ACTA GEOGRAPHICA UNIVERSITATIS COMENIANAE, Vol. 54, 2010, No. 2, pp. 173-181

RAINFALL-RUNOFF MODELLING: ITS DEVELOPMENT, CLASSIFICATION AND POSSIBLE APPLICATIONS

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Abstract: This short introduction into the rainfall-runoff modelling aims to summarize available resources. The focus is given on the definition of modelling and its history, as well as on the classification of rainfall-runoff models, their applications, strengths, weaknesses, and possible future development.

Key words: rainfall-runoff modelling, history, classification, future development

1 INTRODUCTION

The first half of the 20th century is considered to be the beginning of the dynamic development of rainfall-runoff modelling. Since 1950‘s the whole process was even faster thanks to the rapid advancement of technology. At present, it is possible to find models of various complexity designed for various problems in specific watershed conditions. With diversity of models increases the need of their better understanding in order to be able to choose a suitable one.

This short survey offers a basic description of rainfall-runoff models. The main aim is to describe the process of their development, to point out the most important differences in the structure of models, to identify the strengths and weaknesses of currently used models and to sketch some of the future challenges of rainfall-runoff modeling.

2 DEFINITION OF RAINFALL-RUNOFF MODEL

Model is a simplified representation of a real-world system (Wheather, Sorooshian and Sharma, 2008). Similar definition was introduced by Wainwright and Mulligan (2004), who define model as an abstraction of reality in the simplest way that is adequate for the purpose of the modelling. The best model, according to them, is always that which achieves the greatest realism with the least parameter and model complexity.

Huggett (1980) understands model as a system of inter-related components and the relationships between them. The system analysis involves the breaking down its complexity into simple manageable subsystems connected by flows of causality, matter, energy or information. The purpose of systems analysis is to make complex systems more easily understood.

Singh and Frevet (2006) define a concept of watershed models. According to them, watershed models simulate natural processes of the flow of water, sediment, chemicals, nutrients, and microbial organisms within watersheds, as well as quantify the impact of human activities on these processes. Simulation of these processes plays a fundamental role in addressing a range of water resources, environmental, and social problems.

Beven (2001) differentiate three kinds of models in the process of rainfall-runoff modelling, namely perceptual, conceptual and procedural model. The perceptual model is the summary of modeller's perceptions of how the catchment responds to rainfall under different conditions. A perceptual model is necessarily personal. However, a mathematical description is the first stage in the formulation of a model that will make quantitative predictions. The mathematic description is called the conceptual model of the process. By using techniques of numerical analysis one defines a procedural model in the form of the code that will run on the computer.

3 HISTORY OF RAINFALL-RUNOFF MODELLING

The history of scientific rainfall-runoff modelling begun about 3 centuries ago with the report on quantitative measurements in hydrology published by P. Perreault in 1674 (Linsley, 1982 in Mishra and Singh, 2003). By comparing the measured annual rainfall (P_a) and the estimated annual streamflow (Q_a) of the Seine river near Paris, Perreault described a functional relationship as $Q_a = P_a/6$. In the context of modern hydrology, the development of this P_a-Q_a relationship is very primitive, but it was a major finding of the time. It is worth noting that concept of computing runoff as a percentage of rainfall is still in use after 325 years (Mishra and Singh, 2003).

Most of the historical developmental works in the field of rainfall-runoff modelling took place in the first half of the 20th century. The decade of the 1930's experienced an outburst on all fronts of hydrology. As an example serves Sherman's unit hydrograph method elaborated in 1932, to simulate location-specific river runoff with a very simple parameterization and data input. Clearly introduced before the availability of high performance and relatively inexpensive computers, this method "was to dominate the hydrology for more than a quarter of a century, and is one which is still in widespread use today" (Anderson and Burt, 1985 in Moradkhani and Sorooshian, 2008). The Hortonian infiltration theory, introduced in 1933, is another such example (Singh and Frevert, 2002).

According to Mishra and Singh (2003), the Second World War during 1940 – 1945 brought a temporary setback to hydrological advances and the subsequent period from 1945 to 1950 was a period of pause and consolidation.

An extensive acceleration of new discoveries in rainfall-runoff modelling emerged with a digital revolution in 1960's, when the development of models has gone hand-in-hand with increase of computing power. Thanks to new technologies, modellers' focus was shifted from event-based models (originated in the 1930's) to the first hydrological models for continuous simulation of rainfall-runoff processes (emerging in the 1960's with computing power) (Wheather, Sorooshian and Sharma, 2008). The digital revolution triggered also two other revolutions, namely, numerical simulation and statistical simulation (Singh and Frevert, 2006).

Later, in the 1970's and 1980's, advancement in computer technologies enabled physically-based hydrological models to be developed. In the meantime, the rainfall-runoff models started to be applied in areas such as environmental and ecosystems management (Singh and Frevert, 2002).

The engineering viewpoint was stated by Shaw (2005): although many improvements of rainfall-runoff modelling appeared in the 1950s and 1960s, it is only in the last 20 years that the practising engineer has had an access to more powerful computers, and therefore many of the advances in hydrological analysis have remained as research tools. From the 1990s, some of the new techniques are being applied more widely in solving engineering problems.

One of the first conceptual models is the Stanford Watershed Model (SWM) elaborated by Crawford and Linsley in 1966. It was one of the first models trying to model virtually the entire hydrologic cycle (Singh and Frevert, 2006). Over the 40-year evolution of the SWM, it was transformed into its current embodiment as Hydrological Simulation Program FORTRAN (HSPF) within the U.S. EPA Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) system. (Donigian and Imhoff, 2006).

Later on, number of physically-based watershed hydrology models were constructed, e.g. Storm Water Management Model (SWMM), Precipitation-Runoff Modelling System (PRMS), National Weather Service (NWS) River Forecast System, Streamflow Synthesis and Reservoir Regulation (SSARR), Systeme Hydrologique Europeen (SHE), TOPMODEL, Institute of Hydrology Distributed Model (IHDM) and others (Singh and Frevert, 2006).

All of these models have since been significantly improved. SWM, now called Hydrological Simulation Program-Fortran (HSPF), is far more comprehensive than its original version. SHE has been extended to include sediment transport and is applicable at the scale of a river basin (Bathurst et al., 1995 in Singh and Frevert, 2006). TOPMODEL has been extended to contain increased catchment information, more physically based processes, and improved parameter estimation.

In the area of the central Europe various hydrological models have been applied. Changes in the runoff regime due to land use change were estimated using the physically-based with distributed parameters FRIER (Horvát et al., 2009), deterministic lumped model HEC-HMS (Jeníček, 2009; Šraj et al., 2010), semi-distributed model TOPMODEL (Kostka and Holko, 2001) and distributed model HYDROG (Unucka and Adamec, 2008). The impact of land use on floods was studied by spatially distributed model WetSpa (Poórová et al., 2005). The long-term trend of snow water equivalent was modelled by HBV-light model (Pekárová and Hamalová, 2009) and the erosion caused by snowmelt runoff by AGNPS (Pekárová and Miklánek, 2007). Multilinear flood routing model using empirical wave-speed discharge relationships was applied by Szolgay et al. (2008). Several SARIMA models were tested for the long-term prediction of selected pollutant concentrations under various flow and water temperature conditions (Pekárová et al., 2009). The potential impact of climate change on the mean monthly runoff using was evaluated by a conceptual Hydrological balance model (Hlavčová et al., 2008). The comparison of methods for estimating rainfall-runoff model parameters in ungauged basins based on geographical location was presented by Zvolenský et al. (2008). The calibration of NLC, HBV, NAM and HRON models was realized in the catchment of the river Čierny Hron (Kyselová, Podolinská and Šipikalová, 2006).

4 CLASSIFICATION OF RAINFALL-RUNOFF MODELS

The most common applied classification of rainfall-runoff models divides models into three classes: metric (also called data-based, empirical or black box), parametric (also called conceptual, explicit soil moisture accounting or grey box), and mechanistic (also called physically based or white box) model structures.

Metric models, according to Wagener, Weather and Gupta (2004) are empirical models which commonly derive both the model structure and the corresponding parameter values from available time-series. They are therefore purely based on the information retrieved from the data and do not include any prior knowledge about catchment behaviour and flow processes, hence the name black box. Metric models treat the catchment as a single unit. Mulligan and Wainwright (2004) argue that metric models have high predictive power but low explanatory depth, they are thus rather specific to the conditions under which data were collected and cannot be generalized easily for application to other conditions (i.e. other catchments, other forests, other latitudes). Among the currently most popular examples of metric models are those based on artificial neural networks (e.g. Hsu, Gupta and Sorooshian, 1995, Agarwal, Jain, Senthil Kumar and Sudheer, 2004) and transfer functions (e.g. Hubert, Lovejoy, Pecknold, Schertzer, and Tessier, 1996).

Parametric models (Wagener, Weather and Gupta, 2004) are based on the modelling of storages (also called reservoirs), which are filled through fluxes such as rainfall, infiltration or percolation, and emptied through evapotranspiration, runoff, drainage, etc. The structure of parametric models is specified prior to their use and, in contrast to metric models, is defined by the modeller's understanding of the hydrological system. However, these models still rely on time-series of system output, to derive the values of their parameters in a calibration procedure. The parameters describe aspects such as the size of the storage elements or the distribution of flow between them. Most of these models consider the catchment as a single homogeneous unit. The model form originated in the 1960's, when computing power for the first time allowed integrated representation of the terrestrial phase of the hydrological cycle to generate continuous flowsequences (Wheather, Sorooshian and Sharma, 2008). The Stanford Watershed Model is one of the earliest and, with some 16 – 24 parameters, one of the more complex examples. At present, parametric models make up the vast majority of models used in practical applications. Their dependence on flow measurements makes it difficult to apply them to ungauged catchments where lack of information is inevitable, hence the problem of non-identifiability, also called equifinality, arises. However, regionalization approaches, i.e., the attempt to derive statistical relationships between model parameters and catchment characteristics, have been developed which try to overcome this problem. This has been achieved with only limited success so far.

Mechanistic models are models explicitly based on understanding of the physics of hydrological processes and are characterized by parameters that are in principle measurable and have a direct physical significance. They use a spatial discretization based on grids, hillslopes or some type of hydrologic response unit and are therefore particularly appropriate when a high level of spatial discretization is important (Refsgaard and Abbott, 1996 in Wagener, Weather and Gupta, 2004). However, if the main interest simply lies in the estimation of streamflow response at the catchment scale and if calibration data are available, then parametric models normally perform usually at least as well. Extreme data demand, scale-related problems and over-parameterization of models caused that the expectation of their application to ungauged catchments has not been yet fulfilled (Refsgaard and Knutsen, 1996 in Wagener, Weather and Gupta, 2004). Mechanistic based models tend to have good explanatory depth, although on the other hand, they are characterized by low predictive power (Wainwright and Mulligan, 2004). They first became feasible in the 1970s when computing power became sufficient to solve the relevant coupled partial differential equations. One of the best known models is the Systeme Hydrologique Européen (SHE) model, originally developed as a multi-national European research collaboration.

Models can be divided according to the mathematics of models into deterministic and stochastic models. Deterministic models are characterized by the same output when a single set of inputs is given, meanwhile in stochastic models a single set of inputs can produce very different outputs because of random processes within the model.

Further subdivision of rainfall-runoff models is according to spatial representation. In lumped models, the entire river basin is taken as one unit where spatial variability is disregarded (Moradkhani and Sorooshian, 2008). In such a modelling approach the outputs are elaborated without considering the spatial processes, patterns and organization of the catchment. Semi-distributed models may adopt a lumped representation for individual subcatchments. Distributed models break space into discrete units, usually square cells (rasters) or triangular irregular networks (TIN) or irregular objects so the parameters, inputs, and outputs vary spatially. There other spatial classification divides models into one-dimensional, two-dimensional and three-dimensional.

Finally, one has to consider the time representation. Static models exclude time in the process of modelling whereas dynamic ones include it explicitly. Another classification divides models into event-based models, which produce output only for specific time periods and into continuous models, which produce continuous output (Wheather, Sorooshian and Sharma, 2008).

5 APPLICATION OF RAINFALL-RUNOFF MODELS

The tasks for which rainfall-runoff models are used are diverse, and the scale of applications ranges from small catchments, of the order of a few hectares, to that of global models (Wheather, Sorooshian and Sharma, 2008).

Typical tasks for hydrological simulation models include: modelling of gauged catchments (e.g. modelling of river behaviour, real-time flood forecasting, adjusting and evaluation of water resource management); runoff estimation of ungauged catchments; effects of rivers' activity (erosion, sedimentation); prediction of catchment response to changed conditions (e.g. land use change, climate change) and water quality investigations (e.g. nutrients, migration of microbes, salinity and alkalinity of soils, acid precipitation, nonpoint source pollution).

In contemporary practise, rainfall-runoff models are standard tools routinely used for hydrological investigations in engineering and environmental science. Also the topic of watershed management gains an increased attention. Some of the models are also employed in military operations (Singh and Frevert, 2006).

6 FUTURE OF RAINFALL-RUNOFF MODELS

Singh and Frevet (2006) argue that the multitude of watershed models and so their diversity is one the major strengths of the current generation of models. Many of these models are quite comprehensive, mimic reasonably well the physics of the underlying hydrologic processes and are also distributed in space and time. Several of the models attempt to integrate ecosystems and ecology, environmental components, biosystems, geochemistry, atmospheric sciences, and coastal processes with hydrology.

The most ubiquitous deficiencies of the models are their lack of user-friendliness, large data requirements, lack of quantitative measures of their reliability, clear statement of their limitations, and clear guidance as to the conditions for their applicability.

To be able to challenge future, watershed hydrology models will have to embrace rapid advances occurring in remote sensing and satellite technology, geographical information systems, data base management systems, error analysis, risk and reliability analysis, and expert systems. With advancement of technologies increases the probability of development of distributed model for both gauged and ungauged watersheds. Important topic will be also efficiency of storing, retrieving, managing and manipulating of large quantities of data. As challenge is seen the idea that models will become practical tools. In that case they will have to be relatively easy to use with a clear statement of their accuracy. They will need to assess the errors and define the reliability with which they accomplish their intended functions.

7 CONCLUSION

Although rainfall-runoff modelling has already achieved important advancement in the past hundred years, there is still wide room for its further development. Mainly, the introduction of computing technologies offered, and is still offering, a lot of new possibilities. The question is how rainfall-runoff modelling is able to embrace and apply them. Therefore, the application of remote sensing, satellite technology, geographical information systems into modelling as well as efficient work with large data sets and clear defining of reliability of models have already become a subject for further discussion. Clarity, multi-functionality and applicability on the gauged and also ungauged catchments may be in the future considered as one of the criteria.

Acknowledgement

This work was supported by the project UK/79/2010.

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Rainfall-runoff modelling: its development, classification and possible application

Summary

Rainfall-runoff modelling is an elaboration of the model, which is a simplified representation of real watershed describing relationships between its components. Beven (2001) differentiate perceptual, conceptual and procedural model.

Although the first rainfall-runoff models emerged already three hundred years ago, the most rapid development started in the first half of the 20th century, e.g. Sherman's unit hydrograph method (1932) or the Hortonian infiltration theory (1933). Due to the Second World War, a temporary setback emerged during 1940 – 1945 subsequently suppressed by a period of pause and consolidation in 1950's. An extensive acceleration of new discoveries in rainfall-runoff modelling emerged with a digital revolution in 1960's when the focus was shifted from event-based to continuous rainfall-runoff models. Later, in the 1970's and 1980's, the physically-based hydrological models were developed.

The most common classification of the rainfall-runoff models divides models into metric, parametric and mechanistic models according. Further subdivision considers the mathematics of the model according to which are models deterministic and stochastic. If the spatial representation is taken into account, then models are divided into lumped, semi-distributed and distributed. Some of the models are one-dimensional, two-dimensional and three-dimensional. Static models exclude time whereas dynamic ones include it explicitly. Another classification differs models into event-based and continuous models.

Recently, rainfall-runoff models have a wide application. Some of the models are used for hydrological simulations, some for runoff estimation of ungauged basins, for prediction of catchment response to changed conditions as well as for water quality investigations and measurements of meteorological impacts. At present the watershed management gains the attention as well.

The possible future development of rainfall-runoff modelling is likely to be in embracing rapid advances in new technologies, in elaborating model for ungauged catchments, in creating a "user-friendly" environment, and in defining their reliability.