Another Look at the Xinanjiang Model: From Theory to Practice

S. Liu[a,b], X. Mo[a], L. M. Leslie[b], M. Speer[c], R. Bunker[d], and W. Zhao[e]

[a]*Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, P. R. China (moxg@igsnrr.ac.cn)*

[b]*School of Mathematics, The University of New South Wales, Sydney 2052, NSW, Australia (suxia@maths.unsw.edu.au, lml@lighthill.maths.unsw.edu.au)*

[c]*Bureau of Meteorology, Sydney, Australia (mss@bom.gov.au)*

[d]*Rural Fire Office, NSW, Australia (Rees.Bunker@bushfire.nsw.gov.au)*
[e]*Bureau of Hydrology, Yellow River Conservancy Commission, Zhengzhou 510024, P. R. China (weiminz@public2.zz.ha.cn)*

Abstract: By analyzing the soil moisture distribution curve of the Xinanjiang model, it is argued that the value of the exponential parameter *b*, which is the measure of the non–uniformity of the soil moisture storage distribution, should be decided by considering the physical mechanism of runoff generation of the catchment, and not by the catchment size. By practically applying the Xinanjiang model to the Lushi catchment, China, it is shown that as expected, the Xinanjiang model did not do very well in such a catchment as its streamflow/rainfall ratio is very low at around 0.2. However, the results from two different data series show that data with high vegetation cover rate and small precipitation spatial variability can still support modelling for the catchment. The model performance is not senstive to most of initial conditions except the memory length for the unit hydrograph of the surface runoff and does not depend on the calibration data length as reported elsewhere. Finally it is stressed that when calibrating the model parameters by an optimizing method with model efficiency as high as possible, the criterion that the summation of unit hydrograph must be equal to 1 should also be fully considered.

Keywords: Rainfall–runoff modelling; Lushi catchment

1. INTRODUCTION

The Xinanjiang model has been successfully and widely applied in China and overseas since its development [Zhao et al., 1980; Zhao and Liu, 1995; Abudula and Lettenmaier, 1997; Wang, 1997; Boulet et al., 1999; Habets et al., 1999; Senbeta et al., 1999; Etchevers et al., 2001; Xiong et al., 2001]. In applications of the Xinanjiang model the model efficiency is generally high in humid catchments, indicating that climatic factors play the most important role in model performance. However, Gan et al. [1997] showed that good quality hydrological data can still support modelling of dry catchments (streamflow/rainfall ratios of about 0.2) with the Xinanjiang model.

There is some documented discussion on the theoretical structure of the Xinanjiang model [Jayawardena and Zhou, 2000]. In this paper, we firstly present a new explanation of one of the parameters of the Xinanjiang model. The aim is to discuss further the theoretical aspects of the Xinanjiang model, in addition to its application. The Xinanjiang model is then applied to the Lushi catchment, one of the subcatchment of the well–known Yellow River in China, which is located in a semi–arid zone. For semi–arid catchments, the model performance varies from poor to good. Hydrologists in these catchments choose to employ empirical models for river flow forecasting. There has been little research showing why the model's performance is so variable in semi–arid areas. In this study, we firstly investigate the reasons. Then, the effect of calibration data length on the model performance is analyzed. Also the effect on model performance of initial conditions given before the optimization search to calibrate the model parameter, is analyzed. Finally the criterion on which to judge the model performance is further discussed.

2. THE CATCHMENT

The Lushi Catchment is in the upper Luo River, one of the main tributaries of Yellow River, China. The area of the catchment is about 4423 km^2. Based on data from 1980 to 1997, the average annual precipitation is approximately 650 mm. the mean annual potential evaporation is about 889 mm and the mean annual flow at the outlet is 21 $m^3 s^{-1}$, ranging from 3 m^3s^{-1} in 1997 to 59 m^3s^{-1} in 1983. The predominant soil type is sandy. The vegetation consists of mainly arid crops, deciduous broadleaf forest, evergreen needle leaf forest, dwarf and grass. Data from ten rainfall gauges were used to calculate the average precipitation. The coefficient of interannual variation of potential evapotranspiration is 0.113, while those for precipitation and discharge are 0.189 and 0.67 respectively. The streamflow/rainfall ratio is 0.217.

3. THE XINANJIANG MODEL

The rainfall–runoff model used in this study is based on the early version of the Xinanjiang model [Zhao et al., 1980], the structure of which is shown in Figure 1. Its main feature is the concept of runoff formaton on repletion of storage, which means that runoff (R) is not produced until the soil moisture content (W(θ)) of the aeration zone reaches field capacity (WM), thereafter runoff equals the rainfall (P) excess (P–KE×Em) without further loss. The parameter KE is used to transfer pan evaporation measurements (Em) into potential evaporation rate. Evapotranspiration (E) is calculated by a three layer conceptual model, of which WM is further divided into three layers, WUM, WLM and WDM. The parameter C is used to calculate evapotranspiration from deep layer. The runoff, which is further divided into surface flow (RS) and groundwater (RG) by infiltration capacity (FC), is routed to the outlet of the catchment (Q~t) according to linear reservoir (N and NK) and groundwater recession (KG) respectively. Parameter IMP defines the proportion of impermeable area to the total catchment area. The parameter b is used to describe the non–uniformity of the surface condition. By neglecting the spatial variability of precipitation, the input is the areal average precipitation over all the rainfall stations.

All eleven parameters (WM, WUM, WLM, KE, b, IMP, FC, C, N, NK, KG), in the model are to be calibrated by minimizing objective function using genetic algorithms [Wang, 1997]. Termination of the search was made by specifying a total number of objective function evaluation (Neva). The objective function is selected to be R^2, the widely used model efficiency index [Nash and Sutcliffe, 1970]:

$$R^2 = (1 - \frac{\sum_i (Q_{obs,i} - Q_{sim,i})^2}{\sum_i (Q_{obs,i} - Q_c)^2}) \times 100 \qquad (\%) \qquad (1)$$

where $Q_{obs,i}$ and $Q_{sim,i}$ are the observed and simulated discharge at the *i*th time step, Q_c is the mean value of the observed discharge series in the calibration period. The larger the value of R^2, the higher is the model simulation efficiency. The objective function value of R^2, which is always expressed as a percentage, is expected to approach unity (100%) for a perfect simulation.

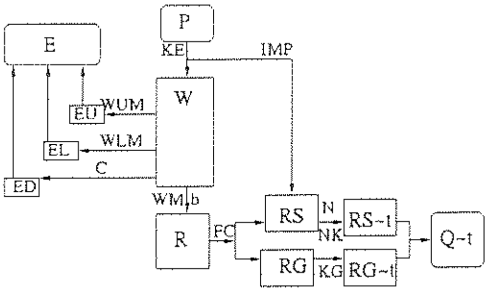

Figure 1. The structure of the Xinanjiang model.

4. A NEW EXPLANATION OF THE PARAMETER "b" IN THE XINANJIANG MODEL

The Xinanjiang model provides an integral structure to statistically describe the non–uniform distribution of runoff producing areas. These features classify the model as a semi–distributed hydrological model. It uses a parabolic curve to represent the spatial distribution of the soil moisture storage capacity over the catchment, where the exponential parameter *b* measures the non–uniformity of this distribution. The term, *f/F*, represents the proportion of pervious area [Jayawardena and Zhou, 2000] of the catchment for which soil moisture storage is less than or equal to the value of *W'm*, which varies from zero to its maximum value *W'mm*. The distribution of runoff can be expressed as,

$$\frac{f}{F} = 1 - (1 - \frac{W_m^{'}}{W_{mm}^{'}})^b, \qquad 0 \le \frac{W_m^{'}}{W_{mm}^{'}} \le 1 \qquad (2)$$

The range of values for the parameter *b* have been determined empirically as 0.1 to 2, or greater, for small to large sized catchments as suggested by Zhao [1992], 0.01 to 5.0, as suggested by Wood et al. [1992], 0.01 to 0.5, as suggested by Dumenil and Todini [1992], and even as small as 0.008 as found by Liang [1994].

The physical meaning of the value of *b* in Figure 2 is now described. As *b* varies from 0 to 1.0 through 100 and beyond the curve of soil moisture storage (*W'm/W'mm~f/F*) varies in position from close to the *Y*–axis to the diagonal line and towards the *X*–axis. The physical meaning when *b=0* is that the catchment looks like a tank with infinite volume, which can receive as much precipitation as possible. When *W'm=0*, the runoff depth generated is always equal to zero. The corresponding naturally occurring areas are surfaces with infinite absorptivity, like a sandy beach. The physical meaning when *b=∞* is that the catchment behaves like a mirrored surface. All the precipitation becomes runoff and occurs on impervious surfaces such as a roof of a building, a tarred road, or a watery surface.

In summary, as the value of *b* increases from 0 to 1.0, the catchment runoff generated, increases gradually from zero. For increasing values of *b* greater than 1.0, the catchment runoff gradually increases at a faster rate until all precipitation becomes runoff as *b* approaches infinity.

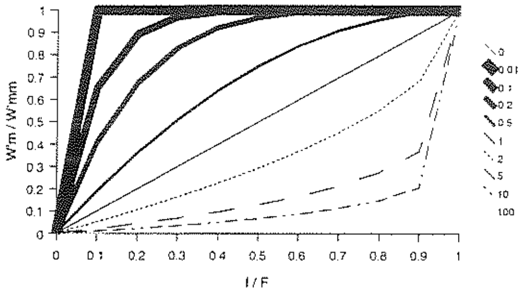

Figure 2. Graph of soil moisture storage distribution for given values of *b* ranging from 0 to 100.

As a result, when applying the Xinanjiang model, the parameter *b* should not be chosen randomly or empirically. It should be determined by considering the physical mechanisms from which the runoff in the catchment is generated, rather than chosen by the size of the catchment, as suggested by Zhao and Liu [1995].

5. SIMULATION RESULTS APPLYING THE XINANJIANG MODEL IN LUSHI CATCHMENT

Eight experimental simulations were carried out with the Xinanjiang model on the Lushi catchment. In Test 1 the Xinanjiang model was calibrated with data from 1980 to 1985 (6 years) and verified with data from 1986 to 1989. In Test 2, the calibration years are from 1990 to 1995 and verification years are from 1996 to 1997. In Test 3, the calibration and verification years are from 1980 to 1989 and from 1990 to 1997, respectively. The reason the data series were separated into two segments is that there is a marked turning point at 1988 in the time variation of discharge, as shown in Figure 3. Two more tests were designed: Test 4 (calibration from 1984 to 1988 and verification from 1989 to 1990) and Test 5 (calibration from 1992 to 1995 and verification from 1996 to 1997), in order to further check the dependency of model performance on the data used for calibration. For parameter ranges between the upper and lower bound, in which the search is conducted, we selcted two methods. One is using narrow ranges, selcted according to Zhao et al. [1980]. Another way is using a wide range, selected with a sufficient expansion around the narrow range, in order to give more searching space. The tests are then denoted as Test1W, Test1N, Test2W, Test2N, and so on. The total number of objective function evaluation, *Neva,* is designed to be 0, 1000, 10000, and 100000 to test the model performance.

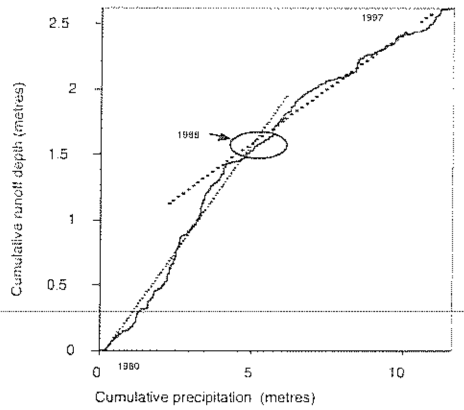

Figure 3. The cumulative runoff depth and precipitation from 1980 to 1997 in the Lushi catchment.

Table 1. The model efficiency (%) in the calibration and verification period for all the tests in the Lushi catchment.

Test	Neva=0	Neva=1E3	Neva=1E4	Neva=1E5
Test1N	13.0/4.7	34.3/23.3	35.4/24.3	35.4/24.3
Test1W	13.0/4.7	36.9/27.3	39.3/27.9	39.3/28.1
Test2N	16.5/24.5	72.2/40.0	77.8/49.4	77.8/50.4
Test2W	16.5/24.5	65.9/61.8	77.7/70.8	77.8/70.8
Test3N	12.1/25.9	32.8/35.9	34.2/23.9	34.2/24.0
Test3W	12.1/25.9	36.4/17.9	38.0/12.1	38.0/17.9
Test4N	13.9/8.5	39.3/18.1	41.0/17.7	41.1/17.7
Test4W	13.9/8.5	37.9/15.0	41.3/10.7	41.3/11.5
Test5N	16.8/24.5	76.0/55.2	81.5/53.2	81.5/51.8
Test5W	16.8/24.5	73.8/39.0	83.5/60.9	83.5/60.9

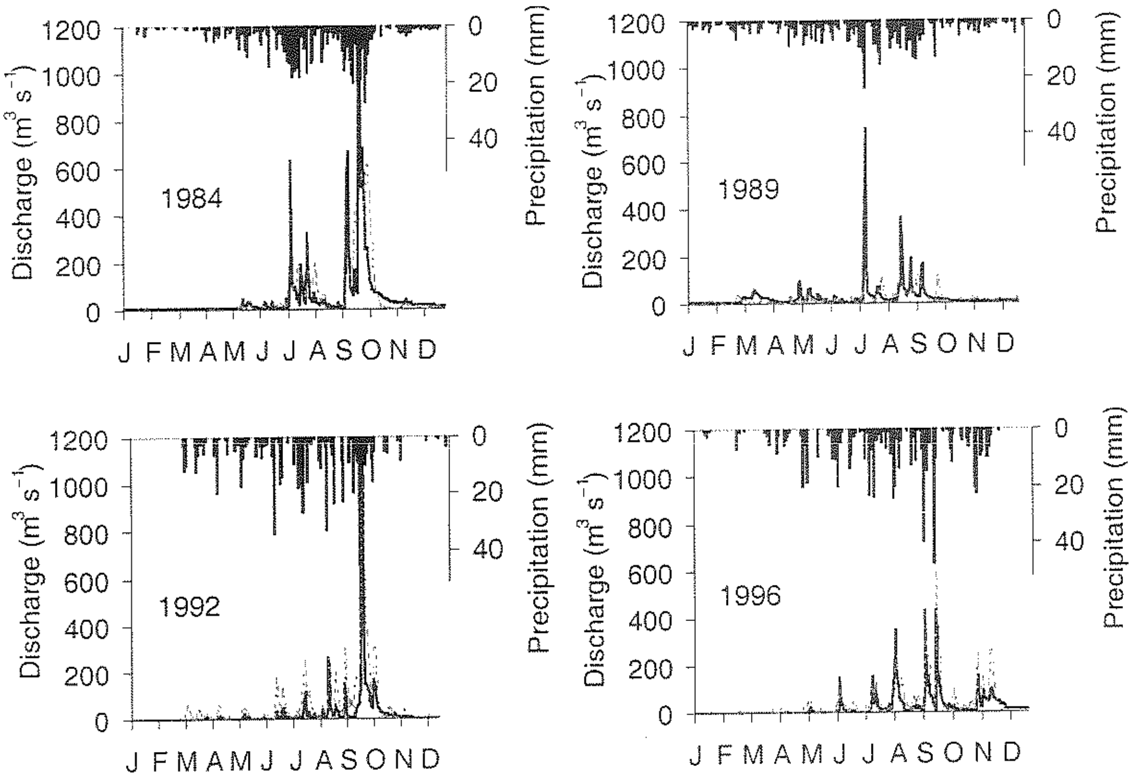

Figure 4. The simulated (doted line) and observed discharge (solid line) in the Lushi catchment using the Xinanjiang model for four typical years (the upper panel is precipitation).

6. WHAT CAUSES THE LOW MODEL EFFICIENCY OF THE XINANJIANG MODEL IN SEMI-ARID CATCHMENTS

As expected, the model efficiency is not high in the Lushi catchment as shown in Table 1, which is consistent with other reports [Zhao and Liu, 1995; Gan et al., 1997]. The Xinanjiang model was originally developed for humid areas, which limits its application in a semi-arid catchment and belies the poor relationship between the precipitation and runoff and the streamflow/rainfall ratio being as low as 0.2, as in the Lushi catchment.

This can be further clarified from the results using the New Zealand Goose model with daily and monthly data in the Lushi catchment [Bardsley and Liu, 2001]. It was found that the model efficiency of the New Zealand Goose model increased from 35.9% with daily data, to 83% with monthly data. The calibration of both the Xinanjiang model and the Goose model greatly rely on the input of precipitation, and the output of discharge data. With the time scale extended from daily to monthly, the role of evapotranspiration becomes weaker. The models do not consider this factor in detail, and thus perform better on monthly data than daily data. Therefore, in catchments such as the Lushi, for which the precipitation / runoff relationship is poor, it is essential to develop a distributed and physically-based hydrological model to fully consider the physical mechanism of runoff generation.

It is interesting to see that although on the whole the model efficiency of the Xinanjiang model in the Lushi catchment is not high, the model still performs relatively well in the 1990s (Test 2) by comparing with the result in the 1980s (Test 1). The Xinanjiang model only captures the basic variation of the discharge in the 1980s but obviously underestimates the high flow, as shown in Figure 4 for typical years 1984 and 1989. Conversely the model almost catches the high flow in the 1990s and the variation tendency of the discharge, as shown in Figure 4 for typical years 1992 and 1996. This interesting result can be explained, in the first place, from historical records which show that the vegetation cover rate increased markedly during the 1990s. This occurred due to the spreading of seeds by aeroplane over the catchment in the 1980s. Secondly, the spatial variability of precipitation decreased in the 1990s compared to that in the 1980s, as shown in Figure 5. It follows that the vegetation and spatial variability of the precipitation, in this case, play a more important role than climatic factors. Thus data, even from semi-arid area, can result a good simulation as long as the catchment has high vegetation cover rate and the spatial variability of precipitation is small.

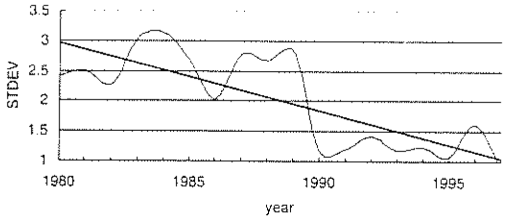

Figure 5. The annual spatial averaged standard deviation of the precipitation in the Lushi catchment from 1980 to 1997 (The straight line is the trend).

The results also tell us that before applying a hydrological model in a catchment it is necessary to check the quality of the data. Obviously in the Lushi catchment, it was necessary to segment the 18 year data series into at least two segments according to Figure 5 and the history record on vegetation cover rate should have been taken into account.

7. SENSITIVITY ANALYSIS

From Table 1, it is evident that :

- As the number of evaluation (*Neva*) increases from 0 to 1000, the model efficiency increases significantly for all tests. However, for *Neva* greater than 1000 the model efficiency does not increase significantly, which means the model results are not sensitive to values of *Neva* greater than 1000.
- The model performance is not sensitive to the length of period used for calibration, as shown in Test 1 and Test 4, and Test 2 and Test 5.

Based on the result of Test3N in Table 1, We also tested the sensitivity of the model results to the initial conditions of soil moisture, groundwater discharge, warming–up period for the simulation and the memory length for the unit hydrograph. It is found that by changing initial soil moisture storage from 56 to 80 mm, the model efficiency remains at 34.22% for calibration and 23.97% for verification. This was also the case by changing the groundwater discharge at the beginning of the computing time from 0.011 to 0.1 mm/day. The model efficiency changes marginally to 34.11% for calibration and remains at 23.97% for verification when changing the length of warming–up period from 60 to 120 days. By changing the memory length for unit hydrograph from 15 to 30 days, the model efficiency changes to 34.20% for calibration and 20.20% for verification. The summation of the unit hydrograph also changed. In brief, most of initial conditions, except the warming–up period for the simulation and the memory length for the unit hydrograph of the surface runoff, have little effect on the model performance.

8. MODEL CRITERION

By applying the Xinanjiang model to the Lushi catchment, it was found that the summation of unit hydrograph is sometimes not equal to 1. This occurred in the calibration with wide range searching, as shown in Test3W with *Neva* equal to 1000, and Test4W with *Neva* equal to 10000. By a further check, it was observed that the range for parameter *NK* and the memory length play a big role in guaranteeing that the summation of unit hydrograph is equal to 1. By enlarging the memory length from 15 to 60, and limiting the parameter *NK* within the range from 1 to 3, it ensures that the summation of unit hydrograph always equals to 1 for all values of *Neva* in the tests.

9. CONCLUSIONS

This paper had revisited the Xinanjiang model from both a theoretical and practical perspective. Theoretically, this paper explores the physical meaning of parameter *b*, which is the measure of the non–uniformity of the soil moisture storage distribution in the Xinanjiang model. It is suggested in the hydrological simulation by using the Xinanjiang model, the parameter value should be determined by considering the physical mechanism of runoff generation of the catchment, and not the catchment size, as reported elsewhere.

As expected, it was found that the model efficiency is not high when applying the Xinanjiang model to the Lushi catchment, China, which climatically classifies as a semi–arid area. However the results from two different data series show that data with high vegetation cover rate and small precipitation spatial variability can still support modelling of such a catchment. In this case, vgetation and precipitation spatial variability thus are more important than climatic consideration of zone dividing.

When the values of the total number of objective evaluation, *Neva,* using genetic algorithm to calibrate model parameters, reaches 1000, the model efficiency changes marginally. The model performance is not sensitive to most of initial conditions and the calibration data length, which corresponds with studies by Gan et al. [1997]. Of the initial conditions, it is important that the memory length for the unit hydrograph should be carefully chosen.

Although the Nash–Sutcliffe model efficiency is very useful in judging the model performance, the experience of applying the Xinanjiang model in the Lushi catchment tells us that the criterion that the summation of unit hydrograph must be equal to 1 should also be fully considered, especially since it is easy to neglect its effect. To ensure the summation equal to 1, the range of parameter *NK* and the memory length must be carefully determined.

10. ACKNOWLEDGEMENTS

This work is supported by a Strategic Partnerships with Industry Research and Training Grant (SPIRT) between The University of New South Wales, the NSW Rural Fire Service and the Bureau of Meteorology, Sydney, Knowledge Innovation Project of the Chinese Academy of Sciences KZCX2-310, Chinese National Natural Science Foundation projects 49771019 and 49890330, Knowledge Innovation Project of Institute of Geographic Sciences and Natural Resources Research CX10G-C00-05-01 and Ministry of Science and Technology of the People's Republic of China project G1999043601.

11. REFERENCES

Abdulla, F. and D.P. Lettenmaier, Development of regional parameter estimation equations for a macroscale hydrologic model, *Journal of Hydrology*, 197(1–4), 230–257, 1997.

Boulet, G., J.D. Kalma, I. Braud and M. Vauclin, An assessment of effective land surface parameterisation in regional-scale water balance studies, *Journal of Hydrology*, 217(3–4), 225–238, 1999.

Bardsley, E. and S. Liu, Simulated the discharge under land use change by the Goose model—Application to the New Zealand catchment and the Chinese catchment, *Journal of Hydrology (submitted)*. 2001.

Dumenil, L. and E. Todini, A rainfall–runoff scheme for use in the Hamburg climate model, In: O'Kane, J. P (ed.). *Advances in theoretical hydrology,* A tribute to James Dooge, European Geophysical Society Series Hydrological Science, 1, Elsevier, Amsterdam, pp. 129–157, 1992.

Etchevers, P., C. Golaz and F. Habets, Simulation of the water budget and the river flows of the Rhone basin from 1981 to 1994, *Journal of Hydrology*, 244(1–2), 60–85, 2001.

Gan, T.Y., E. M. Dlamini and G. F. Biftu, Effects of model complexity and structure, data quality, and objective functions on hydrologic modeling, *Journal of Hydrology*, 192(1–4), 81–103, 1997.

Habets, F., J. Noilhan, C. Golaz, J.P. Goutorbe, P. Lacarrere, E. Leblois, E. Ledoux, E. Martin, C. Ottle and D. Vidal–Madjar, The ISBA surface scheme in a macroscale hydrological model applied to the Hapex–Mobilhy area. Part I: Model and database. *Journal of Hydrology*, 217(1–2), 75–96, 1999.

Jayawardena, A.W., and M.C. Zhou, A modified spatial soil moisture storage capacity distribution curve for the Xinanjiang model, *Journal of Hydrology*, 227, 93–113, 2000.

Liang, X, A two–layer variable infiltration capacity land–surface representation for general circulation models, Technical Report No. 140. Water resources Series, Department of Civil Engineering, University of Washington, Seattle, 208 pp. 1994.

Nash, J.E. and J.V. Sutcliffe, River flow forecasting through the conceptual model, Part 1: A discussion of principles, *Journal of Hydrology*, 10(3), 282–290, 1970.

Senbeta, D.A., A.Y. Shamseldin, and K.M. O'Connor, Modification of the probability–distributed interacting storage capacity model, *Journal of Hydrology*, 227, 149–168, 1999.

Wood, E.F, D.P. Lettenmaier and V.G, Zaretarian, A land–surface hydrology parameterization with subgrid variability for general circulation models, *Journal of Geophysical Research*, 97, 2717–2728, 1992.

Xiong, L., A. Y. Shamseldin and K.M. O'Connor, A non–linear combination of the forecasts of rainfall–runoff models by the first–order Takagi Sugeno fuzzy system, *Journal of Hydrology*, 245(1–4), 196–217, 2001.

Wang, Q.J, Using genetic algorithms to optimise model parameters, *Environmental Modelling & software*, 12(1), 27–34, 1997.

Zhao, R.J., Y.L. Zhuang, L.R. Fang, X.R. Liu and Q.S Zhang, The Xinanjiang model. *Hydrological Forecasting*, Proceedings of the Oxford Symposium, April, IAHS–AISH Publication, No. 129, 351–356, 1980.

Zhao, R.J, The Xinanjiang model applied in China, *Journal of Hydrology*, 135, 371–381, 1992.

Zhao, R.J. and X.R. Liu, The Xinanjiang model, In: Singh, V.P (ed.) Computer models of watershed hydrology, Water Resources Publications, pp215–232, 1995.