Application of scaling equations to deal with the spatial aggregation effect on watershed hydrological modelling

Miguel Barrios[1,2] and Félix Francés[1]

[1] Research Institute of Water and Environmental Engineering (IIAMA), Universidad Politécnica de Valencia, Valencia, Spain
[2] Faculty of Forest Engineering, Universidad del Tolima, Ibagué, Colombia

Introduction

Spatial effects have been identified as a major issue in hydrological science since a few decades ago (Rodríguez-Iturbe and Gupta, 1983; Wood *et al.*, 1986; Sivapalan and Kalma, 1995) and still constitutes an unresolved problem. Scale issues in distributed hydrological modelling are driven by the existence of particular dominant processes at different scales, the nonlinear behaviour of hydrological systems and the presence of spatio-temporal variability at different scales (Blöschl and Sivapalan, 1995; Wigmosta and Prasad, 2005; Tetzlaff *et al.*, 2010). Understanding the role of these factors in watershed hydrology is fundamental to enhance the development of a multiscale theory. Therefore, it is highly relevant enrich the knowledge related to the scaling of hydrological processes, parameterization and linkages of parameters across scales.

The use of effective parameters is a common approach to take into account sub-grid effects and model misconceptualizations through model calibration based on series of historical data (Todini, 2011). However, effective parameters depends on storm size (Binley *et al.*, 1989) and scale, and a good calibration is not a guarantee of a satisfactory model performance for a different scenario (Romanowicz and Beven, 2003; Francés *et al.*, 2007). In this context, the transfer of information across scales is an interesting approach to diminish parameter's dependence on scale and input. The importance of sub-grid variability has been addressed by some hydrology researchers (Sivapalan and Woods, 1995; Woolhiser *et al.*, 1996; Merz and Bárdossy, 1998; Bronstert and Bárdossy, 1999; Liang and Xie, 2001), they have found that sub-grid variability is relevant for medium wetting conditions but the effect is marginal for saturated system states and for dry states in which the entire inflow volume is stored.

In this work we introduce the application of scaling equations to incorporate sub-grid variability of three hydrological parameters (static storage capacity, upper soil saturated hydraulic conductivity and deep soil saturated hydraulic conductivity) in watershed modelling using the TETIS distributed hydrological model. The developed scaling equations estimate non-stationary effective parameters at each time step as a function of input, system state and constant parameters related to the spatial heterogeneity of the hydrological parameters at sub-grid scale. The application of this modelling approach on a real watershed seeks to contrast the hydrological model performance using the scaling equations with its performance without such equations. Moreover, we analyse the decreasing of simulated discharge sensitivity to changes in spatial scale due to the use of scaling equations.

Case study

The study was carried out in Goodwin Creek experimental catchment, which is a sub-catchment of the Yazoo river basin in Mississipi. This catchment has been continuously monitored for more than thirty years and has a dense network of gauging stations to make an intensive number of spatio-temporal validations of model performance. Goodwin Creek drains an area of 21.6 km^2 with the outlet at latitude 34° 13' 55'' and longitude -89° 54' 50''. We used 16 rain-gaging stations to generate interpolated rain fields with a temporal resolution of 5 minutes, 6 stream-gaging stations and a digital elevation model with 30 m of spatial resolution (Figure 1).

Three spatial resolutions of the hydrological parameters were used to test the performance of the scaling equations for storm hydrograph prediction. R1 represents parameter maps with 900 m^2 of spatial resolution; R2 corresponds to a spatial resolution of 3.026 km^2, and R3 represents an average parameter value for the whole catchment (Table 1). Parameter estimation for R1 was conducted by Montoya (2008) through statistical adjustment among environmental variables and the hydrological parameters. Parameter maps with resolution R2 were computed by averaging R1 maps at a resolution of 1740 x1740 m^2 and R3 parameter maps were calculated by averaging R1 maps for the whole catchment.

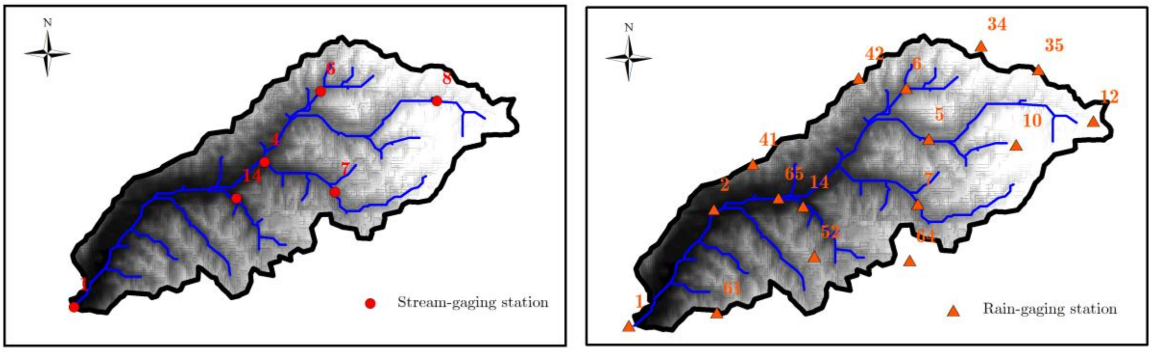

Figure 1. Location of rain-gages and stream-gages

Item	Description
R1	H_u , k_s and k_p maps with a resolution of 900 m^2, without scaling equations
R1+EE	H_u , k_s and k_p maps with a resolution of 900 m^2, with scaling equations
R2	H_u , k_s and k_p maps with a resolution of 3.026 km^2, without scaling equations
R2+EE	H_u , k_s and k_p maps with a resolution of 3.026 km^2, with scaling equations
R3	H_u , k_s and k_p aggregated maps for the whole catchment, without scaling equations
R3+EE	H_u , k_s and k_p aggregated maps for the whole catchment, with scaling equations

Table 1. Spatial resolutions of hydrological parameters H_u, k_s and k_p

Results

We found good efficiency indices (Table 2) for the calibration event in the six model conditions (Table 1). R1, R1+EE, R2 y R2+EE have a similar distribution of mean catchment states, but R3 and R2+EE obtain a smaller simulated mean static storage. The calibrated corrector factors change through the different aggregation scales, even in cases involving the use of scaling equations. This is explained in the fact that parameter maps at the 30 m resolution have a degree of uncertainty related to the spatial heterogeneity estimation; the estimated heterogeneity is partially lost by aggregating them and the variability effect is optimized by the scaling equations' parameters. In Goodwin Creek, the optimized parameters of the scaling equations corresponds to coefficients of variation in the range of 1.5 to 2.5 for H_u, 3 to 4 for k_s and 0.8 to 2 for k_p. This implies that scaling equations tend to represent high sub-grid heterogeneity in the studied hydrological parameters.

The spatial validation shows that the best performances are reached by R1+EE and R2+EE, the indices that display better performance are the time to pick error, RMSE and Nash-Sutcliffe index. Temporal validation does not show differences among R1, R1+EE, R2, R2+EE, R3 y R3+EE, this is attributed to a compensation of errors on channel propagation process. This observation agrees with results of Li et al. (2011), in the sense that comparing simulations with different parameter resolutions at the outlet do not display differences among them. But, the differences are expected at sub-basins outlets.

According to the aforesaid, we found a better performance using the scaling equations in the spatio-temporal validation. The increase of performance is notable for the smallest sub-basins. Figure 2 shows that decreasing basin area the performance of R1+EE and R2+EE is better in contrast to the case of neglecting sub-grid variability via scaling equations (R1, R2, R3). The storm events ‘19/11/83’ and ‘27/08/82’exhibit the largest differences. These storms has the smallest magnitude suggesting that sub-grid variability is more important for small storms, which is consistent with the find of Merz and Plate (1997).

Index	Model					
	R1	**R1+EE**	**R2**	**R2+EE**	**R3**	**R3+EE**
Pick flow error (%)	2.22	-4.13	8.38	9.98	-2.87	-7.83
Time to pick error (%)	0.66	0.33	0.66	0.66	0.00	0.33
Volume Error (%)	-4.88	-3.62	1.51	-9.45	-6.55	-27.55
RMSE	2.68	3.40	3.71	3.66	2.87	6.42
Nash-Sutcliffe	0.98	0.98	0.97	0.97	0.98	0.92

Table 2. Efficiency indices in calibration for the six model conditions

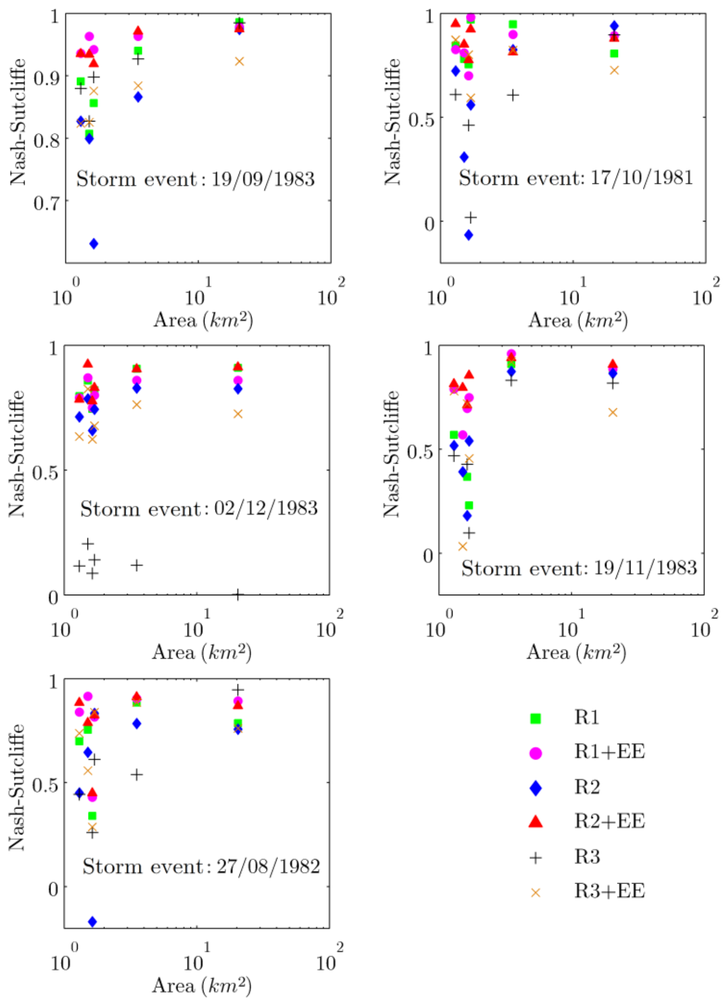

Figure 2. Nash-Sutcliffe efficiencies as a function of basin area for the six model conditions presented in Table 1

Conclusion

The implementation of scaling equations in TETIS and its application in Goodwin Creek catchment using three different levels of parameter aggregation has shown the importance of represent sub-grid variability for hydrological simulation. The use of scaling equations implies a better model performance in spatio-temporal validation, especially in the smallest sub-basins and for the smallest storms. Therefore, the effect of sub-grid variability is more important for small storm events than extreme storms of high return period. This paper illustrated the utility of non-stationary effective parameter concept to address the parameterization of sub-grid variability obtaining a better performance of R1+EE and R2+EE in comparison to the reference model (R1).

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