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Event-based hydrological modeling for detecting dominant hydrological process and suitable model strategy for semi-arid catchments

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ABSTRACT

To simulate the hydrological processes in semi-arid areas properly is still challenging. This study assesses the impact of different modeling strategies on simulating flood processes in semi-arid catchments. Four classic hydrological models, TOPMODEL, XINANJIANG (XAJ), SAC-SMA and TANK, were selected and applied to three semi-arid catchments in North China. Based on analysis and comparison of the simulation results of these classic models, four new flexible models were constructed and used to further investigate the suitability of various modeling strategies for semi-arid environments. Numerical experiments were also designed to examine the performances of the models. The results show that in semi-arid catchments a suitable model needs to include at least one nonlinear component to simulate the main process of surface runoff generation. If there are more than two nonlinear components in the hydrological model, they should be arranged in parallel, rather than in series. In addition, the results show that the parallel nonlinear components should be combined by multiplication rather than addition. Moreover, this study reveals that the key hydrological process over semi-arid catchments is the infiltration excess surface runoff, a non-linear component.

1. Introduction

Floods are the most common natural disaster around the world (Sivakumar, 2011). One of the main goals of hydrology is to seek a better understanding of catchment rainfall-runoff processes and to provide more accurate and efficient predictions of floods. To achieve this goal, hydrological models, from simple conceptual models to physically-based distributed models, as well as event-based models (Sivakumar and Berndtsson, 2010), have been developed and widely used. In humid areas, most of models can simulate hydrological processes appropriately (World Meteorological Organization, 1975), while in semi-arid and arid areas, due to the large spatial and temporal heterogeneities of hydrological characteristics (such as precipitation, runoff generation, evapotranspiration, and soil moisture change) within a catchment (Hassan et al., 2014; Mediero and Kjeldsen, 2014), predictions of floods are challenge (Wheater et al., 2008). Al-Qurashi et al. (2008) applied the physically-based Kineros2 model to an arid catchment in Oman and found that the parameter sets, which were estimated to be optimal for individual events, could not perform well when transferred to other events. Bahat et al. (2009) applied an event-based rainfall-runoff model to a small hyper-arid catchment and obtained the average runoff volume bias with 40% and peak flow bias with 23%. McIntyre and Al-Qurashi (2009) applied ten rainfall runoff models to an arid catchment in Oman, and found that the best performances were poor with an average absolute relative error across events of 53% for flow peaks and 36% for flow volumes. Recently, Zhang et al. (2016) showed the NSE can reach a satisfactory level (around 0.7) when a distributed hydrological model was applied to simulate rainfall-runoff events with hourly resolution in a tributary of the Yellow River basin; however, peak flow simulation was still difficult.

Therefore, development of an appropriate storm runoff model is critical in flood simulation in semi-arid areas. However, it is still a gap to determine a suitable modeling strategy for a given catchment, which requires an understanding of hydrological processes and an identification of dominant runoff generation processes (Sivakumar, 2008a). As noted by Parajka et al. (2013), there are few studies that have systematically examined what modeling strategies would be appropriate for a particular catchment. So the choice of a hydrological model is usually guided by prior knowledge of the hydrological system, the availability of data, and prior practical experience. Hence, in the absence of detailed *a priori* knowledge of the hydrological processes in semi-arid

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Nomenclature

α_1	the discharge coefficient for the first side outlet (in TANK model, Eq. (8))
α_2	the discharge coefficient for the second side outlet (in TANK model, Eq. (8))
β	the parameter associated with the maximum percolation capacity (in SAC-SMA model, Eq. (7))
A	the catchment area (in M1, Eq. (9))
A_f	the area where the free water storage capacity is less than or equal to SW_f (in XAJ model, Eq. (3))
A_p	the total pervious area of the catchment (in XAJ model, Eq. (1))
A_{pi}	the partial area where the infiltration capacity is less than or equal to the rainfall intensity in model simulation (in M1, Eq. (9))
A_{pp}	the partial pervious area where the tension water storage capacity is less than or equal to SW_t (in XAJ model, Eq. (1))
A_s	the runoff producing area (in XAJ model, Eq. (3))
$B1$	the shape parameter of the spatial distribution curve for the tension water storage capacity (in XAJ model, Eq. (1))
$B2$	the shape parameter of the spatial distribution curve for the free water storage capacity (in XAJ model, Eq. (3))
$B3$	an exponent parameter (in SAC-SMA model, Eq. (7))
$B4$	the shape parameter of the spatial distribution curve (in M1, Eq. (9), Eq. (10); in M3, Eq. (12))
C_f	the ordinate value corresponding to SW_{af} (in XAJ model, Eq. (4))
C_t	the ordinate value corresponding to SW_{0t} (in XAJ model, Eq. (2))
d_{sw}	the local storage deficit (in TOPMODEL, Eq. (6))
f	the areal average infiltration rate on the surface (in M1, Eq. (10); in M2, Eq. (11)); the areal average infiltration rate between the upper and lower soil layers (in M3, Eq. (12))
f_0	the initial infiltration rate (in M2, Eq. (11))
f_c	the steady state infiltration rate (in M2, Eq. (11))
f_m	the maximum infiltration capacity (in M1, Eqs. (9), (10); in M3, Eq. (12))
F_m	the percolation capacity when the lower zone is saturated (in SAC-SMA model, Eq. (7))
F_p	the actual percolation rate to the lower zone (in SAC-SMA model, Eq. (7))
h	the water table height in the tank (in TANK model, Eq. (8))
h_1	the height of the first side outlet (in TANK model, Eq. (8))
h_2	the height of the second side outlet (in TANK model, Eq. (8))
i	the index (Eqs. (21) and (22))
j	the index (Eq. (24))
m	model parameter (in TOPMODEL, Eq. (6))
N	the number of flood events (Eqs. (21), (22) and (24))
NQP	the number of satisfied peak flow forecasts (Eqs. (22) and (23))
NQV	the number of satisfied runoff depth forecasts (Eqs. (21) and (23))
NS_{pf}	Nash-Sutcliffe (NS) efficiency for peak flows(Eq. (24))
P	the precipitation (in XAJ model, Eqs. (2), (4) and (5)); the rainfall intensity in model simulation (in M1, Eq. (9))
Q_{op}	the observed peak flows (Eqs. (16) and (24))
$\overline{Q_{op}}$	the average value of the observed peak flows (Eq. (15))
Q_{sp}	the simulated peak flows (Eqs. (16) and (24))
Q_{up}	the index indicating whether the forecasting of peak flow is satisfied (Eqs. (20) and (22))
Q_{uv}	the index indicating whether the forecasting of runoff depth is satisfied(Eqs. (17)–(19), (21))
r_{sr}	the ratio of the runoff producing area (in XAJ model, Eq. (5))
rdl	the soil water deficit ratio of the lower zone (in SAC-SMA model, Eq. (7))
re_{pf}	the relative error of peak flow (Eqs. (16) and (20))
re_{rd}	the relative error of runoff depth (Eqs. (15) and (19))
R	the runoff depth over the whole catchment (in XAJ model, Eq. (2)); the simulated runoff from the tank (in TANK model, Eq. (8))
R_d	the surface runoff depth over the whole catchment (in XAJ model, Eq. (5); in M4, Eq. (13))
R_i	the interflow (in M3, Eq. (12), Fig. 2)
R_{ix}	the infiltration excess runoff (in M4, Eq. (13), Fig. 2)
R_{od}	the observed runoff depth (Eqs. (14) and (15))
R_s	the surface runoff depth over the runoff contributing area (in XAJ model, Eq. (4)); the saturated excess runoff (in M4, Eq. (13), Fig. 2)
R_{sd}	the simulated runoff depth (Eq. (14))
R_u	the amount of the rainwater that can reach the interface (in M3, Fig. 2)
SW	the soil water content (in M2, Eq. (11))
SW_{0f}	the free water content prior to the time interval (in XAJ model, Eq. (4))
SW_{0t}	the averaged tension water content prior to the time interval (in XAJ model, Eq. (2))
SW_{af}	the areal mean free water storage capacity of the surface soil layer (in XAJ model, Eq. (4))
SW_{at}	the averaged tension water storage capacity (in XAJ model, Eq. (2))
SW_f	the free water storage capacity at a point (in XAJ model, Eq. (3))
SW_{mf}	the maximum free water storage capacity of the runoff producing area (in XAJ model, Eq. (3))
SW_{mt}	the maximum tension water storage capacity of the catchment (in XAJ model, Eq. (1))
SW_{uf}	the free water content of the upper zone (in SAC-SMA model, Eq. (7))
SW_{um}	the free water storage capacity of the upper zone (in SAC-SMA model, Eq. (7))
SW_t	the tension water storage capacity at a point (in XAJ model, Eq. (1))
T	subsurface transmissivity with depth (in TOPMODEL, Eq. (6))
T_0	the lateral transmissivity when the soil is just saturated (in TOPMODEL, Eq. (6))
u	a coefficient (in M2, Eq. (11))
ΔR	the runoff depth error (Eqs. (14), (15), (17) and (18))

catchments, this study adopts the approach of flexible modeling strategies for model comparison and identification.

Normally a model consists of several model components, and a component normally consists of several mathematical functions. A component is defined as nonlinear when it includes one or more nonlinear mathematical functions; otherwise, the component is regarded as linear. Proper integration of different components is essential to construct a suitable model. Components can be united