Applying the "abcd" Monthly Water Balance Model for Some Regions in the United States

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Abstract

As watershed models become increasingly functional and useful, there is a need to extend their applicability to other locations to explore the possibility of calibrating and evaluating them in such new locations. This study used the "abcd" monthly water balance model for three catchments in different places in the United States in order to investigate the feasibility of this model in different regions. Although the regional calibration led to nearly perfect regional relationships between catchment model parameters and basin characteristics in catchments with little or no snow, practicality of this model in regions dominated by snow was questionable.

Keywords: "abcd" model, water balance, watershed hydrology, United States

1. Introduction

Watershed models have become an indispensable tool for the assessment, management, and use of water resources. They provide mechanisms to anticipate catchment behavior and evaluate the consequences of natural or human-induced changes. For hydrologists, such models are especially useful in the evaluation of assumptions and theories about the dominant hydrologic processes in a basin. Continuing innovation in data acquisition and computing technologies, and increasing modeling requirements have resulted in models that represent water-related processes with more details in space and time (Martinez, 2007). This paper therefore aims to simulate the streamflow for several catchments in the United States and, at the same time, intends to understand the difficulties involved in water balance model regionalization. In order to accomplish the objective of this study, a simple conceptual model is used. The "abcd" model is applied on monthly time series where the precipitation and potential evapotranspiration are used as inputs and streamflow as an output.

For the data, the model parameter estimation experiment (MOPEX) data set are used to obtain the monthly climate data for the catchments as well as to get other information about the basin characteristics. The study focuses mainly on the "goodness of fit'' between the model predictions and observations as well as robustness of the model performance at the monthly time step over different locations throughout the United States.

2. Methods and Data Sets

2.1. Model Identification

Model identification involved a recursive set of steps including (1) selection of study sites and data, (2) selection of a model hypothesis to be tested, (3) initial simulation, (4) sensitivity analysis: perturbation analysis and response surfaces, (5) calibration of the model, and (6) evaluation of model performance.

2.2. Study Sites and Data Sets

In this paper, three river catchments were selected to run the model on; The St. Johns River catchment which is the longest river in the state of Florida. It is 500 km long and 7940 km^2 catchment area. We obtained the data for this river from the Model Parameter Estimation Experiment (MOPEX, 2010). The river catchment has a dense forest and shrubland cover with minimal urbanization. The second catchment is that of Kickapoo River which is a tributary of the Wisconsin River in the state of Wisconsin, the river is about 210 km long. It is the longest tributary of the Wisconsin River, drains over a large area of land in Monroe, Vernon, Richland, and Crawford Counties. The Kickapoo River catchment encompasses 4369 Km^2 in southwest Wisconsin covered mainly by snow and ice. The third catchment is the Leaf River catchment which is about 290 km long river with vegetated watershed, located in southern Mississippi in the United States. It is a principal tributary of the Pascagoula River, which flows to the Gulf of Mexico (Figure 1). The data include daily values of precipitation, evapotranspiration, and streamflow that were afterwards converted to monthly data. Matlab was used to automate access to the data and to enable processing and analyzing the data.

2.3. Model Hypothesis

The “abcd” model is a physics-based, lumped, and nonlinear watershed model which accepts monthly precipitation and potential evapotranspiration as inputs, producing streamflow as an output. Internally, the model also represents soil moisture storage, groundwater storage, direct runoff, groundwater outflow to the stream channel and actual evapotranspiration. It was originally introduced by Thomas (1981) and Thomas et al. (1983) as a suitable model structure for performing regional water resource assessment using an annual time scale. The “abcd” model was later compared with numerous monthly water balance models (Fernandez et al., 2000).

The “abcd” model has four parameters a, b, c, and d, each having a specific physical interpretation. The parameter a ($0 <= a <= 1$) reflects the propensity of runoff to occur before the soil is fully saturated (Thomas et al., 1983). The parameter b is an upper limit on the sum of actual evapotranspiration and soil moisture storage in a given month. Presumably this parameter depends on the ability of the catchment to hold water within the upper soil horizon. The parameter c is equal to the fraction of streamflow which arises from groundwater discharge in a given month. Over the long term c is then defined simply as the baseflow index (BFI), an index used commonly in studies which develop relationships between drainage basin characteristics and groundwater discharge to a stream channel. The reciprocal of the parameter d is equal to the average groundwater residence time.

The model defines two state variables: W_t, termed “available water” and Y_t, termed “evapotranspiration opportunity”. Available water is defined as:

$$W_t = P_t + XU_{t-1}$$

where P_t is precipitation during period t and XU_{t-1} is upper soil zone soil moisture storage at the previous time step. Evapotranspiration opportunity “Y_t” is water which will eventually leave the basin in the form of evapotranspiration and is defined as:

$$Y_t = E_t + XU_t$$

where E_t represents actual evapotranspiration during period t and XU_t represents upper soil zone soil moisture storage at the current time step. Evapotranspiration opportunity Y_t is postulated as a nonlinear function of “available water” W_t using:

$$Y_t\,(W)_t = \frac{Wt+b}{2a} - \sqrt{\left(\frac{wt+b}{2a}\right)^2 - \frac{wtb}{a}}$$

Evapotranspiration opportunity Y_t is further partitioned into actual evapotranspiration E_t and residual soil moisture storage XU_t by relating the rate of soil moisture loss to potential evapotranspiration, leading to the nonlinear relationship:

$$E_t = Y_t \cdot (1 - \exp(-PE_t /b))$$

Water available for runoff ($W_t - Y_t$) is further partitioned into upper zone contribution to runoff QU_t and recharge to groundwater R_t by the parameter c, according to:

$$QU_t = (1 - c) \cdot (W_t - Y_t) \text{ and } R_t = c \cdot (W_t - Y_t)$$

Recharge R_t is added to the lower soil zone state variable XL_{t-1} and base flow to the stream is computed according to the linear recession relationship $QL_t = d \cdot (XL_t)$. Using continuity, we updated $XL_t = (XL_{t-1} + R_t) \cdot (1 + d) - 1$. Finally total streamflow is computed as:

$Q_t = QU_t + QL_t$ (Figure 2)

3. Initial Simulation

The initial simulation was performed with the following parameters values; a = 0.97, b = 250, c = 0.2, and d = 0.01 for a period of 10 years of monthly data for the three rivers in order to know the model behavior. An acceptable initial simulation was achieved for both the St. Johns River and Leaf River but not for Kickapoo River (Figure 3).

4. Sensitivity Analysis

The purpose of the sensitivity analysis is to investigate how the variation in the model parameters can affect the outputs (streamflow in this study). The main idea of this step is to identify the factors that contribute most strongly to variability and characteristics of the input-output responses. The difference between the simulated outputs and observed output was measured by the Mean Squared Error (MSE) function as:

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(Ot_{Modeled} - Ot_{Observed})^2$$

Which measures the fit of the modeled streamflow ($Ot_{Modeled}$) to the observed streamflow ($Ot_{Observed}$) in order to evaluate the performance of the model. The value of MSE is expected to be close to zero for a good simulation of the total volume of the observed streamflow series.

4.1. Perturbation analysis

It includes perturbing one parameter at a time and fixing the other parameters. The mean squared error criterion (MSE) is used to evaluate the perturbation and to determine the nominal value for each parameter separately. Following the same procedure for each parameter (i.e. perturbing the parameter at a time and fixing the other three parameters), the nominal value for each parameter was obtained.

Parameter a

This parameter has a range between (0 - 1), Fernandez et al. (2000) found that parameter a falls in the range of (0.95 - 0.99) across broad regions in the United States and it decreases with urbanization and deforestation. Since the three catchments in the current study have not been experienced any notable deforestation or urban buildup, this parameter is expected to have high values (close to one) in such places and it is so (i.e. we obtained values that are fairly close to one). We figured out that the more the parameter moves away from one, the more the residuals get bigger.

Parameter b

This parameter has a wide range (260 - 1900) according to (Vandewiele et al. 1992). In this study, its optimal values were around 700.

Parameter c

Sometimes called baseflow index (BFI), has a range of (0 - 1). This parameter is expected to have small values in the current study as our catchments have small hydraulic conductivity according to (MOPEX, 2010) data set, therefore, the infiltrated water and consequently the baseflow index should be small. Also, the model is very sensitive to this parameter as the perturbation analysis shows (Figure 4).

Parameter d

It ranges between 0 and 1. It highly influences the model. The optimal values for this parameter are very small (close to zero).

As shown in the figures below, the model is very sensitive to parameter d followed by parameter c and a. Effect of parameter b variation on the model simulation -if any- is minimal (Figure 4).

5. Response Surfaces

Six 2-parameter combinations were used (i.e. a-b, a-c, a-d, b-c, b-d, and c-d). For example: for the combination (a-b), the other two parameters (i.e. c and d) were fixed at specific values while parameters a and b were perturbed to determine their coexist values that make the MSE minimum and so on for other combinations. Figure (5) displays six 2-parameter combinations of response surfaces for St. Johns River.

6. Calibration

In order to fully develop the model simulation, we used many data for our catchments to test the performance of the model. Model testing normally includes two steps, i.e. calibration and evaluation. Correspondingly, the whole data set was divided into two parts, i.e. the calibration period (10 years) and the evaluation period (7 years). Calibration refers to the process of using the first part of data set to find the optimum values of the unknown model parameters. By optimizing the model, we obtained the following optimum values of the model parameters for St. Johns River: a = 0.994, b = 700, c = 0.1, and d = 0.03 (Figure 6). Furthermore, we figured out that the residuals get bigger with higher streamflows (Appendix 1).

In order to check the model feasibility in other places that receives little or no snow, we applied the model on the Leaf River using the same optimum parameters values that we already obtained for St. Johns River. Since the climate patterns and the basin characteristics for both St. Johns and Leaf River are somewhat similar, we wanted to investigate if the optimum parameters in one place could work well in the other in an attempt to test the regionalization of the model. Applying the same optimum parameter values of St. Johns River for Leaf River resulted in acceptable simulation (Figure 7).

For Kickapoo River (a snowy catchment), we tried to calibrate the model to represent such type of systems (a catchment with snow), but unfortunately we could not get any acceptable simulation (Figure 8). Our findings were compatible with Martinez and Gupta (2010) who stated that “For regions dominated by snow dynamics, constructing of an augmented abcd-snow model by including a simple temperature-based snow accumulation and melt component is necessary to get acceptable model performance”.

7. Evaluation

The second part of the data (7 years) for St. Johns River was used to conduct the model evaluation (the process of using the second part of data set to justify the persistence of the model performance operating with the parameter values obtained in the calibration period). Only when the performance of the model is satisfactory, both in the calibration and in the evaluation periods can the model be used with confidence in practice. As shown in Figure 9, the model performance, with evaluation, is still satisfactory.

Furthermore, model evaluation was also conducted for Leaf River, and satisfying model performance was also obtained (MSE = 8.25, result not shown).

8. Conclusions

- Four parameters (a, b, c, and d) are sufficient to represent the system characteristics thoroughly in the “abcd” model.
- Parameters a and b are easy to estimate (they fall within specific ranges in the literature) in contrast to parameters c and d.
- The model is very sensitive to parameters c and d.
- In two catchments located in mild climate (warm and humid) the “abcd” model exhibits an intermediate level of performance. The “abcd” model in these regions achieves an MSE statistic value of around 8 and captures the main features of the streamflow hydrograph.
- The “abcd” model in its normal structure does not work perfectly in regions located in continental climate that dominated by snow. If it has to be applied in such regions, it should be account for snow impact.
- It is figured out that the residuals get bigger with higher streamflows indicating that the model work better for lower streamflow periods.

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Figure 1. Study sites, outlet locations of the studied catchments

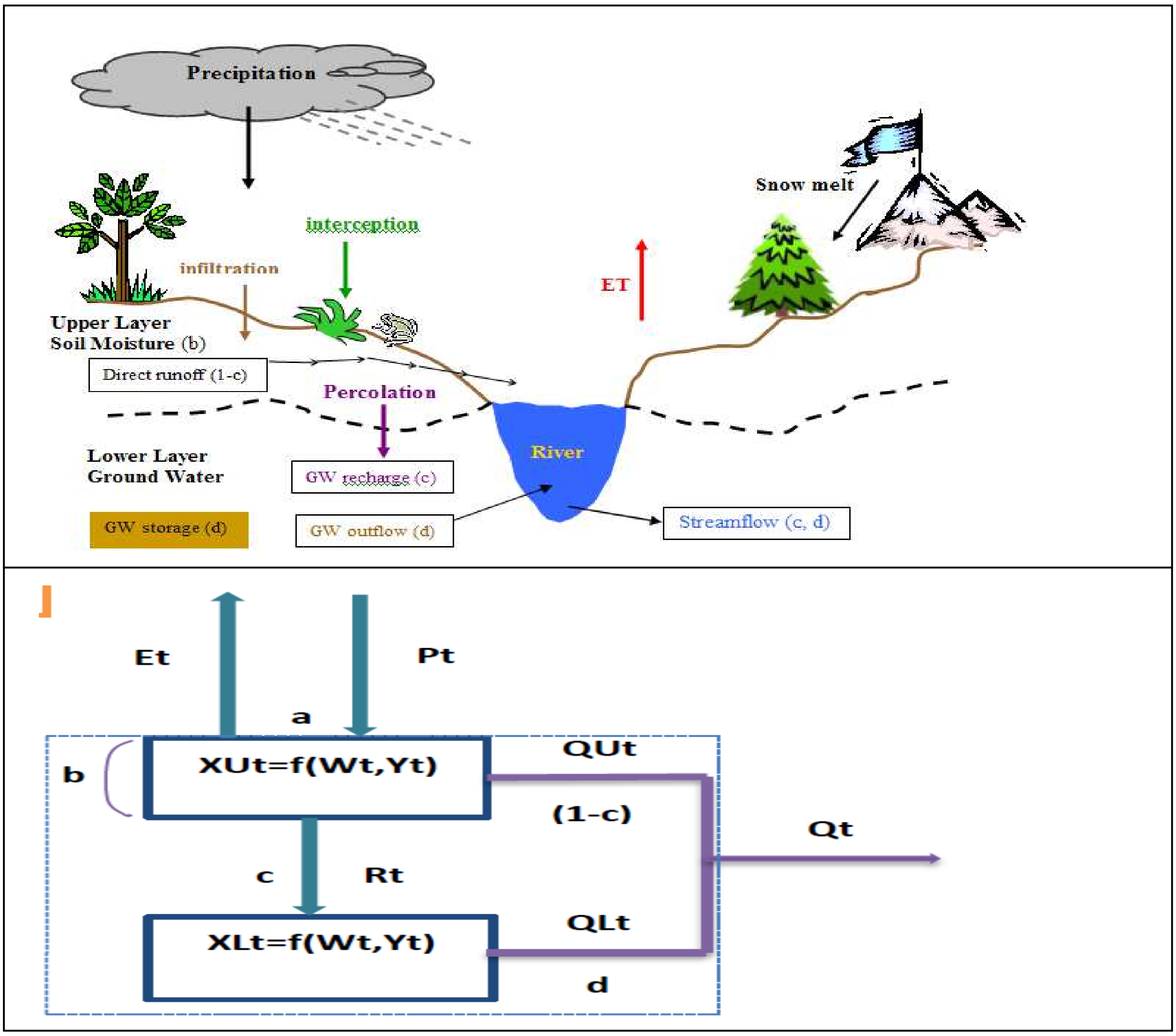


Figure 2. Structure of the “abcd” model

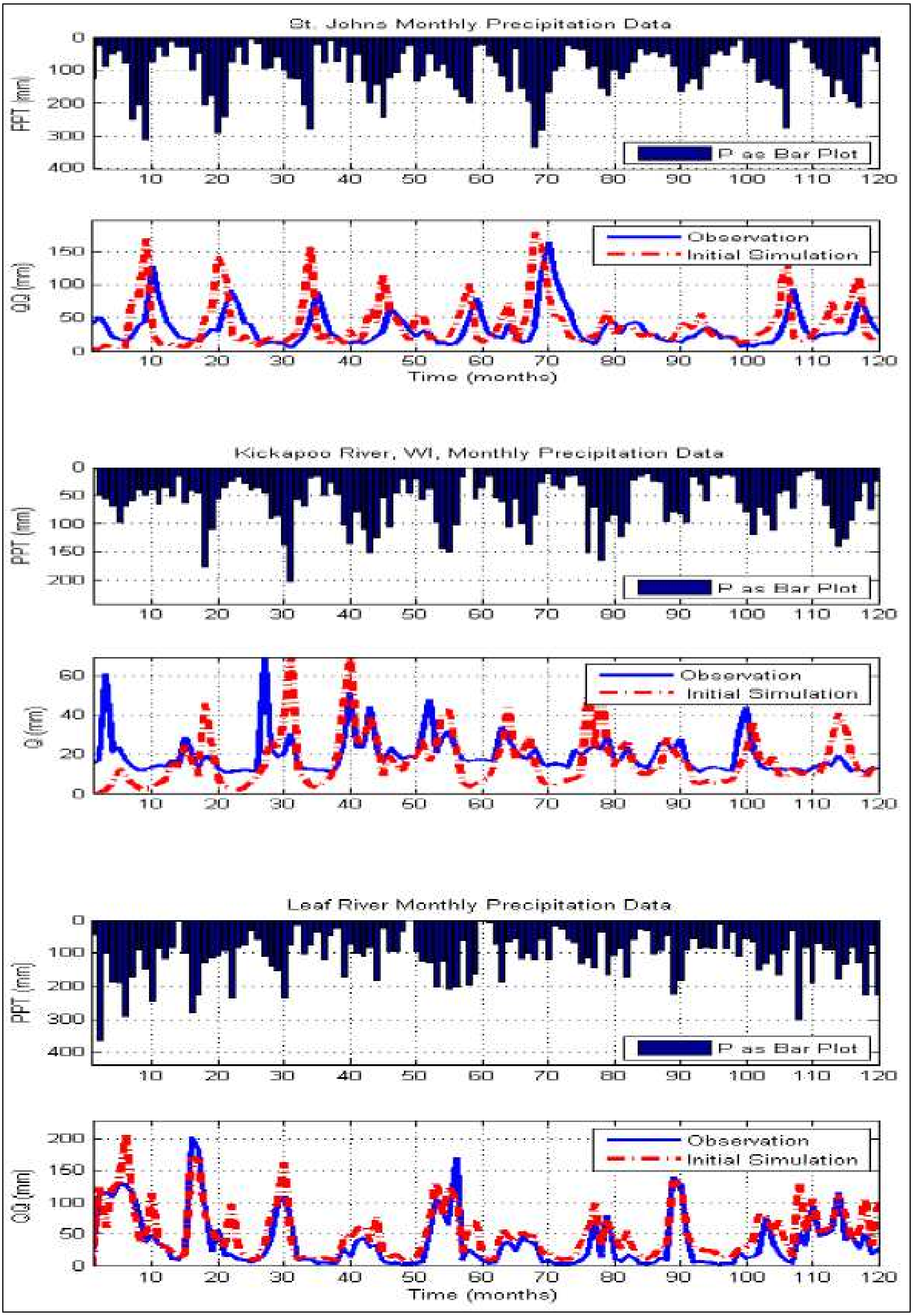


Figure 3. Initial simulation for St. Johns, Kickapoo, and Leaf Rivers. (a = 0.97, b = 250, c = 0.2, and d = 0.01) for 10 years of monthly data (1948-1958)

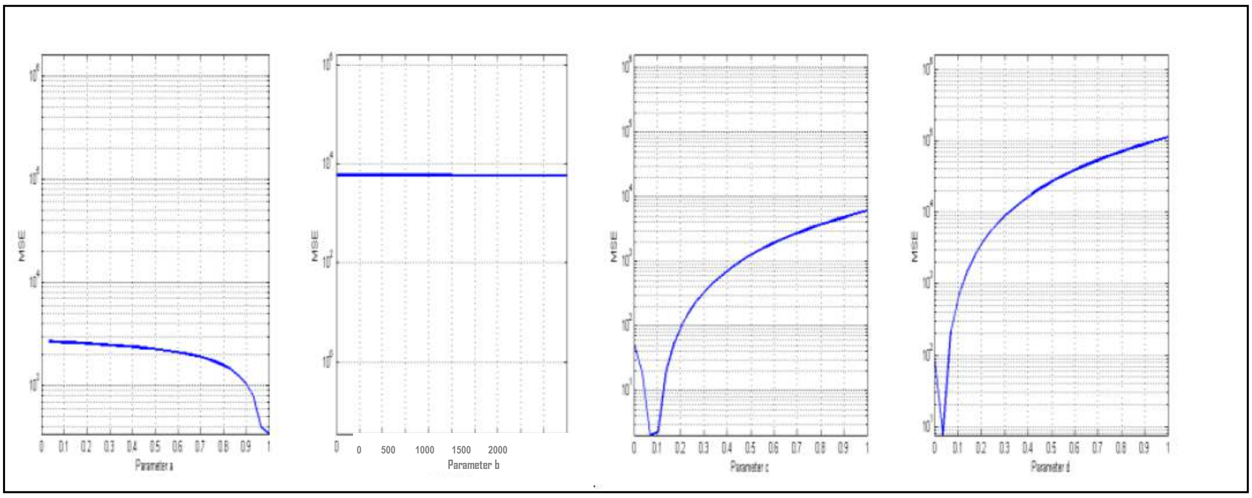


Figure 4. Perturbation analyses for parameters (a, b, c, and d), St Johns River

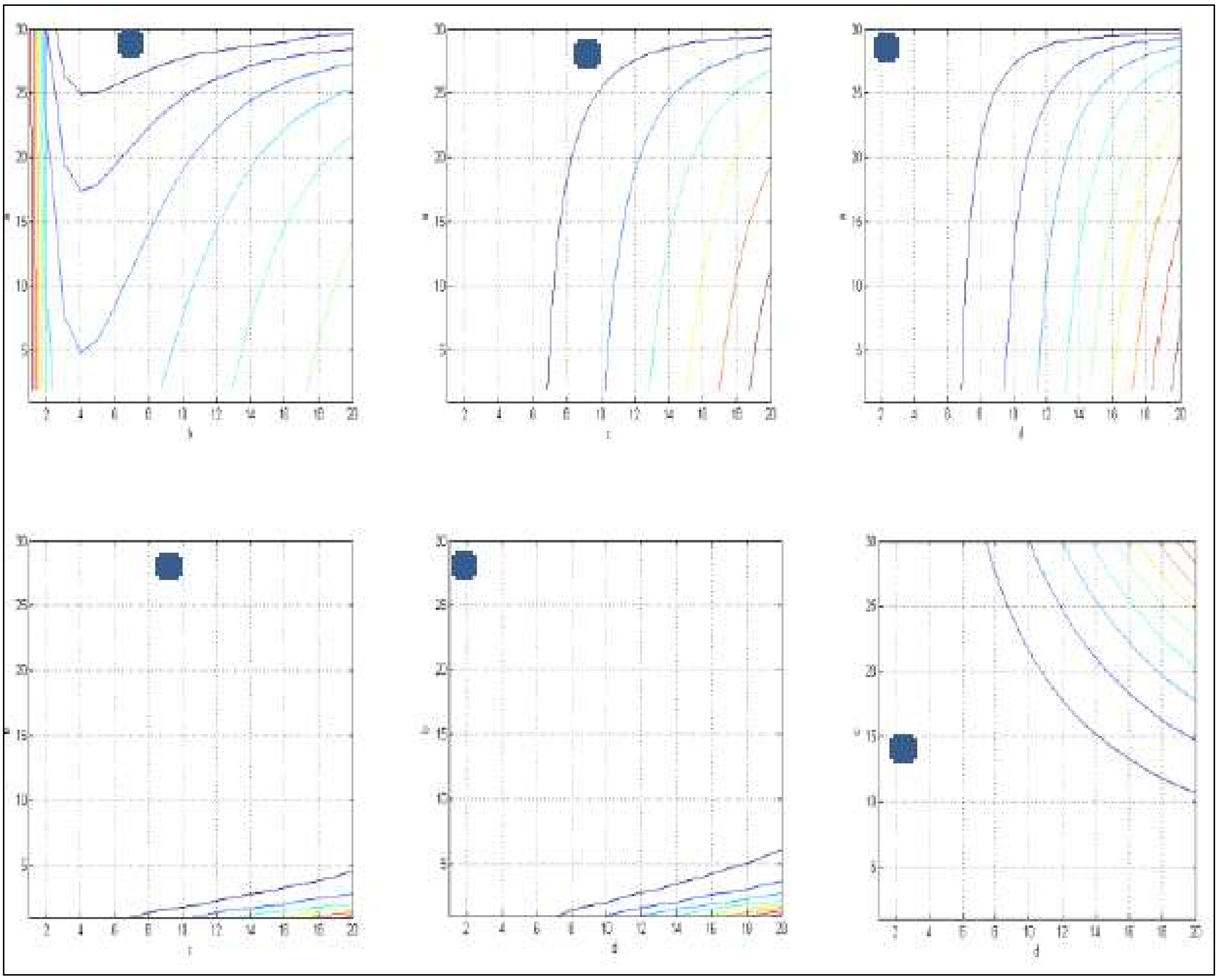


Figure 5. Six 2-parameter combinations of response surfaces for St. Johns River. Up: from left to right (a-b, a-c, and a-d combinations). Down: from left to right (b-c, b-d, and c-d combinations)

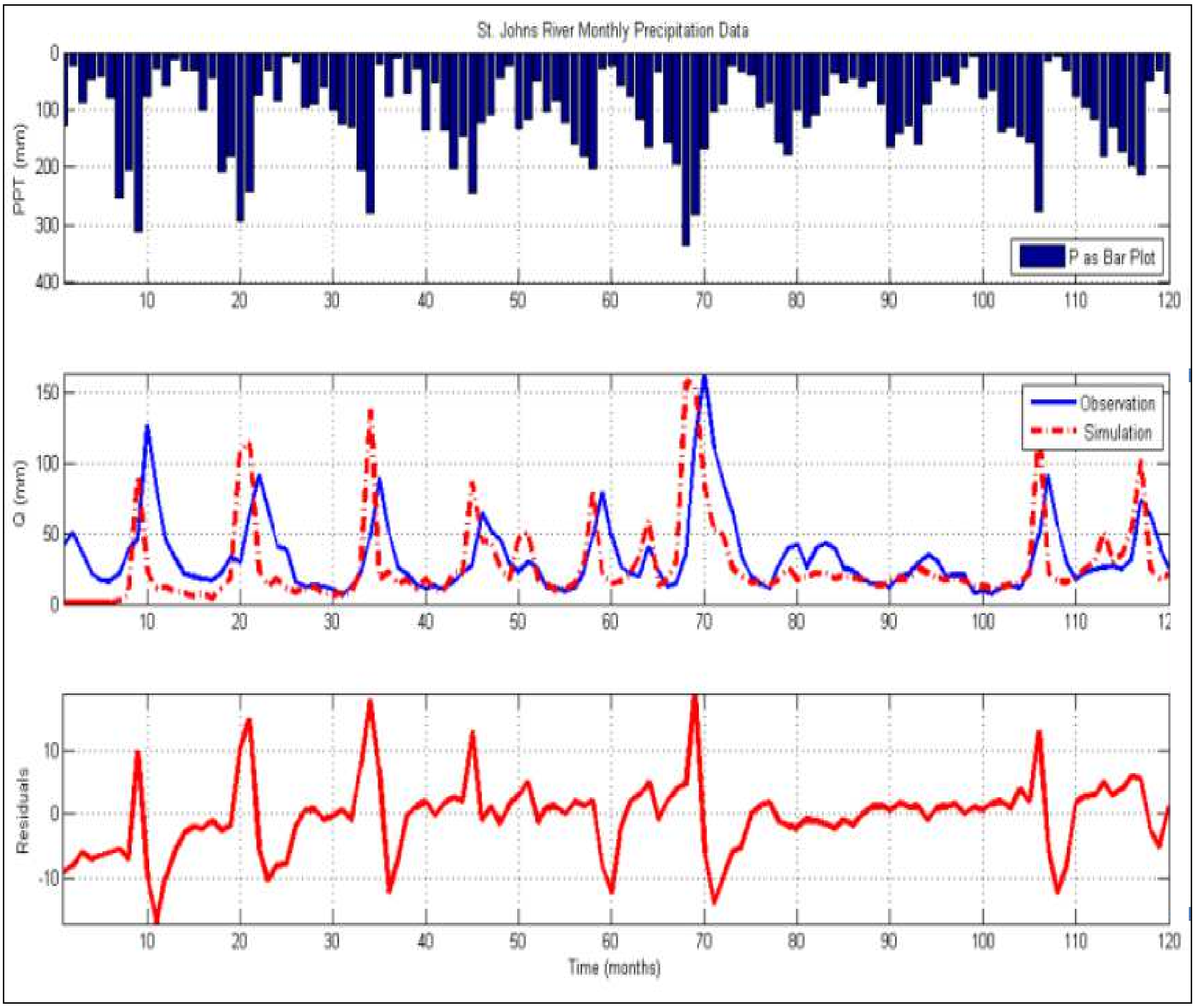


Figure 6. Applying the "abcd" model for St. Johns River, MSE= 5.31, a = 0.994, b = 700, c = 0.1, and d = 0.03

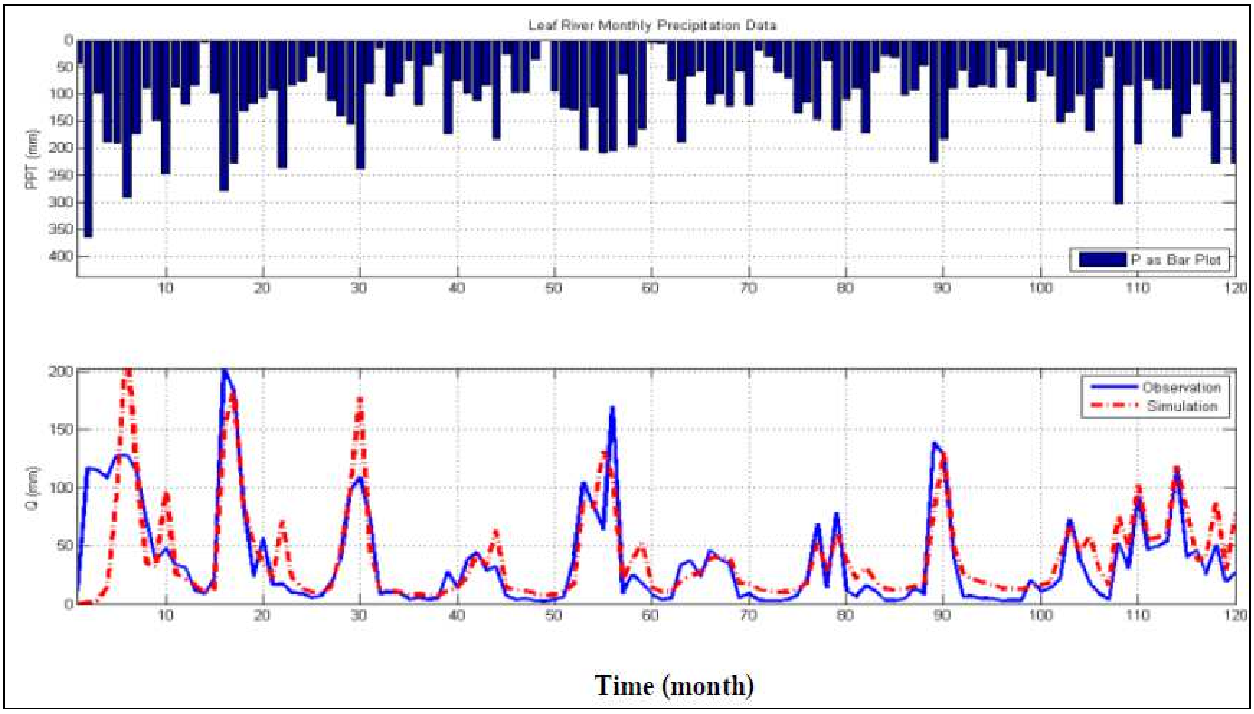


Figure 7. Applying the "abcd" model for Leaf River, MSE = 6.68

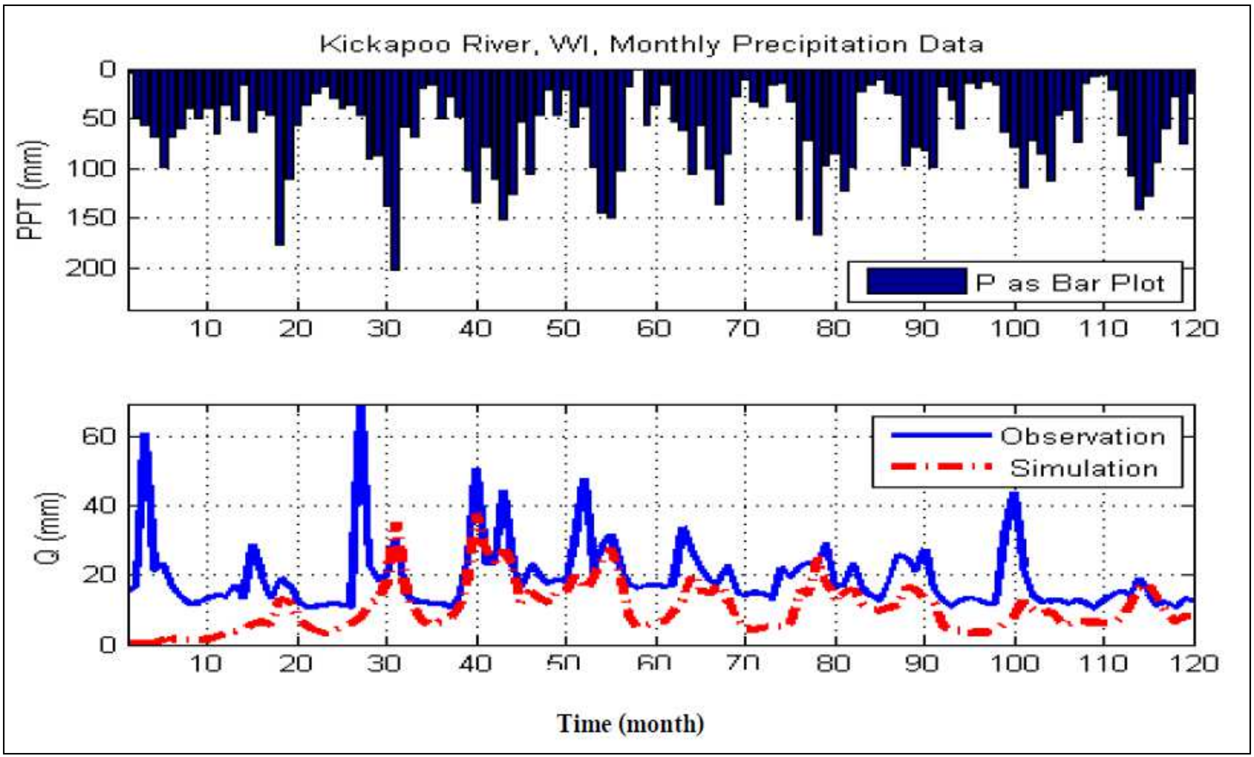


Figure 8. Applying the "abcd" model for Kickapoo River

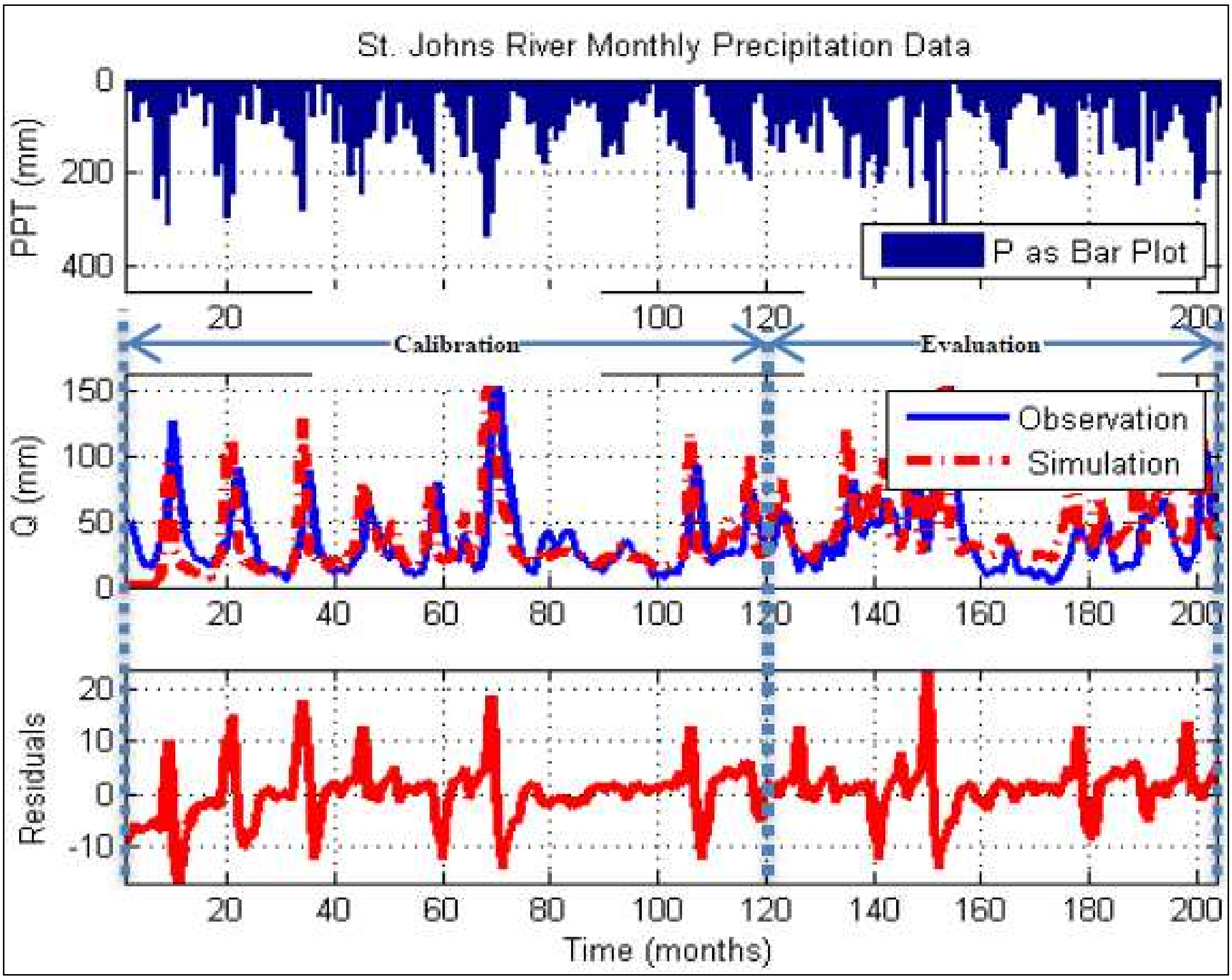
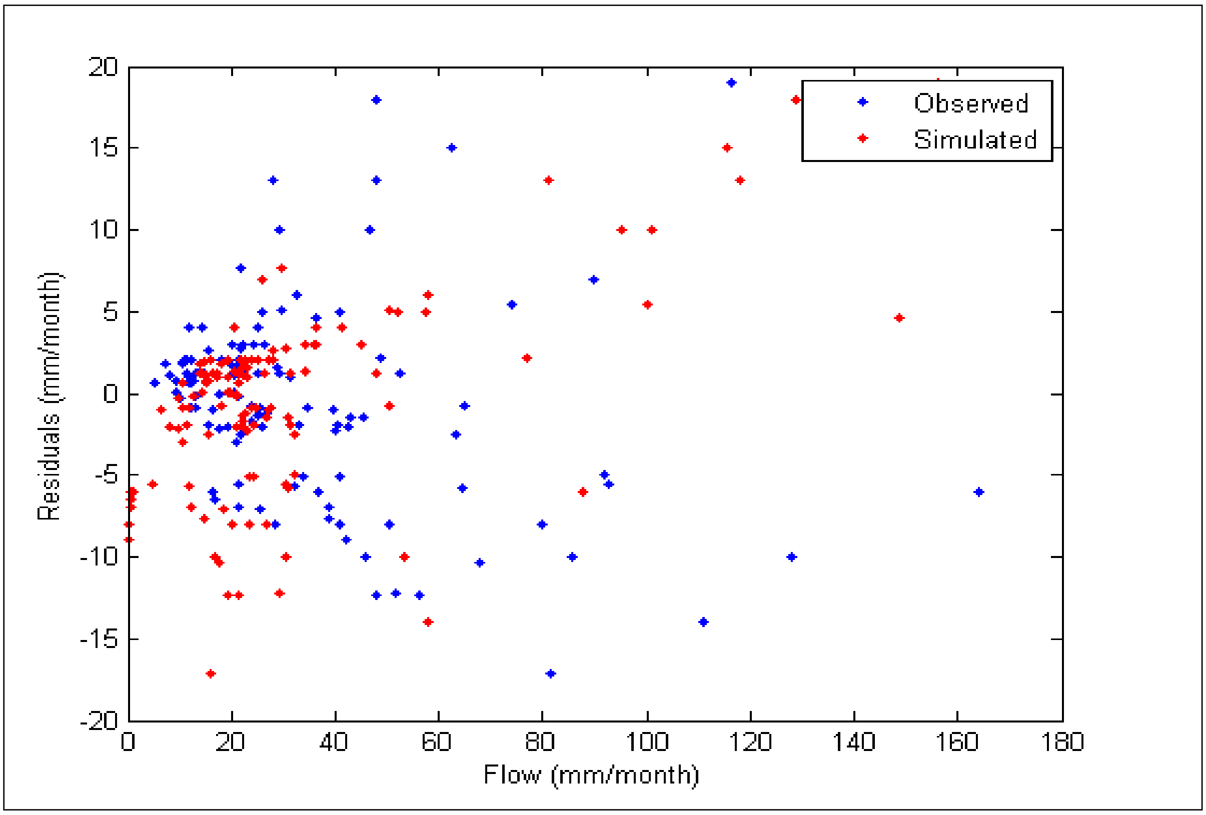
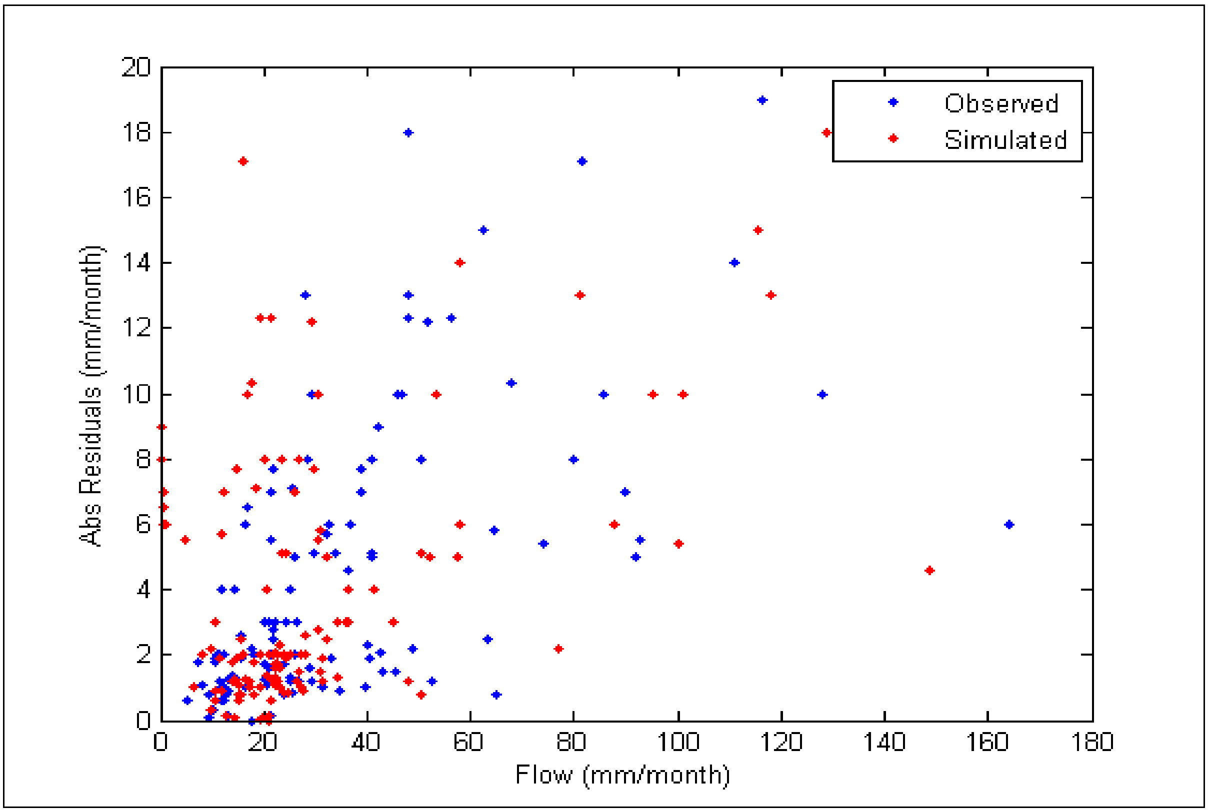


Figure 9. Evaluation of the “abcd” model (St. Johns River). MSE = 7.14

APPENDIX 1. Residuals and absolute residuals versus flows (St. Johns River)





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