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A Review on Theoretical Consideration and Types of Models in Hydrology

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ABSTRACT
The conception of modeling in hydrology is involved with relationships of water, climate, soil and land use. Moreover, hydrological models include temporal and spatial features. Behavior of each feature controlled by its own and therefore it makes a vast variety for types of hydrological models. Hydrological models are the main tools for hydrologists with different purposes to use such as water resource management, ground water modeling, urban and rural watershed management and so on. Many hydrological models have been developed and refined during the past four decades and it is required to fully understand their characteristics to effortlessly employ them. Therefore, hydrologists need to familiarize themselves with the classification of hydrological models and understand the theoretical definition behind them. However, in regard to this issue, only a few discrete studies had been done. Classification of hydrological models is not exact and different hydrologist may give different definitions. The reason is that the nature of models is often the same but many models have overlapping characteristics. Thus, this study was aimed at showing the dominant classifications for hydrological models alongside the different views from past to present but generally, they have common meaning even though they may be classified under different categories. In addition, although there are overlapping features in different hydrological models, their nature is not that hard to understand.

Key words: Watershed models, hydrological models, classification models

INTRODUCTION
Chow *et al*. (1988) stated that hydrology is a subject of great importance to human and the environment, which deals with all phases of the earth's water. Hydrology has many practical uses such as in the design and operation of hydraulic structure, water supply, wastewater, irrigation, flood control, erosion and sediment control, pollution abatement, recreational and so on (McCuen, 1998; Firouzi *et al*., 2010). Generally, hydrology science offers guidance for planning and management of water resources and it applies engineering and geography principles that are important for the study of hydrology (Davie, 2002). Thus, it is often difficult to separate them from one another, particularly when hydrologists enter into hydrological research and need to confront problems such as prediction of stream flows, precipitation, pollutant concentration point source, water level and etc. (ASCE, 2000).

Following the digital revolution in hydrology science since the 1960s, the power of computers has been remarkably recognized in this field. In fact, two ways of computation procedure released, namely the numerical and statistical simulations are often used in many researches. Advancement in watershed models was mainly on the improvement of the Stanford Watershed Model (SWM) developed by Crawford and Linsley (1966). Indeed, SWM was the first try for modeling hydrological cycle in watersheds. Then, there was development in a number of watershed hydrology models in the 1970s and 1980s by mathematical means. Singh and Frevert (2006) noted that the bureau of reclamation collected a list of 64 watershed hydrology models and divided them into four categories. Besides that, there are some literatures for collection of hydrological models (Singh and Frevert, 2002a, b). In addition, there are still some discussions on the development of the hydrological models and their capabilities and characteristics.

For the last four decades, researchers tried to formulate different characteristics of catchments in models, resulting in a plentiful of mathematical models for watersheds simulation used in evaluation of surface and ground water flow modeling (Alam *et al.*, 2011). Generally, these models vary from empirical to physical, or stochastic to distributed models. In this review, as there are limited literatures on classification of hydrological models, efforts are focused on the collection of basic information to get familiar with the hydrological models' nature and classification on the hydrological models with their definition terms (Jajarmizadeh *et al.*, 2011a, b). Having knowledge from classification of hydrological models and definition terms helps to improve understanding of model structures and their capability in use. All these will be further discussed in the subsequent sections. In this study, it was found that the features of hydrological models are the most important factor in classification.

BACKGROUND OF WATERSHED HYDROLOGY AND WATERSHED MODELS

A basin can be explained with a division by topographic or groundwater. It is defined as the terrain area contributing surface stream flow into a river network or to any point of interest (Chow *et al.*, 1988; Dingman, 2002; Viessman and Lewis, 2003). The features of a basin like geography, geology and land use have a significant role in specifying the quantity, quality and timing of stream flow. Watershed hydrology is regularly based on physical laws and protection of mass. Basic physics rules like the Newton's laws of motion and the law of thermodynamics are some important rules in studying hydrology. For the protection of mass concept, the hypothesis is that the quantity of water going into a catchment can be equivalent to the total of water going out of the basin. The net change in losses and storage throughout the watershed can be simplified using the following equation:

$$\text{Input water-Output water} = \text{Net change in losses and storage}$$

Nowadays, it seems hard to deal with problems of environment and water resources without applying some kind of watershed models (Tokar and Johnson, 1999). In fact, watershed models are the main tools in environmental and water resource problems such as water resource development, planning and management watersheds (Singh and Frevert, 2006). Thus, it will be beneficial to review the impacts of watershed management strategies linked to human actions for a basin to protect of environmental and water resources using watershed models (Rudra *et al.*, 1999; Mankin *et al.*, 1999).

MODELING

Models are constructed to serve as proof of an idealized logical structure and they are an important element of methodical theories (Adem, 2005). A model is an expression to show a part of the natural or human created world which can be in the form of a physical, analog or mathematical model (Dingman, 2002). As a simple definition for models, a physical model is defined as a scaled-down form of a real system (Brooks *et al*., 1991; Salarpour *et al*., 2011). The analog model is the result of a simulated process that is used to represent a natural process. Mathematical models, on the other hand, include clear chronological set of relation, numerical and logical steps that change numerical inputs into numerical outputs. Today, mathematical models are more preferred due to the rapid development of computer technology.

In terms of hydrological model, mathematical models were given more consideration starting the second half of the nineteenth century to estimate some related parameters such as maximum flow, surface runoff and so on. These models help to solve problems like design of drainage systems and dams, flood flow outlets and sewage systems. In other words, earlier mathematical models already started to serve as better decision making models for related project implementation. These models, until this very day, are faster and more economical methods. Other advantages include the fact that mathematical models give high speed and high accuracy calculations, which can avoid wasting time and making undesirable mathematical mistakes. On the contrary, deficiencies of a hydrologic model can be due to its user-unfriendliness, large data requirement, lack of reliable measuring and other unclear limitations (Singh and Frevert, 2006).

There are many hydrological models with unique and common characteristics that are being developed day by day (Wang *et al*., 1996; DHI, 2004). In this case, the unique and common characteristics of many models make classifications of hydrological models an important issue so that the capabilities and limitations of each model can be identified accurately. Proper classification can be helpful for engineers, experts and researchers to understand the characteristics of models before deciding to employ them for their works. However, the categorizations of hydrological models can be hammered by considerable overlapping characteristics among various classes of models. As a result, even the classification of hydrological models may vary depending on justification (Gosain *et al*., 2009).

BASIS OF HYDROLOGICAL MODELS

The American Society of Civil Engineers (ASCE) introduced the basic terms for various types of mathematical model, namely analytical models; deterministic models; dynamic models; empirical models; heuristic models; interactive models; linear and nonlinear models; numerical models; probabilistic (stochastic) models; semi-empirical models; simulation models and theoretical models (ASCE, 1982). However, comprehensively, hydrological models described by one or more terms are mostly mathematical structures from four basic categories, namely simulation basis, spatial representation, temporal representation and method of solution. Moreover, each category can be subdivided into more detailed subcategories. Simulation basis includes physically based, conceptual, empirical or regression and stochastic time series. In addition, spatial representation category consists of lumped, distributed and coordinate system, meanwhile temporal representation category comprises of steady state, steady-state seasonal, single-event and continuous representations. Finally, in the method of solution category, there are four classes, namely the 0-dimensional, formal-analytical and formal-numerical and hybrid solutions. Generally, these terms are the basis of classification and definition of hydrological models (Dingman, 2002).

PREVALENT TYPES OF CLASSIFICATIONS FOR HYDROLOGICAL MODELS

Shaw (1983) stated that the power of digital computers provides two main facilities-capability of carrying out huge numbers and calculations and capability to review the simulated projects. Through, these facilities, mathematical models are produced with logical programming languages to explain the land phase of hydrological cycle in space and time. By considering mathematic structures, hydrological models can be divided broadly in two categories, namely deterministic and stochastic. In deterministic category, conceptual models prevail and they are used to describe the catchment processes using mathematical rules, for example by an equation for evaporation. The stochastic models are more prominent in scientific studies because they consider the occurrence of events in space and times. In hydrology, stochastic models consider chronological results of hydrological events by aiming at explanation for the non- regularity of happening such as in the forecasting of floods (Azadi and Zakeri, 2010). Generally, the movement of water in a land phase is in a deterministic path, whereas its magnitude and time of various processes are stochastic. Therefore, a combination of deterministic and stochastic procedure provides an excellent modeling approach. Figure 1 presents the classification of hydrological models according to Shaw (1983).

Chow *et al.* (1988) stated that hydrological models can be classified into two major categories, namely physical models and abstract (mathematical) models. Furthermore, physical models can be divided into two classes again, namely scale models and analog models. A scale model can be called as a scaled down model of a real system and on the contrary, an analog model applies physical system having the same characteristic with the first sample.

Besides that, abstract models are used to show a system in a mathematical form. The model is operated with a set of equations, input and output data. Variables in these models can be as the representation of space and time or in the form of probabilistic and/or random variables. In this case, the classification of hydrological model can be further divided into two subcategories, namely stochastic and deterministic. A deterministic model does not give randomness, which means it models with a given input for all time and create the same output. A stochastic model, on the other hand, will produce outputs that have partial randomness. As a result, it is possible to say a deterministic model makes a forecast while a stochastic model creates a prediction (Chow, 1964). Figure 2 presents the classification of hydrological models according to Chow *et al.* (1988).

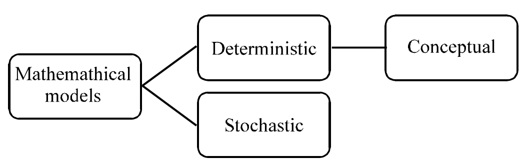

Fig. 1: Hydrological models classification by Shaw (1983)

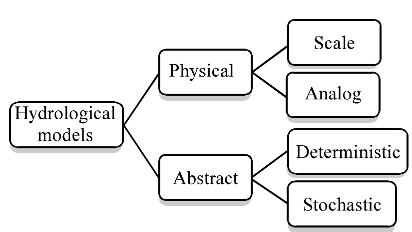

Fig. 2: Hydrological models classification by Chow *et al.* (1988)

Cunderlik (2003) further classified deterministic hydrologic models into three major categories. Firstly, the lumped model, which assess the catchment response simply at the outlet without obviously counting for individual sub-basins responses. Furthermore, the lumped processes regularly do not characterize physical characteristic of the hydrologic processes. Secondly, the semi-distributed model, which is partly permitted to change in space with division of catchment into an amount of sub-basins. The benefit of semi-distributed model is that it is a more physically-based structure in comparison with the lumped model. Moreover, it requires lesser amount of input data in contrast with the fully distributed model. The final model is the distributed model, which has its parameters permitted to change in place at a resolution normally chosen by the client. A distributed model usually requires large amount of data for parameterization (Arnold *et al.*, 1998). However, the main physical processes are processed in detail and therefore can offer the highest degree of accuracy. Nevertheless, Beven (2001) explains that the distributed model does have some problems with its nonlinearity, scale, uniqueness and uncertainty.

Willems (2000) considered that categories of hydrological models are totally based on the representation method of the hydrologic cycle. Indeed, the representation models can be classified according to their degree of representation of the concerned physical processes (Sajikumar and Thandaveswara, 1999). Normally, each individual representation model only represents one physical process and the model's input and output relation is explained with a large number of mathematical equations. Conceptual model can be as a more macroscopic explanation of the process in the classification of hydrological model. It means that processes are represented in the way they are observed and that an abstraction is made on the several microscopic processes that underlie the observation (Willems, 2000). Table 1 presents the classification of hydrological models according to Willems (2000).

In regard to mathematic equations, Oogatho (2006) noted that it can be used to define a new classification for hydrological models. Therefore, according to law and assumptions, the new classification consists of empirical models that come from experimentation or observed input-output correlations, besides those theoretical (physically-based) models which are derived from physical laws and assumptions. Empirical models can be further divided into deterministic model and stochastic model. A deterministic model has governing equations for every parameter under given condition. In contrast with the deterministic model, a stochastic model (probabilistic) applies probability equations for describing the parameters of model or input data partially or totally.

The other determining factor for the classification is based on the quality of input data processing. Spatial variability for input data is considered for distributed models but in lumped models, the variability is assumed to be homogeneous. In accordance to the time steps, hydrological models can also be divided into event-based (single-event) and continuous models. Event-based models simulate a specific event for a short time phase, while a continuous model can be applied

Table 1: Schematic overview of different model types as presented by Willems (2000)

Modeling types		
Detailed physically-based models	White box	Most model parameters can be measured
Partly physically-based models		
Conceptual models	Grey box	Model parameters need calibration (e.g. using measurements for model output variables)
Empirical models	Black box	Also the model-structure building depends on the measurements for the model output variables

Physically-based modeling level decreased descently for simulation of an event for several years. Another type of classification which will be mentioned here is the analytical and numerical models. For an analytical model, mathematical analysis is performed according to its governing equations. On the other hand, a numerical model uses arithmetic operations for its equations. Nevertheless, all mathematical models involved in the program or software are beneficial in evaluation of environment and under various conditions (Razi *et al.*, 2010). Figure 3 presents the classification of hydrological models according to the criteria mentioned above.

Lewarne (2009) stated that hydrological models can be classified into five groups in accordance to the definition of mathematical models under polar condition. Category one divides the models into two-linear and non-linear. In linear models, there is a simple correlation between the input and output data but for non-linear, there are chaos and irreversibility that make a model more difficult to study. Category two divides the models into deterministic and probabilistic (stochastic) models. Deterministic models have an initial given condition which is defined and parameterized. In comparison with deterministic models, probabilistic models have random structure and only present probable results. Category three divides the models into static and dynamic, where the time element plays a significant role. Dynamic models usually apply difference equations or differential equations in their structures in comparison with static models. In fact, dynamic models consider time as an independent variable (Viessman and Lewis, 2008). Category four is based on the role of parameters. Lumped models are for homogenous states in a system, whereas distributed models imply various states throughout a system. Generally, lumped models reduce difficulty and are more convenient. It is good to know that the selection of lumping or distributing models can be important, depending on the degree of accuracy regarding the characteristics of watersheds anticipated. Category five divides the models into physical and conceptual models. In a physically-based model, equations are applied in a modular situation to compatible physical processes in the hydrological cycle. However, a conceptual model applies data modeling with two interrelated processes, namely the logical and physical processes. The main aim of conceptual models is to show the meaning of a word or concepts by domain experts to explain on the problem and to find a proper correlation between them. In fact, conceptual models do not need to have empirical measurements. Figure 4 presents the classification of hydrological models according to their polar definitions.

Gosain *et al.* (2009) noted that a broad classification for hydrological models can emerge from the development of hydrological models from the old days but generally the models can be simply defined as a black-box, conceptual or deterministic model. Undoubtedly, there are also subdivisions for these categories.

Black-box models: Black-box models explain the relation of the input and output data mathematically (Nor *et al.*, 2007). In this type of model, physical processes are normally not under

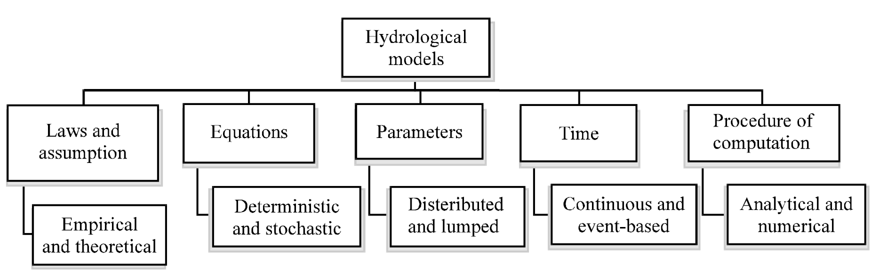

Fig. 3: Hydrological models classification by criteria

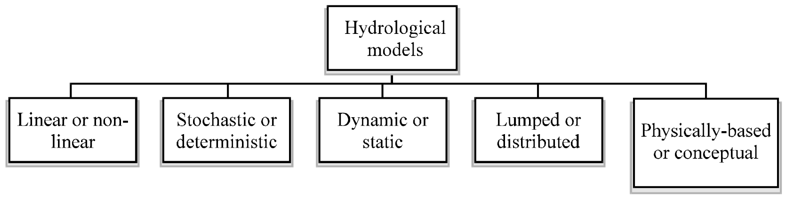

Fig. 4: Hydrological models in polar definition

consideration. These models are often good for modeling with available and analyzed data for specific region. It is logical to say that the main reason for the successfully performance of black-box models can be due to their mathematical structure underlying the physical system. Nevertheless, the prediction is entirely based on mathematics.

Deterministic models: Deterministic models have complex physical theory and need to have a large amount of data and computational time. Liddament *et al.* (1981) cited that due to the complexity and long computational time of these models, they are very expensive to develop and hard to work with (Gosain *et al.*, 2009). These models apply non-linear partial differential equations which describe the hydrologic processes. It is important to know that solutions based on analytical operation generally cannot solve the equations. One of the important advantages of the deterministic models is that they present the inside view of a process which enables better understanding of the hydrological system.

Conceptual models: As a simple definition, conceptual models are a substitution between deterministic and black-box models. Generally these models are formulated with a number of conceptual elements which are simple representations of a reference system. One of the advantages of conceptual models is its non-linearity which reflects the threshold presence in hydrological system. Based on the characterization of conceptual models, there is a classification that divides the models into event and continuous models. Event models simulate a system in a single event for a period ranging from an hour or less to several days (Salarpour *et al.*, 2011). On the other side, continuous models work over an extended period. One of the advantages of continuous models is that they can be more successful for un-gauged catchment and the study of a system's long term characteristics.

Clearly, proper parameters for conceptual models are very essential and the degree of accuracy for these models also depends heavily on the proper parameters. Based on this, conceptual models can be divided in two major groups, namely lumped and distributed models. Lumped models show the average characteristics of a system and water balance equation is the basis of a lumped conceptual model in hydrological models. In practice, water balance equations are applied in five classifications, namely groundwater aquifers, watersheds, farms, particular zone such as glaciers and urban water supply and demand (Ghandhari and Moghaddam, 2011). On the other hand, spatial variability is considered particularly in distributed conceptual models. One of the advantages of distributed conceptual models is the discretization of a system into a number of zones that have similar hydrological characteristics. For example, REA (representative element area), HRU (hydrological response units) and GRU (grouped response unit) are a few kinds of discretization in distributed conceptual model (Leon *et al.*, 2002; Neitsch *et al.*, 2005).

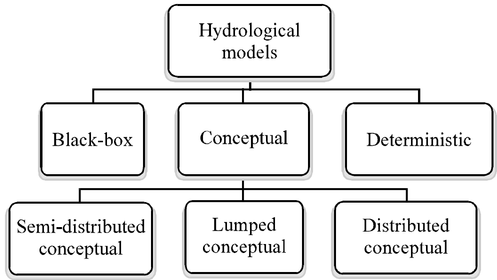

Fig. 5: Hydrological models classification by Gosain *et al.* (2009)

Semi-distributed conceptual models: To overcome the difficulties of distributed models, researchers developed another semi-distributed model as a compromise between lumped and fully distributed models. The algorithms in semi-distributed conceptual models are simple but physically-based (Arnold *et al.*, 1993). In these models, the average of observable physical characteristics in a catchment is used to represent spatial heterogeneity. Therefore, these models combine the distributed effects of contributing areas during modeling and the model parameters are estimated from measurements accessed in the field. Figure 5 presents the classification of hydrological models according to Gosain *et al.* (2009).

According to Wagener *et al.* (2004), a combination of linear and non-linear functions has been developed and implemented into software applications since the early 1960s. Wagener *et al.* (2004) hence developed a comprehensive definition for different classes of hydrological models to classify them into three major distinct classes called metric, parametric and mechanistic models. Metric models are also called data-based, black-box or empirical models, whereas parametric models are also named grey box or conceptual models (Dawson and Wilby, 2001). In addition, mechanistic models are called white box or physically-based models (Davie, 2002).

Metric models develop both the model corresponding parameter value and structure by using time-series information. They are in accordance to the information that is accessed from data and since there is no any prior knowledge about the hydrology process, they are called black-box models. Generally, metric models are spatially lumped and they model a system as a single unit. In contrast to metric models, parametric models are explained through the modeler's understanding of the hydrological system and for this reason they are termed conceptual models. Parametric models have a structure that is specified prior to their use and many modeled processes are integrated in spatial and temporal features into a single parameter that cannot be readily accessed through field measurement. Recently, an approach which is called semi-distribution has promoted the segmentation of a catchment into sub-catchments. Mechanistic models became practical in use since the 1980s due to improvement in computer power. Moreover, they are preferred because of its ability to conserve mass, momentum and energy. However, these models suffer from extreme data demand, scale-related problems and over parameterization. One characteristic of these models that is worthy of mention is their spatial discretization on grids and HRUs. This means that they become important and appropriate when high level of spatial discretization is needed in modeling. Figure 6 presents classification of hydrological models according to Wagener *et al.* (2004).

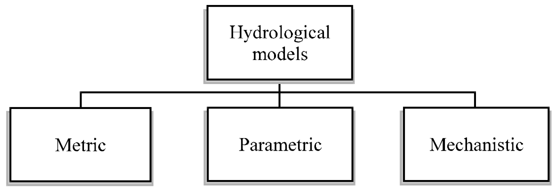

Fig. 6: Hydrological models classification by Wagener *et al*. (2004)

RESULTS AND DISCUSSION

There are different classifications of hydrological models that are all aimed to make the models simple to understand and operate. However, it should be noted that most hydrological models are not very different from each other, the main difference lies in their setting up and operating procedure, not in their concept.

An empirical model is a representation of a real system with mathematical explanation using experimental data without really trying to explain using general physical laws. This kind of model is developed by instinct, usually from research on simple data sets. Many primary hydrological models are empirical and have important role in developing science of hydrologic models. These models are invaluable in designing flood protection in basins when there is little or no gauging data. In these models, it is assumed that the catchment is static and climate boundary is unmodified. However, they cannot apply land use or soil moisture changes. An empirical model identifies the mean annual flood by a correlation. Another type of empirical model considers temporal variability and is applied in real-time flood forecasting. For example, IHACES and Instantaneous Unit Hydrograph (IUH) are empirical models that show unit hydrographs (Littlwood and Jakeman, 1994; Noorbakhsh *et al*., 2005). IHACRES applies the non-linear modules for processing of rainfall. Therefore, empirical models often use a statistical approach to perform a statistical analysis of data set for a given system under specified conditions. These statistical analyses are employed in two ways, namely linear and multiple regressions to provide relationship between variables.

Conceptual models are limited representations of the processes occurring in the hydrological system. Movement of water is often complicated in the land segment of hydrological cycle. Therefore, simplification of this process comes with conceptual models that assume the hydrology of the watersheds from precipitation to stream release at the outlet is like series of interlinked processes and storages (Noureddine and Martineau, 2005; Rahnama and Noury, 2008). Conceptual models work using mathematical technique and treat storages are as a reservoir for water budgets. In every stage of computation, conceptual models are treated as deterministic models because their models are in accordance to dissimilar storages and interchanges, where the combinations of processes and every structure needs to have specific data as input to give determined output within selected time intervals. Conceptual models are useful for various purposes. For example they can be used for infilling the lost data or reconstruction of flow sequences. Due to its easiness to formulate and that it needs relatively little computing resources; conceptual models are convenient to use. Not only conceptual models are suitable for a catchment's simulation, they can also be applied for simulation of water supply such as reservoir systems. In conceptual models, explanation of relationship between input and output data is readily available. Conceptual models are different from physically-based models because they are not based on physical processes; they simulate a behavior system based on perception. One of the most famous conceptual models is the Stanford Watershed Model by Crawford and Linsley (1966).

Physically-based models try to represent relevant process by physically considering the meaning of the full procedure in a hydrological system (Hapuarachchi *et al.*, 2003). These kinds of model can allow different prediction of a system under any condition because the physical processes and measurable system characteristics are the basis of determining the behavior of a system. In these models, it is assumed that collection of all data required by model is possible from field or laboratory. However, these models are so hard to develop that they can only be used in limited physical system or for specific research. Flood defense projects are suitable with physically-based models because these models provide a representation from relevant sections of a channel or river (Shokoohi, 2008). In fact, they can model the routing of flood in a channel with specified size and duration. An example of physically-based models is the SHE (Systeme Hydrologique Europeen) model, which is also complicated (Aboott *et al.*, 1986).

Spatial features in hydrological models: Hydrological models are sometimes classified as lumped, semi-distributed and distributed models because they can simulate any scale of the catchments. In this case, lumped models represent the complete hydrological system as a homogeneous unit. They do not give any information about the spatial distribution of input and output variables but they render the average situation of a system. It is important to know that many conceptual models are lumped models since the catchment is often represented by a series of conceptual stores that give spatially average treatment of the system. Generally, these models are suitable for large-scale area and are applied only for interpretation of main output in a model.

Semi-distributed or semi-lumped models lie between lumped and distributed models. Semi-distributed models are a kind of developed lumped models which consider a catchment as a series of lumped models. Therefore, a semi-distributed model simulates the average behavior through small homogeneous units for the entire catchment. These models demand less data in comparison with fully-distributed models but they have some of the disadvantages of lumped models.

Besides lumped and semi-distributed models, fully-distributed models are employed to calculate values for time-dependent variables at specific grid locations in a hydrological system. They can be used in any scale such as in experimental plots or entire watersheds. Fully-distributed models tend to be physically-based because all parameters can be measured. One of the main reasons to employ a fully-distributed model can be to acquire all related values. In fact, this can be a problem for this kind of models. Generally, fully-distributed models are time-consuming in setting up and they need considerable computer resources. Also, the generation of results takes a long time. However, they are useful tools for the development of groundwater resources or evaluation of the concepts of land use such as drainage networks, terrain slope, catchment boundaries and drainage divides (Ghaffari, 2011).

Temporal features in hydrological model: Hydrological models work based on time series or time steps. Sometimes, hydrological models are named temporarily distributed models when their results are distributed in time. Time steps in hydrological models give changing results according to time and obviously, for rapid changing in a subjected time, the time steps should be of short intervals spanning over a long time. Time steps can vary from one second to months in hydrological models and distributed models usually have shorter time steps than lumped models. For example, some distributed models work on a weekly time step (Rushton and Fawthrop, 1991). Longer time step will minimize the amount of calculation required but it is only good for short term simulation and it reflects the researcher's limited accessibility to time variant input data.

CONCLUSION

Development in the computing technology leads to new computation methods in hydrological science and computer modeling. For many years, hydrological models have been developed with different characteristics and purposes. In order to understand the configuration and operation procedures of the models, researchers have tried to define them through different classifications where most of them are based on mathematical definition. However, a definite classification for hydrological models is not possible as most models have overlapping characteristics (Gosain *et al.*, 2009). Different views make the diversity of hydrological models classifications to come under four basic terms, namely simulation basis, spatial presentation, temporal presentation and method of solution (Dingman, 2002). These categories show the comprehensive and explicit perspective of classifications for hydrological models. By comparing the different classifications and reviewing these from different aspects, a deeper understanding of the models' characteristics can be obtained. All in all, it can be concluded that proper classification helps experts to select and apply the desired hydrological models for their researchers and works. Also, different types of classifications for hydrological models actually have the same meaning in nature but they are categorized differently due to different views and overlapping characteristics.

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