

## A distributed hydrological model applied to Heihe mountainous basin in western China

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**Abstract:** The development of western China is confronted with serious challenges on water resources due to the ecosystem's vulnerability and the increasing demand on water. Water cycle modelling to a changing environment is the base of sustainable water management. The main aim of this paper is to develop a distributed hydrological modelling coupled physical process grid with the Time Variant Gain Model (TVGM) that was developed by the first author during the 1990s at the University College of Galway, Ireland, as a nonlinear system approach applied to river flow forecasting. It can be shown that the integrated hydrological system approach (TVGM), with distributed physical process or conceptual units, could obtain a flexible result for hydrological modelling given the scarcity of fully physical process data. By preliminary application and examination in the Heihe mountainous basin of northwest China with an area of about 10 000 km<sup>2</sup> in arid and semiarid regions, it was found that this model is successful, with more advantages than the conditional distributed model applied in China. Further research on this approach is addressed in this paper.

**Key words** coupling; distributed hydrological modelling; system approach; China

### INTRODUCTION

The problem of water resources has become more urgent in western China because of global change and socio-economic development, which bring new challenges to hydrological sciences. Research on the water cycle process and its space-time change are innovation issues in the field of international geography.

A distributed watershed hydrological model is an effective way to represent the time-space changes of the hydrological cycle, which are based on DEM/GIS coupled with a unit hydrological model. At present, there are three modelling approaches: (a) fully distributed physical models, such as SHE (Beven, 2001) and similar physically based rainfall-runoff models, establishing the temporal and spatial relationship between grid elements applying numerical analysis; (b) distributed conceptual models, such as distributed Xinanjiang model and SWAT (Soil and Water Assessment Tool) (Arnold *et al.*, 1997), integrating existing lumped conceptual models with each grid element or sub-basin; (c) semi-distributed models, such as TOPMODEL (Beven, 2001; Takeuchi, *et al.*, 1999), simulating hydrological processes by applying topographic information.

The physically-based rainfall-runoff models, represented by SHE, have the advantage that they are based on physical theory. However, they are difficult to apply

because of their demands of both input data, much of which is not directly measurable, and computational resources. This has led to the development of simplified distributed models by a combination of physical or conceptual processes with a system approach.

This paper develops such distributed hydrological modelling, called the Distributed Time Variant Gain Model (DTVGM). It will be shown that DTVGM can be applicable in the case of input information imperfections such as the lack of enough precipitation and evaporation observations for distribution modelling, and it has few parameters, which can be estimated in terms of system identification approach to reduce uncertainty. Using a case study of distributed hydrological modelling in the Heihe mountainous basin in west China, it was shown that the DTVGM can obtain higher efficiency than that of the present SWAT model, and that hydrological modelling can satisfy the requirement of water resources management.

## MODEL DEVELOPMENT

### Introduction to TVGM

The first author developed the Time Variant Gain Model (TVGM) during the 1990s in the University College of Galway, Ireland, as a nonlinear system approach applied to river flow forecasting (Xia *et al.*, 1989, 1995, 1997, 2002). It can be shown that a complex nonlinear system process formulated by the Volterra functional series could be replaced by a simple time variant gain model (TVGM), which can also significantly improve the efficiency of rainfall-runoff forecasting for semiarid or monsoon influenced basins related to present linear system approaches.

Observed data of many basins show that hydrological system gain  $G$  is time-variant and has a relation to basin wetness that could be represented by the soil moisture content ( $S$ ) or the antecedent precipitation index ( $API$ ):

$$G(t) = g_1 \cdot S(t)^{g_2}, \text{ or } G(t) = g_1 \cdot API(t)^{g_2} \tag{1}$$

The linear expression of equation (1) can be written as:

$$G(t) = g_1 + g_2 \cdot S(t) \text{ or } G(t) = g_1 + g_2 \cdot API(t) \tag{2}$$

where,  $g_1$  and  $g_2$  are parameters in the time-variant gain function.

The effective rainfall calculation in runoff generation component can be written as:

$$R(t) = G(t) \cdot X(t) = g_1 X(t) + g_2 API(t)X(t) \tag{3a}$$

$$\text{or } R(t) = g_1 X(t) + \int_0^t g_2 U_0(t - \sigma) X(\sigma) X(t) d\sigma \tag{3b}$$

where  $X(t)$ ,  $R(t)$ ,  $U_0(t - \sigma)$  are precipitation, effective rainfall and response function of the API model, respectively.

It could be proved that the time-variant gain in equations (2)–(3a) and flow routing process in the basin are represented as a simple relationship, i.e.:

$$Y(t) = \int_0^m U(\tau) R(t - \tau) d\tau \tag{4}$$

where,  $Y(t)$  is runoff,  $U(\tau)$  is a linear response function of the flow routing sub-system and  $m$  is finite memory length of response function.

Owing to the introduction of time-variant gain component, basin system behaviour could be formulated equivalent to a Volterra nonlinear system, given by:

$$Y(t) = \int_0^m H_1(t-\tau)X(\tau)d\tau + \int_0^m \int_0^m H_2(t-\sigma, t-\tau)X(\sigma)X(\tau)d\tau d\sigma \quad (5)$$

where  $H_1(\tau) = g_1U(\tau)$ ,  $H_2(\sigma, \tau) = g_2U_0(\sigma)U(\tau)$ .

It can be verified that TVGM has higher efficiency of hydrological modelling than the present simple hydrological system approach (see Xia, 1997, 2002).

**Model structure of DTVGM**

DTVGM includes two components: one is the runoff generation process on grid elements; the other is the flow routing process on ranked grids. At present, the runoff generation process is divided into two layers in the vertical direction: the upper layer is the surface flow based on the concept of TVGM; the lower layer is the subsurface flow

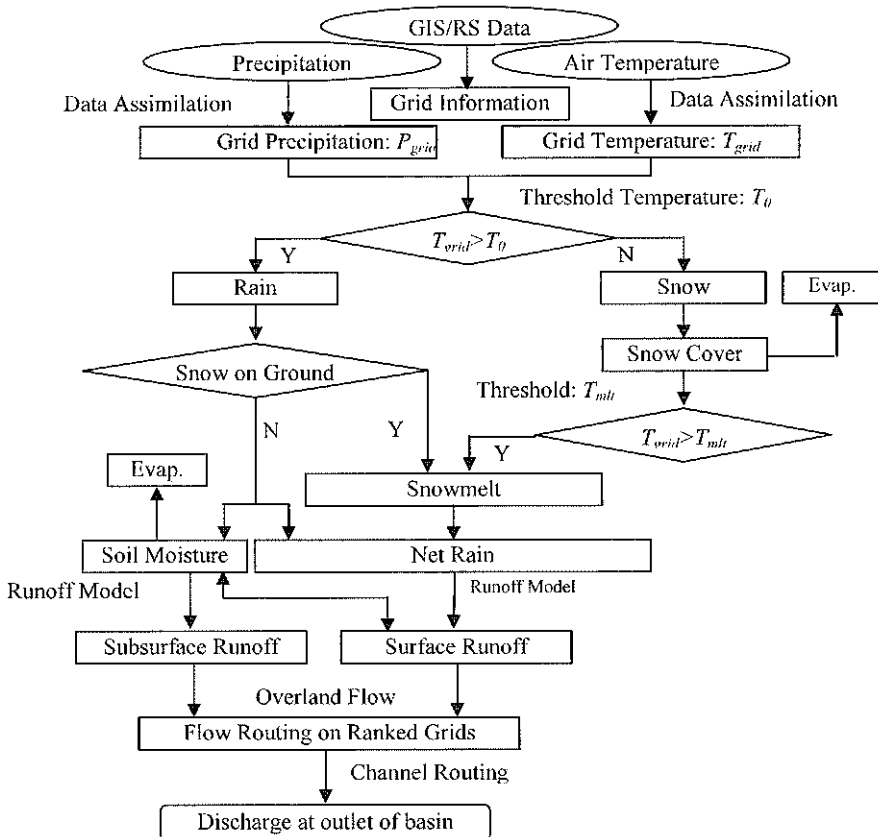


Fig. 1 Model structure of DTVGM. (Y: yes, N: no, Evap: evapotranspiration,  $T_0$ : a threshold temperature to separate rain and snow,  $T_{mlt}$ : a threshold temperature of snowmelt).

developed through a control volume approach, including a water balance equation and a storage–outflow equation. DTVGM combines surface runoff and subsurface runoff processes by soil moisture content. In contrast, the kinematic wave models are applied to simulate the flow routing process. The model structure of DTVGM is shown in Fig. 1.

### **Runoff generation model**

To calculate runoff generation on grids, the first step is to separate rain from snow according to the local temperature  $T_{av}$  (Yang & Zeng, 1999). The total runoff on each grid consists of surface runoff and subsurface runoff. The surface runoff on grids is based on the concept of TVGM; and the subsurface runoff model is developed through a control volume approach, including a water balance equation and a storage–outflow equation. In addition, the widely used degree-day method (Beven, 2001) is applied to simulate the snowmelt process.

Moreover, the evapotranspiration estimation is also an important process. Many equations have been developed to estimate potential evapotranspiration  $E_p$ . These equations use combinations of meteorological variables in addition to plant information to estimate  $E_p$ , such as the Hargreaves method, the Priestley-Taylor method and the Penman-Monteith method (Arnold *et al.*, 1997). The Hargreaves method is the simplest and uses air temperature as the primary independent variable for determining  $E_p$ . Modelling actual evapotranspiration typically involved calculating potential evapotranspiration by one of the above equations and then modifying it by some function of soil moisture content (Thompson, 1999).

### **Flow routing model**

The flow routing model includes two issues: the flow route and the routing method. In DTVGM, the flow route can be described as ranked grids according to the flow directions of grid elements. We define the outlet grids as the first rank, and the grids from which water flows into the first ranked grids as the second rank, the rest may be deduced by analogy, so the most upstream grids are defined as the highest rank. Flow routing is undertaken from those grids having higher rank onto the grids having lower rank. The kinematic wave routing is adopted as the routing method in DTVGM, which is a more physically-based modelling approach (Thompson, 1999).

## **CASE STUDY ON HEIHE MOUNTAINOUS BASIN**

### **Heihe mountainous basin**

The Heihe River is one of the three inland rivers in the Hexi Corridor Region of north-west China, which has an area of about 143 000 km<sup>2</sup> and consists of 35 rivers. The mainstream area is 116 000 km<sup>2</sup>. The upstream above Yingluo Gorge, with a drainage area of 10 009 km<sup>2</sup> and river length of 303 km, is the main runoff generation region, the

so-called Heihe mountainous basin, with the outlet Yingluo Gorge hydrology station (38°48'N, 100°11'E). The basin altitude ranges from 1737 to 5010 m (average 3670 m).

Because of its arid and high-cold traits, the Heihe River basin has few hydrological and meteorological stations to collect data, which makes it difficult for hydrological modelling. The complex hydrological models are not suitable for such a basin because the necessary data and parameters can't all be collected. However, simple models like DTVGM are advantageous for dealing with the problem.

The DEM of the Heihe mountainous basin (see Fig. 2) is extracted and divided into 38 277 grids. The area of each grid (500 m × 500 m) is 250 000 m<sup>2</sup>, so the extracted area is 9569.25 km<sup>2</sup>. In addition, the grids of the basin are partitioned into 456 ranks (see Fig. 3).

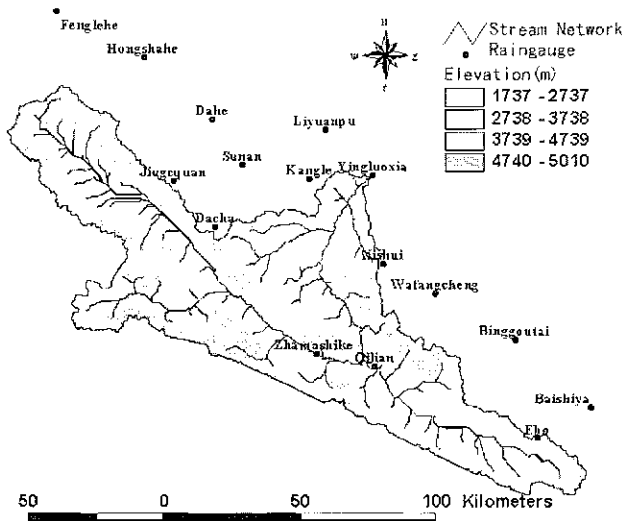


Fig. 2 DEM and stream network of the Heihe mountainous basin.

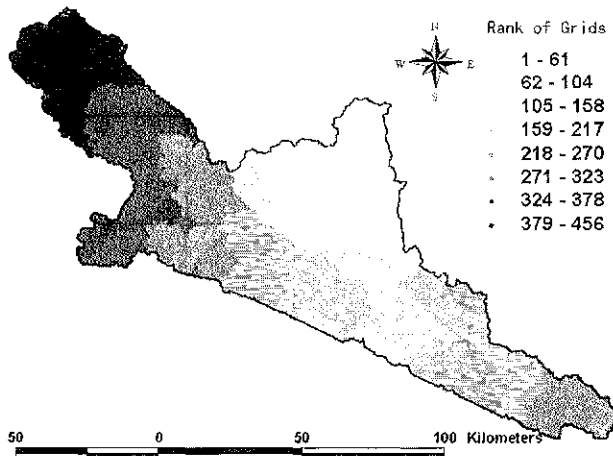


Fig. 3 Rank of grids of the Heihe mountainous basin.

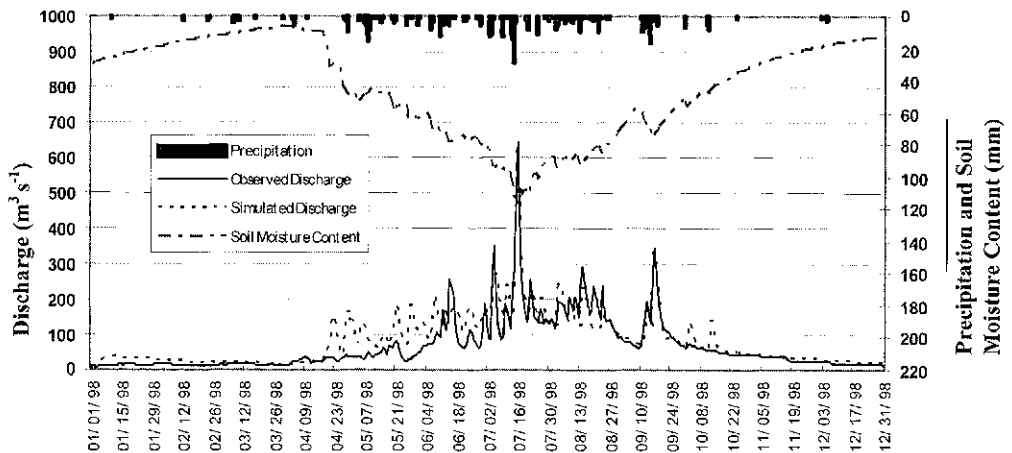


Fig. 4 Comparison between observed and simulated runoff of the Heihe mountainous basin.

Table 1 Simulated result of streamflow peaks.

Observed:		Simulated by DTVGM:		Error:	
Date	Discharge (m <sup>3</sup> s <sup>-1</sup> )	Date	Discharge (m <sup>3</sup> s <sup>-1</sup> )	Relative error of discharge (%)	Time error of peaks (day)
1998-6-15	257	1998-6-16	183	-28.8	1
1998-7-5	348	1998-7-6	274	-21.3	1
1998-7-16	645	1998-7-16	640	-0.8	0
1998-7-22	254	1998-7-23	225	-11.4	1
1998-8-15	293	1998-8-15	240	-18.1	0
1998-9-13	192	1998-9-14	185	-3.6	1
1998-9-17	344	1998-9-17	338	-1.7	0

Model efficient coefficient:  $R = 0.75$

Model efficient coefficient:  $R = \left[ 1 - \frac{\sum(Q_c - Q_o)^2}{\sum(Q_o - \bar{Q}_o)^2} \right] \times 100\%$  where  $Q_o, Q_c, \bar{Q}_o$  represent observed discharge simulated discharge and observed mean discharge, respectively.

## RESULTS

The distributed input module includes data assimilation (the spatial distribution calculation of precipitation and air temperature) and the spatial distribution initialization of soil moisture content, etc. (Luo, 1997; Wang, 1999; Weisse *et al.*, 2001). The computing module consists of runoff generation and flow routing processes. Daily streamflow of 1998 is simulated and the results are shown in Fig. 4 and Table 1.

The application results by DTVGM indicate the following points: (a) the simulated discharge process is similar to that observed, the model efficiency coefficient reaches 0.75, which is more successful in distributed hydrological modelling; (b) the simulated streamflow peaks, especially the larger discharge, have relatively high precision;

(c) the distributed inputs and variables in DTVGM ensure that the model can produce a positive response to spatial variations; (d) compared with the simulation by SWAT (the model efficiency coefficient is less than 0.60), the simulation by DTVGM is more successful; and (e) DTVGM can be coupled with other modules according to the basin characteristics; for example, it is coupled with a snowmelt model to enhance its physical mechanism in the case of the Heihe mountainous basin because of it being a high-cold region. Moreover, research is going on to build a linkage of time variant gain factor,  $G(t)$ , in the TVGM with land remote sensing, to analyse impact of land use and cover change on hydrological response.

## CONCLUSIONS

Distributed hydrological models have a higher requirement for data than lumped models. DTVGM could overcome some of the present difficulties of space–time modelling of hydrological processes due to the scarcity of fully physical process data.

Further research needs to be done on the following: (a) quantity and quality of observed data and the data assimilation method have a great impact on simulation by case study; (b) snowmelt estimation has been considered in the application study, but the initial conditions related to snow cover are absent, which affected the snowmelt simulation; (c) the runoff mechanism of frozen earth should be involved in DTVGM to improve the subsurface runoff model; and (d) establishing the relationship between land use and land cover change. The Gain factor,  $G$ , is a key issue of this model application in further research.

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## REFERENCES

- Arnold, J. G., Williams, J. R., Srinivasan, R. & King, K. W. (1997) Model theory of SWAT. US Dept of Agriculture, Agricultural Research Service, Grassland, Soil and Water Research Laboratory, USA.
- Beven, K. J. (2001) *Rainfall–Runoff Modelling*. John Wiley & Sons Ltd, Chichester, West Sussex, UK.
- Luo, Q. L. (1997) Data processing in meteorological data assimilation. In: *Systems Engineering - Theory and Practice* (in Chinese with English abstract), 98–103.
- Takeuchi, K., Ao, T. Q. & Ishidaira, H. (1999) Introduction of block-wise use of TOPMODEL and Muskingum-Cunge method for the hydro-environmental simulation of a large ungauged basin. *Hydrol. Sci. J.* **44**(4), 633–646.
- Thompson, S. A. (1999) *Hydrology for Water Management*. A. A. Balkema, Rotterdam, The Netherlands.
- Wang, Y. S. (1999) Data assimilation—its cause, its meaning and main procedures. *Marine Forecasts* (in Chinese with English abstract) **16**, 11–19.
- Weisse, A., Michel, C., Aubert, D. & Loubagne, C. (2001) Assimilation of soil moisture in a hydrological model for flood forecasting. In: *Soil–Vegetation–Atmosphere Transfer Schemes and Large-Scale Hydrological Models*. (ed. by A. J. Dolman, A. J. Hall, M. O. Kavvas, T. Oki & J. W. Pomeroy) (Proc. Maastricht Symp., July 2001), 249–256. IAHS Publ. no. 270.
- Xia, J. (1989) Part 2-Nonlinear system approach. Research Report of the Third International Workshop on River Flow Forecasting, University College Galway, Ireland (unpublished).
- Xia Jun, O'Connor, K. M., Kachroo, R. K. & Liang, G. C. (1997), A nonlinear perturbation model considering catchment wetness and its application in river flow forecasting. *J. Hydrol.* **200**, 164–178.
- Xia, J. (2002) A system approach to real time hydrological forecasts in watersheds. *Water Int.* **27**(1), 87–97.
- Yang, Z. N. & Zeng, Q. Z. (1999) *Glacier Hydrology* (in Chinese), 159–203. Chongqing Press, Chongqing, China.