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Hydrological modelling of imperfectly gauged basins: a new challenge

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Abstract Prediction in Ungauged Basins (PUB) is a recent initiative undertaken by the International Association of Hydrological Sciences (IAHS). As the biggest developing country in the world, China has to face the difficulty that many basins are ungauged or, at best, imperfectly gauged. This paper discusses major directions of research on PUB in China, and in particular the unit hydrograph methods applied to the prediction of flooding in ungauged basins in China. Moreover, this paper describes the advantages of using new systematic theories and methods that rely on computer technology and remote sensing. Numerical simulation models will be the new way for PUB. This paper suggests a comparison study between well-gauged and ungauged basins. Furthermore, some new theories and technologies used for ungauged basin simulation are appraised, such as distributed hydrological modelling, remote sensing, and four-dimensional data assimilation systems. Finally, some thoughts on hydrological studies in ungauged basins are presented.

Key words China; hydrological prediction; PUB; ungauged basins

INTRODUCTION

Many countries presently face a shortage of water and, at the same time, lack scientific support for water management. Unscientific water management is partly responsible for this water shortage. In order to administer and utilize water resources based on scientific understanding, a region's hydrological status should first be thoroughly understood. At present, there are many gauges located in Europe, America and other developed regions. However, many developing countries and regions do not have enough hydrological stations to build hydrological models with a high degree of accuracy. Across the world, the density of hydrological networks is continuously decreasing. For example, in the former Soviet Union and many developing countries, the number of hydrological stations has been reduced by 25 to 40%. Faced with such embarrassing conditions, hydrologists have to develop methods to obtain data to use for water resource management in ungauged or imperfectly gauged basins. The International Hydrological Programme (IHP), World Climate Research Programme (WCRP), and International Geosphere-Biosphere Programme/Biospheric Aspects of the Hydrological Cycle (IGBP/BAHC) are all concerned, at some level, with research in ungauged basins (Jun & Ge, 2002; Zhu *et al.*, 2002). The International Association of Hydrological Sciences (IAHS) has made Prediction in Ungauged Basins (PUB) its decadal programme, and a kick-off workshop on PUB was held in Brasilia in November 2002.

PUB RESEARCH IN CHINA

As the biggest developing country in the world, China has more than 3400 national hydrological stations, which is still insufficient in view of its 960×10^4 km^2 surface area. These stations are distributed unequally across the country. The majority is located in central and eastern China, whereas in western China, where the headwaters of many rivers such as the Yangtze and Yellow rivers are located, the drainage area of one station could be more than 1000 km^2. For example, in the case of the Black River in the western province of Gansu, most runoff comes from the upstream portion of the basin—the Qilian mountain area. There are 19 precipitation gauges in the entire Black River basin, but only three of these are located in the mountains that produce the runoff, and the altitude of all three stations is below the mean altitude of the runoff-producing area. As a result, it is hard to investigate the effect of the spatial distribution of precipitation on runoff production. There are many regions and basins that have similar conditions to those found in the Black River basin. To deal with this problem, the Chinese government initiated a large project in the 1980s: hydrological processes were investigated in 1500 basins in 27 provinces (Guo, 1999). This research project resulted in many theories and technologies for systematic analysis of hydrological data. The following sections show some examples.

Regionally synthesized unit hydrograph

Based on the Nash unit hydrograph method, the unit hydrograph of an ungauged basin is derived from a well-gauged basin by analysing relationships between unit hydrograph factors and physical geography factors. The instantaneous unit hydrograph (IUH) approach needs comparatively few hydrological stations because the physical geography factors can provide most information needed to draw the unit hydrograph. A special advantage of the instantaneous unit hydrograph is its character of nonlinear external extensionality, i.e. when the relationship between the instantaneous unit hydrograph and nonlinear factors is derived, the unit hydrograph can be modified and extended to the entire basin. Some values of instantaneous unit hydrograph parameters in typical basins in China are presented in Table 1.

Geomorphic instantaneous unit hydrograph

In some very poorly gauged basins, the instantaneous unit hydrograph method still has difficulty in predicting flow with sufficient accuracy. In the 1970s and 1980s, the geomorphic instantaneous unit hydrograph (GIUH) was developed. The GIUH is extracted from regional geomorphic and hydraulic factors. A GIUH derived overseas

Table 1 Formulas of IUH parameters in Chinese typical basins.

Basin	Parameter formula
Gullied area in Loess Plateau	$m = 0.692\ (F/J)^{0.184}$
South area in AnHui Province	$m = 3.4\ (F/J)^{0.18}$
Karst area in south of China	$m = 0.768\ F^{0.355} f^{0.126} J^{0.302} L^{0.264}$
Coastal area in east of China	$m - 2.8\ F^{0.137} J^{0.24}$

m is flow concentration parameter equal to product of n, k in Nash model, F is catchment area, J is stream channel mean gradient, and f is surface river specific weight defined as:

$f = (F_{total} - F_{groundwater})/F_{total}$

can only be used for three to four river grades at most, and seldom involves a quantitative method for determining hydraulic factors. Chinese researchers have derived the GIUH for any river grade, and have provided several ways of calculating hydraulic factors.

Inference formula

The probable maximum peak flow is a basic product of prediction in ungauged basins. Peak flow is correlated with rainfall characteristics and basin conditions. Rainfall in ungauged basins can be estimated by isohyetal methods from information in well-gauged basins. When using isohyetal analysis, the data's applicability must be tested. Using the inference formula approach simplifies analysing runoff processes by solving the correlated factors extension problem. Parameter synthesis consists of two parts: part one is using a station's collected flow data to synthesize the parameters for that station and to extend the parameters' scope; part two is using data from multiple stations to synthesize parameters based on basin characteristics or parameter type. Figure 1 shows some results of the application of inference formula to obtain runoff parameters for ungauged basins in China.

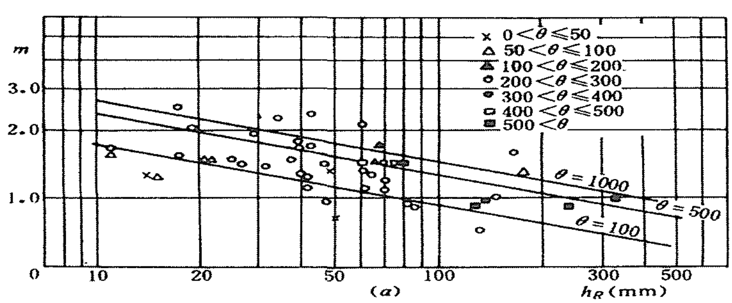

Fig. 1 Relationship of $m \sim \theta \sim h_R$ where m is a runoff parameter, θ is basin shape defined as $\theta = L / J^{1/3}$, h_R is depth of effective rainfall, L is maximum length from basin outlet to divide along the main river, and J is river channel mean gradient.

PUB METHODS

Traditional hydrology focuses on hydrological measurements, using mathematical and physical methods as the study tools. Modern hydrology should introduce new theories, methods and tools to solve research problems. These new methods include distributed numerical modelling of hydrological process, databases, 3S technologies (GIS, GPS and RS), and data assimilation. Systems theory, information theory, and cybernetic theory are all useful to hydrological analysis. Grey-systems theory, artificial neural networks, wavelet analysis, and fractal geometry should be used to analyse and forecast the temporal and spatial patterns in hydrological information.

Methodology

There are many kinds of hydrological models, such as the early model of runoff generation under saturated conditions, the model of runoff resulting from excess rainfall (in China, these are called the XinAnJiang model and the ShanBei model, respectively) and the newest, distributed hydrological models. An important question is how to evaluate these models in the PUB context. To understand exactly what happens in ungauged basins, we should begin our research in well-gauged basins. A well-gauged basin is defined as a basin that has enough stations with observation sequences long enough to disclose the hydrological processes. Initially, runoff data from some stations can be deliberately concealed by stochastic methods or by some spatial rules. Several numerical hydrological models can then be used to simulate and predict the missing data, and each model's accuracy and efficiency can be tested by comparing the simulated and observed data.

Distributed hydrological models

The distributed hydrological model (DHM) is one of the highlights of modern hydrology. It can use remote sensing data as input to simulate hydrological processes in a basin in a spatial grid, and then couple the grid cells through the hydraulic connection. In ungauged basins, a DHM could be constructed using remote sensing and GIS. The drainage network is extracted from a DEM (Digital Elevation Model), and a runoff generation and conjunction model could be coupled on the grid scale. A DHM is based on physics, and is not a statistical or empirical model. Because remote sensing data on ungauged basins is comparatively easy to obtain, distributed hydrological models will be the main approach for PUB.

Spatial interpolation

For ungauged basins, spatial interpolation is an absolutely necessity. Spatial interpolation can be carried out using geometrical, statistical, functional and stochastic methods (Li & Cheng, 2000). There is no method of spatial interpolation that is absolutely the best for all purposes. Under different conditions, different spatial interpolation methods should be chosen. The interpolation result should be strictly tested, and the interpolation method should have suitable interface for the database used.

Four Dimensional Data Assimilation System

A Four Dimensional Data Assimilation (FDDA) system is based on the temporal and spatial distribution of the data, and introduces new, observed data during the numerical model runs (Daley, 1991; Talagrand, 1997). FDDA theory comes from climatology and oceanography, and involves error estimation, cybernetics and optimization. Over the past 20 years, FDDA has developed rapidly. In the 1991–1994 American National Report for IUGG, McLaughlin (1995) stated that data assimilation was not yet a unique area in hydrology, and that a distributed model using FDDA had not yet been developed. Since the late 1990s, land surface data assimilation has received increased attention (Entekhabi *et al.*, 1994; Galantowicz *et al.*, 1999; Hoeben & Troch, 2000; Houser *et al.*, 1998; Shuttleworth, 1998), with off-line land surface process models assimilating microwave remote sensing data as one of its distinct characteristics. Land surface data assimilation truly involves the coupling of numerical models and observations. It therefore has theoretical and practical meaning for studying the hydrology of ungauged basins. Building a land surface data assimilation system could disclose relationships between land surface process models and hydrological models, and many fundamental scientific questions about soil moisture and snow melt could be answered.

CONCLUSIONS

Research on the hydrology of ungauged basins has received increased attention since the 1990s. PUB is not only a task for hydrologists, but also involves others disciplines. Research will be greatly advanced by the participation of researchers in climatology and remote sensing. At present, some conclusions can be drawn:

(a) There are several sides to hydrological research on ungauged basins, with IAHS taking prediction as the current research focus to meet the needs of society. Nevertheless, global change and safety of water resources have drawn more and more attention, and hydrological prediction should also expand its research field. The hydrological effects of environmental change, in particular land use and land-cover change, should be considered. With the further development of remote sensing technologies, land-cover information can be used to address the lack of hydrological data in ungauged basins. Consequently, hydrological models for ungauged basins should be able to use these new kinds of data. Precipitation, for example, could be adjusted during the model runs. DEM, land-surface change indexes (such as NDVI), soil moisture and other land surface information could all be used in modern hydrological models. Hydrological models should also incorporate disturbance resulting from human activity.

(b) A multi-disciplinary research group is needed for hydrological studies. Specialists in remote sensing, meteorology, geochemistry and computation are required for this research. They can contribute to hydrological modelling in areas such as the analysis of remote sensing images, land surface processes, isotope hydrology, and calculation implementation and efficiency.

(c) Research on ungauged basins should be based on well-gauged basins. These basins can serve as a benchmark to judge the accuracy and efficiency of numerical hydrological models. A key project entitled the Northern China Water Resources Safety Problems Research was awarded funding recently by the Chinese Academy of Science. The main tasks have been identified as analysing the variation in time and space of the water cycle and the distribution of water resources at the basin scale. The North China hydrological study could provide a solid foundation for PUB.

(d) To address the decrease in the number of gauging stations, hydrological information should be expanded in scope. Traditional data such as river discharge, water stage, and peak flow are lacking in ungauged basins. A new kind of database for hydrological models should be set up. This new database should contain critical data such as DEM, land-cover index, soil type, soil moisture, traditional meteorological parameters, snow (ice) area and thickness, and related socio-economic data. The new database should also have an interface that can provide easy replacement and maintenance.

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REFERENCES

Daley, R. (1991) *Atmospheric Data Analysis*. Cambridge University Press, New York, USA.

Entekhabi, D., Galantowicz, J. F. & Njoku, E. G. (1994) Solving the inverse problem for soil moisture and temperature profiles by sequential assimilation of multifrequency remotely sensed observations. *IEEE Trans. Geosci. Remote Sens.* **32**(2), 438–448.

Galantowicz, J. F., Entekhabi, D. & Njoku, E. G. (1999) Test of sequential data assimilation for retrieving profile soil moisture and temperature from observed L-band radiobrightness. *IEEE Trans. Geosci. Remote Sens.* **37**(4), 1860–1870.

Guo, S. (1999) *Modern Flood Prediction Methods* (in Chinese). China WaterPower Press, Beijing, China.

Hoeben, R. & Troch, P. A. (2000). Assimilation of active microwave observation data for soil moisture profile estimation. *Water Resour. Res.* **36**, 2805–2819.

Houser, P. R., Shuttleworth, W. J., Famiglietti, J. S., Gupta, H. V., Syed, K. H. & Goodrich, D. C. (1998) Integration of soil moisture remote sensing and hydrologic modeling using data assimilation. *Water Resour. Res.* **34**, 3405–3420.

Li, X. & Cheng, G. (2000) Comparison of spatial interpolation methods. *Adv. Earth Sci.* **15**(3), 260–265.

McLaughlin, D. (1995) Recent advances in hydrologic data assimilation. In: *US National Report to the IUGG (1991–1994)*, Reviews of Geophysics, Supplement, 977–984.

Shuttleworth, W. J. (1998) Combining remotely sensed data using aggregation algorithms. *Hydrol. Earth System Sci.* **2**(2–3), 149–158.

Talagrand, O. (1997) Assimilation of observations: An introduction. *J. Met. Soc. Japan* **75**(1B), 191–209.

Jun, X. & Ge, T. (2002) Hydrological Science towards global change: progress and challenge (in Chinese with English abstract). *Resour. Sci.* **24**(3), 262–269.

Zhu, Y. (2002) A primary study on the theories and process of water resources carrying capacity (in Chinese with English abstract). *Progr. Geogr.* **21**(2), 180–188.