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# RAINFALL-RIVERFLOW MODELLING APPROACHES: MAKING A CHOICE OF DATA-BASED MECHANISTIC MODELLING APPROACH FOR DATA LIMITED CATCHMENTS: A REVIEW

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## ABSTRACT

Hydrological modelling provides a means for the investigation of the interaction between climate and riverflow. It also acts as a vehicle for the assessment of the impact of human activities on hydrological regimes. Within this paper a review of some of the approaches employed in rainfall-riverflow modelling is presented. The paper highlights the rationale and structure of the modelling approaches, and their strengths and weaknesses which may assist in making an informed choice of a modelling approach for hydrological studies.

**Keywords**: DBM, blackbox, conceptual, modelling, physics-based.

## INTRODUCTION

Generally, in environmental science, modelling is the representation of a complex natural system in a simplified form through the use of logical mathematical statements. In hydrological modelling the complex natural system which is represented in a simplified form includes the components of the hydrological cycle and the processes within the cycle. The processes within the hydrological cycle usually include precipitation, evaporation, condensation, overland flow, infiltration, percolation and riverflow. Knowledge of the interactions between these components and the processes within them are very crucial because they provide the sustenance of mankind and nature as a whole.

Modelling techniques are employed to link these processes together and to simulate the natural system. Deterministic hydrologic models have some desirable properties. They allow explicit study of causal relations in the climate-water resources system for estimating the sensitivity of river basins to changing climatic conditions. In addition, when regional climatic forecasts are available, possible runoff changes in different hydro-climatic environments may be simulated for water planning and management. Perhaps the most comprehensive assessment of the effect of climate change on water resources was a recent report that focused on the US by the American Association for the Advancement of Science Panel on Climatic Variability, Climate Change and the Planning and Management of US Water Resources (Waggoner, 1990).

Generally, hydrological modelling is done to achieve one or more of the following objectives (Freeze and Harlan, 1969; Clarke, 1973; Chappell, 2005):

a) To extend riverflow records in areas where long rainfall records are available and the corresponding riverflow records are very short. In order to facilitate the planning of water supply provision and design of hydrological structures based on hydrologic extremes such as floods and droughts. A classical example of models applied to achieve this purpose is the Rational Method (Shaw, 1994; Beven, 2001a; Nyarko, 2002).
b) To synthesise past hydrological records in order to capture the long-term variation in the records, such as periodicity and trends (e.g. see: Young *et al*., 1997; Chappell *et al*., 2001; Koranteng and McGlade, 2001; Boochabun *et al*., 2004; Vongtanaboon, 2004).
c) To forecast riverflow in order to warn inhabitants of flood prone areas of looming danger in case of floods, to ensure rapid evacuation of life and properties and in hydropower generation projects, and identify when to open flood gates in order to prevent dam breaks. Riverflow forecasting techniques have been presented by Yazicigil *et al*. (1982), Liang (1988), Cluckie *et al*. (1990), Lees *et al*. (1994), Tsang (1995), Young and Beven (1994), Burnash (1995), Young (2002), and Damle and Yalcin (2007).
d) To predict possible changes in the hydrological system, particularly in riverflow, as a result of proposed physical changes within a catchment, such as, river abstraction, dam construction, and land-use changes (e.g. deforestation, agriculture and

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urbanisation). Such applications have been reported by Gellens and Roulin (1998) and Legesse *et al*. (2003).

e) To use modelling techniques as a vehicle to develop new hydrological theorems and greater understanding of processes (e.g. see: Young and Beven, 1994; Young *et al*., 1997; Sefton and Howarth, 1998; De Roo, 1998; Chappell *et al.*, 1999; Nyarko, 2002; Lhomme *et al*., 2004; Young, 2005; Chappell *et al.*, 2006; Jain *et al*., 2004).

Hydrological modelling approaches have been classified in numerous ways in the literature (e.g. see: Clarke, 1973; Freeze and Harlan, 1969; Beck, 1991; Wheater *et al*., 1993; Leavesley, 1994; Refsgaard, 1996; Legesse *et al*., 2003; Chappell, 2005) with some of the classifications having common characteristics. For example, classification based on the process description, scale and solution technique have been presented by Singh (1995b). In this study, following Chappell (2005), hydrological models have been classified as physics-based distributed models (white box models), conceptual models, black box models and Data Based Mechanistic (DBM) models.

Critical examination of these approaches, and their strengths and weaknesses is very useful and cannot be overemphasized because of the role hydrological modelling plays in water resource planning, development and management (Sellers, 1981; Servat and Dezetter, 1993; Venema, *et al*., 1996; Legesse *et al*., 2003; Nyarko, 2002). In this regard the paper presents a critical look at the rationale and structure of these models and their strengths and weaknesses which may be taken into account when a decision is to be taken in the choice of a model for a hydrological study. This may facilitates the selection of an appropriate modelling method among the available approaches as the primary modelling technique.

## Physics-based, distributed models

### Rationale and structure

The operation of physics-based distributed models is mainly based on the solution of well established hydrological laws by using numerical methods that maintain the mass balance of the system. Examples of these ‘laws’ are the Richards equation for unsaturated flow and Saint Venant equation for overland flow.

The Physics-based distributed modelling approach was first introduced by Freeze and Harlan (1969) in their blueprint for a physically-based, digitally-simulated hydrologic response model. Since then, several physics-based distributed modelling approaches have been developed. Examples include the Système Hydrologic Européen (SHE) model (Abbott *et al*., 1986a,b), Institute of Hydrology Distributed Model (IHDM) (Beven *et al*., 1987; Calver and Wood, 1995), MIKE SHE (Refsgaard and Storm, 1995; Refsgaard *et al.*, 1999), and Precipitation-Runoff Modelling System (PRMS) (Leavesley and Stannard, 1995).

### Strengths and weaknesses

Physics-based distributed models are capable of giving detailed spatial description of the hydrological processes taking place in a catchment and help to improve our understanding of the *modus operandi* of the hydrological system. They are, therefore, good tools for the simulation of the effects of land-use changes on hydrological response of a catchment (e.g. see: Legesse *et al*., 2003). Within the approach, many model parameters, which require process interpretation, are necessary (Beven, 1991; Beven and Binley, 1992; Wheater *et al*., 1993; Young, 2001).

Recent reports indicate that distributed hydrological models produce spatially explicit predictions that allow more detailed analysis in decision-making than the old fashioned lumped models. Managers in the environmental field usually query the magnitude of a hydrological attribute and occasionally query the spatial distribution of the attribute. The presence of spatial predictions has grown out of the increased availability of spatial data sets and cheaper computing power required to process these data (Grayson and Blo¨schl, 2000). Some notable issues relating to the uncertainty in such predictions is largely due to uncertainty in model inputs and structure. Quantifying the uncertainty in these predictions has been the subject of continued research and debate in the last two decades. Recognition of the limitations with distributed hydrological modelling has resulted in several general methodologies for assessing uncertainty being proposed and further research (Klemes, 1986; Beven, 1993; Refsgaard, 1997).

In Physics Based Distributed modelling field observations, data preparation and experimentation are very expensive and also require a lot of time. For instance, in the application of a distributed physics-based model (MIKE-SHE) in Zimbabwe by Refsgaard *et al*. (1995), data preparation alone included, the preparation of land-use maps from aerial photographs, collection of data on soil and vegetation characteristics, hydrogeology, water rights and digitisation of topographical maps. Andersen *et al*. (2001) also report that they used numerous data sets in the application of a modified form of MIKE-SHE in the Senegal River basin.

Beven (1989) points out that in the application of the SHE model to the Wye catchment in the United Kingdom, about 2400 catchment parameters were specified even without taking into account topographic parameters. These examples highlight the time, labour and the cost involved in the application of physics-based distributed models. Beside the time and the cost, the large number of parameters means that the set up and calibration of the model is very difficult. Most critically, the resulting model is structurally complex and highly parameterised (Beven, 1989; 2001b; Young, 2001; Chappell *et al.*, 2004b) with the computation based on the lumping of parameter and grid-cells usually of dimensions between 100 x 100 m and 1000 x 1000 m in surface area (Wheater *et al*., 1993).

Refsgaard *et al*. (1995) report that in their rainfall-riverflow modelling studies in catchments in Zimbabwe, no significant difference between the efficiency of physics-based distributed model in simulating riverflow as compared to a simple lumped conceptual model (NAM) was found. Based on the cost and the time involved in setting up the model, they recommended that simple lumped conceptual models like the NAM should be used in such studies. This recommendation has also been emphasised by Storm and Refsgaard (1996).

## Conceptual models

### Rationale and structure

In hydrology, conceptual modelling is the numerical modelling procedure where the representation of the complex hydrological processes within a catchment in a simplified form is based on the perception of the hydrologist of the essential component processes within the catchment e.g. overland flow, riverflow and soil moisture storage. Within this methodology, model parameters are normally optimised by calibration to observed data (Blackie, 1979; Refsgaard, 1996). Generally, two types of conceptual models are employed in hydrological modelling. These are lumped conceptual and semi-distributed, conceptual models.

The lumped conceptual model averages all the parameters in the model and any other variables over the whole catchment. The Stanford Watershed Model (SWM) which was first introduced by Crawford and Linsley (1966) is a typical example of a lumped conceptual model. The model considers the catchment as a series of stores linked together, through which precipitation is transformed into riverflow.

Since the introduction of the SWM, several lumped conceptual rainfall-riverflow models have been developed. These include Institute of Hydrology Lumped Conceptual Model applied by Blackie (1979) to investigate possible interpretations of water balance data in the Kericho and Kimakia catchments in East Africa, the application of the NAM Model in rainfall- riverflow modelling studies in Zimbabwe (Refsgaard *et al*., 1995), the SMAR in rainfall-riverflow modelling studies in the Kilombero River basin in Tanzania (Yawson *et al.*, 2005), the ACRU model to investigate catchment changes and hydrological response in the Densu catchment in Ghana (Bekoe, 2005), the TANK model (see: Tingsanchali and Gautam, 2000) and others which may be found in Shaw (1994) and Singh (1995a).

Semi-distributed, conceptual models are conceptual models which take into account of some of the spatial characteristics of the catchment while other characteristics within the model are lumped over the entire catchment, like lumped conceptual models. Models which have been developed using this concept include BROOK, MAGIC, WEPP, HEC-HMS, TOPMODEL and ARNO. TOPMODEL takes into account the spatial distribution of the topographic index (Beven and Kirkby, 1979; Beven *et al*., 1984; Quinn *et al.*,1991; Beven *et al*., 1995; Beven, 1997) while the ARNO model integrates the geomorphology of the catchment such as average catchment elevation, catchment surface area and length of the stream into the model (Todini, 1996).

### Strengths and weaknesses

Conceptual models have fewer parameters and simpler model structure and tend to be less time consuming and cost effective to parameterise as compared to physics-based distributed models. They are usually used: (i) in rainfall-riverflow modelling, typically for the extension of riverflow records when long rainfall records are available, (ii) for riverflow forecasting (Blackie, 1979; Refsgaard, 1996; Yawson *et al*., 2005) and (iii) to aid in the understanding of hydrological phenomenon; a key example is TOPMODEL (Beven and Kirkby, 1979; Beven *et al*., 1984; Beven *et al*., 1995; Beven, 1997). In spite of the good attributes of conceptual models outlined above, there are problems with their application in hydrological modelling. Some of the problems summarised from Beven (1989), Franchini and Pacciani (1991) and Chappell (2005) are as follows:

a) Errors are introduced in the model structure because of the approximation in the equations used to represent the processes within the catchment.
b) Heterogeneities may need to be described explicitly to properly describe processes.
c) Errors in the observed rainfall input and riverflow output usually lead to errors in model parameters calibrated.
d) If an attempt is made to simulate all the important hydrological processes conceptualised within a catchment, the model will become too complex and parameter estimates too uncertain for use.

In addition to the numerous problems associated with the application of the conceptual techniques highlighted above, they may be inaccurate for the prediction of the effects of land-use changes in a catchment. This is because their development is generally based on prior assumptions of the dominant behaviour of the hydrological system and these may not be accurate (Blackie, 1979; Refsgaard *et al*., 1995; Refsgaard, 1996; Tingsanchali and Gautam, 2000; Yawson *et al*., 2005). Another difficulty in the application of conceptual models is that they require the model builder or operator to have a good knowledge of both the operation within the model and the hydrological processes within the catchment in order to obtain realistic simulations.

### Black box models

#### Rationale and structure

Black Box models are statistical techniques or empirical relationships used in hydrological modelling to relate rainfall (input) directly to riverflow (output) without taking into account the physical hydrological process as taking place within the hydrological system (catchment). Within this methodology the simulation of the output response from the input is mainly based on time-series records from the catchment under study. These models have no physical meaning and are usually used to predict floods within a short term with least uncertainty (Chappell, 2005).

A typical example of Black Box models applied in hydrological studies is the unit hydrograph method by Sherman (1932). It is a simple method which assumes linearity, superposition and time invariant relationship between the input and the output responses. Detailed description and the derivation of the procedure abounds in the literature (e.g. see: Mutreja, 1980; Linsley *et al*., 1988; Shaw, 1994). The application of Black Box modelling techniques in hydrological studies has been presented by Liang (1988), Liang and Nash (1988), Liang *et al.* (1994), Duban *et al*. (1993), Kothyari and Singh (1999) and others. Beside the unit hydrograph method, Artificial Neural Network (ANN) models, which are also Black Box models, have attracted a great deal of attention in hydrological studies in recent years (e.g. see: Hsu *et al*., 1995; Raman and Sunilkumar, 1995; Kumar and Thandaveswara, 1999; Zealand *et al*., 1999; Ahmed and Simonovic, 2005; Chian *et al*., 2007).

#### Strengths and weaknesses

The application of Black Box models in hydrology is less data intensive and hence cost effective, because the models can be developed by circumventing the complex hydrological processes which take place within a catchment. Unlike conceptual and physics-based distributed models, the model operator does not require any prior knowledge on catchment processes before applying the model. A difficulty in the application of Black Box models in hydrology is that, modification of the internal structures of the models according to a land-use change is normally not possible and, therefore, renders these sorts of models unsuitable for land-use studies. Hydrological (or climatic) processes also cannot be interpreted from these models.

### Data-based mechanistic models

#### Rationale and structure

Data-Based Mechanistic (DBM) modelling (Beck and Young, 1975; Whitehead and Young, 1975; Young, 1978, 1983, 1984, 1986, 1992, 1993; Young and Minchin, 1991; Young and Lees, 1993) is a modelling technology gaining credence in recent hydrological science (e.g. see: Young and Beven, 1994; Tsang, 1995; Young *et al*., 1997; Young, 1998, 2001, 2002, 2003, 2005; Chappell *et al*., 1999, 2001, 2004a, 2004b, 2006; Lees, 2000; Mwakalila *et al*., 2001; Bidin, 2004; Bidin *et al*., 2004; Vongtanaboon, 2004; Vongtanaboon and Chappell, 2004; Romanowicz *et al*., 2006; Vigiak *et al*., 2006; Solera-Garcia *et al*., 2006). The DBM approach involves three steps, resulting in efficient, simple and ‘parsimonious’ models (Young and Beven, 1994; Young *et al*., 1997; Young, 1998; Chappell *et al*., 1999, 2004b, 2006; Lees, 2000; Romanowicz *et al*., 2006).

These 3 steps are:

a) Extraction of information from the rainfall and riverflow records by fitting models to the data.
b) Identification of a range of models and their associated hydrological system parameters using objective statistical tests.
c) Selection of the model with the most plausible physical explanation of the data.

The various DBM routines within the 3 stages can be found in the DBM-CAPTAIN toolbox (see: Taylor *et al*., 2007).

The DBM approach is a modelling technique which does not make prior assumptions about the complex hydrological processes operating within a catchment. The approach, unlike physics-based and conceptual modelling techniques, which fit data to preconceived ideas, allows the data to speak for itself (i.e. the data defines the model). It identifies the nature and structure of the model directly from the observed hydrological data series in an objective manner, using statistical identification and estimation methods.

The technique identifies a range of models, often incorporating transfer functions, time-variable parameters and nonlinear dynamics which are capable of simulating the hydrologic response of the catchment efficiently and without over-parameterisation. The statistically acceptable model which has the most sensible physical interpretation is then accepted (Young and Beven, 1994; Young *et al*., 1997; Chappell *et al*., 1999). In effect, the DBM approach is the combination of Black Box (metric) and Physics-Based (white box) approaches as conceptual to hydrological modelling. Such models have been classified as Hybrid Metric Conceptual (HMC) models by Wheatear *et al*. (1993).

#### Strengths and weaknesses

In the DBM approach, there is no need to assume the nature of the hydrological system, and define an uncertain structure of the model, prior to any analysis (i.e. the model is not constrained by pre-conceived and possibly false ideas). For example, the assumption of a single quick and a single slow flow pathways is not fixed prior to modelling (e.g. see: Sefton and Howarth, 1998), but only described in these terms after the modelling if appropriate (Young and Beven, 1994; Young *et al*., 1997; Chappell *et al*., 1999). This contrasts with the sort of structural information that cannot be interpreted from Black Box models (e.g. ANN models: Hsu *et al*., 1995; Raman and Sunilkumar, 1995; Kumar and Thandaveswara, 1999). Furthermore, the DBM approach does not normally assume the nature of nonlinear behaviour of the hydrological system. It is rather identified through the application of non-parametric and parametric statistical procedure (e.g. see: Young, 1993, 2001, 2006; Young and Beven, 1994; Chappell *et al*., 1999). However, assumptions could be made, if information on the nonlinear behaviour of the hydrological system is available, from past DBM modelling.

DBM models are less data intensive and very cost effective as compared to physics-based, distributed and conceptual models, because the models can be identified without spatially distributed field parameterisation (of permeability, porosity etc) within a catchment. The model requires smaller number of parameters. For instance, in rainfall-riverflow modelling, reported by studies which have applied the technique, less than ten parameters were required (e.g. see: Young and Beven, 1994; Young *et al*., 1997; Chappell *et al*., 1999, 2004a, 2006; Lees, 2000; Ampadu, 2007) as compared to the numerous parameters required by physics-based, distributed models (e.g. see: Abbott *et al*., 1986a, b; Beven *et al*., 1987; Beven, 1989; Refsgaard and Storm, 1995; Refsgaard *et al*., 1995; Anderson *et al*., 2001).

In rainfall-riverflow modelling, rainfall alone could be used as input by the approach to obtain a model (e.g. see: Young *et al*., 1997; Lees, 2000; Chappell *et al*., 1999, 2004a, 2004b; Young, 2005; Ampadu, 2007). For instance, in the application of the technique by Young *et al*. (1997) and Chappell *et al*. (2004a), DBM models using only rainfall as input explained 95.8% and 88% of the dynamics of the riverflow, respectively. These studies highlight the cost effectiveness of the technique in terms of input data required. The approach is also capable of quantifying the uncertainty in the estimated parameters explicitly, and because a smaller number of parameters are required by the model, the parameter uncertainty is less.

The DBM routines ideally require data which is rich enough to completely identify the dominant modes of the behaviour of the hydrological system. The absence of such data leads to greater uncertainty in the resultant simulations and parameter estimate (e.g. time constant).

### Choice of a model

The modelling approaches discussed above have been used successfully in numerous hydrological studies. In selecting a modelling procedure for hydrological studies the key issue at stake is, can the model achieve our aims and objectives? Many models may have the ability to help us to achieve our aims, but we are limited by financial constraints, and in some parts of the world there is the problem of availability of spatially-distributed data and even human resources to undertake the simulations.

In carrying out hydrological modelling studies there is, therefore, the need to search for an economic and efficient approach. Thus, a modelling procedure which requires a smaller number of parameters to be defined and fewer time series inputs, have the ability to avoid over parameterisation, can give physical interpretation of the resulting model and above all can be consistent with the local hydrology (Mwakalila *et al*., 2001; Bidin *et al*., 2004; Boochabun *et al*., 2004; Chappell *et al*., 1999, 2001, 2004a, 2004b, 2006; Vongtanaboon and Chappell, 2004; Vongtanaboon, 2004).

Considering the study area, the objectives of the study, and a choice of an economic approach and efficient model as defined here, the model technique which appeared to be appropriate choice among the approaches available could therefore be selected as the primary modelling technique.

### Choice of a model for data limited catchments

The DBM approach as highlighted in above is advantageous for application in data limited catchments as usually found in Africa, as compared to the other methodologies because it results in simple models with parameters which are meaningful and interpretable in a hydrological sense. The technique also quantifies explicitly, the uncertainty in the estimated parameters and because, a smaller number of parameters are required, parameter uncertainty is much reduced. The approach is also economical as compared to physics-based distributed models, and could even utilise only rainfall, to derive effective model which could explain the variance in the riverflow dynamics. These attributes of the approach form the basis for its recommendation for application in data limited catchments.

## CONCLUSION

A review of modelling approaches used in rainfall-riverflow modelling, namely Physics-Based Distributed, Conceptual, Black Box and DBM approaches have been presented in this paper. These include their rationale and structure, strengths and weaknesses. Physics-based distributed models take into account all the hydrological processes taking place within the catchment by solving numerical equations based on hydrological laws of the catchment. This type of model requires several data inputs and parameters which need to be measured, thus making its operation highly expensive and time consuming. However, they are good tools for the simulation of the effects of land-use changes on hydrological response of a catchment.

Conceptual modelling approach is based on the perception of the hydrologist of the dominant hydrological processes within the catchment and depends on the successful application of the expertise of the hydrologist on the local hydrological system. The model inputs and parameters are fewer as compared to physics-based, distributed models. However, if all the important hydrological processes conceptualised within a catchment are to be simulated, the model will become complex and cumbersome to calibrate. The model structure is subject to errors due to approximation in the equations which represent the processes. The approach may not give accurate information about the flow pathways within the catchment because of the over simplification or derivations originally developed for another catchment with a very different hydrological response.

Black Box models require few input data and parameters but they are not able to provide physical interpretation of the hydrological system. Their internal operations cannot be seen, and are therefore, not suitable for studies on the a) effects of internal controls or components in the overall river response, b) effects of land-use change on hydrological system or c) planning and management of catchment activities. A key advantage of the Black Box models is that the model operator does not need to have any knowledge of the local hydrological system in order to calibrate the model parameters and simulate river response.

The DBM models require few data inputs and parameters. They do not make prior assumption of the nonlinear behaviour of the hydrological system unless it has been quantified by past DBM modelling. The approach is capable of quantifying the uncertainty in the parameters and because few parameters are required the parameter uncertainty is less. However, the approach requires data which is rich enough to completely identify the dominant modes of the behaviour of the hydrological system and the lack of this type of data results in greater uncertainty in the simulations and the parameters.

Modelling hydrological response requires an approach which is very robust, data economic and above all can also give physical interpretation of the resulting model. The hydrological modeller will therefore make an objective choice of a model for a hydrological study if information on the rationale and structure and the strengths and weaknesses of the model are made available as presented in above.

Modelling hydrological response in a data limited region requires an approach which is very robust, data economic and above all can also give physical interpretation of the resulting model. Such an approach is the recommended DBM methodology.

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