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Research Paper

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ABSTRACT

Selection of a fitting up-to-date hydrological model using an evaluation of the functionality, modeler's requirements, and modeling experiences are very important for water resources management in rural watersheds. Similarly, the selection of appropriate objective function is equally crucial in hydrological modeling processes. Accordingly, A review study was carried to select an appropriate model and objective function for water resources modeling in the predominantly rural watershed. Hydrological models namely HEC-HMS, MIKE SHE, SWAT, TOPMODEL, and SWMM, and objective functions namely NSE, RMSE, MRAE, and RAEM were reviewed. Hydrological models were reviewed under several criteria viz. temporal scale, spatial scale, hydrological processes, documentation, resources requirement, user interface and, model acquisition cost. Whereas, criteria for the review of objective functions were mathematical implication, flow regime, and modeling purpose. Each of the review criteria was comprised of several factors. The criteria-based evaluation was done to quantify the review outcome of the hydrological model and objective function. SWMM was found to be the most suitable model for simulating rural watersheds for water resources management purposes whereas, MRAE was found to be the most appropriate objective function to evaluate the performance of the model selected for rural watershed modeling.

Keywords: Hydrological model; Objective function; Rural watershed, Criteria-based evaluation.

INTRODUCTION

In a period where water resources are becoming scarce due to increasing population and human activities, it is very important to have appropriate models for water resources management especially in a rural context. Rural watersheds are usually heterogeneous and expose a modeler to an issue of spatial and temporal data constraints. Most of the available hydrological model has user-friendly user interfaces, elaborated modeling tools and physics-based sub-model processes but requires large and complex data.

A model is a simplified representation of the real world and no model can be identified as ideal for all range of hydrological conditions. The best model is one which gives result close to reality with the use of least parameter and model complexity (Devia et al., 2015). Hydrological model selection is not supposed to be solely reliant on its predictive performance (Marshall et al., 2005). The modeler's preference and familiarity in using particular models, the aim of the modeling task, the time available to develop and apply a model, and the level of accuracy required should also be taken into account. The selection of appropriate objective function is equally crucial in hydrological modeling. Hydrologic simulation models are calibrated by comparing observed data with data generated by the models. A function of the difference between computed and observed data during model calibration and validation is termed an objective function. The type of engineering application for which an objective function is used is determined by its mathematical formulation. However, the choice of the objective functions to be used for any given model is a subjective decision that influences the values of the model parameters and the performance of the model (Diskin and Simon, 1977). Hence, the selection of a fitting up-to-date model and objective function evaluating the functionality, modeler requirements and modelling experiences has become imperative for rural watershed management.

Method

Among the commonly used hydrological models, 5 (five) models viz. Hydrological Modelling System (HEC-HMS), MIKE SHE, Soil and Water Analysis Tool (SWAT), Strom Water Management Model (SWMM), and TOPMODEL were selected for the review. The review criteria for the model selection were sorted out viz. as (1) temporal scale (2) spatial scale (3) hydrological processes (4) documentation (5) resources requirement (6) user interface and (7) model acquisition cost. Similarly, some commonly used objective function namely Nash-Sutcliffe (NSE), Root Mean Square Error (RMSE), Mean Ratio of Absolute Error (MRAE), Ratio of Absolute Error to mean (RAEM) were selected for the review. The criteria for the review of the objective functions were (1) mathematical implication, (2) flow regime, and (4) modeling purpose.

Each review criterion was comprised of several factors. The factors were then ranked into three classes viz. high preference, moderate preference, and low preference. The score was assigned to each of the class on a scale of 1-3: 1 being for less preferred and 3 for the highly preferred. Rank and score for a particular criterion and their respective factor for the selection of the model and the objective function are given in Table 1 and Table 2 respectively. Characteristic and feature of 5 (five) shortlisted model and 4 (four) objective function were then reviewed. Finally, their features were listed in the order of the classified factor with respective scores.

Table 1. Criteria, Factors, Ranks and Scores for the Selection of Model

Criteria	Factors	Highly Preferred [3]	Moderately Preferred [2]	Low Preferred [1]
Temporal Scale	*Event/Continuous*	Both	Continuous	Event only
	Times steps	(Min/hours/day)	Hours/day	Day

Spatial Scale	*Spatial representation*	Semi-distributed	Distributed	Lumped
	Nature of watershed	Flexible	Rural	Urban
Modelling Process	*Theory*	Conceptual	Physics Based	Empirical
	Flow routing	Dynamic	Kinematic	Muskingum
	Process integration (Hydraulic/hydrologic)	Integrated	Semi-Integrated	Not integrated
Documentation	*Availability of Reference Manual*	User manual and Technical manual	User manual or Technical	Poor
Resources Requirement	*Hydro-met data Requirement*	Station wise data	Aggregated data	Gridded
	Physical data Requirement	Reasonable data demand	Moderate data demand	Intensive data demand
User Interface	*GUI*	Advance GUI	Moderate	No GUI
	Optimization	Auto optimization	Third party	Manual
Acquisition cost	*Availability*	Public Domain	Exclusive	Commercial

Table 2. Criteria, Factors, Ranks and Scores for the Selection of Objective Function

Criteria	Factors	Highly Preferred [3]	Moderately Preferred [3]	Low preferred [3]
Mathematical Implication	*Error and variance*	Relative error	Standard Error	Normalized Variance
Flow Regime	*High, Moderate, Low flows*	Good for intermediate flows	Good for low flows and moderately good for intermediate flows	Good for high flows (only)
	Overall hydrograph	Favorable for overall hydrograph	Moderate for overall hydrograph	Not favorable for overall hydrograph
Modelling Purpose	*Water resources modelling*	Water resources modelling	Water resources & drought modelling	Flood modelling

Review of the Hydrological Models

Hydrological Modelling System (HEC-HMS)

HEC-HMS is an open-source hydrological model developed by the US Army Corps of Engineers in 1998. It is primarily a lumped and event-based model, and most of the processes are empirical(Feldman, 2000). However, it is widely being used for continuous simulation of rainfall and runoff. (Gebre, 2015). It is being applied in both rural and urban watersheds(Gholami et al., 2010; Suriya and Mudgal, 2012). HEC-HMS uses mainly the kinematic wave method and Muskingum's wave method for flow routing. It takes both points and gridded rainfall and streamflow data. Physical data required for HEC-HMS are Digital Elevation Model (DEM) or contours for slope, maximum height, basin width, soil map for infiltration parameters, and Landuse map (Baumbach et al., 2015). It has an advanced Graphical User Interface (GUI) and an inbuilt automatic optimization option for the users (Halwatura and Najim, 2013; Kamali et al., 2013). Hydrological Engineering Centre provides both the user manual and technical reference manual of this model.

Soil and Water Analysis Tool (SWAT)

SWAT is a semi-distributed, physics-based river basin model developed by the United States Department of Agriculture (USDA) Agricultural Research Service (ARS) (Neitsch et al., 2002). It is widely used and highly flexible in addressing a boarder range of water resource problems, as a result of the comprehensive nature of the model, strong model support, and open access status of the source code(Gassman et al., 2014).

It can be used for both event-based and continuous simulation of runoff quality and quantity(Borah et al., 2007). It uses Muskingum's wave method for flow routing(Lévesque et al., 2008). SWAT incorporates station-wise point data for rainfall and streamflow and model usually in daily time step. It doesn't allow the user the flexibility to integrate additional hydraulic modeling features into it. Physical data required for SWAT models are DEM, Land use map, soil map, and slope map(Tuo et al., 2016). It does not have its own GUI, therefore, integrates with the Geographical Information System platform for the modeling process(Olivera et al., 2006). Besides, Automatic parameter optimization is an inbuilt feature of the SWAT(Li et al., 2010; Ozdemir and Leloglu, 2019).

MIKE SHE

MIKE SHE is a commercial engineering software package developed at the Danish Hydraulic Institute (DHI). It is a fully distributed model operating in hourly time steps mainly used for continuous modeling of large river basins (Sandu and Virsta, 2015). It is a strictly physics-based hydrological model; however, its flow routing process is governed by a simplified empirical stage-discharge relation method (Ma et al., 2016). MIKE requires hydro-metrological and physical data in a gridded format. It is an intensive data demanding model as it requires more than 100 input parameters for the calibration process (Jaber & Shukla, 2012). Hydraulic modeling is not possible in MIKESHE however, a separate hydraulic model MIKE 11 developed by DHI itself can be coupled with it (Clilverd et al., 2016). Automatic model parameter optimization can be performed with its advance and user-friendly GUI (Ma et al., 2016).

TOPMODEL

The development of TOPMODEL was initiated by the University of Leeds in the mid-1970s. The model was further developed by Keith Beven at Lancaster University. Since 1974 there have been many variants of TOPMODEL but never a "definitive" version. TOPMODEL was developed to provide a physically realistic but parametrically simpler rainfall-runoff model that can predict different types of hydrological responses(Beven, 1997). TOPMODEL is an open-source, continuous, semi-distributed, and conceptual hydrological model programmed in FORTRAN and DOS(Beven, 1997). It generally operates on daily time steps but there have been few studies using TOPMODEL on hourly time steps as well (Blazkova et al., 2002; Holko and Lepisto, 1997). It uses Muskingum's method for routing the overland flow (Takeuchi et al., 1999). TOPMODEL does not have the option of coupling additional hydraulic models and does not have a well-documented user manual as well.

Strom Water Management Model (SWMM)

SWMM is open-source, conceptual hydrodynamics, a semi-distributed model capable of simulating events or continuous runoff quality and quantity developed by the United States Environment Protection Agency (USEPA) in 1977 (Rossman & Huber, 2015). It is considered to be a widely used model throughout the world for planning, analysis, and design-related stormwater runoff, combined sewers, and other drainage systems. SWWM was primarily developed for urban watershed modeling but its application is not limited only to the urban watershed (Rossman and Huber, 2015). The flow routing method in SWMM is governed by the conservation of mass and momentum equations i.e., Saint-Venant's equation. It allows users options for flow routing namely the steady flow routing; the kinematic wave routing; or the full dynamic wave routing (Cambez et al., 2008). The user's manual and reference manual of SWMM are well documented and made easily available by US EPA. SWMM operates on its own GUI (Lin et al., 2010; Rossman & Huber, 2015). SWMM do not have an automatic optimization option, however, a third-party program like PCSWMM can be used (Barco et al., 2008; Jin et al., 2011; Tscheikner-Gratl et al., 2016)

Review of the Objective Functions

Nash-Sutcliffe Efficiency (NSE)

The Nash-Sutcliffe Efficiency (NSE) is a normalized statistic indicator that determines the relative magnitude of the residual variance compared to the measured data variance (Nash and Sutcliffe, 1970).

$$\mathrm{NSE} = 1 - \left[\frac{\sum_{i=1}^{n}(Qobs - Qcal)^2}{\sum_{i=1}^{n}(Qobs - Qmean)^2}\right] \tag{1}$$

where, Q_{obs}= Observed Discharge; Q_{cal}= Simulated Discharge; Q_{min}= mean discharge

Krause et al. (2005) stated the largest drawback of the NSE is that the differences between the observed and simulated values are calculated as squared values. As a result, larger values in a time series would be overestimated whereas lower values would get neglected. While quantifying the runoff, NSE leads to an underestimation during low flow conditions.

Moriasi et al. (2015) stated that Nash- Sutcliffe efficiency (NSE) is the best objective function to reflect the peak flow matching on a hydrograph. Nash-Sutcliffe efficiency is the widely used objective function for flood modeling (Chen et al., 2017; Komi et al., 2017; Monte et al., 2016; Skhakhfa and Ouerdachi, 2016) but it is not preferred objective function on modeling for water resources management purposes.

Root Mean Square Error (RMSE)

Root-mean-square error (RMSE) is a frequently used measure of the differences between values predicted by a model and the values observed. Root mean square error is the standard deviation of residual or prediction error.

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(\mathrm{Qobs,i} - \mathrm{Qcal,i})^2}{n}} \tag{2}$$

where, Q_{obs} = Observed Discharge; Q_{cal} = Simulated Discharge; n = is the number of observations.

RMSE has been used widely for low flow modeling. Nicolle et al. (2014) used RMSE as an objective function for benchmarking hydrological models for low-flow simulation and forecasting on French catchments. Similarly, Demirel and Booij (2009) used RMSE as an objective function for an appropriate low flow forecast for the Meuse River. Li (2017) stated that RMSE is a commonly used measure for assessing the predictive accuracy however it is unit/scale-dependent and the accuracy cannot be ascertained.

Ratio of Absolute Error to Mean (RAEM)

The ratio of Absolute Error to Mean one of the objective functions recommended by the World Meteorological Organization(WMO, 1975) is as given below.

$$\mathrm{RAEM} = \frac{1}{n}\frac{\sum|\mathrm{Qobs} - \mathrm{Qcal}|}{(\mathrm{Qobs})\mathrm{mean}} \tag{3}$$

where, Q_{obs}= observed Discharge, Q_{cal}= simulated discharge, (Q_{obs}) mean= mean of observed discharge

Jayadeera and Wijesekera (2016) in a study of developing the mathematical model in the Kalu river basin had used RAEM as a secondary objective function. Jayadeera and Wijesekera (2016) states this objective function indicates the ratio between observed and calculated discharge to the mean of obrved discharges. It depends on the characteristics of the observed flow series. When there are big and small peaks, the error values may not enable easy comparison, and the mean of observed flow does not reflect the real mean value of the flow series. Therefore, RAEM is not the preferred objective function for water resources assessments.

Mean Ratio of Absolute Error (MRAE)

Mean Ratio of Absolute Error (MRAE) is defined as the difference between calculated and observed flow to that particular observation.

$$\mathrm{MRAE} = \frac{1}{n}\sum\frac{|\mathrm{Qobs} - \mathrm{Qcal}|}{\mathrm{Qobs}} \tag{4}$$

where, Q_{obs}= observed streamflow, Q_{cal}= calculated streamflow & n= number of observations. Best fit between observed and calculated values would have a zero value of MRAE. Musiake and Wijesekera (1990) had used MRAE as the objective function for the streamflow modeling of Mahaweli Ganga of Sri Lanka. Later number of successful uses (especially in the tropical watershed of Sri Lanka) of MRAE has been reported (Thapa and Wijesekera, 2017; Wanniarachchi, 2013; Wijesekera and Rajapakse, 2013). Since this objective function compares the errors with respect to each observed flow, it gives a better representation when contrasting data are present in the observed data set. It provides information about the predicting capability as well as the distribution of the prediction errors of the model (Jayadeera and Wijesekera, 2016).

Results and Discussions

The characteristics and features of hydrological models and objective functions as per the specified criteria and factors were identified, scaled, and ranked. The cumulative scores obtained from the criteria evaluation for hydrological models viz. SWMM, HEC-HMS, SWAT, MIKE SHE, and TOPMODEL are respectively 36, 35, 28, 26, and 22. Similarly, for that of objective function namely MRAE, RAEM, RMSE, NSE are 12, 8, 7, and 5. The detailed result of criteria evaluation of hydrological models and objective functions provided in Table 3 and Table 4, respectively.

Table 3. Criteria evaluation for the selection of the model

Evaluation Criteria	Factors	Models, Ranks and Scores				
		HEC HMS	**SWAT**	**TOPMODEL**	**MIKE SHE**	**SWMM**
Temporal Scale	Event/ Continuous	Both	Both	Both	Both	Both
		HP [3]	HP [3]	HP [3]	HP [3]	HP [3]
	Simulation time	Flexible	Hours/day	Hours/day	Flexible	Flexible
		HP [3]	MP [2]	MP [2]	HP [3]	HP [3]
Spatial Scale	Spatial representation	Semidistributed	Semi distributed	Semi distributed	Distributed	Semi distributed
		HP [3]	HP [3]	HP [3]	MP [2]	HP [3]
	Nature of watershed	Rural/Urban	Rural/Urban	Rural/urban	Rural	Urban/Rural
		HP [3]	HP [3]	HP [3]	MP [2]	HP [3]
Process	Theory	Empirical	Physics based	Conceptual	Physics based	Conceptual
		LP [1]	MP 2]	HP [2]	MP [2]	HP [3]
	Flow Routing	Kinematic	Muskingum	Muskingum	Stage discharge	Dynamic
		MP [2]	LP [1]	LP [1]	LP [1]	HP [3]
	Process integration	Semi integrated	Not Integrated	Not Integrated	Semi Integrated	Fully Integrated
		MP [2]	LP [1]	LP [1]	MP [2]	HP [3]
Documentation	Reference Manual	User/ Technical	User/ Technical	None	User/ Technical	User/ Technical
		HP [3]	HP [3]	LP [1]	HP [3]	HP [3]
Evaluation Criteria	Factors	HEC HMS	SWAT	TOPMODEL	MIKE SHE	SWMM

Resource requirement	Hydro met data	Station wise data	Station wise data	Aggregated data	Gridded data	Station wise data
		HP [3]	HP [3]	LP [1]	MP [2]	HP [3]
	Physical data	Reasonable data demand	Intensive data demand	Moderate data demand	Intensive data demand	Reasonable data demand
		HP [3]	LP [1]	MP [2]	LP [1]	HP [3]
User Interface	GUI	Advance GUI	Moderate GUI	No GUI	Advance GUI	Moderate GUI
		HP [3]	MP [2]	LP [1]	HP [3]	MP [2]
	Optimization	Inbuilt automatic optimization	Inbuilt automatic optimization	Manual optimization	Inbuilt automatic optimizatio n	Third party optimizatio n
		HP [3]	HP [3]	LP [1]	HP [3]	MP [2]
Acquisition	Availability	Public domain	Public Domain	Public domain	Commercial	Public domain
		HP [3]	HP [3]	HP [3]	LP [1]	HP [3]
Cumulative SCORE		**35**	**28**	**22**	**26**	**37**

Table 4. Criteria evaluation for the selection of the model

Criteria	Factors	NSE	RMSE	RAEM	MRAE
Mathematical Implication	Error and variance	Relative Measures	Scale Dependent Measures	Measure Based on Relative Error	Measure Based on Relative Error
		LP [1]	MP [2]	HP [3]	HP [3]
Flow Regime	HML flows	High flows	Low flows	Intermediate flows	Intermediate flows
		LP [1]	MP [2]	HP [3]	HP [3]
	Overall hydrograph	Moderate	Not favorable	Moderate	Favorable
		MP [2]	LP [1]	MP [2]	HP [3]
Modelling Purpose	Water resources modelling	Flood modelling	Drought modelling	No application	Water resources modelling
		LP [1]	MP [2]	N/A	HP [3]
Score		**5**	**7**	**8**	**12**

Note: HP: Highly Preferred, MP: Moderately Preferred, LP: Less Preferred

Discussion

Selection of hydrological model

A review and criteria-based evaluation were carried out to identify the suitable hydrological model for water resources management purpose in a rural watershed. There are numerous hydrological models with various temporal resolutions in terms of modeling applicability. The model flexible for both event and continuous simulation of streamflow is generally preferred. Similarly, it is desired that the model can operate in a shorter time step and capture the effect of sub-daily variability of the watershed with the input data in the daily resolution.

Hydrological models are selected depending upon the level of requirement of accuracy and availability of data to deal with the complexity of the modeling process. The complexity of the modeling process increases in the order of 'lumped' to 'distributed'. However, a semi-distributed model can overcome the limitation of the lumped model and can predict the streamflow at a defined sub-unit with relatively less amount of data and computation complexity than with a fully distributed model (Jajarmizadeh et al., 2012). Therefore, semi-distributed models are generally chosen for rural watershed modeling considering the limitation of data scarcity in the rural catchment.

A model can be classified as empirical, conceptual, and physics-based based on its underlying theory and assumption. Empirical models are based on experimental observations whereas physics-based models describe the natural system in detail with a mathematical expression (Refsgaard and Knudsen, 1996). However, due to data intensiveness and complexity in the modeling process physics-based models are not considered a desired alternative. If the value of the physics-based model has to be estimated or guessed due to lack of availability of data then the results are not likely to be reliable than the result obtained from a simple conceptual model. Therefore, conceptual models that conceptualize the physical process of the natural system in the model are considered a suitable option for water resources modeling.

There are three options of flow routing in hydrological modeling namely Kinematic wave, Muskingum wave, and Dynamic wave. Kinematic wave is well established among the existing methods to solve unsteady, one-dimensional, gradually varied open-channel flow (Ponce, 1991). However, the kinematic wave method is valid only if the local accelerations are negligible and a slope of surface water is assumed the same as the bed slope (Chaudhry, 2008). Muskingum wave on the other hand is a simple method of flow routing but it produces output hydrograph wave flow routing only at one point of the river and attenuates the flow wave (Askari and Shayannejad, 2015; Singh and McCann, 1980). Whereas the Dynamic wave method uses the finite element method, finite volume method, and finite difference method to solve the unsteady-flow equations considering all the terms of the momentum equation: the pressure gradient, inertia, gravity, and flow resistance terms (Zhang, 2005). Hence, the dynamic wave flow routing is most appropriate, realistic as a method of flow routing in natural streams (Barati et al., 2012). In the field of water resources, combined hydrologic and hydraulic modeling is a tool commonly used for engineering analysis. A combined hydrologic/hydraulic model allows a user to evaluate the impacts of various scenarios and the benefits that would be achieved. There are several cases where hydrological and hydraulic models are coupled for flood modeling, sediment analysis, water resources management, etc.(Anselmo et al., 1996; Biancamaria et al., 2009). Hence, fully integrated hydraulic hydrological models are as highly preferred as possible.

The hydrological model uses precipitation data in mainly three forms namely grided, station wise, and averaged. Gridded precipitation data are rarely available in a daily resolution and so most of the gridded data are interpolated from station data itself (Liebmann and Allured, 2005). Averaged data are processed precipitation data from external or secondary data sources. Whereas, station wise data are generally available in the watershed all over the world. Therefore, hydrological models which use station wise data are preferred for water resources modeling. It is also desired that the hydrological models have an advanced graphical user interface (GUI), give an option for automatic optimization of parameters, provides the user with an updated reference manual, and available on an open-source.

Selection of objective function

Objective functions are classified as Scale Dependent Measures (SDM), Measures Based on Relative errors (MBR), and Relative Measures (RM)(Hwang et al., 2012). Scale-dependent Measures (SDM) can provide a good measure of model performance, however significant variations may occur while assessing different verity data sets. The variations in evaluation measure are due to their dependency on the scale of the data set. Whereas, the Relative Measures (RM) overestimates the larger values in a time series are and neglects the lower values. Measures based on Relative Errors (MBR) are scale-independent and are popularly used to compare the performance of models dealing with a variety of data sets. This measure is less sensitive to the larger errors that usually occur at higher magnitudes of flow waves. Despite some limitations, MBR is the most favorable measure for comparing the model performance.

Hydrological flow is classified into low, intermediate, and high. Risley et al. (2009) classified 5th and 10th percent exceedances as high flow, considers the 95th percent exceedance as low flows. Wijeseraka (2018)states that high streamflow leads to floods while low flows are considered essential for the sustenance of the riverine environment. Intermediate flows are the most important when planning infrastructure to harness water as a resource. Therefore, in the case of water resource assessment's objective functions favorable for intermediate flows are highly preferred.

Conclusion and Recommendation

As per the criteria and factors considered for the review, SWMM was found to most suitable model for simulating rural watersheds for water resources management purposes whereas, MRAE was found to be the most appropriate objective function to evaluate the performance of the model selected for rural watershed modeling.

The criteria evaluation technique can be used for the rational selection of an appropriate hydrological model and objective function considering numbers of criteria and factors. The technique also justifies the selection of the model as per the modeling purpose, area of application, the requirement of the data etc. A similar approach is recommended for several selection processes in hydrological modeling where rational decision-making is required.

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