RIVER RUNOFF MODELING

Yu. B. Vinogradov
State Hydrological Institute, St. Petersburg, Russia

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Contents

Summary

This article is devoted to the most important aspect of modern hydrology - mathematical modeling of runoff formation processes. Some drawbacks in the practice of mathematical modeling in hydrology due to conscious or inadvertent abuse of mathematical device that is not always adequate, have been noted. The additional hindrances appear as a result of the contradictions between the necessity and the possibility of the essential description of the natural processes. They are due to the poor development of experimental hydrology. Attention has been primarily paid to the consideration of the construction principles of the deterministic models and the peculiarities of the work involved with them. Really promising models are the physically-based ones with distributed parameters, but several additional problems arise in connection with their realization.

Some dead-ends of the modern modeling practice, connected with the inadequacy of mathematical approximations to describe natural phenomena and processes that are related to the scale problem and to the rules of model calibration and validation have been noted. The ways out of the dead-end situations have been indicated.

The generality of the stochastic models used in hydrology and other sciences has been specially emphasized. Therefore, stochastic hydrology doesn't have some "purely hydrological" methodological specificity at its disposal, though it contains some traces of its sometimes pathological perception of statistical reality.

The promises of deterministic - stochastic modeling in hydrology have been emphasized. Just this approach will form new hydrological methods for computation and prediction. In this context the importance of the construction of stochastic weather models which are required to provide meteorological input of the deterministic models of runoff formation, has been noted.

The prospects of hydrology are closely connected with those of mathematical modeling of runoff formation.

1. Introduction

Every natural process may be represented by a model, which should correspond in some features to the original. On the whole a complex of models can represent an understanding of the process under study. The closer the model to the original, the more valuable it is. The possible model types are conceptual or mental, verbal, graphic, physical, and mathematical. Only the last one is of practical significance in hydrology (it will be a case in question further), though mental and verbal models pave way towards every mathematical model. In the 1950s - 1960s mathematical modeling was supported in parallel with analogue and numerical computing systems. In analogue modeling the possibility, to study the functioning of some specially constructed electronic schemes simulating the same differential equations as those of hydrological phenomena, was exploited. Nowadays, the preferred option is numerical computing as it dominates many fields of research as a valuable tool.

Mathematical model and mathematical modeling are notions which have broadened their scope in modern science so that they have changed their purely methodological basis of the past nearly into a world view. Really, the application of mathematics for nature description is based on the use of mathematical models and modern mathematical physics is a theory of mathematical models for the physical phenomena. Therefore, the application of methods of mathematics to natural sciences and hydrology in particular is based exclusively on mathematical modeling.

Mathematical models are approximate descriptions of natural phenomena and processes expressed with the help of mathematical rules and symbols. Mathematical modeling is a way of research of the objects, phenomena and processes based on the application of mathematical models.

Some time ago two complementary approaches - traditional one and that of mathematical modeling were rivaling in hydrology. Now one can unequivocally assert that mathematical models are the basic, if not the unique, means of conducting hydrological researches. This doesn't mean at all that the traditional methods of hydrology sank into the myth since there are still several orthodox hydrologists following this scientific paradigm. And for all the true achievements of traditional hydrology there will always be a place appropriate to them in modern "modeling hydrology".

Can we assert that mathematical modeling has provided the necessary scientific exactitude and effectiveness to today's hydrology? Unfortunately, no! The crisis of modern hydrology, according to the thinking of many hydrologists, is caused just by the problems and dead-ends of mathematical modeling.

2. Discrepancy of the Term "Mathematical Model"

Mathematical modeling should be the basis for creation of new methods to perform hydrological calculations and make predictions. It is always necessary to remember mathematics is not the end in itself. For successful modeling it is necessary to know the object of modeling - processes of runoff formation - very well. So, the problem boils down to methodological aspects of modeling as the same phenomenon can be modeled in different ways.

The word combination "mathematical model" appears to bring all the modelers to an equal level before the hydrological establishment. Though among the latter there are both specialist-dabs and people knowing the necessary set of the "key words" very well but abused by the trust of simpletons. Many examples of mathematical manipulations in hydrology without any use for the science are known. The antimathematical fanaticism of hydrologists - supporters of the orthodox views is also dangerous.

The way is the wide and confident use of mathematics and simultaneous liberation from its hypnotism. Mastering mathematical methods by hydrologists will allow them to see the absence of a great sense from hydrological point of view in many models that will promote bridging the separate pseudo-scientific tendencies.

There is one more important aspect: the word "model" can mean both a single equation and the most complicated system, a detailed algorithm the description of which can occupy a whole book. Below, by the term model or modeling system, rather high-grade mathematical description of runoff formation processes in all their diversity, interrelation and complexity, is meant.

3. Two Essentially Different Classes of Mathematical Models

The division and comprehension of the essential ingredients of models of two fundamentally different classes - deterministic (physical, genetic) and stochastic (probability, statistical) is necessary.

Deterministic models of runoff formation generalize, regulate, and “encapsulate” all the essential information which modern theoretical and experimental hydrology possesses. The main task of deterministic modeling is transformation of meteorological impact on the river basin into the runoff hydrograph at the point of concentration.

Stochastic models describe systems based on the concepts of the theory of probability and mathematical statistics - random events, values, functions (processes), and fields. A specific branch of modern hydrology - “stochastic hydrology” is developed on the application of stochastic models. Various sorts of random (stochastic, probability, statistical) structures are analyzed or, on the contrary, are reproduced within the framework of the latter.

The important, in some way, fundamental property of stochastic models is their suitability for description of numerical files organized in one way or other, concerning any sphere of human knowledge. So, stochastic hydrology is hydrological only due to the origin of the data.

Often hydrologists - statisticians and hydrologists - determinists use the same term - “hydrological process”. But in one case it is consecutive change of states in the development of natural runoff formation phenomenon in the watershed, and in the other one these are time series, i.e. simply observed sequences of some hydrological values (discharges, precipitation depths, runoff, and evaporation).

Among the proponents of stochastic hydrology there is an opinion that a stochastic process is more general and complicated than its deterministic analogue. But then this deterministic process should be extremely primitive to expect the existence of its stochastic “double”. If one proceeded only from this premise, the existence of hydrology as it is would be senseless.

An inappropriate question was often posed and still continues to be posed: which model is more preferable - deterministic or stochastic one? These models always solve different problems: for example, for deterministic model computation of runoff hydrographs is typical, for stochastic model - the analysis or reproduction of fluctuations of runoff characteristics. It is simply impossible to act on the contrary.

4. Deterministic Modeling

4.1. The Purposes of Modeling

Modern mathematical modeling is able to solve any traditional and many new tasks in hydrology. It is both studying of runoff formation processes with the help of model including various sorts of numerical experiments and purely applied tasks - receiving of runoff hydrographs from the unexplored basins, prediction estimation of runoff changes under the influence of landscape and climate changes, operative forecast (short-term and long-term) during different phases of runoff regime. Models provide information on the elements of water balance (precipitation, runoff, evaporation) and on the state variables in different points of the basin (water equivalent in snow pack, soil moisture, level of ground waters) simultaneously. Together with geochemical and ecological models, runoff formation models make the basis for a scientific substantiation of the actions for the protection of the environment.

4.2. Lumped and Distributed Models.

First off all one should distinguish two essentially different approaches to the description of runoff formation processes in a river basin which is considered both as an object of the particular realization of general conformities with the laws of these processes and as a certain dynamic system. The first approach is directly connected with the traditional methods of calculations and predictions of runoff, which are based on the postulate about the perception of the basin as a homogenous united whole. And it is also preserved in so-called lumped models. The desire to take into account a spatial heterogeneity of weather and other factors determining runoff, (i.e. the second approach) leads to distributed models. Distributed here are input, parameters, state variables and most of the other variables.

There is a definite distinction between lumped and distributed models having pretensions to some fundamentality: the former are described by ordinary differential equations, the latter - by partial differential equations. Such a, formal and in general wrong, definition raises a lot of questions: there are many other ways of model description, partial differential equations can be successfully replaced by the systems of ordinary differential equations, the existence of approximations and solutions as finite (algebraic and transcendental) equations in the model algorithms is natural. And in general, it is necessary to distinguish substantiation of model algorithms and the algorithms themselves.

For complicated natural processes the very distribution principle which can be realized by the various means is important.

The modern mathematical model of runoff formation certainly should be distributed. Only in this case a real opportunity to take into account all the multitude of natural situations within the river basins especially large and very large is revealed.

4.3. Some Usually Distinguished Types of Models

The terminology connected with mathematical modeling is contradictory, not always unequivocal and is not standard. Moreover, some concepts have undergone significant changes lately. Therefore, one has to distinguish between used and expedient terms all the time.

There is an opinion that description of runoff formation processes should be considered as a task of mathematical physics. And some models, particularly distinguished by the number of features should be called physico-mathematical. It is by no means simple and harmless question; it comes to the essence of difference between physics and sciences about the Earth.

Physics studies the simplest and the most general laws of natural phenomena. It considers the elementary processes and phenomena, i.e. basic, free from a set of accompanying details, refined, and selected from complicated natural processes and phenomena. Physics contains a relatively small number of fundamental theories which are a quintessence of knowledge about the character of physical processes and phenomena. Hydrology as the other sciences about the Earth is guided by the laws of physics but faced with exceptional multiple-factor and interrelated phenomena; it has to find simpler solutions and approximations of the revealed relations. Parallel appearance and existence of two, in general close to each other, sciences as hydromechanics (a part of physics) and hydraulics can be regarded as historically earlier and more obvious examples. Hydraulics, unlike hydromechanics, is based on more approximate relations, more often in one-dimensional resolution and it widely uses empirical and semi-empirical approaches. Not without reason those models of runoff formation which were put forward as physico-mathematical ones, finally with the attempts of more or less wide their use lead to the avalanche-like growth of problems. One shouldn't ignore examples of science history.

The well known term "conceptual model" arose out of the necessity to take into account the counterbalance between models such as the "black box" model, and the existing physical ideas about runoff formation. The defects of conceptual models, such as the necessity of calibration (identification) of parameters and orientation to a particular watershed, are to be noted. The necessity to remove the defects led to "physically-based" models. The degree of physical validity is rather a vague concept, more so as during the work with physically-based models use of parameter calibration has been almost preserved.

The events that followed led to the unification of the terms giving rise to terms such as "lumped conceptual models" and "distributed physically-based models". And for the models intended not for the particular basins but almost for any of them without changes of algorithms and computer programs the term "modeling system" is used.

Probably, the emphasis on concepts or physical basis and also applicability of the model for different basins is hardly expedient. All this can't be absent in any modern model of runoff formation.

4.4. A System of Models or a United Universal Model?

What is preferable – a system of models differing in the kind of runoff (snow melt, pluvial, underground) and regional peculiarities or a generalized universal model? In hydrological scientific community there are supporters for both. A rather complicated but promising task is the creation and use of an integrated model unifying all the kinds of runoff, suitable for river basins of all sizes and applicable to any natural zone and taking into account all the regional peculiarities parametrically. The advantages of such an approach will become obvious immediately when the individuals will have to “stick” their models together for common use. Assembling suitable models in various combinations from readily available modules is not only difficult but the unification process is not without undesirable consequences. Any expert can get into a dead-end before the problem: from which “building” blocks model should be assembled in each particular case. Whether it is necessary, for example, to include the block which for the given basin can “work” only once in a century? And everything is in this way. The “correct” model should be planned not only for ordinary but for any extreme events. Let’s the model and not a human with his a priori prejudices quantitatively estimates a real frequency of any phenomena. As a result of simulation it is possible even to find a situation which in the given place has not been observed at all yet.

4.5. Designing Principles of Mathematical Models of Runoff Formation

All the principles listed below are very important and they have to be fully taken into consideration to be able to get an efficient modeling system. And, as it almost always happens, among these principles there is the basic one, on infringement of which, others may not be spoken about.

The first and the main principle is the following: the model should be adequate and close enough to nature. This natural, even trivial rule seems to be fulfilled always or almost always. Actually, it is far from being so. Even relative adequacy, not to mention complete one, is met amazingly rarely. A careful reconsideration of our ideas about the system of hydro-meteorological processes united under the name of “runoff formation processes”, is necessary for a sufficiently detailed and adequate mathematical description of the modeling objects. The experience of modeling has shown that there is no quantitative information on many aspects of the phenomena about which hydrologists used to have only qualitative and superficial idea. Moreover, we often have misrepresented or even possess incorrect ideas about runoff formation itself, its peculiarities in different physico-geographical conditions and about the accompanying processes. The gaps in our knowledge need to be filled with the help of theory and experiment.

The second principle is that approximations and mathematical descriptions should be as simple as possible and at the same time admissible.. In general, the balance between simplicity and complexity in the design of the model is essential. The blocks of the runoff formation model for computation of individual processes should be much simpler than the independent models intended only for their description. Some specialists in the individual spheres of hydrology with special interests in the individual models have often criticized the generalists for their lack of detail.

It is a dangerous error. The combination of highly detailed models of individual processes often leads to a failure if the resulting integrated model. On the other hand, oversimplification defeats the very purpose of mathematical modeling which is required to be adequately efficient. To show tact and impartiality when designing model, preserving the unity of the form and style in its various parts appears to be so difficult that one may only dream of the approximation to the ideal.

The third principle is not to allow the physical aspects of hydrological phenomena to be subdued by the mathematical device. This seemingly impossible situation unfortunately does often arise but is gradually averted.

The fourth principle is that model should be orientated towards the really existing meteorological information.

The fifth principle is that of the mathematical model design should be accompanied by the systemization of its parameters. Since the parameters should reflect the objective physical characteristics of watersheds, they should be organized in the same way in all models of runoff formation. Unless there is a majority of these parameters, models can't be considered as physically-based. It is absolutely necessary to ensure *a priori* setting of physically meaningful parameters for the estimation of which laboratory and field methods, measurements and calculations are already established. So, model parameters should be generalized and standardized by forming a certain part of data base for runoff modeling.

The sixth principle is that a guide to the use of the given modeling system should be prepared. It must be helpful not only to the possible user, but should also have a definite disciplined impact on the designers.

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Biographical Sketch

Vinogradov Yury Borisovich was born on 7 December 1932, Samarkand, former USSR. He is a leading scientific researcher in the State Hydrological Institute, St. Petersburg, Russia. He was educated at the Central Asiatic State University, Tashkent, Uzbek SSR Academy of Sciences, Tashkent and received Candidate of Technical Sciences and Doctor of Technical Sciences in 1960 and 1972 respectively. He was with the Institute of Water Problems and Hydraulic Engineering, Tashkent, during 1958-1964, Kazakh Research Hydrometeorological Institute, Alma-Ata, 1964-1978 and is with the State Hydrological Institute, St. Petersburg, Russia, since 1978.

He was Chairman of Debris Flows Committee, Scientific Boards of the USSR Committee on Science and Technology, and of the Academy of Sciences on Engineering Geology and Hydrogeology, 1979-1991. His publications include the following:

- 1967. The Problem of Hydrology for Rainfall Floods at Small Watersheds of Central Asia and South Kazakhstan.
- 1977. Glacier Outburst Floods and Debris Flows
- 1980. Sketches about Debris Flows
- 1988. Mathematical Modelling of the Processes of Runoff Formation. Experience of the critical Analysis

He organized and conducted the expeditions on studying of runoff formation and debris flows in various mountain regions of the former USSR (1957-1991). In 1970-1977 he as the head of a group of specialists carried out a number of experiments on artificial reproducing of natural Debris Flows of high density (Zailiyskiy Alatau Range, near Alma-Ata). Presently he is working on an important generalizing monograph, devoted to the original methods of mathematical modeling of runoff formation, its contamination and catastrophic hydrological phenomena, development of methods of hydrological calculations and predictions of the new generation, ecological understanding of hydrology, questions of interaction of physical and stochastic hydrology and in the whole to the problems of the necessary changes in approaches, conceptions and methods of fundamental hydrological science.