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ORIGINAL RESEARCH ARTICLE

AN OVERVIEW OF SOME HYDROLOGICAL MODELS IN WATER RESOURCES ENGINEERING SYSTEMS

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ABSTRACT

Researches in hydrological modelling are aimed to the understanding of the behavior of hydrologic systems in an attempt to make better predictions and to address the major challenges in water resources systems. Hydrological modelling concept is concerned with the relationship of water, climate, soil and land use. Hydrological models are classified either as: conceptual or physical, lumped or distributed, deterministic or stochastic. Hydrological models are the main tools that hydrologist use with different purposes such as water resources management, storm water management, reservoir system analysis, flood prediction, climate change assessment and among others. Many hydrological models have been developed for different purposes. The methodology for using hydrological models include: definition of the problem and specifying the objectives, studying the data available, specifying the economic and social constraints, choosing a particular class of hydrological models, selecting a particular type of model from the given class, calibrating and validating the model, evaluating the performance of the model, and finally using the model for the specified purpose. Some recently developed, frequently used, and powerful hydrological models including WEAP, SWMM, HEC-HMS, HEC-RAS, and HEC-ResSim were herein assessed taking into cognizance their applications in solving challenges in water resources engineering systems.

1.0 Introduction

The science of hydrology deals with the occurrence and movement of water on and over the surface of the earth. It also deals with the various forms of moisture that occur, and the transformation between the liquid, solid, and gaseous states in the atmosphere and in the surface layers of land masses (Wilson, 1990). Water-related challenges are large and are likely to increase in the future (Tundisi, 2008). Current and future water-related challenges are location and time specific and these include wide myriad of issues such as fluvial hydraulics, reservoir operations, water quality issues in rivers, and the impact of climate change among others. In response to these challenges, hydrological models have been developed to understand, analyze, and explore sustainable solutions to water resources management.

Hydrological models are simplified conceptual representation of a part of the hydrologic cycle, and are primarily used for hydrologic prediction and understanding of the hydrologic and water resources systems (Gayathri et al., 2015). With the advancements in the field of hydrology and water resources coupled with the application of computers in the field, institutions and scientists are prompted to develop variety of softwares for designing and modelling of water resources systems. Some of these models include but not limited to Water Evaluation and Planning (WEAP), Storm Water Management Model (SWMM), Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS), Hydrologic Engineering Center-River Analysis System, (HEC-RAS), and Hydrologic Engineering Center-Reservoir System Simulation (HEC-ResSim) to achieve speedy and accurate modelling compared to the traditional methods.

This paper reviewed some hydrological models and presents a number of available public domain (free) and commercial softwares that are used in hydrologic and water resources systems modelling.

2. Hydrological Modelling

Modelling is a simplified representation of a complex system. Thus, most hydrologic systems are extremely complex and their behaviors cannot be understood in detail, but through experience, scientists were able to model and predict the behavior of environmental change (Chong-yu, 2002).The best model is the one which gives results close to reality with the use of least parameters and model complexity. Models were designed to aid generation of synthetic sequences of hydrologic data for facility design or for use in forecasting potential impacts of changes in landuse or climate (Chong-yu, 2002; Gayathri et al., 2015).

2.1 Classification of Hydrological Models

Hydrological models may be classified as conceptual or physically-based models according to the description of the physical processes, which considers the physical laws but in highly simplified form; lumped or distributed models according to the spatial description of catchment processes, which considers the homogeneity of a process; deterministic or stochastic models according to the information about the physical processes involved, which considers probability distribution of the process (Gayathri et al., 2015).

2.2 Selection of a Hydrological Model

Hydrological practice would be improved if models are objectively chosen on the basis of making the best use of the information available and following some systematic procedure of selection and verification. However, the choice of the best model depends to a large extent on the prevailing problem and should incorporate accuracy of prediction, simplicity of the model, consistency of parameter estimates and sensitivity of results to changes in parameter values.

2.3 Model Calibration and Validation

For any chosen model, there are some constants used to represent the physical process. These constants are called parameters of the model, and must be assigned fixed numerical values before the model may be used for prediction (Stadnyk et al., 2013). Calibration is a process of adjusting the parameters of the model to appropriately simulate historical observations. Calibrating a model involves both quantitative and qualitative evaluation of the hydrologic response of the catchment.

Validation of a model after the parameter values were estimated is the third level of model analysis. Model validation is also referred to as "diagnostic checking". As no model is perfect, verification requires both subjective and objective judgments on many aspects to determine whether the results provide adequate information for answering the question facing the decision-makers (Stadnyk et al., 2013).Faulty results may stem from a variety of causes, such as errors in the data used in calibration, use of a period of record that does not contain enough events of the physical processes and inadequate or misrepresentation of hydrological processes in the model.

2.4 Model Performance Evaluation

The evaluation of model performance is indispensable to examine both accuracy and reliability of models (Pachepsky et al., 2016). The common model evaluation statistical indices used in hydrology include the Nash-Sutcliffe Efficiency, NSE (Nash and Sutcliffe, 1970; Bai et al., 2009), the Percent Bias, PBIAS (Leong and Lai, 2017), and the coefficient of determination, R2 (Pachepsky et al., 2016; Leong and Lai, 2017) among others.

The Nash-Sutcliffe model Efficiency (NSE) assesses the predictive power of a hydrological model and indicates how well the plot of observed versus simulated data fits the 1:1 line (Leong and Lai, 2017). It is given by Eqn. 1

$$\mathrm{NSE} = 1 - \left[\frac{\sum_{i=1}^{n}\left(Q_i^{obs} - Q_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Q_i^{obs} - \overline{Q}^{obs}\right)^2}\right] \tag{1}$$

where:

Q_i^{obs} = ith observed data

Q_i^{sim} = ith simulated data

$\overline{Q}^{obs}$ = mean of observed data

NSE ranges between $-\infty$ and 1.0 (1 inclusive). When; NSE = 1 it implies a perfect match of simulated to the observed data (optimal value). NSE Values between 0.0 and 1.0 are generally viewed as acceptable levels of performance, whereas values < 0.0 indicates that the mean observed value is a better predictor than the simulated value, which indicates unacceptable performance. Essentially, the closer the NSE is to 1, the more accurate is the model.

Percent Bias (PBIAS) measures the average tendency of the simulated data to be larger or smaller than their observed counterparts. The optimal value of PBIAS is 0.0, with low values indicating accurate model simulation. Positive values indicate model underestimation bias, and negative values indicate model overestimation bias (Leong and Lai, 2017). PBIAS is expressed as Eqn. 2;

$$\mathrm{PBIAS} = \left[\frac{\sum_{i=1}^{n}\left(Q_i^{obs} - Q_i^{sim}\right)\times(100)}{\sum_{i=1}^{n} Q_i^{obs}}\right] \tag{2}$$

where:

Q_i^{obs} = ith observed data

Q_i^{sim} = ith simulated data

The coefficient of determination (R2) outlines the degree of co-linearity between simulated and observed data. It further describes the proportion of the variance in measured data explained by the model. Its value ranges from 0 to 1, higher values indicating less error variance. Values that are greater than 0.5 are considered acceptable (Santhi et al., 2001). The computation of R^2 is shown as Equation 3:

$$R^2 = \left[\frac{\sum_{i=1}^{n}(Q_i^{sim} - \bar{Q}^{sim})(Q_i^{obs} - \bar{Q}^{obs})}{\sqrt{\sum_{i=1}^{n}(Q_i^{sim} - \bar{Q}^{sim})^2 \sum_{i=1}^{n}(Q_i^{obs} - \bar{Q}^{obs})^2}}\right] \quad (3)$$

where:

Q_i^{sim} = ith simulated data

Q_i^{obs} = ith observed data

$\bar{Q}^{sim}$ = mean of simulated data

$\bar{Q}^{obs}$ = mean of observed data

3. Brief Description of some Hydrological Models and their Applications

3.1 WEAP

WEAP was developed by Stockholm Environment Institute, USA for integrated water resources planning. It provides a comprehensive, flexible and user-friendly framework for analysis. The software of this model is commercial available, but it is free for students and academic organizations in developing countries for a period of one year only. WEAP attempts to assist rather than substitute for the skilled planner. As a database, WEAP provides a system for maintaining water demand and supply information. As a forecasting tool, WEAP simulates climate change impacts on water demand, supply, flows, storage and pollution generation, treatment and discharge. As a policy analysis tool, WEAP evaluates a full range of water development and management options, and takes account of multiple and competing uses of water systems.

Operating on the basic principle of a water balance, WEAP is applicable to municipal and agricultural systems, single catchments or complex trans-boundary river systems. Moreover, WEAP can address a wide range of issues, such as sectoral demand analyses, water conservation, water rights and allocation priorities, groundwater and stream-flow simulations, reservoir operations, hydropower generation, pollution tracking, ecosystem requirements, vulnerability assessments, and project benefit-cost analyses (SEI, 2016). One of the advantages of the model over others is that it places the demand side of the water balance equation on equivalence with the supply side, and proffer solutions to some problems of water decision support systems. However, the model rely solely on the development of scenarios that can be quantified, placing less concern over their development for which some are outside the system architecture.

In assessing the effects of climate change on river systems, Kumar et al. (2018) evaluates the future stress of Pasig-Marikina River, Manila, Philippines, due to combined effect of climate change and rapid urbanization. In their studies, Pasig-Marikina River was analysed for current and future timescale using population growth, land use change, wastewater production and treatment scenarios, for three indicators of aquatic ecosystem health; Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD) and Nitrate (NO3). The results clearly indicate that the water quality in the future will rapidly deteriorate and will not be suitable for any aquatic life in terms of water quality. Hence, it called for immediate and inclusive action by policy makers. Thus, the model was able to inform decision makers on the need for implementation of integrated sewerage and seepage management programme on priority basics considering population density and growth changes for both short and long term measures.

3.2 HEC-HMS

HEC-HMS is a product of the Hydrologic Engineering Center (HEC) within the United States Army Corps of Engineers. It is a public domain software and was designed to simulate the complete hydrologic processes of dendritic watershed systems. The software of this model includes many traditional hydrologic analysis procedures such as event infiltration, unit hydrographs, and hydrologic routing. It also includes procedures necessary for continuous simulation such as evapotranspiration, snowmelt, and soil moisture accounting. It also features a completely integrated work environment including a database, data entry utilities, computation engine, and results reporting tools. It is a graphical user interface (GUI) that allows the user seamless movement between the different parts of the software. As a numerical model, it can predict runoff volumes, peak flows and timing of flows by simulating the behavior of the entire watershed. The model offers a number of advantages over other hydrological models because it can be applied to watersheds of varying size, shape and parameters. Also, calibration is performed using optimization algorithm. More so, it is compatible with other HEC-programs due to common data storage system. However, it cannot model back water in a stream network, and no support is provided for users other than U. S. Army Corps of Engineers. Simulation results are stored in HEC-DSS (Data Storage System) and can be used in conjunction with other software for studies of water availability, urban drainage, flow forecasting, future urbanization impact, reservoir spillway design, flood damage reduction, floodplain regulation, and systems operation (USACE, 2002).

Abdullah et al., (2018), used HEC-HMS 4.1 software to predict the runoff and sediment load inflow to Hemrin reservoir, in Baghdad for the period of 1981 – 2014. The calibration processes were performed using field measurement data for flow of water from Diyala River. The result obtained showed that the load of sediment entering the reservoir is directly affected by the precipitation received by the basin. This occurs during the peak precipitation period which is normally November every year accounting to 94% of sediment entering the reservoir. Thus, management strategies need to be implemented to control sediment deposit in the river.

3.3 SWMM

SWMM is a public domain software developed by Water Supply and Water Resources Division of the U.S. Environmental Protection Agency's National Risk Management Research Laboratory. The software of this model is a dynamic rainfall-runoff simulation model used for single event or long-term (continuous) simulation of runoff quantity and quality from primarily urban areas. The runoff component of SWMM operates on a collection of sub catchment areas that receive precipitation and generate runoff and pollutant loads. The routing portion of SWMM transports this runoff through a system of pipes, channels, storage/treatment devices, pumps, and regulators. SWMM tracks the quantity and quality of runoff generated within each sub catchment, and the flow rate, flow depth, and quality of water in each pipe and channel during a simulation period comprised of multiple time steps (Lewis, 2015). The model simulate pollutant loading and is capable of importing world coordinate files and exporting DXF files. However, the software is analytical and not design tool, and cannot model manhole or inlet loss directly.

Urban flood modelling evaluates storm drain capacities, blockage of storm drains, climate change and improper storm network planning. A study conducted by Swathi et al. (2018) evaluated the applicability of SWMM in analyzing storm network flooding at Birla Institute of Technology and Science (BITS), Pilani-Hyderabad Campus, India. The model was calibrated for 2006 rainfall event using Horton and Dynamic wave methods for Infiltration and flow routing of the watershed respectively. The results showed that there were no nodes flooded and no overflow sections in the entire catchment. Thus, it was concluded that the campus storm network system has been well planned and has sufficient carrying capacity to cater the simulated rainfall event.

Bedient et al., (2007) modeled urban flood using two softwares HEC-HMS and SWMM. They created hydrographs in HEC-HMS which were treated as input to nodes for storm drain network in SWMM. The results obtained from study clearly demonstrated usefulness and understanding of the storm network.

3.4 HEC-RAS

HEC-RAS was developed by the Hydrologic Engineering Center (HEC). HEC-RAS is a public domain software designed for interactive use in a multi-tasking environment. The system is comprised of a graphical user interface (GUI), separate analysis components, data storage and management capabilities, graphics and reporting facilities. It was designed to perform one-dimensional steady flow; and one and two-dimensional unsteady flow calculations for a full network of natural and constructed channels, overbank/floodplain areas, levee protected areas, sediment transport/mobile bed computations, and water temperature/water quality modeling (USACE, 2016). The software has the ability to import data from other software's like MIKE II cross section. Also, all its components use a common geometric data representation and common geometric and hydraulic computation routines. However, modelling skews of hydraulic structures is limited to zero, and cannot currently account for steep slopes above 10% inside the model.

Estimating the magnitude of flash flood including water velocity and depth for a river system can be simulated using HEC-RAS. Ezz (2017) used ArcGIS and HEC-RAS tools to model the water depths and velocities along a flood path on Assiut Plateau in Egypt using estimated peak discharge flows developed from high rainfall events uniformly over the Plateau. The predicted water levels were compared with the proposed road level passing through the flood path for two rainfall events scenarios. Both scenarios showed that the water levels in the flood path is safely lower from the proposed road. Yet, it was recommended to install a proper flood protection system at the intersection of the tributaries with the main flood path under the proposed road. This could help the decision makers in protecting the proposed road and to minimize flood hazards.

3.5 HEC-ResSim

HEC-ResSim is a public domain software developed by the U.S. Army Corps of Engineers, Institute for Water Resources, Hydrologic Engineering Center. It is used to model reservoir operations at one or more reservoirs for a variety of operational goals and constraints. The software simulates reservoir operations for flood management, low flow augmentation and water supply for planning studies, detailed reservoir regulation plan investigations, and real-time decision support. HEC-ResSim can represent both large and small scale reservoirs and reservoir systems through a network of elements (junctions, routing reaches, diversion, and reservoirs) that the user builds. The software can simulate single events or a full period of record using available time-steps (USACE, 2013). The software models improvement, efficiency and effectiveness of existing reservoir. However, it does not model water quality and, streamflow hydrographs are generated elsewhere and imported to the model.

Simulation of reservoir systems using HEC-ResSim was applied by Calvo-Gobbetti (2017) for evaluating of different projects for new water sources in the Panama Canal. The model was used to evaluate the discharges in spillways during the rainy months, hydroelectric generation at Gatun and Alhajuela Lakes, volumes available for navigation, municipal and industrial consumption at Gatun Lake and volumes supplied at Alhajuela Lake for municipal and industrial use. Comparison was made to the storage–yield relationships of the reservoir systems developed by Vogel et al., (1999).The results indicated the generality of storage–yield curves, which are similar to those developed by Vogel et al., (1999), and can be used as guides for the development of new water source projects.

4. Conclusion

Five hydrological models were reviewed: WEAP, HEC-HMS, SWMM, HEC-RAS and HEC-ResSim. Each model has its unique features and corresponding applications. Some of them are comprehensive in using hydrological processes distributed over space and time. The models are used for flood forecasting, water resource systems planning, watershed management, reservoir simulation, erosion and sedimentation, life loss and economic changes, land use and climate change etc. Furthermore, three different statistical performance evaluation criteria were discussed for model assessment and identifying its accuracy in simulation.

A proper knowledge of hydrologic processes and characteristics is necessary otherwise it will create adverse effect on model calibration. However, researches are still going on to make better predictions and to face major challenges.

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