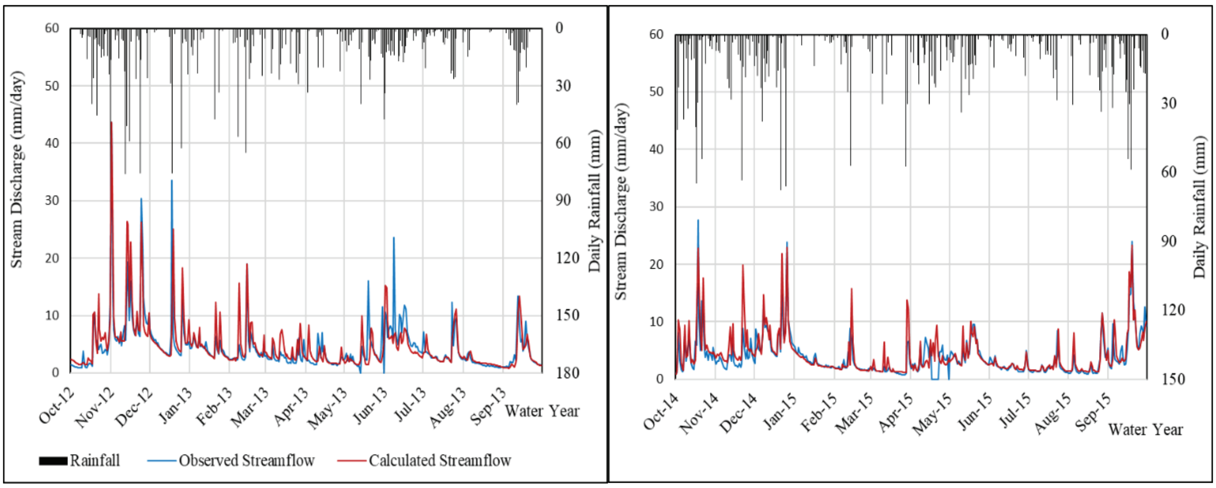

Figure 4 - Comparison of Observed and Calculated Streamflow of Urawa Sub-Watershed during Calibration (left) & Validation (right)

Overall flow, high flow and intermediate flow of both watersheds were predicted excellently by the models as indicated with highly acceptable MRAE values. Further, the accuracy in the annual average water balance was very high, with a value of 75% - 93% during both calibration and validation periods for both watersheds. The average water quantity error in annual water balance was 126.4mm/year and 96.7mm/year during calibration, and 338.4mm/year and 299.3mm/year during validation in Pitabeddara main-watershed and Urawa sub-watershed, respectively.

The comparison of flow duration curves as shown in Figure 5 and Figure 6 confirmed that both model predictions are having an almost similar frequency of occurrence as observed streamflow during the calibration period. Although during validation, a slightly higher estimation for the same frequency of occurrence was observed in both model predictions, the overall error in FDCs was 0.32 for both models.

Therefore, overall, both models were calibrated and validated to a satisfactory level. Accordingly, the optimized parameters of the Tank Model for both watersheds are outlined in Table 4.

3.2 Performance in Spatial Transferability Approach

The calibrated parameters for both watersheds were spatially transferred within the main and sub-watersheds, and goodness-of-fit of the model predictions was evaluated by referring to each evaluation indicator.

Table 5 shows the efficiency of the model predictions with transferred parameters for both watersheds. Good efficiency is observed in both models for overall flow with acceptable MRAE values of 0.35 and 0.39 for *Option 1* and *Option 2*, respectively. According to the values of MRAE, the model for the main watershed with spatially transferred parameters achieved better matching in high and intermediate flow regimes compared to the model predictions for the sub-watershed as illustrated in Table 5**.**

Table 4 - Optimized Model Parameter Values for Both Watersheds

Parameter	Optimized value for Urawa	Optimized value for Pitabeddara
A0 (1/day)	0.4009	0.2988
A1 (1/day)	0.0935	0.1060
A2 (1/day)	0.1736	0.5393
B0 (1/day)	0.0386	0.0334
B1 (1/day)	0.0288	0.0422
C0 (1/day)	0.0124	0.0123
C1 (1/day)	0.0181	0.0260
D1 (1/day)	0.000082	0.0001
HA1 (mm)	0.11	2.10
HA2 (mm)	13.57	28.45
HB1 (mm)	42.99	41.62
HC1 (mm)	33.00	81.00

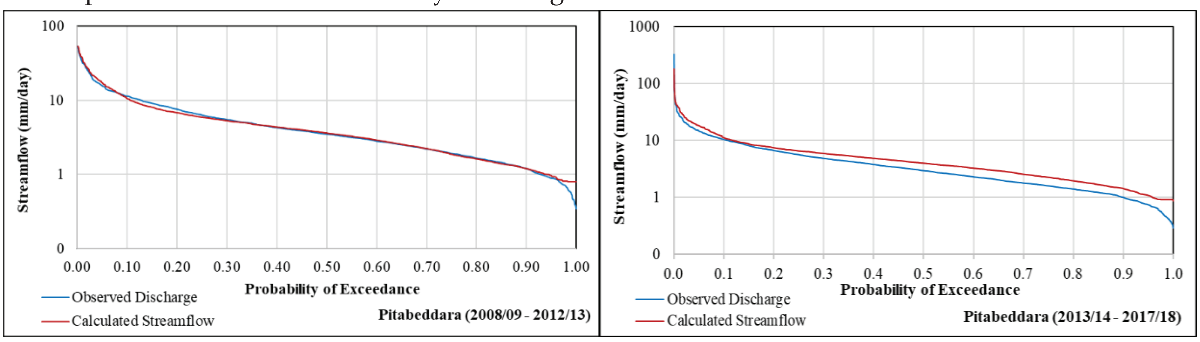

Figure 5 - FDC for Main-Watershed during calibration (left) & validation (right)

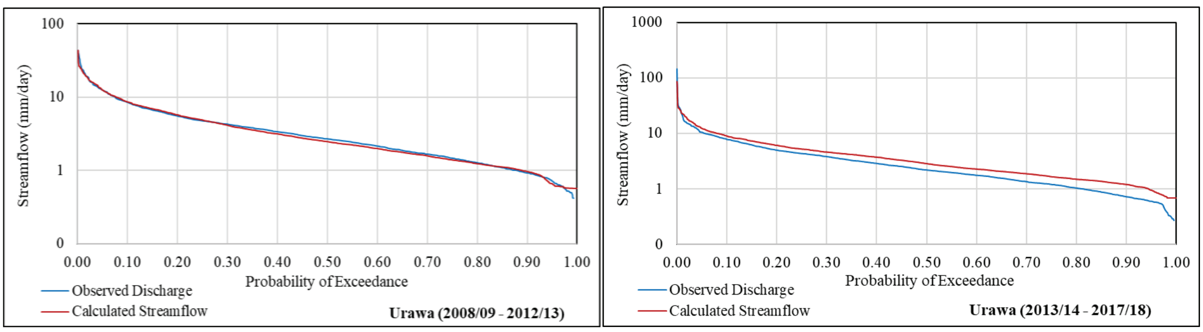

Figure 6 - FDC for sub-watershed during calibration (left) & validation (right)

Table 5 - Model Performance in Spatial Transferability Approach

Transferring Option	MRAE Value			
	All	HF	IF	LF
Option 1 [sub to main]	0.35	0.31	0.30	0.71
Option 2 [main to sub]	0.39	0.59	0.39	0.29

The comparison of hydrographs of observed and estimated streamflow in both transferability options demonstrated a good matching, but slight overestimation in the main watershed (under *Option 1)* and underestimation in the sub-watershed (under *Option 2)* during a few water years were also observed. The comparison of hydrographs in a typical year under each transferability option is shown in Figure 7.

The model with transferred parameters highly overestimated low flows in main watershed under *Option 1* as observed in Figure 7 resulting in a high MRAE value of 0.71. Though, most of the peaks in main watershed were underestimated as observed in Figure 7 and Figure 8, high flows had a good MRAE value of 0.31 under *Option 1*.

According to hydrograph comparison, in Urawa sub-watershed under *Option 2*, most of high peaks were satisfactorily quantified which confirmed in comparison of FDCs as in Figure 8 also, but there was slight shifting in time to peak, leading to a high MRAE of 0.59.

Comparison of annual water balance is shown in Table 6. Accordingly, error in annual water balance for predictions of *Option 2* was

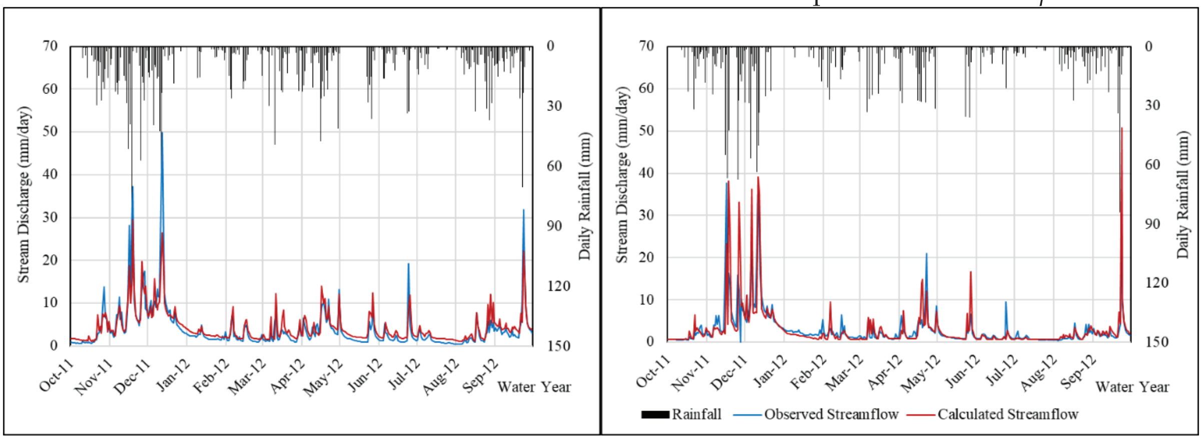

Figure 7 - Comparison of Observed and Calculated Streamflow of *Option* 1 (left) & *Option* 2 (Right) under Spatial Transferability Approach

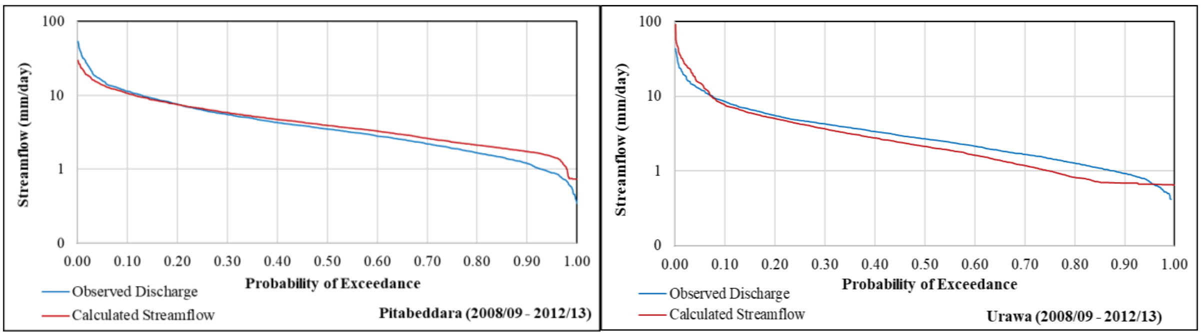

Figure 8 - Comparison of FDCs for 1(left) &*Option* 2(right) under Spatial Transferability Approach

Table 6 - Comparison of Annual Water Balance under Spatial transferability approach

Water year	Option 1 – Sub to Main				Option 2 – Main to Sub			
	Annual Rainfall (mm)	Annual Obs. Streamflow (mm)	Annual Cal. Streamflow (mm)	AWB Error	Annual Rainfall (mm)	Annual Obs. Streamflow (mm)	Annual Cal. Streamflow (mm)	AWB Error
2008/09	2750.4	1817.6	1671.0	8.1%	2525.3	1573.6	1483.3	5.7%
2009/10	2653.7	1705.6	1670.4	2.1%	1968.1	1283.8	1062.2	17.3%
2010/11	3366.8	2534.4	2248.7	11.3%	2942.1	1823.9	1934.8	6.1%
2011/12	2691.5	1460.6	1618.2	10.8%	2111.5	1070.1	1126.5	5.3%
2012/13	3357.4	2267.9	2295.1	1.2%	2715.1	1616.9	1728.3	6.9%
Average Annual Water Balance Error				**6.7%**				**8.2%**

5.3%- 6.9% in four years and 17.3% in the water year 2009/10, resulting in an average annual water balance error of 8.2% with a water quantity error ranges 56.4-221.6mm/year within the modelling period.

Similarly, in *Option 1* as shown in Table 6, the average annual water balance error was 6.7% where errors were within the range of 1.2%-11.3% during all five water years. Further, the water quantity error in the annual water balance under *Option 1* was 27.1-285.7mm/year during the water year 2008/09 to 2012/13.

4. Discussion

This paper has assessed the accuracy of spatial transferability of the Tank Model parameters for predictions in two watersheds within Nilwala River Basin in Sri Lanka. During the present study, the accuracy of model predictions under the parameter transferability was evaluated quantitatively and qualitatively while observing the matching of high, intermediate, and low flow regimes.

4.1 Model Development for Watersheds

According to the statistical and graphical evaluation indicators, the models for both watersheds performed well, both in calibration and validation periods, as a lumped model. During calibration, the models reproduce the observed streamflow of main and sub-watersheds with an accuracy of 68% and 69% respectively, as the MRAE values were 0.32 and 0.31, which are highly acceptable. This was confirmed during the comparison of FDCs as in Figure 5 and Figure 6, which showed almost similar frequency of occurrence between observed and predicted flows during calibration. Although, during validation, the accuracy of model predictions was slightly low with values of 52% and 46% for main and sub-watersheds respectively, due to high mismatching in low flow regime.

The matching of high flows was having a better accuracy where the accuracy of high flow predictions in the main watershed was 60% - 61% and, in the sub-watershed was 65% - 68% during model optimization. However, nearly 36% - 45% and 31% - 51% of high flows were underestimated in the main and sub-watershed, respectively, during the optimization period. Phien & Pradhan (1983) [22] also mentioned that the Tank Model is weak in matching high flows. Results of studies done by Gooarzi et al. (2021) [5] also showed less accuracy in matching high flows. However, further studies need to be done for proper conclusiveness.

Further, a good agreement in intermediate flow matching was observed during calibration and validation as the accuracy was 70% and 55% in the main watershed and 69% and 52% in the sub-watershed respectively, which was confirmed in the comparison of FDCs in Figure 5 and Figure 6 as the curves for observed and calculated flows were almost overlapping.

The accuracy of low flow matching during the validation period was 23% and 01% for the main-watershed and sub-watershed respectively as of the overestimation observed in FDCs of Figure 6 and Figure 5. According to the comparison of FDCs, nearly 92% and 85% of low flow events in the main and sub watersheds were overestimated by a margin of 20% or more during the validation period. Low flow in a watershed is governed by sub-base and base flows resulted from infiltration and percolation, which phenomena are controlled by the heterogeneity of soils and land use patterns of the watershed [30]. Since this study modelled the watersheds as lumped, which have different soil types & land use patterns as indicated in Table 1, infiltration/percolation rates within the model may differ from the actual condition causing overestimation in low flows in the models. Wickramarachchi & Wijesekera (2022) [6] also stated that Tank Model is not stable during the moisture transition from unsaturated to saturated conditions when low flows are generated. This might also lead to low agreement in low-flow matching.

Further Song et al. (2019) [8] stated that the model performance in each flow regime might have a significant impact from the selection of an objective function during model optimization. For an example, Krause et al. (2005) [46] mentioned that Nash-Sutcliffe Efficiency (NSE) is highly sensitive for high flows where minor mismatching in high flow may lead to a bad NSE value thereby NSE is more suitable for evaluating high flows. Further they have stated that the Coefficient of Determination (squared value of Coefficient of Correlation) provide very good value for unsatisfactory predictions. In that context, combining several statistics or using multi-objective functions may lead to balanced model evaluation [8], [14], [47]. Therefore, additional studies should be done for further improvements of the study to predict the high and low flows more accurately.

However, since the accuracy of annual water balance is 75%- 93% during model optimization for both watersheds as indicated in Table 3, it can be confirmed that the models for both watersheds are capable of interpreting the annual water cycle satisfactorily.

Therefore, overall model performance confirmed that the four storage Tank Model is capable of forecasting the daily streamflow of the concerned watershed with highly acceptable accuracy and the model parameters are temporally stable. As mentioned by Abraham et al. (2022) [43], such stability in parameters establishes a strong argument for extrapolating the parameters spatially.

4.2 Performance in Spatial Transferability Approach

4.2.1 Model Performance during *Option 2: Main*-to-Sub Parameter Transferability

The model for the sub-watershed with spatially transferred parameters of the main watershed has predicted the daily-observed flow with an accuracy of 61%, which is highly acceptable. The accuracy of intermediate and low flow matching were 61% and 71%, respectively. However, the accuracy of high flow estimation was low with a value of 41% as nearly 50% of high flow values were underestimated by a 20% or more margin.

In the Tank Model, high flows are generally dominated by the outlet coefficients in the top tank (A1 & A2) and heights to those outlets (HA1 & HA2) [20], [24] where significant differences were observed in calibrated values of these parameters in the two watersheds according to Table 4. Accordingly, the transferred outlet coefficient values (A1 & A2) are higher than the calibrated parameter values of the sub-watershed (refer to Table 4) which predicted the high flows with an accuracy of 66%. Similarly, the transferred values of height to outlets (HA1 & HA2) of the top tank were having very high values compared to calibrated values for the sub-watershed where they limit the generation of runoff from the top tank resulting in an underestimation of high flows in the sub-watershed. However, overall, aggregated annual streamflow of the Urawa sub-watershed was having an average accuracy of 91.8%with an error in the quantity of 118.1mm/year confirming the model's ability to interpret the annual water cycle of the watershed.

4.2.2 Model Performance during *Option 1:* Sub-to-Main Parameter Transferability

Daily observed streamflow of the main watershed from 2008/09 to 2012/13 had been reproduced under *Option 1* with an accuracy of 65%. Conversely, high and intermediate flows of the main watershed were predicted satisfactorily with accuracy levels of 69% and 70% respectively by the model with transferred parameters. However, according to the comparison of hydrographs in Figure 7, it was observed that most of the peak events were not predicted well. The high value in infiltration coefficient (A0) and low value in outlet coefficients in the top tank (A1 & A2) transferred from the sub-watershed may lead to less generation of high peaks.

Since under *Option 1,*the model has overestimated nearly 85% of low flows by 20% or more margin as observed in Figure 8, the accuracy of low flow prediction was only 29%. This might be due to the high value in infiltration coefficient (A0) and low value in HC1 transferred from the sub-watershed, which lead to creating more sub-base and base flow. Further, Karki et al. (2023) [40] stated that performance in parameter transferability also depends on the performance of the hydrologic model, thereby lesser accuracy in low flow matching might be due to the low performance of the Tank Model during the optimization stage.

However, annual streamflow aggregated from predicted daily streamflow was having very satisfying accuracy with an average actuary of 93.3%, though in two water years accuracy was less than 90%, demonstrating the capability to interpret the annual water cycle accurately.

Although, the ratio between the main and sub-watershed area was 5.6:1, both *Option 1* and *Option 2* transferability approaches showed competitively excellent performance in daily streamflow prediction with an accuracy between 61% - 65% in overall prediction. But, this contradicts with the conclusion of the study done by Sheng et al. (2020) [48] with a different lumped model that, when the difference between sizes of donor and target watersheds are increasing, the objective function has lost its value drastically which implies that the difference between sizes of donor and target watersheds have a significant impact on the performance of transferability. This demonstrates the suitability of the Tank Model for parameter transferability, but further studies should be done in the future with different sizes of watersheds for more generalized conclusions.

Therefore, with data from either the Urawa gauging station or Pitabeddara gauging station, Tank Model is reliable to predict the daily streamflow of both concerned watersheds. Thus, these results confirmed that the Tank Model with spatially transferred parameter values is capable of estimating the daily streamflow of Nilwala River Basin.

4.3 Applicability of Models with Spatially Transferred Parameters for Water Resources Management

An accurate assessment of the quantity of water resources on a monthly scale is the baseline for developing managing & planning alternatives [3], [16]. Therefore, the estimated daily streamflow under the spatial transferability approach was aggregated on a monthly scale.

Table 7 - Performance in Monthly Scale under Spatial Transferability Approach

Month	Pitabeddara Main watershed Sub-to-Main transfer			Urawa Sub-watershed Main-to-Sub transfer		
	Monthly avg. observed flow (mm)	Monthly avg. calculated flow (mm)	Error	Monthly avg. observed flow (mm)	Monthly avg. calculated flow (mm)	Error
October	159.2	149.4	6.2%	117.9	116.0	1.5%
November	318.9	272.9	14.4%	238.1	263.0	10.5%
December	304.9	271.2	11.0%	249.3	262.1	5.2%
January	132.7	137.9	3.9%	125.4	102.7	18.1%
February	97.5	102.1	4.8%	73.7	77.5	5.1%
March	96.5	117.9	22.2%	73.1	116.8	59.8%
April	168.2	163.9	2.6%	120.8	139.2	15.3%
May	195.1	191.7	1.7%	142.0	118.6	16.5%
June	173.3	167.7	3.2%	124.3	85.6	31.1%
July	106.5	107.4	0.8%	69.0	54.3	21.3%
August	81.9	91.8	12.2%	58.4	47.4	18.8%
September	122.6	126.7	3.4%	81.8	83.8	2.5%
Average monthly error			**7.2%**			**17.1%**

The streamflow estimated under the spatial transferability approach for both watersheds showed significant accuracy in monthly estimation. The monthly estimation in the sub-watershed showed more than 80% of accuracy in all months except in March (41%) and June (69%). However, monthly-scaled estimations in the main watershed have achieved an average of more than 85% of accuracy in 11 months as illustrated in Table 7 whereas, in March, the accuracy of estimations was 78%.

In addition to the monthly scale comparison, a seasonal scale comparison was also conducted to observe the seasonal flow accuracy which showed satisfying results. Under the *Option 1*, the accuracy of seasonally aggregated predictions was more than 87% except in one Yala season, while the same under *Option 2* was more than 85% except in two seasons. The comparison is given in Wickramarachchi (2020) [49].

Therefore, according to these results, the predictions based on the spatial transferability approach are suitable for conducting water resources management studies. The present study showed the best results for the concerned two watersheds within Nilwala River Basin. It will be more valuable if this study was able to extend more sub-watersheds within the Nilwala River Basin. Since there were only two river gauging stations that are functioning, the present study had to be limited to the two watersheds. Though, there are uncertainties with base data and model parameters that hinder the model performance, thereby further studies have to be carried out for further improvements [8].

5. Conclusions

The following are the conclusions:

1. The Tank Model with MRAE values less than 0.32 for Calibration and same between 0.48 and 0.54 for Verification, demonstrated its excellent capability to model the daily streamflow of both watersheds in the Nilwala River Basin.
2. The best Tank Model results in both Urawa and Pitabeddara watersheds are in the intermediate flow region with an average accuracy of 63% from 2008/09 to 2017/18 water years. The average estimation accuracy for the high flow in daily temporal resolution was 62% while the same for the low flow was 37%.
3. The present study concluded that the Tank Model has a very good overall capability to estimate daily streamflow either from the main watershed to a sub-watershed or from a sub-watershed to the main watershed with an accuracy between 61% to 65%.
4. Due consideration should be given for low flow matching of the predictions under transferability from a sub-watershed to the main watershed, and high flow matching of the predictions under transferability from the main watershed to a sub-watershed.
5. The monthly estimates from daily streamflow estimations of the Tank Model in Urawa and Pitabeddara watersheds also demonstrated the high parameter transferability potential with respective average accuracy levels of 83% and 92%, amounting to average errors of 18.2 and 12.4mm/month, respectively.
6. The present study with the results of the model performance in daily and monthly streamflow estimations and also in case of the potential of parameter transferability

confirmed that Sugawara's Tank Model is excellent for water resources management in the Nilwala River Basin.

7. The results of the present study using two gauged datasets of Nilwala River Basin showed that with only a single well-managed streamflow gauging station and the Tank Model can optimally use available resources to sustainably manage the streamflow of the basin.

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References

1. Deletic, A., & Wang, H., "Water Pollution Control for Sustainable Development," *Engineering*, Vol. 5, 2019, pp. 839–840.
2. Miranda, L. S., Deilami, K., Ayoko, G. A.,Egodawatta, P., & Goonetilleke, A., "Influence of Landuse Class and Configuration on Water-Sediment Partitioning of Heavy Metals," *Sci. Total Environ.*, 2022.
3. Nruthya, K., & Srinivas, V. V., "Evaluating Methods to Predict Streamflow at Ungauged Sites Using Regional Flow Duration Curves: A Case Study," *Aquat. Procedia*, Vol. 4, 2015.
4. Guo, Y., Zhang, Y., Zhang, L., & Wang, Z., "Regionalization of Hydrological Modeling for Predicting Streamflow in Ungauged Catchments: A Comprehensive Review," *WIREs: Water*, 2020.
5. Goodarzi, M. S., Amiri, B. J., Azarnivand, H., &Waltner, I., "Watershed Hydrological Modelling in Data Scarce Regions; Integrating Ecohydrology and Regionalization for the Southern Caspian Sea Basin, Iran," *Heliyon*, Vol. 7, 2021, p. 13.
6. Wickramarachchi, M., & Wijesekera, N. T. S., "Hydrological Modelling with the Tank Model for Water Resource Management of Nilwala River Basin," *Eng. J. Inst. Eng. Sri Lanka*, Vol. LV, No. 1, 2022, pp. 85–94.
7. Yang, X., Magnusson, J., Rizzi, J., & Xu, C. Y., "Runoff Prediction in Ungauged Catchments in Norway: Comparison of Regionalization Approaches," *Hydrol. Res.*, Vol. 49, No. 2, 2018.
8. Song, J., Her, Y., Suh, K., Kang, M., & Kim, H., "Regionalization of a Rainfall-Runoff Model: Limitations and Potentials," *Water*, Vol. 11, No. 2257, 2019.
9. Yokoo, Y., Kazama, S., Sawamoto, M., &Nishimura, H., "Regionalization of Lumped Water Balance Model Parameters Based on Multiple Regression," *J. Hydrol.*, Vol. 246, 2001.
10. Nepal, S., Flügel, W. A., Krause, P., Fink, M., & Fischer, C., "Assessment of Spatial Transferability of Process-Based Hydrological Model Parameters in Two Neighbouring Catchments in The Himalayan Region," *Hydrol. Process.*, Vol. 31, 2017.
11. He, Y., Bárdossy, A., & Zehe, E., "A Review of Regionalisation for Continuous Streamflow Simulation," *Hydrol. Earth Syst. Sci.*, Vol. 15, No. 11, 2011, pp. 3539–3553.
12. Amiri, B. J., Fohrer, N., Cullmann, J., Hörmann, G.,Müller, F., & Adamowski, J., "Regionalization of Tank Model Using Landscape Metrics of Catchments," *Water Resour. Manag.*, Vol. 30, No. 14, 2016, pp. 5065–5085.
13. Qi, W. Y., Chen, J., Li, L., Xu, C. Y., Li, J., Xiang, Y., & Zhang, S., "Regionalization of Catchment Hydrological Model Parameters for Global Water Resources Simulations," *Hydrol. Res.*, Vol. 53, No. 3, 2022, pp. 441–466.
14. Golian, S., Murphy, C., & Meresa, H., "Regionalization of Hydrological Models for Flow Estimation in Ungauged Catchments in Ireland," *J. Hydrol. Reg. Stud.*, Vol. 36, 2021.
15. Parajka, J., Viglione, A., Rogger, M., Salinas, J. L., Sivapalan, M., & Blöschl,G., "Comparative Assessment of Predictions in Ungauged Basins-Part 1: Runoff-Hydrograph Studies," *Hydrol. Earth Syst. Sci.*, Vol. 17, No. 5, 2013.
16. Razavi, T., & Coulibaly, P., "Streamflow Prediction in Ungauged Basins: Review of Regionalization Methods," *J. Hydrol. Eng.*, Vol. 18, No. 8, 2013, pp. 958–975.
17. Xu, C. Y., & Singh, V. P., "Review on Regional Water Resources Assessment Models under Stationary and Changing Climate," *Water Resour. Manag.*, Vol. 18, 2004, pp. 591–612.
18. Abeynayake, J. C., "Peakflow Estimation in Ungauged Watersheds Using Flood Transposition: A Study of Watersheds in the Wet Zone of Sri Lanka," University of Moratuwa, 2000.
19. Basnayake, B. M. L. A., "Prioritization of Sub-Basins of Nilwala River Basin for Flood Exposure using Multi Criteria Decision Analysis," *Eng. J. Inst. Eng. Sri Lanka*, Vol. 55, No. 1, 2022.
20. Sugawara, M., Watanabe, I., Ozaki, E., & Katsuyama, Y., "Tank Model with Snow Component : Research Notes of the National Research Center for Disaster Prevention," National Research Center for Disaster Prevention, 1984.
21. Sugawara, M., Ozaki, E., Watanabe, I., & Katsuyama, Y., "Tank Model and Its Application to Bird Creek, Wollombi Brook, Bikin River, Kitsu River, Sanaga River and Nam Mune. Research Note of the National Research Center for Disaster Prevention.," 1974.

22. Phien, H. N., & Pradhan, P. S. S., "The Tank Model in Rainfall-Runoff Modelling," *Water SA*, Vol. 9, No. 3, 1983, pp. 93–102.

23. Kuok, K. K., Harun, S., & Chiu, P., "Investigation Best Number of Tanks for Hydrological Tank Model for Rural Catchment in Humid Region," *J. Inst. Eng. Malaysia*, Vol. 72, No. 4, 2011.

24. Sugawara, M., "Chapter 6: Tank Model," in *Computer Models of Watershed Hydrology*, V. P. Singh, Ed. Water Resources Publications, 1995.

25. Wijesekera, N. T. S., "Conceptual Model Structure Development for Streamflow Simulation in the Tropics," University of Tokyo, 1993.

26. Wijesekera,N. T. S., "Parameter Estimation in Watershed Model : A Case Study Using Gin Ganga Watershed," *Transactions 2000, Annual Sessions of the Institution of Engineers of Sri Lanka*, Vol. 1, No. Part B, 2000, pp. 26–32.

27. Phuong, H. T., Tien, N. X., Chikamori, H., & Okubo, K., "A Hydrological Tank Model Assessing Historical Runoff Variation in the Hieu River Basin," *Asian J. Water, Environ. Pollut.*, Vol. 15, No. 1, 2018, pp. 75–86.

28. Setiawan, B. I., Fukuda, T., & Nakano, Y., "Developing Procedures for Optimization of Tank Model ' s Parameters," *Agric. Eng. Int. CIGR J. Sci. Res. Dev.*, 2003.

29. Cooper, V. A., Nguyen, V. T. V., & Nicell, J. A., "Calibration of Conceptual Rainfall – Runoff Models Using Global Optimisation Methods with Hydrologic Process-based Parameter Constraints," *J. Hydrol. Eng.*, Vol. 334, 2007.

30. Basri, H., "Development of Rainfall-runoff Model Using Tank Model : Problems and Challenges in Province of Aceh, Indonesia," *Aceh Int. J. Sci. Technol.*, Vol. 2, No. 1, 2013, pp. 26–36.

31. Wagener, T., Wheater, H. S., & Gupta, H. V., *Rainfall-Runoff Modeling in Gauged and Ungauged Catchments*. Imperial College Press, 2004.

32. Kim, S., & Kim, H., "A New Metric of Absolute Percentage Error for Intermittent Demand Forecasts," *Int. J. Forecast.*, Vol. 32, 2016.

33. Gracia, F., Folton, N., & Oudin, L., "Which Objective Function to Calibrate Rainfall–Runoff Models for Low-Flow Index Simulations?," *Hydrol. Sci. J.*, 2017.

34 Kamran, M., & Rajapakse,R. L. H. L., "Effect of Watershed Subdivision and Antecedent Moisture Condition on HEC-HMS Model Performance in the Maha Oya Basin , Sri Lanka," *Int. J. Eng. Technol. Sci.*, Vol. 5, No. 2, 2018, pp. 22–37.

35. Dissanayake,P. K. M., "Applicability of a Two Parameter Water Balance Model to Simulate Daily Rainfall Runoff – Case Study of Kalu and Gin River Basins in Sri Lanka," University of Moratuwa, 2017.

36. Beven, K., *Rainfall-Runoff Modelling: The Primer*, Second. Wiley-Blackwell, 2012.

37. Jie, M. X., Chen, H., Xu, C. Y., Zeng, Q., & Tao, X. E., "A Comparative Study of Different Objective Functions to Improve the Flood Forecasting Accuracy," *Hydrol. Res.*, Vol. 47, No. 4, 2016.

38. Kang, M. G., Lee, J. H., & Park, K. W., "Parameter Regionalization of a Tank Model for Simulating Runoffs from Ungauged Watersheds," *J. Korea Water Resour. Assoc.*, Vol. 46, No. 5, 2013.

39. An, J. H., Song, J. H., Kang, M. S., Song, I., Jun, S.M., & Park, J., "Regression Equations for Estimating the Tank Model Parameters," *J. Korean Soc. Agric. Eng.*, Vol. 57, No. 4, 2015.

40. Karki, N., Shakya, N. M., Pandey, V. P., Devkota,L. P., Pradhan, A. M. S., & Lamichhane, S. "Comparative Performance of Regionalization Methods for Model Parameterization in Ungauged Himalayan Watersheds," *J. Hydrol. Reg. Stud.*, Vol. 47, No. 101359, 2023.

41. Moriasi, D. N., Arnold, J. G., Van Liew, M. W.,Bingner, R. L., Harmel, R. D., & Veith, T. L., "Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations," *Am. Soc. Agric. Biol. Eng.*, Vol. 50, No. 3, 2007, pp. 885–900.

42. Lee, J. W., Dong, C. S., & Lee, S. O., "A Review of Tank Model and its Applicability to Various Korean Catchment Conditions," *Water*, vol. 12, No. 3588, 2020.

43. Abraham, T., Liu, Y., Tekleab, S., & Hartmann, A., "Prediction at Ungauged Catchments through Parameter Optimization and Uncertainty Estimation to Quantify the Regional Water Balance of the Ethiopian Rift Valley Lake Basin," *Hydrology*, Vol. 9, No. 8, 2022.

44. Patil, S., & Stieglitz, M., "Modelling Daily Streamflow at Ungauged Catchments: What Information is Necessary?," *Hydrol. Process.*, 2014.

45. Patil, S., & Stieglitz, M., "Comparing Spatial And Temporal Transferability of Hydrological Model Parameters," *J. Hydrol.*, Vol. 525, 2015.

46. Krause, P., Boyle, D. P., & Bäse, F., "Comparison of Different Efficiency Criteria for Hydrological Model Assessment," *Adv. Geosci.*, Vol. 5, 2005.

47. Althoff, D., & Rodrigues, L. N.,"Goodness-of-Fit Criteria for Hydrological Models: Model Calibration and Performance Assessment," *J. Hydrol.*, Vol. 600, 2021.

48. Sheng, S., Chen, H., Guo, F. Q., Chen,J., Xu,C. Y., & Guo, S., "Transferability of a Conceptual Hydrological Model across Different Temporal Scales and Basin Sizes," *Water Resour. Manag.*, Vol. 34, No. 9, 2020, pp. 2953–2968.

49. Wickramarachchi, M., "Evaluation of Transferability of Tank Model Parameters for Ungauged Catchments in Nilwala River Basin," University of Moratuwa, 2020.