The sensitivities of the parameters in the WetSpa Extension model for the flood forecasting outputs (with an application to Ve catchment)

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ABSTRACT

This study focuses on the sensitivity estimation of parameters in WetSpa Extension applying to Ve catchment in Quang Ngai Province, Vietnam. The results show that the groundwater recession coefficient K_g has the strongest sensitivity on the peak runoff and total discharge volume, and strong interaction with other parameters in the model. Surface runoff exponent corresponding to minimum rainfall intensity K_{run} is the parameter noticeably affecting on the time to the peak discharge.

Keywords: Sensitivity analysis, Morris method, WetSpa extension model, flood forecasting, Vietnam

INTRODUCTION

Due to the data shortness, and insufficient perception of the physical processes or the ability of technology to meet the measurement of hydraulic factors, at the moment in Vietnam as well as in the world, scientists have to use many hydrological model to calculate the hydraulic characteristics and to simulate flow distribution in the basin. These models have advantages when the accuracy of the models is not high because of lack of high performance computers. This, the centralized parameter models were often preferred for their simplicity using little number of parameters. However, development of information technology can have the models get higher degree of accuracy using a massive set of parameters.

The reliability of each hydrological model depends on the design of its structure and parameter set. There are many parameters estimated from the topography of the basin, physical properties of soil type, aquifers zones, and land use condition. It is difficult to determine these parameters because the values cannot be measured directly. Therefore, they are often assumed a certain initial values, and then, adjusted to optimal parameters for higher efficiency of models.

So far, Hydrologic Engineering Center (HEC) - U.S. Army Corp of Engineers, MIKE - Danish Hydraulic Institute has been developed and widely used. However, even for these models, validation and simulating processes, which makes it difficult to find a suitable set of parameters for each basin.

There are two methods to determine parameters; try-and-error and optimization. Try-and-error method is more widely used because of its simplicity, although it takes time and subjective to exploit experience. Thus, it is suitable for less parameter models. Optimization method is objective and convenient for exploring the distributed parameter models. In order to reduce calculating steps in optimization method, it is needed to limit the number of adjusted parameters. This process is so-called sensitivity analysis for searching the important parameters in calibration process.

Sensitivity analysis can assess the effects of inputs on outputs of the model by investigating several parameters. What the most important for preliminary assessment of models are to understand the sense of each parameter used in the models. The parameters that are not explicit should not be adjusted since the adjustment may assign inconsistent values with the physical features. Definition of sensitive parameters leads to better estimation of their values and to reduce the operating time for modeling. Some sensitivity analyzing methods have been applied to refine the model parameters before calibration.

Werner et al [23] used Generalized Likelihood Uncertainty Estimation to assess the uncertainty value of the land using distribution in the interaction 1D, 2D hydrodynamic model in Meuse river basin. Bahremand and De Smedt [2] validated and sensitivity analyzed parameters using a model-independent parameter estimator PEST with WetSpa model for the Torysa basin- the quite large area in Slovakia and has achieved advantage results. Ryan Fedak [18] has studied the influence of grid cell size in the two models HEC-1 and TopModel. In addition, we must mention the research of Iman and Helton [10], Campolongo and Saltelli [5], Nguyen and De Kov [16],...

In Vietnam, the sensitivity analysis has not been adequately attended. Apart from several projects, there is not so many researches concerning on sensitivity analysis. This study should be conducted due to the usefulness for not only model development and adjustment but also to reduce uncertainty in the simulation process.

From the above problem, the objective of this research was to assess the sensitivity of the parameters in the WetSpa model, a relatively new model, which has been applied in Vietnam recently for data collecting, calibration, validation and advanced using in practice.

Selecting the sensitivity analysis methods is usually based on the complexity of the model and analyze target. Morgan et al [15] gave four selection criteria as follows: 1) Uncertainty in model form, 2) The essence of the model, 3) Analyze requirements, and 4) The base conditions. Based on these criterions, Morris which is a global sensitivity analysis method has been shown to be quite effective in previous studies; therefore, the method of Morris was used in this study.

Spatial range and scientific scope of the project was flood simulation for Ve Catchment, An Chi stations, Quang Ngai province, Vietnam.

MORRIS METHOD

The purpose of this method was to improve the economy of a sensitivity analysis. "The economy of a design will be defined to be the number of elementary effects it produces divided by the number of experimental runs." Morris [14].
This method has an economy of:

$$\frac{k}{k+1} \quad (1)$$

Where, k is the number of parameters taken to account.
This economical design is based on the construction of a B^* matrix with rows that represent input vectors x and columns represent parameters. Each run, only one parameter is in progress, the number of steps is a linear function of the number of parameters. Then the corresponding experiment provides k elementary effects from $k+1$ runs.

Variation range of parameters

The first step of the Morris method is to set the ranges for the different parameters taken into account. Afterwards the values for k and p have to be set, where k is the number of parameters and p is the number of parameter sets (p has to be even). In the below B^* matrix, the values of p and k are 4 and 3, respectively, and then we calculate the value of delta:

$$\Delta = \frac{p}{2(p-1)} = \frac{2}{3} \quad (2)$$

Number of steps:

$$m = k+1 = 4 \quad (3)$$

For each parameter, one base value is randomly chosen from this set:

$$Set = \left\{0, \frac{1}{p-1}, \frac{2}{p-1}, \ldots, 1-\Delta\right\} = \left\{0, \frac{1}{3}\right\} \quad (4)$$

For the example x^* can be chosen like this:

$$x^* = \left(0, \frac{1}{3}, \frac{1}{3}\right) \quad (5)$$

Create *B** matrix

To build a B^* matrix, the first step is the selection of a $m*k$ matrix B with elements that are *0s* and *1s*, such that in every column there are two rows of B that differ in only one element. The easiest way to create this matrix is making a triangular of *1s* starting at the second row. Furthermore a $J_{m,k}$ matrix of *1s* and a k-dimensional D^* matrix with elements either *+1* or *-1* with equal probability has to be build. At least a $k*k$ dimensional P^* matrix which is a random permutation matrix and contains in each column one element equal to *1* and all others to *0*, such that no two columns have *1s* in the same position.

$$B_{m,k} = \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 1 & 1 & 0 \\ 1 & 1 & 1 \end{bmatrix} \quad J_{m,k} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix},$$

$$D^*_{k,k} = \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \quad P^*_{k,k} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}, \quad (6)$$

The B^* matrix would be given by:

$$B^* = \left\{J_{m,1}x^* + (\Delta/2)\left[(2B - J_{m,k})D^* + J_{m,k}\right]\right\}P^* = \begin{bmatrix} 2/3 & 1/3 & 1 \\ 0 & 1/3 & 1 \\ 0 & 1/3 & 1/3 \\ 0 & 1 & 1/3 \end{bmatrix} \quad (7)$$

Then the B^* was multiplied by the ranges of the parameters. Since every column in the B^* matrix is standing for a parameter and every row gives a random number for this parameter, every column has to be multiplied by the interval of the corresponding parameter and add the minimum value of the interval. This can be expressed by the following formula:

$$parinput = B^*_{m,1} \times range + min \quad (8)$$

Where, *parinput* is the parameter set with randomly generated values for the parameters.

Elementary effects

Suppose that the output function is $y = f(x_1, x_2, \ldots, x_k)$, the elementary effect of each input has to be defined.
Each row in B^* differs only in one column from the row below, moreover this difference is always equal to $-\Delta$ or $+\Delta$. Therefore, during the simulation of the *parinput*, n runs will provide $n-1$ elementary effects. After running the model with the *parinput* files, the values of the elementary effects could be calculated. Therefore is used the following statement with corresponding formula; where j is the number of row (to calculate all elementary effects of one input file it has the repeat k times) and Δ is the same as during the calculation of the B^* matrix:
If $B^*_{j+1} - B^*_j > 0$ then:

$$d_j(parinput_j) = \frac{y(parinput_{j+1}) - y(parinput_j)}{\Delta} \quad (9)$$

Else

$$d_j(parinput_j) = \frac{y(parinput_j) - y(parinput_{j+1})}{\Delta} \quad (10)$$

After simulation of the first *parinput* this action will be repeated r times. Therefore, in total there are needed $r*m$ runs of the model.

Sensitivity analysis

From these values, the means and the standard deviations of the different parameters and input variables could be calculated.
Standard deviation

$$\sigma = \sqrt{\frac{1}{1-n}\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2} \; with \; \bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \quad (11)$$

and mean

$$\mu = \frac{1}{r} \times \sum_{j=1}^{r} d_j \quad (12)$$

These values could be used to analyze the sensitivities of each parameter. The high mean value shows the important global impact when large standard deviation corresponds to the interaction with other factors or nonlinear impact.

WETSPA EXTENSION MODEL

"The WetSpa (extension) model is a GIS based-distributed hydrological model for flood prediction and water balance simulation on catchment scale" Bahremand & De Smedt [2]. The WetSpa extension model used in this research was developed from the WetSpa and WetSpass extension models. WetSpa is an acronym for "Water and Energy Transfer between Soil, Plants and Atmosphere". It is a physically based model and the hydrological processes considered in the WetSpa model are precipitation, depression storage, snowmelt, surface runoff, infiltration, evapotranspiration, percolation, interflow, and groundwater flow. It can simulate runoff and hydrological characteristics at certain point in the river network and their distribution in grid cell scale.

Twelve global parameters are included in the model: time step d_t (hour), scaling factor for interflow computation K_i, groundwater recession coefficient K_g, initial soil moisture K_{ss}, correction factor for potential evapotranspiration K_{ep}, initial groundwater storage in water depth G_0 (mm), maximum groundwater storage in water depth G_{max} (mm), base temperature for snow melting T_0 (^{0}C), base temperature for snow melting K_{snow} (mm/^{0}C/day), rainfall degree-day coefficient for estimating snowmelt K_{rain} (mm/mm/^{0}C/day), surface runoff exponent when the rainfall intensity is very small K_{run} and the threshold rainfall intensity P_{max} (mm/hour), Liu & De Smedt [11].

These global parameters have physical interpretations that are very important in controlling runoff production and hydrographs at the basin outlet. Nevertheless, it is very difficult to assign them properly over a grid scale. Therefore, it is preferable to calibrate these parameters against observed runoff data in addition to the adjustment of the spatial distributed model parameters.

Among those inputs, the time step d_t is constant, and for the Vietnamese catchments, because ice snow rarely occurs, the three parameters T_0, K_{snow}, K_{rain} can be eliminated from the sensitivity analyzing progress. Furthermore, due to the lack of the evapotranspiration data, K_{ep} would be taken into account in another form that is a part of precipitation (%):

$$x_{model} = x \times K_r \quad (13)$$

Where, x_{model} is the input precipitation, x is the measured precipitation, K_r is the evaporation recession coefficient (%).

There are some parameters, which values are set in the WetSpa model; therefore, they were also taken into account in this research. The parameter b set to 1.35 in the original model controls the shape of the variation curve for the interception storage. The other parameter m, is put in the groundwater flow equation and get the value of *1* for linear reservoir and *2* for nonlinear reservoir. This parameter can vary between *1* and *2*. Liu & De Smedt [11].

Refering from the previous study about sensitivity analysis of parameters of Liu [12], Bahremand and De Smedt [2] with the condition of Vietnamese area, this research put only seven global parameters K_i, K_g, K_{ss}, G_0, G_{max}, K_{run}, P_{max}, rainfall coefficient K_r and two parameters b and m into sensitivity analysis applied for the Ve catchment.

INPUT DATA

Study area

The study area, Ve river basin is located in the Quang Ngai province in the central region of Vietnam. The total basin has a surface area of 1300 km^2 and the length of 91 km. Within this research, only the upstream part from An Chi was taken into account. This part covers an area of 757.32 km^2.

The basin is rather small and has steep slope, so flood process is very complicated. Located on the biggest rainy center of Quang Ngai Province, heavy rainfall can cause flash flood in the upstream with many serious damages. For Ve basin, the problems need to be solved in flood forecasting are to raise the degree of accuracy and to extent the foresee time of predicting water level in Ve river in order to prevent and reduce damages caused by flood.

Geographic location

Ve river rises from Truong Son - the high mountainous region, with geographic coordinate of 14^{0}32'25" in the North, 108^{0}37'4" in the East. An Chi station is 14^{0}58'15" in the North and 108^{0}47'36" in the East. The study area is totally in Quang Ngai Province, is bounded by Tra Khuc river in the Northern and the Western, by Binh Dinh Province in the Southern and by Dong sea (South-China Sea) in the Eastern.

Topographical characteristics

The topography of the basin can be divided into two types:

The mountainous area is very slope, concentrate water rapidly, and easy to form violent flood with short transform duration.

The plain with quite tableland relief is blocked by sand dunes, which protects flood from abstraction, and causes flooded easily. Locates in the Eastern side of Truong Son mountain, Ve river basin have a complex topography. It consists of mountainous, midland and plain with many offsets coming from Truong Son Mountain to coastal plain, forms Southwest and Northeast direction valleys. The average height of the basin varies from 100 to 1000m. Land is slope, territory trends lower in the Southwest – Northeast and West – East directions. The midland involves rough low hills with height is from 100 to 500m, quite slope. Plain area is not so flat, and height is about 100m.

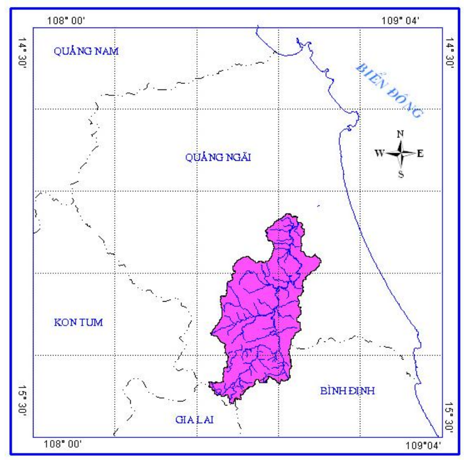

Figure (1). The Ve river basin

Geology

Study area lies along the meridian line, consists of many geological structures with different forming regulations and structural petrologies.

The most common geological characteristic of Ve river basin is rapid change in topographical gradient in profile from the continent to the sea. Therefore, most of the rivers in the region are short and vertical erosion is principal. Deposition and bank erosion occur mainly in coast plain.

Vegetarian cover

Natural forest in the basin, which rarely remains, is mainly medium forest and poor forest which most distributes in the high mountainous. There are a lot of valuable forests and local products. Mountainous and hilly regions have a very little area of forest, most area are shaven hill and industrial soil, or clump. The downstream have cultivated land and inhabitant zone.

Climatic conditions

Ve river basin locates in the Southern of Hai Van pass where has the climate of Mid-Midland climate zone.

In the summer, warm and moist tropical air current of Indian Ocean, equatorial air and the cooler and moister summer Trade winds – tropical air current coming from Pacific Ocean affect the watershed. The air current coming from the Indian Ocean forms rain in the early summer, and becomes hot and dry once it pass the Truong Son mountain.

The winter is not cold, average annual temperature is about 26 – 26.5^{0}C.
There are two main wind seasons in a year: the Northeast monsoon and the Southwest monsoon. Depending on terrain conditions, prevailing wind in each season differs from each area. Winter monsoon is usually in the West, Northwest and Northeast direction. In the summer, prevailing winds are in the West and Southwest direction. Some noticeable weather phenomenon is nimbus, storm and warm dry Western wind.
The number of rainy days is approximately 140 days per year and each year has 1700 sunshine hours.
Average annual air temperature varies between 20 and 22^{0}C in the mountainous (higher than 500m) and from 25 to 26^{0}C in coastal plain.
Average annual absolute air humidity is 23.6 mb. In summer, average monthly absolute air humidity is from 28 to 31 mb in valleys and plain. In winter, average monthly absolute air humidity is from 21 to 28 mb, and the lowest value is about 19-22.5 mb in January.
Average annual evaporation (measured by Picher) varies between 640 and 900 mm.
Precipitation is rather big, especially in the upstream. In the plain, total yearly precipitation is 2000-2200 mm; in the upstream, it exceeds 3000m, even 4000m in Quang Nam mountainous area. Average annual precipitation is spatially highly variable which is from 1600 to 3600 mm and trends rising from the Eastern to the Western.
Annual rainy system has two seasons: rainy season and dry season. The rainy season starts late, usually in September, and ends in December. The amount of rainfall over these four months is about 65 – 85% the total amount of annual precipitation while the dry season lasts in eight months but makes up only 15 – 35% of the total amount of annual precipitation.

Hydrological characteristics

Comparing to different river systems in coastal South-Midland area, the study area (consider from upstream to An Chi station) is quite small, makes up about 64.6% of the total area of Ve river basin. The whole study area lies in Quang Ngai Province. The main stream is 91 km long, sourcing from Nuoc Vo at the height of 1070m to the Dong sea at Long Khe estuary.
Drainage density is quite dense at 0.79m/km^2. Located in the coastal zone, mountainous occupies a very small area. The meandering index of mainstream is 1.3. Having many residual mountains and sand dunes in coastal zone, hydrographic network is interlaced.
Flood season lasts in three months from October to December, occupies 70.6% total annual discharge. Dry season lasts in nine months from January to September and makes up 29.4% total annual discharge. With a plentiful precipitation, in average, there are from six to eight floods occur in a year.

Spatial data

Spatial data for the WetSpa extension includes three digital maps: digital elevation map (DEM), soil type map and land use map. In addition, to compare and calculate basin characteristics, river network and hydrological station network maps also needed. All these maps have the grid cell size of 90x90 m.

Meteorological data

Precipitation data at four stations An Chi, Son Giang, Gia Vuc and Ba To were used to calculate the stream flow in the basin. Among of those, Ba To and An Chi stations are located inside the basin, the two others are outside. The hourly rainfall data calculated from the six-hour data measured in these four stations were used to draw the Thiessen polygons and interpolate data over the entire basin.

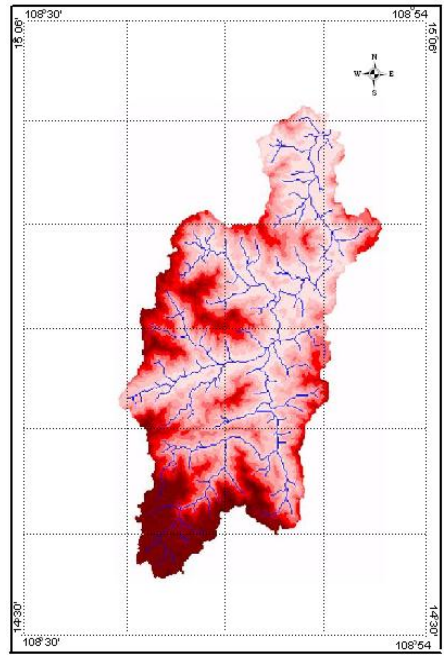

Figure (2). The elevation map

Stream flow data

Flow data series at An Chi station was used to compare to output results from WetSpa model. The hourly data was collected in the storm on November 1999.

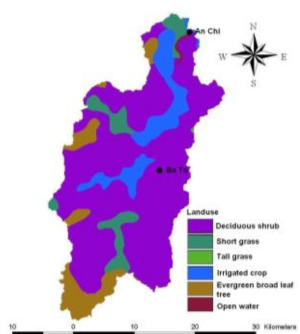

Figure (3). Land use map

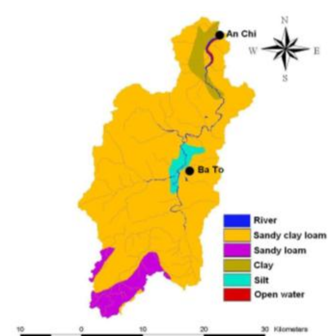

Figure (4). Soil type map

SENSITIVITY ANALYSIS

Calibration process

Initial calibration process to find out variation limits of the parameters in the matrix *B** was done by Tom [20] by the two method Random Sampling and Latin Hypercube Sampling with the below results.

Table (1). Variation range of the parameters

No	1	2	3	4	5	6	7	8	9	10
Parameter	K_r	K_i	K_g	K_{ss}	G_0	G_{max}	K_{run}	P_{max}	b	m
Minimum value	0.9	2	0.002	0	0	50	0	0	0.4	1
Maximum value	1.1	11	0.06	1.5	50	150	10	500	1.6	2

Simulating the output flow

Automatic operation of the model was carried out based on the modified source code in Fortran instead of the original model. Then instead of calculating the output volume for each certain set of parameters one-by-one, the model can execute with all the set (contained in the matrix *B**) in one-time operation. The output will be flow data at downstream corresponding to each set of parameters. In this study, 10,000 calculated parameters gave out 10,000 flooding volume values at An Chi station.

DISSCUSIONS

The sensitivity analysis was done by Morris method for the three output factors peak discharge, total discharge volume and time to the peak discharge.

The Figure (5) presents the graph of the sensitivity of the model inputs and parameters regarding to the highest point in the flow data series. Parameters K_g (3) and K_{run} (7) have high standard deviation, indicating strong interaction with other parameters. K_r (1), K_i (2), P_{max} (8) and *b* (10) have relatively large standard deviations that demonstrate the ability to interact with each other and with other parameters. K_r (1), K_i (2) and K_g (3) have a high mean value. That represents the influence on peak flow values. P_{max} (8) and *m* (10) have relatively large mean value, coresponding to significant influence to the output. The remaining factors K_{ss} (4), G_0 (5) and G_{max} (6) are not sensitive to the peak discharge of streamflow.

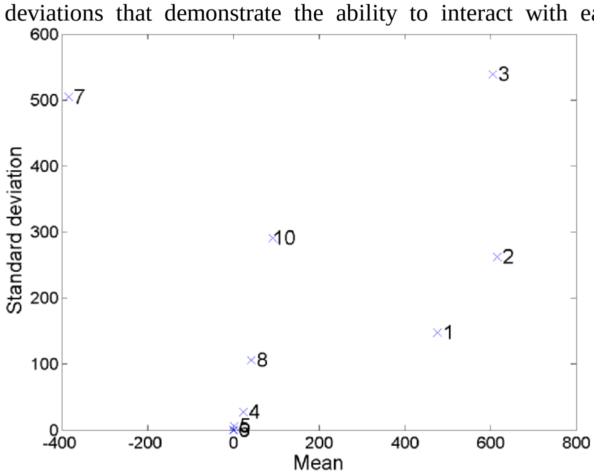

Figure (5). Sensitivity for the peak discharge

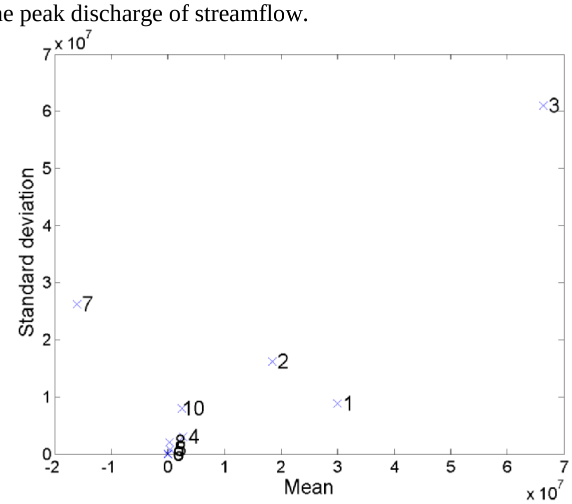

Figure (6). Sensitivity for the total discharge volume

The results of sensitivity analysis for the total value are shown in figure (6). Parameters K_g (3) have a very high standard deviation, indicating a strong interaction with other parameters. Parameter K_r (1), K_i (2), K_{run} (7) and *m* (10) have relatively large standard deviations demonstrate their interaction ability. Parameter K_r (1), K_i (2) and K_g (3) have a high average value shows the influence on flooding volume. The remaining ones are not sensitive in this case.

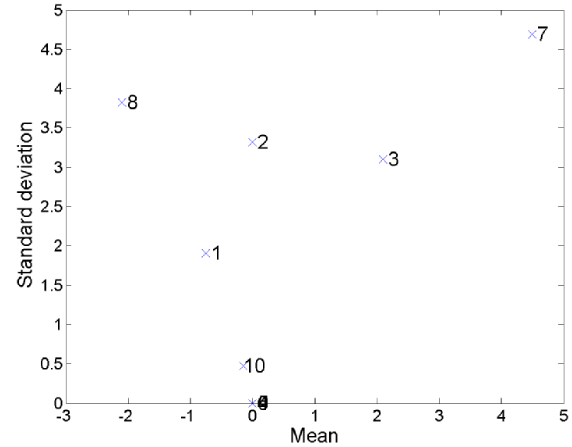

Figure (7). Sensitivity for the time to the peak discharge

It can be seen very clearly from Figure (7) that the parameters all ave very small standard deviation. Therefore, there is almost no interaction between them. Furthermore, only parameters K_g (3) and K_{run} (7) have mean values greater than 1, or ability of changing the delay time an hour. For the hourly flood data, it seems to be like that they are not sensitive for the delay time.

CONCLUSIONS

From the above results, apparently that K_g (3) parameters is the most sensitive one for both the flood peak and the total volume of flooding water amount. Beside of that is the interaction with other parameters in the model. This is the most important factor worth to notice in the calibration period.

The standard deviation of K_{run} is also rather high, reflecting the ability to interact with other parameters. Also this parameter affects the most significant on the delay time.

K_r (1), K_i (2) has strongly influence on the peak as well as the total amount stream flow.

The same test was done for some more storms in the Ve catchment and the obtained results were similar.

From sensitivity analysis by the Morris method, the proposed comclusion is when using WetSpa extension for flood forecasting in Ve river basin, operators need to focus on adjusting values of the groundwater recession coefficient K_g, the surface runoff when the rainfall intensity is very small K_{run}, the evaporation recession coefficient K_r, and the scaling factor for interflow computation K_i.

The Morris method has many advantages in the sensitivity analysis. However, the biggest limitation is that only the sensitivity of each parameter is evaluated, but not the interaction between the parameters. Moreover, the method may neglect the degree of uncertainty of each parameter. In fact, these parameters can be very sensitive but have stable value, or even when the sensitivity is not very large, but uncertainty is quite significant. Therefore, to achieve greater efficiency in calibration process, the further research is needed to assess the sensitivity and uncertainty of the parameters at the same time, or we may use additional methods for sensitivity analysis.

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