CALIBRATION AND APPLICATION OF LUOM IN SOUTHERN GUAM WATERSHEDS WITH AND WITHOUT FLOW DATA

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Abstract

In southern Guam, there are a few watersheds with both rainfall and streamflow data. But some other watersheds have only rainfall data but no streamflow data. In the watersheds without streamflow data, it is obviously difficult to carry out watershed management studies which require streamflow data. Meanwhile, there are two problems with most of the watersheds with streamflow data. One is that the streamflow gage is not always located at the watershed outlet but a distance upstream of the outlet. The other is that there are many missing data in the streamflow data. These problems also induce difficulties to the watershed management and plans.

The objective of this study is to calibrate and validate the watershed model – LUOM (Luo, 2007) in the southern Guam watersheds in which there are both rainfall and streamflow data, and then to apply the calibrated models to the southern Guam watersheds both with and without streamflow gages to generate long term time series of streamflow for the whole watershed.

The Large-scale, Unified and Optimization Model, LUOM (Luo, 2007) is a fully physically based, two-dimensional distributed watershed model which simulates the hydrologic cycle on a watershed scale. The model discretizes the watershed into rectangular grid cells and makes use of spatial distributed GIS (Geographic Information Systems) data such as DEM (Digital Elevation Model), vegetation, and soil data. The model comprises of a series of sub-models for climate data distribution, evapotranspiration, infiltration, groundwater, surface flow, etc. The surface flow sub-model solves the two-dimensional shallow water equations using the diffusive wave approximation. With the input of climate data, mainly precipitation, temperature and wind speed, the model is able to generate not only one-dimensional output – discharge hydrographs, but also two-dimensional hydrologic quantities such as evapotranspiration, infiltration, soil moisture, groundwater table and surface water depth. Simulation of the impacts of land use (vegetation) transformation and global climate changes is within the model's capability.

In this study, DEM, vegetation, soil, rainfall and streamflow data have been collected and processed, hydrologic watershed boundaries and stream networks have been delineated, and the LUOM (Luo, 2007) has been calibrated and validated in Ugum watershed and verified and recalibrated in the other 4 watersheds with both rainfall and streamflow data, which are Lasafua, Umatac, Inarajan, and Puliluc (at Tinago station), and the calibrated models were applied to a total of 12 watersheds including the 5 calibration watersheds and the other 7 adjacent watersheds. Fifty four (54) years of long term rainfall data have been composed from the observation data collected at the 9 climate stations in southern Guam, which have 15 years of or longer rainfall records. Using these long term rainfall data as input, the model generated long term time series of steamflow. The final output of the long term time series of streamflow is a combination of the observation streamflow data collected at the USGS gage if the watershed has one and the long term simulation result from the model.

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Chapter 1. Introduction

1.1 Hydrologic issues in southern Guam watersheds

Southern Guam has been delineated into 14 major watersheds (Khosrowpanah et al., 2008) and about 31 major hydrologic watersheds were identified in this project. Development of effective watershed management plans in southern Guam requires having a better understanding of the streamflows passing through the watershed outlets that reach to the coastal areas. Meanwhile, hydrologic designs such as construction of reservoirs and hydraulic designs such as water intake weirs need consecutive long term streamflow data for the statistical analysis. For decades, US Geological Survey (USGS) has been collecting streamflow data from 21 installed streamflow gages in southern Guam. However, only 7 gages have streamflow data lasting until 2009 and most of the data are inconsecutive. There are also many missing data in these flow data. Table 1 lists all the USGS streamflow gages available in southern Guam and their data time spans.

Table 1. USGS streamflow gages and their data spans (* Gages with data until 2009)

No.	Flow Gage	Data								Remark
		FROM	TO	FROM	TO	FROM	TO	FROM	TO	
1*	Almagosa RV	4/1/1972	3/24/1992	1/29/1993	4/30/1994	3/22/1997	10/11/2009			
2	Almagosa SP	10/1/1951	12/31/1967	12/1/1971	9/30/1975					
3*	Aplacho	10/1/1999	12/8/2004	9/1/2006	10/9/2009					
4	Cetti	3/1/1960	9/30/1967							
5	Fena Dam Spillway	10/1/1951	7/31/1952	12/1/1952	9/30/1973					
6	Finile	4/1/1960	12/31/1982							
7	Geus	5/1/1953	9/30/1975							
8*	Imong	4/1/1960	3/10/1994	7/15/1997	4/2/2002	6/1/2003	8/26/2005	2/28/2006	10/9/2009	Missing data
9	Inarajan	10/1/1952	12/31/1982							
10*	Lasafua	5/1/1953	6/29/1960	10/1/1976	4/30/1984	6/20/2000	10/14/2009			
11	Longfit	10/1/1951	3/31/1960							
12*	Maulap	1/1/1972	3/10/1994	7/10/1997	2/3/2002	7/1/2002	10/11/2009			
13	Pago	10/1/1951	12/31/1982	9/26/1998	12/6/1999	5/1/2000	7/14/2002	9/4/2003	10/30/2009	Missing data
14	Talofofo	12/1/1951	6/30/1962							
15	Tinago	11/1/1952	9/30/1985							
16	Tolaeyuus Lower	6/1/1994	5/23/1995	10/2/1996	3/2/1997	7/11/1997	7/4/2002			
17	Tolaeyuus upper	10/1/1951	6/30/1960							
18*	Ugum above Talofofo	6/1/1977	6/12/1995	3/7/1997	5/14/2002	6/1/2003	10/12/2009			
19	Ugum near Talofofo	6/19/1952	9/30/1970							
20*	Umatac	10/1/1952	10/7/1976	9/13/2001	3/27/2002	10/1/2002	2/26/2009			
21	Ylig	7/1/1952	3/31/1986	4/1/1987	5/2/1995	7/13/1997	7/12/2002			

The information in Table 1 was summarized from the streamflow data downloaded from USGS Pacific Islands Water Science Center website http://hi.water.usgs.gov/guam/guam_tab.htm, which is no longer available after January 2010 and has been replaced by http://wdr.water.usgs.gov/nwisgmap/?state=gu. Also some of the inactive streamflow stations (and inactive rain gages as well) have been removed from the new website.

Inconsecutiveness of streamflow data hinders the statistical analysis for hydrologic and hydraulic design and therefore it is difficult to carry out water resources planning, such as watershed management, land development, and water quality studies in the watersheds.

In addition to inconsecutiveness of the streamflow data, some of the streamflow gages are located in the reaches a distance upstream the watershed outlet leaving a large portion of the drainage area unaccounted for. An example is the Ugum River that supplies drinking water for southern Guam. Figure 1 shows that the currently active streamflow gage, Ugum above Talofofo (as UGUM AB TAL in the figure) is about 4 km (2.5 miles) upstream the watershed outlet leaving about 20% of the watershed area uncounted for the steamflow data collected at this station. To determine the total volume that flows into the ocean requires having a reliable numerical method.

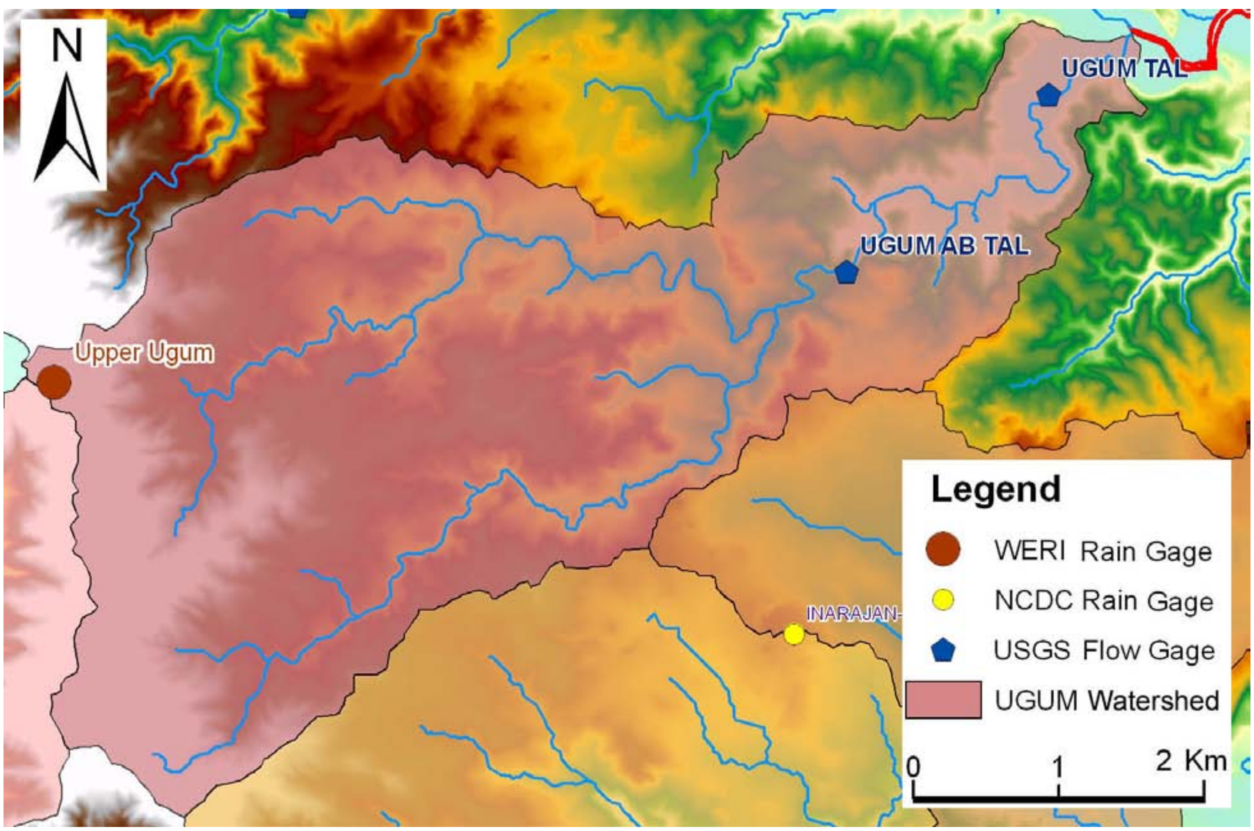


Figure 1. Ugum watershed (pink) and the active USGS flow gage, Ugum above Talofofo
(UGUM AB TAL in the figure, which is 4 km/2.5 miles upstream the watershed outlet)

Besides the water quantity problem, there is a water quality issue. Guam Water Authority (GWA) that operates the Ugum water treatment plant has faced an increasingly difficult task of keeping the plant operating at full capacity when the river is running with high turbidity rates. This highly turbid water has increased operational costs and, along with poor operation and maintenance practices, has led to premature failure of many components of the treatment plant system. Water that passes the Ugum treatment plant intake eventually makes its way to the outlet of the watershed and into the estuary and reef environment. The negative impact of sediment loading on the aquatic environment of Guam has been recorded by several researchers (such as Rogers, 1990; and, Richmond, 1993). The USGS streamflow gage is located in the upstream reach of the intake structure. This makes about 20% area of the watershed that contribute turbid water into the Ugum River be unaccounted for. This is true for other major streams such as Pago and Ylig Rivers. There is a need to develop a methodology that enables researchers to obtain the streamflow at any section of the watershed for effective water resources management.

1.2 Selection of an effective watershed model

In order to tackle effectively the issues which are faced with in the hydrologic study of southern Guam watersheds, it is necessary to take the spatial variability of the watersheds into account. This spatial variability is reflected by the distributed Geographic Information System (GIS) data such as DEM (Digital Elevation Model), vegetation and soil data. Presently, there are about a total of 12 climate stations available in southern Guam. A watershed model, which is a numerical representation of hydrologic cycle within a watershed, should be able to make full use of these distributed GIS data and the climate data from all the available stations so as to give simulation results of higher quality. Based on these considerations, a fully physically based, two-dimensional distributed watershed model, the LUOM (Luo, 2007), which is able to run not only on a single climate station but also on multiple climate stations, was adopted in this project. Using DEM, vegetation, soil and multi-stationed climate data as inputs, the model generates hydrographs at any location of the stream, and other distributed hydrologic quantities such as evapotranspiration, infiltration, soil moisture, and groundwater table as well if necessary. The model has been successfully applied to a large-scale watershed, the Tone River Basin with an area of about 16,000 km^2 (6,250 square miles) and other watersheds in Japan (Luo, 2007). The model concepts, structure, numerical solution of the governing equations, and sub-models will be introduced in detail in Chapter 2.

1.3 Objective and benefits of this project

The objective of this study was to calibrate and validate the LUOM (Luo, 2007) in the southern Guam watersheds in which there are both rainfall and streamflow data, and then to apply the calibrated models to the southern Guam watersheds both with and without streamflow gages to generate long term time series of streamflow for the whole watershed. Based on the criteria of similar watersheds and using the LUOM (Luo, 2007), this project developed the methodology to generate long term time series of streamflow in watersheds without a streamflow gage. The model was calibrated in the upstream part of Ugum Watershed, which is gauged by USGS. The calibrated models will be applied to the southern Guam watersheds both with and without streamflow gages.

The benefits of this project will be enormous not only to Guam but also to other islands in the Western Pacific. Researchers will be able to implement various watershed management practices within the watersheds. For example, by having streamflow data, researchers could develop a correlation between stream flow, rainfall, and turbidity at various sections of a watershed for studying the impact of various watershed management practices. The model will benefit to Agencies such as GWA for exploring potential sources of drinking water in southern Guam. By having steamflow data, potential sites for developing drinking water supply such as construction of small dams could be identified.

The model could benefit to other islands in the Western Pacific (for example island of Pohnpei), where there is no or few streamflow gages. When the political status of the Federated States of Micronesia with the United States changed from Trusteeship into Free Association in 1986, all the streamflow monitoring that was provided by the USGS before was halted and the streamflow gages have been abandoned. Since 1994 there has been no information on streamflows running through the rivers and no information about sediment being carried to the reefs. The hydrologic model could be applied to the streams of Pohnpei.

1.4 Steps of model application

Figure 2 in the next page is a flowchart showing the model calibration, validation, verification, recalibration and final application for long term simulation. Before the model running, the input data have been processed and prepared. The model was first calibrated and validated in Ugum watershed which has both rainfall and streamflow data. And then, the calibrated model was further verified and recalibrated in the immediately adjacent 4 watersheds which also have rainfall and streamflow data. And finally, the calibrated models were applied to a total of 12 watersheds in southern Guam including the 5 calibration watersheds to generate long term time series of streamflow. The final output of long term time series of streamflow (54 years or longer) for a watershed with streamflow data is the combination of observation data collected at the USGS streamflow gage and the simulation result, while that for a watershed without streamflow data is only the simulation result.

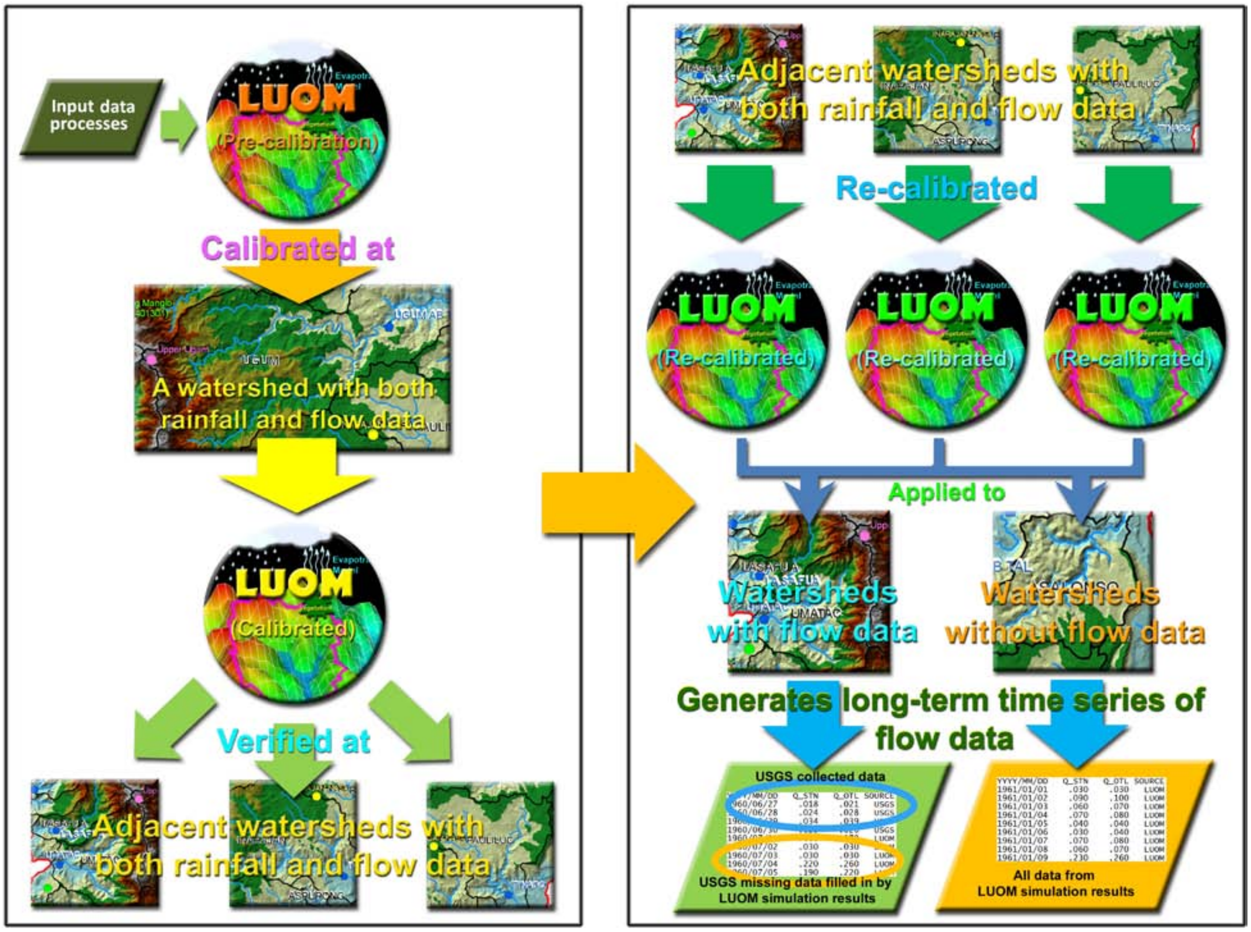


Figure 2. Flowchart of model application in southern Guam watersheds

1.5 About this report

In this report, there are totally 5 chapters including this introduction chapter and a chapter that briefly describes the watershed model – LUOM (Luo, 2007) including model structure, governing equations and the scheme of numerical solution, a chapter relating GIS, climate and streamflow data processes including delineation of watershed boundaries and stream networks and distribution of daily rainfall to hourly rainfall, a chapter about model calibration and validation in Ugum watershed and verification and recalibration in the other 4 adjacent watersheds, and a chapter presenting the long term simulation in a total of 12 southern Guam watersheds and the simulation results. At the end of this report, there is an appendix assembling figures of the simulated hydrographs of the last 4 years for the watersheds without observation streamflow data and comparisons of simulated and observed hydrographs in the latest 4 years of available observation data for the watersheds with streamflow data.

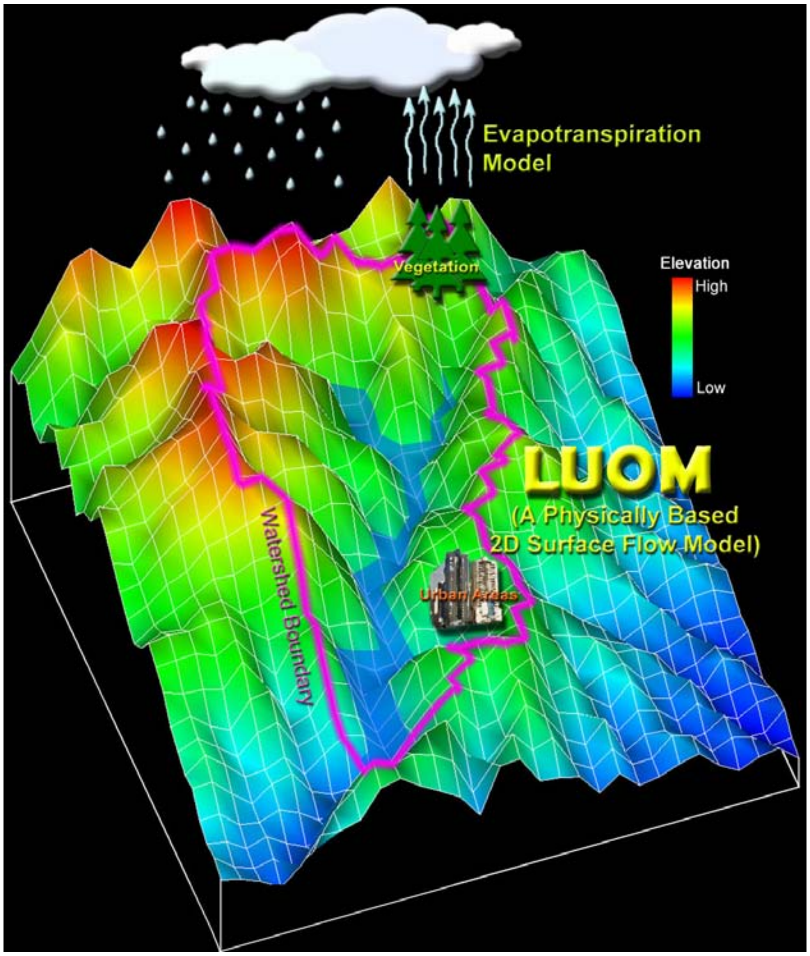
Chapter 2. The Watershed Model - LUOM

2.1 Model properties and structure

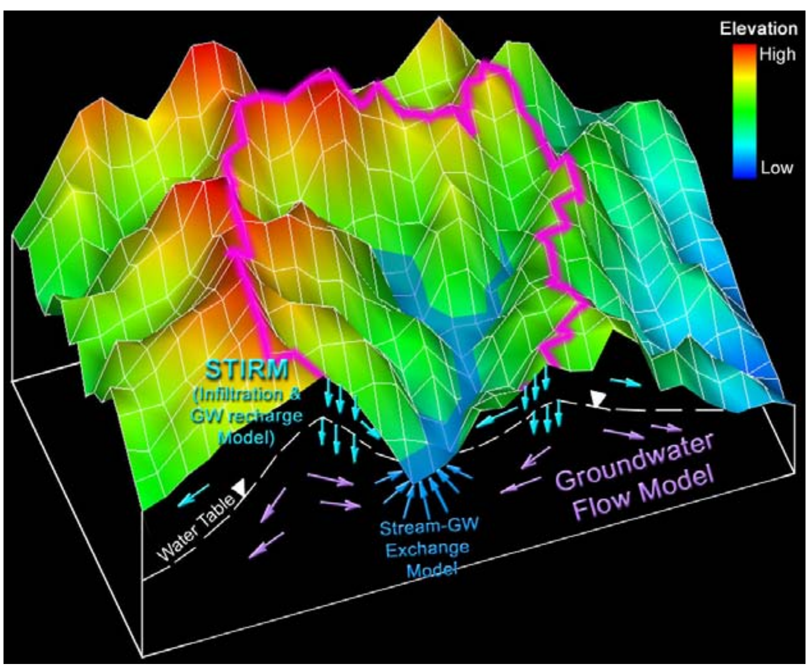
The Large-scale, Unified, and Optimization Model (LUOM) (Luo, 2007), which is a fully physically based, two-dimensional distributed watershed model, is the main facility and tool that was used in this project. The diffusive wave approximation of the two-dimensional free surface shallow water flow equations are employed as the governing equations for the surface flows including both overland and channel flows. The diffusive wave model is able to simulate the backwater phenomenon, in which the water may flow from the downstream reaches or the estuary back to the upstream reaches in a river. The model is also able to simulate the flows on the overland areas with a zero slope. In this model, both overland and channel flows are placed in the same physical domain, in which a channel grid cell exchanges mass and momentum with the eight adjacent grid cells of overland, channels and water bodies. The finite difference method based on the staggered grid scheme, in which the vectors of velocity are defined at the borders of the grid cell and the water depth is defined at the center of the grid cell, is utilized to discretize the governing equations and the optimization numerical scheme, SIMPLE, is employed to solve the finite difference equations using a tri-diagonal matrix.

The surface flow model is coupled with models for evapotranspiration, infiltration and groundwater recharge, water exchanges between aquifers and channels, groundwater, and spatial distribution of climate data. In the evapotranspiration model (Luo, 2000), the combined method of energy balance and aerodynamics is used to calculate the potential evapotranspiration or reference crop evapotranspiration. The actual evapotranspiration is obtained by multiplying the reference crop evapotranspiration by a crop coefficient and a soil coefficient if the soil moisture supply is sufficient; otherwise the actual evapotranspiration is controlled by the maximum soil water or moisture that could be evaporated. In the infiltration and recharge to groundwater model, the two-layer Green-Ampt infiltration model is employed to calculate the infiltration. The water exchanges between aquifers and channels are computed by Darcy's law, and the groundwater flow model is the numerical solution of the Boussinesq equation using the finite difference method. In the model, vegetation plays an important role in the surface flow, evapotranspiration, and infiltration simulation. For each grid cell, Manning coefficient, crop coefficient, initial soil moisture and infiltration rate are close related to the vegetation type of the grid cell.

Figure 3 shows the model structure of the LUOM (Luo, 2007). The pink line is the watershed boundary and the thick transparent blue lines inside the boundary are the streams. Figure 3 (a), upper, shows the relationship of the surface flow model and the evapotranspiration model, and Figure 3 (b), lower, shows the relationship of the surface flow model and the underground models – the infiltration model and the groundwater model.



(a) Sub-models on and above the land surface: surface flow model and evapotranspiration model



(b) Underground sub-models: infiltration model and groundwater model

Figure 3. Model structure of LUOM

2.2 Model concepts and governing equations

In the model, overland grid cells and channel grid cells are different with respect to their flow status and hydraulic characteristics. A channel always has a certain flow course and maintains a base flow during all or much of the year, and hydraulic roughness is relatively small. The overland area does not have a definite flow course or a steady base flow, and the hydraulic roughness is relatively large. However, these differences may diminish during flooding or inundation. In order to manifest the common characteristics of overland flows and channel flows, the LUOM (Luo, 2007) places both overland flows and channel flows together in the same physical domain. One of the advantages of a distributed model over a lumped model is that each grid cell in the watershed possesses its own hydraulic parameters such as roughness coefficient, land use, elevation, water depth, etc. In the model, channel grid cells and overland grid cells are placed in the same grid sheet while their unique parameters and state variables are maintained. This means that the whole watershed is meshed with a single grid sheet, in which each grid cell is marked as either a channel cell or an overland cell. Those grid cells of water bodies such as lakes and reservoirs outside the cells of stream central lines are marked as overland cells but have the land use of water body and non-zero initial water depths. Dry overland cells can be inundated and water body cells may dry out. Figure 4 is a conceptual grid sheet illustrating both overland grid cells (white) and river grid cells (colored).

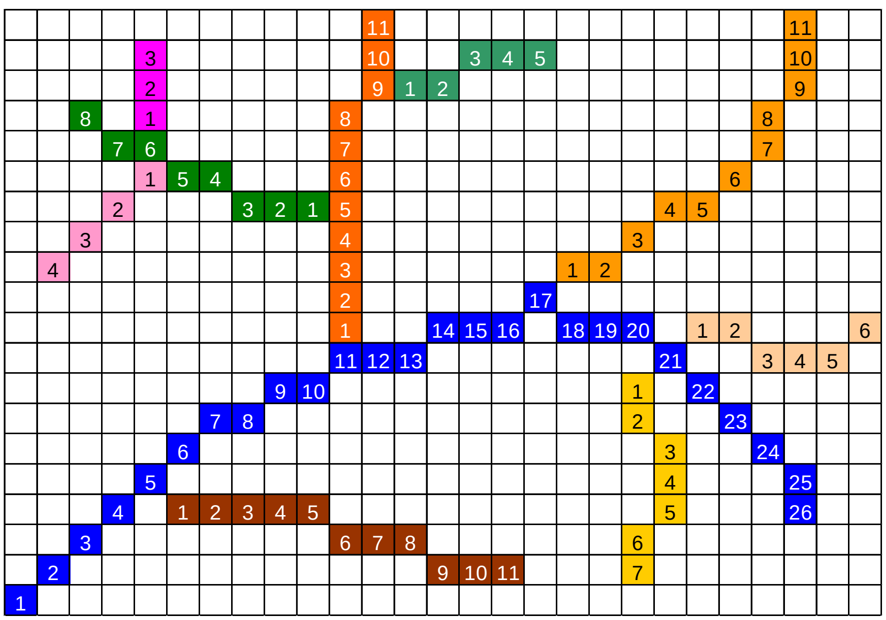


Figure 4. A conceptual grid sheet illustrating overland cells and river cells in LUOM

Under this unified conceptual scheme, the channel is not running along the edges of the adjacent grid cells as MIKE SHE but running across the grid cells and the channel flows are not the boundary conditions of the overland flows. All watershed grid cells including overland, water bodies, channels links, junctions of tributaries and diversions of channel loops are physically connected to each other by the model topology, and are mathematically connected to each other via the unified two-dimensional governing equations derived in the next subsection.

As both channel flows and overland flows are placed in the same physical domain in this study, the two-dimensional diffusive wave approximation of the free surface flow equations are utilized as the governing differential equations for both channel flows and overland flows. The diffusive wave equations can be written as below:

$$\begin{cases} \frac{\partial(uh)}{\partial x}+\frac{\partial(vh)}{\partial y}+\frac{\partial h}{\partial t}=q \\ \frac{\partial z}{\partial x}+S_{fx}=0 \\ \frac{\partial z}{\partial y}+S_{fy}=0 \end{cases} \tag{1}$$

where u and v are the x and y components of the flow velocity, respectively; h is the water depth; z is the water surface elevation, where $z=h+z_0$; z_0 is the land surface elevation; q is the lateral flow in the vertical direction; S_{fx} and S_{fy} are the friction slopes in x and y directions, respectively. The friction slopes can be obtained from the following Manning equations when the Strickler/Manning-type law for the friction slopes is applied in the same directions as the flow velocities are defined:

$$\begin{cases} S_{fx}=\left(n_x^2 u|u|\right)/\left(h^{4/3}\right) \\ S_{fy}=\left(n_y^2 v|v|\right)/\left(h^{4/3}\right) \end{cases} \tag{2}$$

in which n_x and n_y are the Manning coefficients in x and y directions respectively.

First of all, only overland grid cells are considered. The continuity equation in equations (1) is written into a difference form:

$$\frac{\Delta(uh)}{\Delta x}+\frac{\Delta(vh)}{\Delta y}+\frac{\Delta h}{\Delta t}=q \tag{3}$$

in which Δx and Δy are grid sizes in x and y directions respectively, h is the average water depth over the whole grid, and Δt is the time step. The lateral flow q is the sum of vertical inputs and outputs such as net precipitation, infiltration, and sources such as water supply and input from drainage systems, but does not include the horizontal flows to or from the adjacent grid cells (included on the left-hand side of the equation). The lateral flow q has the unit of velocity, and physically it is the average water depth over the whole grid cell per unit time. Multiplying Δx and Δy to both sides of equation (3), the following equation can be obtained:

$$\Delta(uh\Delta y)+\Delta(vh\Delta x)+\frac{\Delta h}{\Delta t}\Delta x\Delta y=q\Delta x\Delta y \tag{4}$$

If A_x is defined as the cross-section area of the flow in direction x, A_y as the cross-section area of the flow in direction y, and A_g as the horizontal area of the grid cell for holding water vertically. For an overland grid cell, these areas can be written as:

$$A_x = h\Delta y,\ A_y = h\Delta x,\ A_g = \Delta x\Delta y \tag{5}$$

Substitute equations (5) into equation (4), which becomes:

$$\Delta(uA_x) + \Delta(vA_y) + \frac{\Delta h}{\Delta t} A_g = q\Delta x\Delta y \tag{6}$$

in which the terms on the right-hand side remain unchanged for the further use of $\Delta x\ \Delta y$. It is noticed that:

$$Q_x = uA_x,\quad Q_y = vA_y \tag{7}$$

where Q_x and Q_y are discharges in *x* and *y* directions respectively, and equation (6) becomes:

$$(\Delta Q_x + \Delta Q_y) + \frac{\Delta h}{\Delta t} A_g = q\Delta x\Delta y \tag{8}$$

This is the continuity difference equation for overland flows.

Now, channel grid cells are taken into consideration. Figure 5 shows the possible channel flow directions. If the channel runs in the *x* or *y* direction (Figure 5, left), equation (8) is applied. However, in this study, a channel may flow along the diagonal directions (Figure 5, right). Under this assumption, an increment of channel discharge Q_{ch} must be added to the first term inside the parentheses on the left-hand side of equation (8):

$$(\Delta Q_x + \Delta Q_y + \Delta Q_{ch}) + \frac{\Delta h}{\Delta t} A_g = q\Delta x\Delta y \tag{9}$$

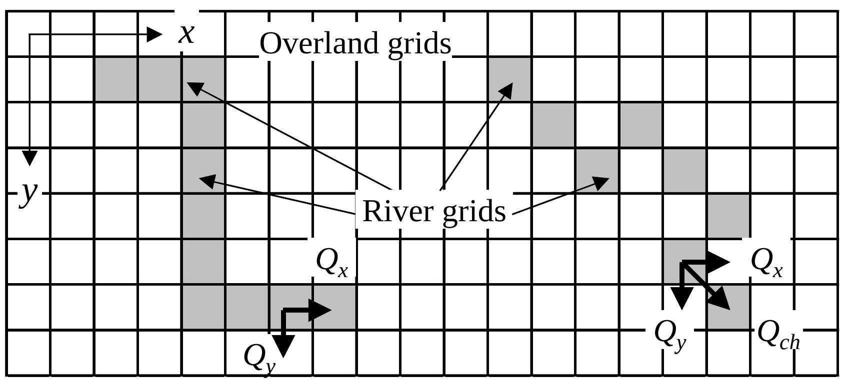


Figure 5. Possible channel flow directions

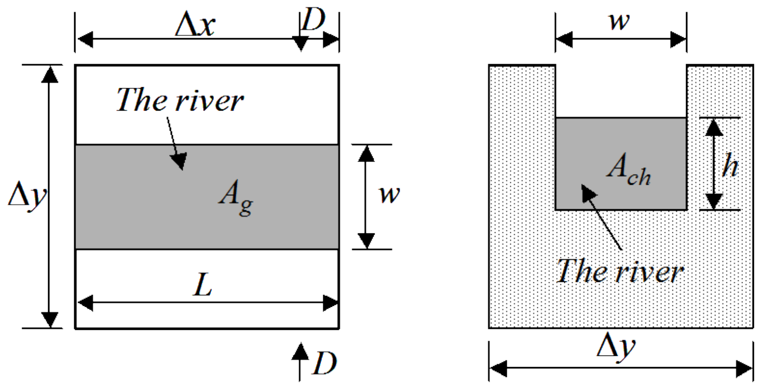
Dividing both sides with Δx and Δy, and substituting equation (7) into the first term of equation (9), which becomes:

$$\frac{1}{\Delta x\Delta y}\left[\Delta(uA_x) + \Delta(vA_y) + \Delta(u_{ch}A_{ch})\right] + \frac{\Delta h}{\Delta t}\frac{A_g}{\Delta x\Delta y} = q \tag{10}$$

in which u_{ch} is the velocity of the channel flow, and A_{ch} is the cross-section area of the channel flow. This is the unified continuity equation for both overland flows and channel flows. For an overland grid, u_{ch} and A_{ch} are zero and $A_g = \Delta x\Delta y$, equation (10) reduces to equation (3) or (8).

Next, A_{ch} and A_g in equation (10) are calculated for channel grid cells. Figure 6 shows a river grid cell in detail, and the channel runs in *x* direction for convenience of explanation. In Figure 6, *h* is the water depth, *w* is the channel width, and *L* is the channel length inside the grid cell:

$$L = \begin{cases} \Delta x, & \text{For flows in } x \text{ direction} \\ \Delta y, & \text{For flows in } y \text{ direction} \\ \sqrt{\Delta x^2 + \Delta y^2}, & \text{For flows in diagonal directions} \end{cases} \quad (11)$$



(a) Top view (b) D-D section

Figure 6. A river grid cell

In a channel grid cell, the horizontal area of the grid cell for holding water vertically is the river surface area, and the channel flow cross-section area is the product of water depth and the river width:

$$\begin{cases} A_g = Lw \\ A_{ch} = hw \end{cases} \quad (12)$$

Comparing equations (12) with equations (5), one can see the A_g in a river grid cell is the same as that in an overland grid cell only if the channel width is the same as the grid size and the channel does not run in a diagonal direction.

If the momentum equation for channel flows is used in the unified model after some rearrangement, together with the continuity equation (equation 10), the unified difference governing equations for surface flows including both overland flows and channel flows can be written as:

$$\begin{cases} \dfrac{1}{\Delta x \Delta y} \sum_{xi}^{x,y,ch} \Delta(u_{xi} A_{xi}) + \dfrac{\Delta h}{\Delta t} \dfrac{A_g}{\Delta x \Delta y} = q \\ u_{xi} A_{xi} = -\left(\dfrac{A_{xi} R_{xi}^{2/3}}{n_{xi}} \left| \dfrac{\Delta z}{\Delta x_i} \right|^{-1/2} \right) \dfrac{\Delta z}{\Delta x_i}, \quad x_i = x, y, ch \end{cases} \quad (13)$$

where R is the hydraulic radius. In equation (13), the first term on the left-hand side of the continuity equation has all the three terms only if the grid cell is a channel grid cell and the channel runs in a diagonal direction. If the grid cell is an overland grid cell, there is no channel flow term, and if it is a channel grid cell and the channel runs in x or y direction, the overland flow term in the same direction is replaced by the channel flow term. This is also true for the momentum equations.

2.3 Numerical solution

The finite difference method based on the staggered grid scheme (Versteeg and Malalasekera, 1995) is utilized to discretize the governing equations and the optimization numerical scheme, SIMPLE (Patanka and Spalding, 1972), is employed to solve the finite difference equations using a tri-diagonal matrix. SIMPLE is the acronym of Semi-Implicit Method for Pressure-Linked Equations. This method is essentially a guess-and-correct procedure for the calculation of pressure based on the staggered grid scheme. Pressure is a concept in fluid dynamics and the relevant concept in hydrology is water head or water depth.

In the LUOM (Luo, 2007), channel flows are no longer the boundary conditions of overland flows. Both channel flows and overland flows are placed in the same physical domain and governed by the same two-dimensional diffusive wave equations, and share the same modeling characteristics. Between a channel grid cell and an overland grid cell, there are exchanges of not only mass but also momentum, which may not be simply neglected if flooding or inundation occurs.

2.4 Boundary conditions and initial conditions

For the surface flow model, there are two types of boundaries, overland boundary and basin outlet boundary. As the overland boundary conditions, all water depths at the boundary grid cells are set to zero. Because there are no tidal observation data available in this study, the water surface level at the outlet grid cell is held constant. Upstream ends or sources of tributaries are not boundaries, and the water depths are given by the numerical solutions of all equations. Junctions and diversions are not boundaries either. Initial conditions are the initial water depths. All initial water depths on overland grids, except water bodies, are set zero. For channel grid cells, since there are no measured data of water depth available, the initial water depths are obtained from the computation results of a simplified numerical model using the discharge data at the gauge stations. Initial water depths of water bodies are obtained by extrapolating the water depths of stream central lines.

2.5 Introduction to the evapotranspiration sub-model

The evapotranspiration model plays an importance role in the water balance model, which determines the lost part of water from precipitation. There are many methodologies to calculate potential evapotranspiration and all kinds of evapotranspiration models have been developed. In this research, the combined method of energy balance and aerodynamics is adopted to calculate potential evapotranspiration or reference crop evapotranspiration. The actual evapotranspiration is obtained by multiplying the reference crop evapotranspiration by a crop coefficient and a soil coefficient if the soil moisture supply is sufficient, otherwise, the actual evapotranspiration is control by the maximum soil water or moisture that could be evaporated. Meteorological observation data are usually available at some observation stations only, and therefore an interpolation model is involved to interpolate the limited observation data over all grids of a watershed in a distributed watershed model.

The potential evapotranspiration is the evapotranspiration from an open water surface. According to the two factors control the open water evapotranspiration, the energy supply and vapor transportation ability, there are two methods to calculate potential evapotranspiration, one is the energy balance method and the other is the aerodynamic method. These two methods together require detailed climatological data like net radiation, air temperature, humidity, wind speed and air pressure. When some of these data are not available, the accuracy of both methods is influenced. In order to diminish bias estimation due to data deficiency and meanwhile make full use of the available data, the combined method of energy balance and aerodynamics are adopted to calculate the potential evapotranspiration (Luo, 2000). The combined method can be delineated by the following Penman equation:

$$E_{rc} = \frac{\Delta}{\Delta + \gamma} E_b + \frac{\gamma}{\Delta + \gamma} E_a \tag{14}$$

where E_{rc} is the reference crop evapotranspiration or the potential evapotranspiration, E_b is the evaporation calculated by the energy balance method, E_a is the evaporation calculated by the aerodynamic method, Δ is the gradient of the saturated vapor pressure curve at air temperature T, and γ is the psychrometric constant.

2.6 Introduction to the infiltration sub-model

In the LUOM (Luo, 2007), the Green-Ampt infiltration model (Rawls et al., 1993) is adopted to calculate the infiltration rate. This is a method from an approximation of Darcy’s law, intended to estimate the infiltration in a deep homogeneous soil with ponded water at the top whose depth can be neglected. Water is assumed to infiltrate into the soil with a sharply defined wetting front, which separates the saturated and unsaturated zones. The Green-Ampt model can be described by the following equation:

$$f = \frac{dF}{dt} = k_s \left(1 + \frac{\psi_w (\theta_s - \theta_0)}{F} \right) \tag{15}$$

Equation 15 is the differential form of Green-Ampt model, and the integrated form is:

$$F(t) = k_s t + \psi_w (\theta_s - \theta_0) \mathbf{ln} \left(1 + \frac{F(t)}{\psi_w (\theta_s - \theta_0)} \right) \tag{16}$$

In the above two equations, f is the infiltration rate, F is the cumulative depth of water infiltrated into the soil in time t, k_s is the saturated hydraulic conductivity, ψ_w is the suction head at the wetting front, θ_s is the saturated soil moisture content and θ_0 is the initial soil moisture content. Equation 16 can be solved by the Newton’s iteration method if soil parameters are available.

2.7 Introduction to the groundwater sub-model

Governing equation for an isotropic confined aquifer is shown as below:

$$\frac{\partial}{\partial x}\left(T\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(T\frac{\partial h}{\partial y}\right)=S\frac{\partial h}{\partial t}-R \tag{17}$$

where T is the transmissivity of the aquifer, h is the elevation of water head, S is the specific storage coefficient, R is the source term that includes recharge to groundwater and pumping out of groundwater or is the sum of the recharge and pumping, which is positive if it is a input to the system and negative if it is a output from the system.

Before writing out the governing equation for unconfined aquifer, it is convenient to re-give the definition of transmissivity in an integrate form:

$$T=\int_b^h k\,dz=k(h-b)=kH \tag{18}$$

in which h is the elevation of water table, b is the elevation of aquifer bottom, k is the hydraulic conductivity, and $H=h-b$ is a variable groundwater depth from the aquifer bottom. Substituting equation 18 into 17 yields:

$$\frac{\partial}{\partial x}\left(k(h-b)\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k(h-b)\frac{\partial h}{\partial y}\right)=S_y\frac{\partial h}{\partial t}-R \tag{19}$$

where S_y is the specific yield of the aquifer. This is the basic governing equation for an isotropic unconfined aquifer. If we substitute $h=H+b$ into equation 19, and assume the aquifer bottom is uniform (b is a constant), equation 19 reduces to:

$$\frac{\partial}{\partial x}\left(kH\frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(kH\frac{\partial H}{\partial y}\right)=S_y\frac{\partial H}{\partial t}-R \tag{20}$$

This is the Boussinesq equation. This is the governing equation for unconfined aquifer. By realizing that:

$$H\frac{\partial H}{\partial x}=\frac{1}{2}\frac{\partial H^2}{\partial x} \text{ and } H\frac{\partial H}{\partial y}=\frac{1}{2}\frac{\partial H^2}{\partial y} \tag{21}$$

equation 20 can be re-written as:

$$\frac{\partial}{\partial x}\left(k\frac{\partial H^2}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial H^2}{\partial y}\right)=2S_y\frac{\partial H}{\partial t}-2R \tag{22}$$

or:

$$\frac{\partial}{\partial x}\left(k\frac{\partial h^2}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial h^2}{\partial y}\right)=2S_y\frac{\partial h}{\partial t}-2R+2P \tag{23}$$

in which k is the hydraulic conductivity, S_y is the specific yield, and the former source term R is divided into two terms: the recharge term which is still denoted as R and the pumping-out term which is denoted as P. Executing partial differentiation inside the brackets in the left side of equation 23, and it becomes:

$$k\frac{\partial^2 h^2}{\partial x^2}+\frac{\partial k}{\partial x}\frac{\partial h^2}{\partial x}+k\frac{\partial^2 h^2}{\partial y^2}+\frac{\partial k}{\partial y}\frac{\partial h^2}{\partial y}=2S_y\frac{\partial h}{\partial t}-2R+2P \tag{24}$$

Equation 24 is discretized by central difference for both spatial and temporal differentiation:

$$\begin{aligned}&k_{ij}\frac{h_{ij+1k}^2-2h_{ijk}^2+h_{ij-1k}^2}{\Delta x^2}+\left(k_{ij+1}-k_{ij-1}\right)\frac{h_{ij+1k}^2-h_{ij-1k}^2}{4\Delta x^2}+\\&k_{ij}\frac{h_{i+1jk}^2-2h_{ijk}^2+h_{i-1jk}^2}{\Delta y^2}+\left(k_{i+1j}-k_{i-1j}\right)\frac{h_{i+1jk}^2-h_{i-1jk}^2}{4\Delta y^2}=S_{yij}\frac{h_{ijk+1}-h_{ijk-1}}{\Delta t}-2R_{ijk}+2P_{ijk}\end{aligned} \tag{25}$$

in which subscript i and j indicate spatial steps of y and x, and subscript k is for time steps. It is noticed that the water table h in the above equation is the true value. However the modeling data are not true value and may include a measurement error e_o and an interpolation error e_i: $\tilde{h}=h+e_o+e_i$, and when the modeling data of wata table are substituted into equation 25, a residual term relating to the measurement error and interpolation error is yielded:

$$\begin{aligned}&k_{ij}\frac{\tilde{h}_{ij+1k}^2-2\tilde{h}_{ijk}^2+\tilde{h}_{ij-1k}^2}{\Delta x^2}+\left(k_{ij+1}-k_{ij-1}\right)\frac{\tilde{h}_{ij+1k}^2-\tilde{h}_{ij-1k}^2}{4\Delta x^2}+\\&k_{ij}\frac{\tilde{h}_{i+1jk}^2-2\tilde{h}_{ijk}^2+\tilde{h}_{i-1jk}^2}{\Delta y^2}+\left(k_{i+1j}-k_{i-1j}\right)\frac{\tilde{h}_{i+1jk}^2-\tilde{h}_{i-1jk}^2}{4\Delta y^2}=S_{yij}\frac{\tilde{h}_{ijk+1}-\tilde{h}_{ijk-1}}{\Delta t}-2R_{ijk}+2P_{ijk}+r_{ijk}\end{aligned} \tag{26}$$

in which r_{ijk} is the residual term. If S_y, R, P, and r are know in equation 26 and there is a time series of observation data of water table, it is sure that equation 26 has a unique solution of hydraulic conductivity k, or if k, R, P, and r are know, the specific yield S_y can be solved from equation 26. However, the residual term r in equation 26 is actually an unknown, and it is difficult to obtained detailed pumping-out data in a large-scale basin. Moreover, neither the hydraulic conductivity k nor the specific yield S_y in most watersheds are available, and both of which must be estimated simultaneously. Therefore, equation 26 is practically indeterminate, even if the optimization problem approach is applied. A numerical solution of this equation was given by Luo (2000) in detail.

2.8 Spatial and temporal steps

The model was first developed in the Tone River basin, Japan, which is a large-scale watershed with an area of 15,630 km^2 and the numerical solution in the model involves iteration at each time step, a relative large grid size of 1 km is used to reduce computation time for the original model. However, the grid size is not fixed and can be any number in the model. The basic time step is one hour and will be automatically reduced to a smaller one, which could be as short as a couple of seconds depending on the intensity of the rainfall when the precipitation is larger than zero in order to guarantee numerical convergence and computation accuracy. However, the shortest temporal interval for the model output is one hour, and daily, monthly and annually outputs are also available. In this study, the daily output is used for model calibration and validation and for the final results of tong term simulation.

2.9 Model output

The models are able to output not only point data, such as the hydrograph at the watershed outlet or at any other sections in the stream network, but also distributed quantities, such as maps of precipitation, evapotranspiration, surface water depth, infiltration, soil moisture, recharge to groundwater, and groundwater table. Figure 7 shows two examples of distributed output of the model (the Tone River basin, Japan, A=15,628 km^2.)

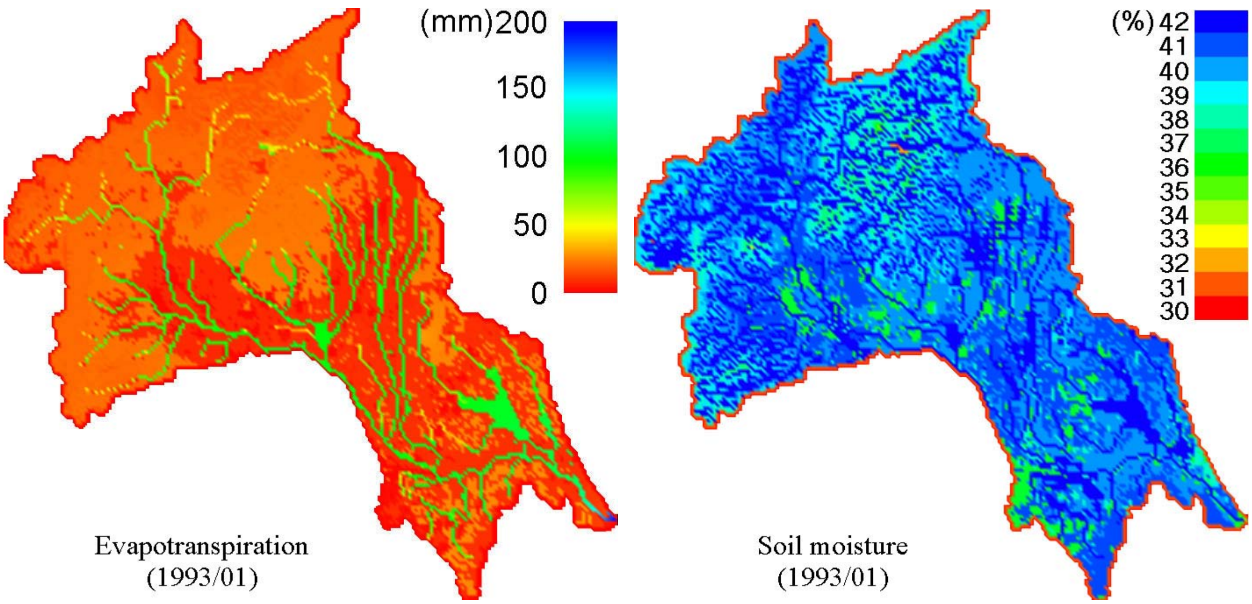


Figure 7. Two examples of distributed model output from LUOM
(Evapotranspiration and soil moisture)

Chapter 3. Data Processes

3.1 Necessary data for modeling

The model requires three categories of data, GIS data, climate data and stream flow data. The GIS data include DEM (digital elevation model) data, vegetation data and soil data. DEM data are used to delineate watershed boundaries and stream networks, and also as input elevation data of modeling. Vegetation data and soil data are used to determine the model parameters such as crop and soil coefficients for the evapotranspiration model, initial soil moisture and saturated infiltration rates for the infiltration model and the groundwater model, and the Manning roughness coefficient for the surface flow model. These GIS data are available at Water and Environmental Research Institute of the Western Pacific (WERI) at University of Guam (UOG) and originally from USGS.

The second category of data is climate data that mainly include rainfall, temperature, and wind speed. These data comprise the time series with a certain temporal step, an hour as required in the model, as the model input during model simulation. In this project, climate data are mainly from four sources, USGS, National Climate Data Center (NCDC), National Oceanic and Atmospheric Administration (NOAA) of US Department of Commerce, and WERI at UOG. Spatial and temporal coverage of these data sources will be discussed in section “3.3 Process of climate data.”

The last category of data is the time series of streamflows, which is used for model calibration and validation. USGS has streamflow gages located in some of the southern Guam watersheds. The streamflow data recorded at the USGS stations will be discussed in detail in section “3.5 Process of streamflow data.” Table 2 summarizes these data sources.

Table 2. Data Sources

Category	Data	Sources	Format	Usage
GIS data	DEM	USGS	IMG files	Delineation of watershed boundaries and stream networks, and model input of elevation
	Vegetation & soil	USGS	IMG & shape files	Determination of model parameters for evapotranspiration, infiltration, groundwater, and surface flow modeling
Climate data	Rainfall, etc.	USGS, NCDC, NOAA, WERI	Daily / Hourly	Model input
Discharge data	Stream-flows	USGS	Daily	Model calibration and validation

3.2 Process of GIS data

GIS data include DEM data, vegetation data, and soil data from USGS. DEM data used in this project are in raster IMG format with a horizontal resolution of 10 meters (33 ft) (grid size=10m/33ft), while the vertical accuracy is 1 meter (3 ft), which means that the elevation data are integers. For watershed modeling, 10-meter grid size is fine enough, but 1-meter elevation accuracy is very rough. Vegetation data are originally in IMG format with an attribute table containing vegetation types. Soil data are in polygon shape files with an attribute table including soil ID and names. The IMG files of vegetation and shape files of soil can be converted into raster grid files in any desired resolution. The attribute tables of vegetation and soil types are useful for numerical simulation in the model. Process of DEM, vegetation and soil data will be related separately in detail below.

3.2.1 DEM data

DEM data are fundamental in the study and provide the source data for delineation of watershed boundaries and stream networks. DEM data are also the model input data of geomorphology as the grid cell elevation. DEM data used in this study is a single IMG file for the whole island of Guam with a horizontal resolution of 10 meters (33 ft) and a vertical accuracy of 1 meter (3 ft). Figure 8 shows a map of Guam from the DEM data for the whole island (rain gages available in the whole island are also shown). From Figure 8, it can be seen that the elevation varies from 0 to 404 meters (1325 ft), and the southern Guam terrain is featured with a large variety of elevation from the lowest 0 meter to the highest 404 meters (1325 ft). This feature makes southern Guam into an area of hydrologic diversity and surface water resources abundance. Because of this, stream networks and watersheds are well developed in southern Guam during the geological history. This is very different from northern Guam which did not develop any stream network because that the terrain of this part of the island is relatively lack of variety in elevation.

For hydrologic modeling purpose, 10-meter horizontal resolution is sufficient for the model to generate high accuracy hydrologic output because the model spatial step or size of grid cells in this study is 100 meters. However, the vertical accuracy of 1 meter (all values of elevation are integers) is relative coarse because the model solves the two-dimensional shallow-water differential equations numerically, which yields highly accurate results when the change of elevation is small enough. In order to increase the model accuracy of simulation at a grid size of 100 meter, the 10-meter IMG file of DEM is first converted into a TIN file with the aid of ArcMap. Then, a raster grid of 100-meter resolution is generated from the TIN file, and the output elevation is re-calculated at the center of a 100-meter grid cell using the linear average method. By doing so, the values of elevation are no longer rounded to integers anymore and the vertical accuracy (elevation) is increase from 1 meter (3.3 ft) to 0.01 meter (0.4 in). However, this does not mean that the DEM data accuracy increases by itself, but rather the model accuracy increases by using this DEM data of float numbers.

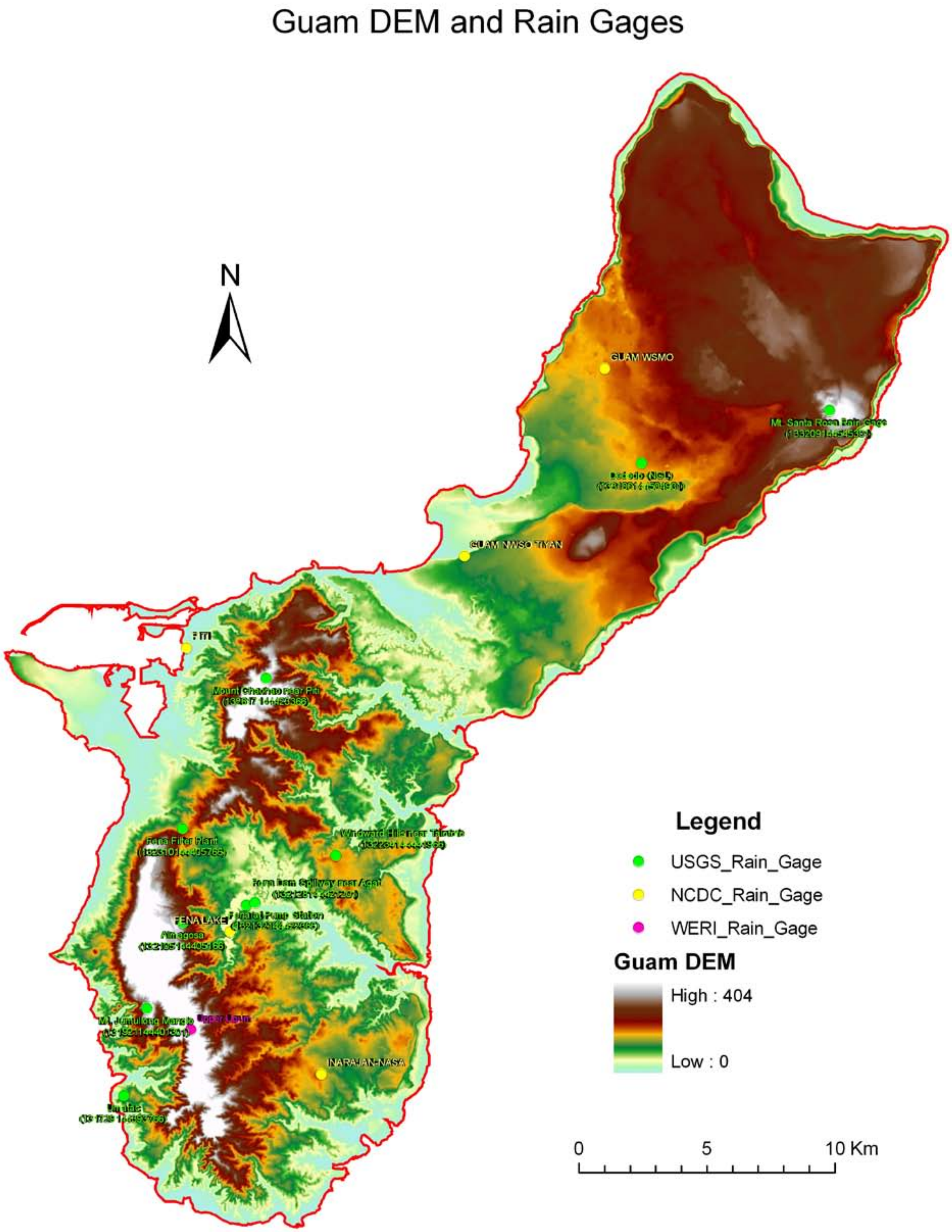


Figure 8. Map of Guam from DEM data

(All rain gages available in Guam also shown)

3.2.2 Delineation of stream networks and watershed boundaries

Stream networks and watershed boundaries are important hydrologic features and accurate definition or delineation of steam networks and watershed boundaries are critical for correct numerical simulation in two-dimensional watershed modeling. Stream networks are the watershed grids in which a non-zero water depth is always maintained during the simulation. A watershed boundary is a drainage boundary that determines which of the rainfall falling onto the area will flow in the watershed and gradually be accumulated to the watershed outlet. With the aid of GIS software – ArcMap, the stream networks and watershed boundaries are delineated using "Hydrology" and "Map Algebra" functions of the "Spatial Analyst Tools." The stream networks are first delineated in the following steps:

1) Fill in the sinks of the DEM data with the "Fill" function. The filled DEM data will be only used for stream network delineation but not used for modeling;
2) Using the filled DEM data as input, generate a flow direction grid with the "Flow Direction" function;
3) Using the flow direction grid, generate a flow accumulation grid with the "Flow Accumulation" function; and,
4) Finally, using the flow accumulation grid, generate a stream network grid with the "Map Algebra" function – "Single Output Map Algebra" by selecting an inflow number which is equal to and greater than 3000.

Due to the accuracy of the DEM data, some of the generated stream networks are not correct in the lower and flat areas by comparing with the Guam Map. These parts of stream network are modified manually to reflect the real situation. The watershed boundaries are delineated in the following steps:

1) Create a point feature file to hold the "pour points" in ArcCatalog;
2) Add the Pour Points file to the map and use the "Edit" tool to input the "pour points." A pour point is a point that water from the adjacent grid cells is supposed to flow to. Pour points should snap to the stream network. When finish input, save the pour points file for the use in the next step.
3) Using the flow direction grid and the pour points file as input, delineate the watershed boundary with the "Watershed" function of the "Spatial Analyst Tools."

Figure 9 shows the southern Guam watershed boundaries and stream networks delineated in this project. All rain gages and streamflow gages available are also shown in the figure. The background is a terrain map produced with the GIS TIN data, which was converted from the 10-meter DEM data. The figure shows a total of 31 major watersheds/stream networks that have been delineated for southern Guam.

The delineation of watershed boundaries in this project emphasizes the hydrologic characteristic that a watershed is the drainage area that drains all the rain water falling in it to a single common point, which is the watershed outlet. In southern Guam, a watershed outlet is always an estuary to the sea or ocean. It can be seen from the figure that not all of southern Guam's lands are included in the watersheds. Some of the shore lands do not belong to any watershed because the rain water falling in them does not flow to a common point that can be taken as a watershed outlet.

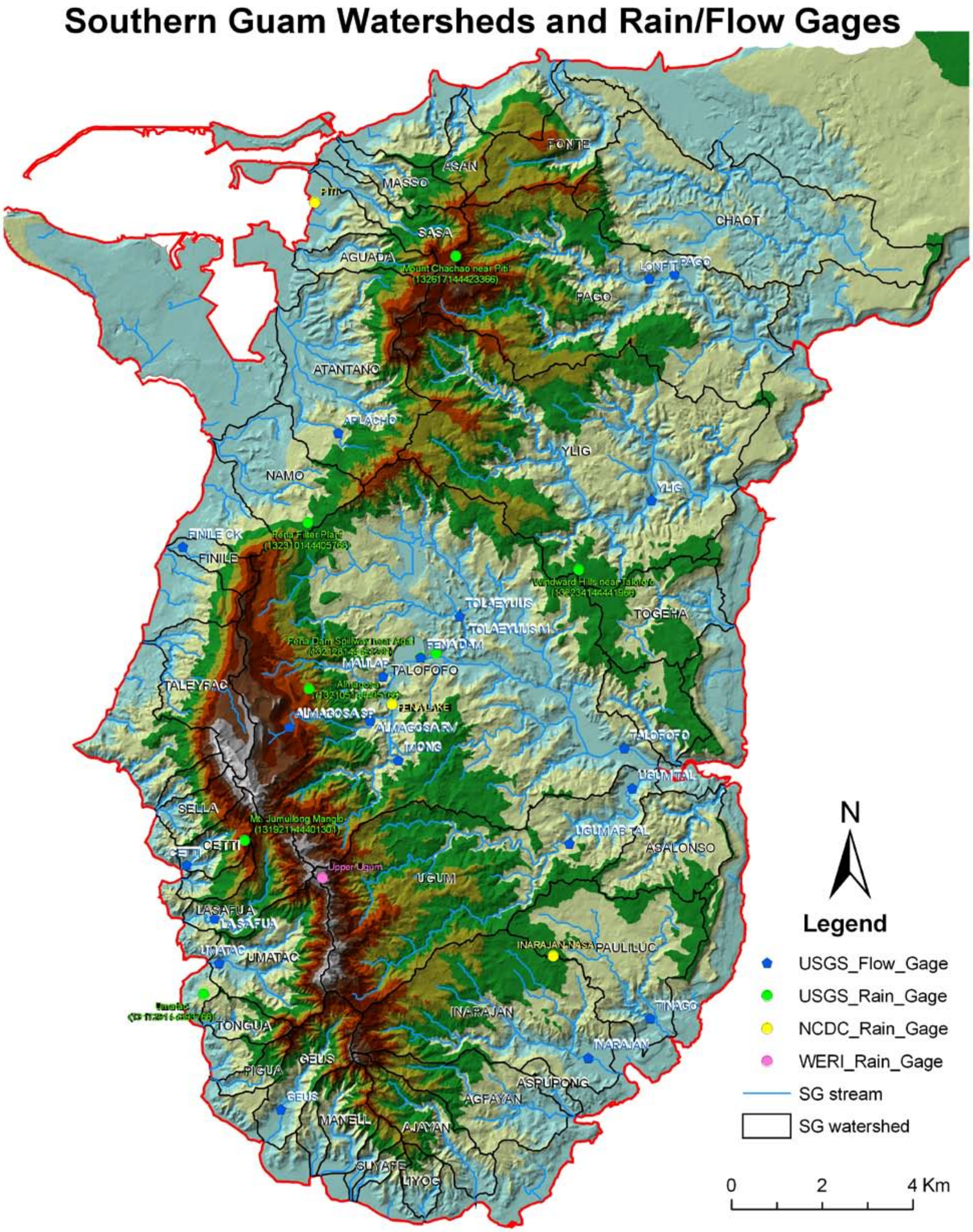


Figure 9. Southern Guam watersheds and stream networks delineated in this project

(All rain gages and streamflow gages available in southern Guam also shown)

One also can see in Figure 9 that some of the watersheds of the minor creeks or very small rivers are not delineated even though their stream networks have be delineated. Sub-watersheds are not delineated in this study because the LUOM (Luo, 2007) does not require the watershed to be further divided so that the simulation is able to be carried on.

3.2.3 Vegetation data

Vegetation data are originally stored in an IMG file but later have been converted into a shape file. Twelve major categories of vegetation in Guam are identified in the attribute table of the IMG file, while the LUOM (Luo, 2007) classified vegetation or land uses into six categories based on their hydrologic characteristics. Table 3 shows the vegetation categories originally used in the shape file and those used in the model. The first 5 columns are the vegetation codes and classes from the shape file, while columns 6 and 7 listed the codes and classes used in the model. In this study, the original class "water" becomes a similar class "water body" in the model, classes "ravine forest" and "limestone forest" are converted into "tall vegetation," "barren" into "bare soil," "urban" into "impermeable," "urban cultivated" into "agriculture," and other classes are converted into "short vegetation" according to our site inspection.

Table 3. Original types of vegetation and their equivalents in LUOM

ID	L2class	L2classname	L1class	L1classname	LUOM_CODE	LUOM_CLASS
0	0		0		4	Short Vegetation
1	1	Ravine Forest	1	Forest	2	Tall Vegetation
2	2	Limestone Forest	1	Forest	2	Tall Vegetation
3	3	Savanna Complex	2	Rangeland	4	Short Vegetation
4	4	Scrub Forest	1	Forest	4	Short Vegetation
5	5	Limestone Scrub Forest	1	Forest	4	Short Vegetation
6	6	Urban	3	Urban	6	Impermeable
7	7	Urban Cultivated	2	Rangeland	3	Agriculture
8	8	Barren	4	Barren	5	Bare Soil
9	9	Water	5	Water	1	Water Body
10	10	Wetlands	1	Forest	4	Short Vegetation
11	11	Plantations	1	Forest	4	Short Vegetation
12	12	Clouds and Shadow	6	Clouds/Shadow	4	Short Vegetation

Figure 10 shows the vegetation distribution in southern Guam and the vegetation is classified into 12 categories as it was in the original IMG file of the shape file. And Figure 11 shows the vegetation distribution in southern Guam and the vegetation is classified into 6 classes as the model does. Figure 11 is for the purpose of hydrologic study and therefore reflects the hydrologic characteristics of vegetation more clearly than Figure 10.

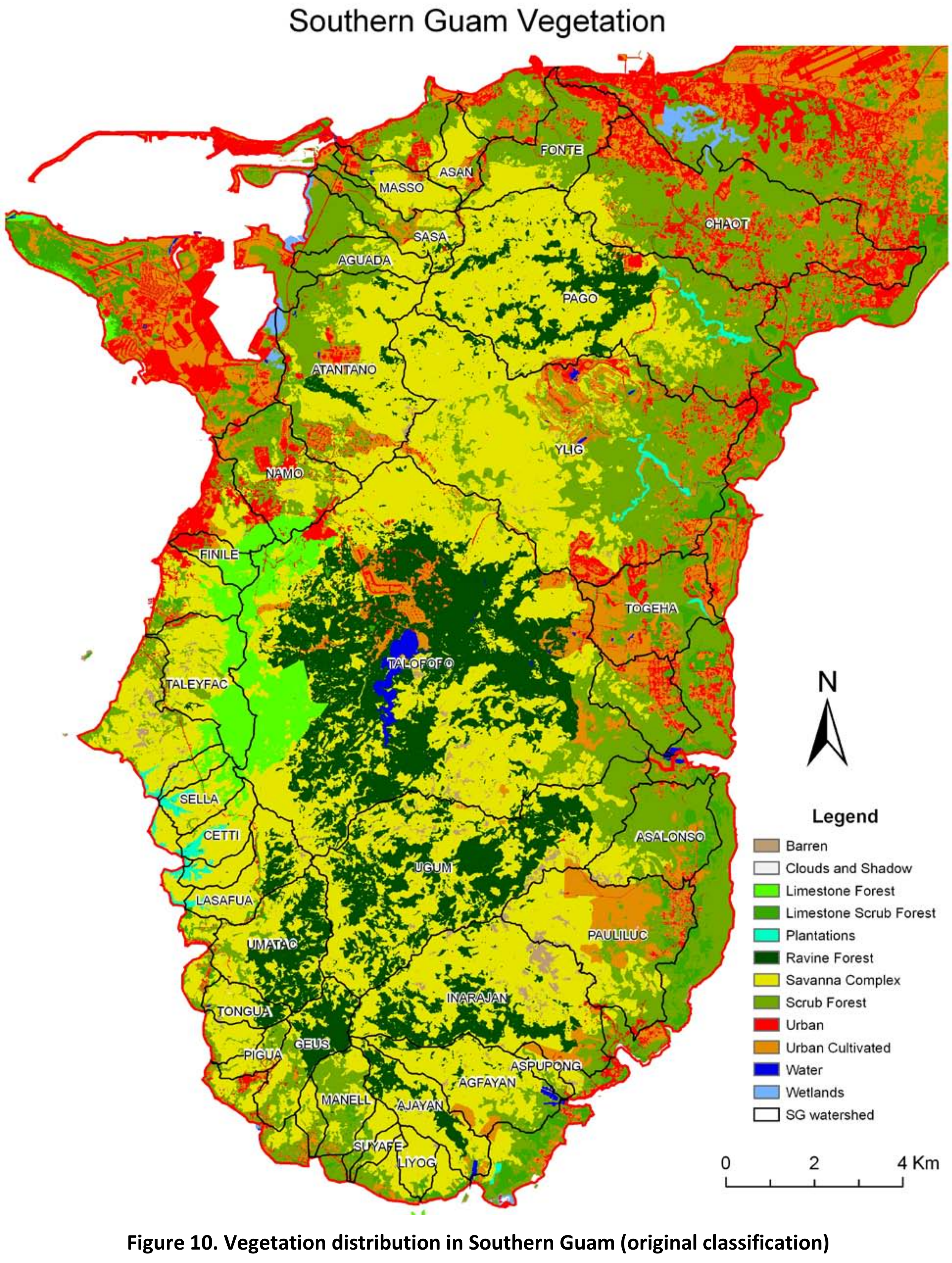


Figure 10. Vegetation distribution in Southern Guam (original classification)

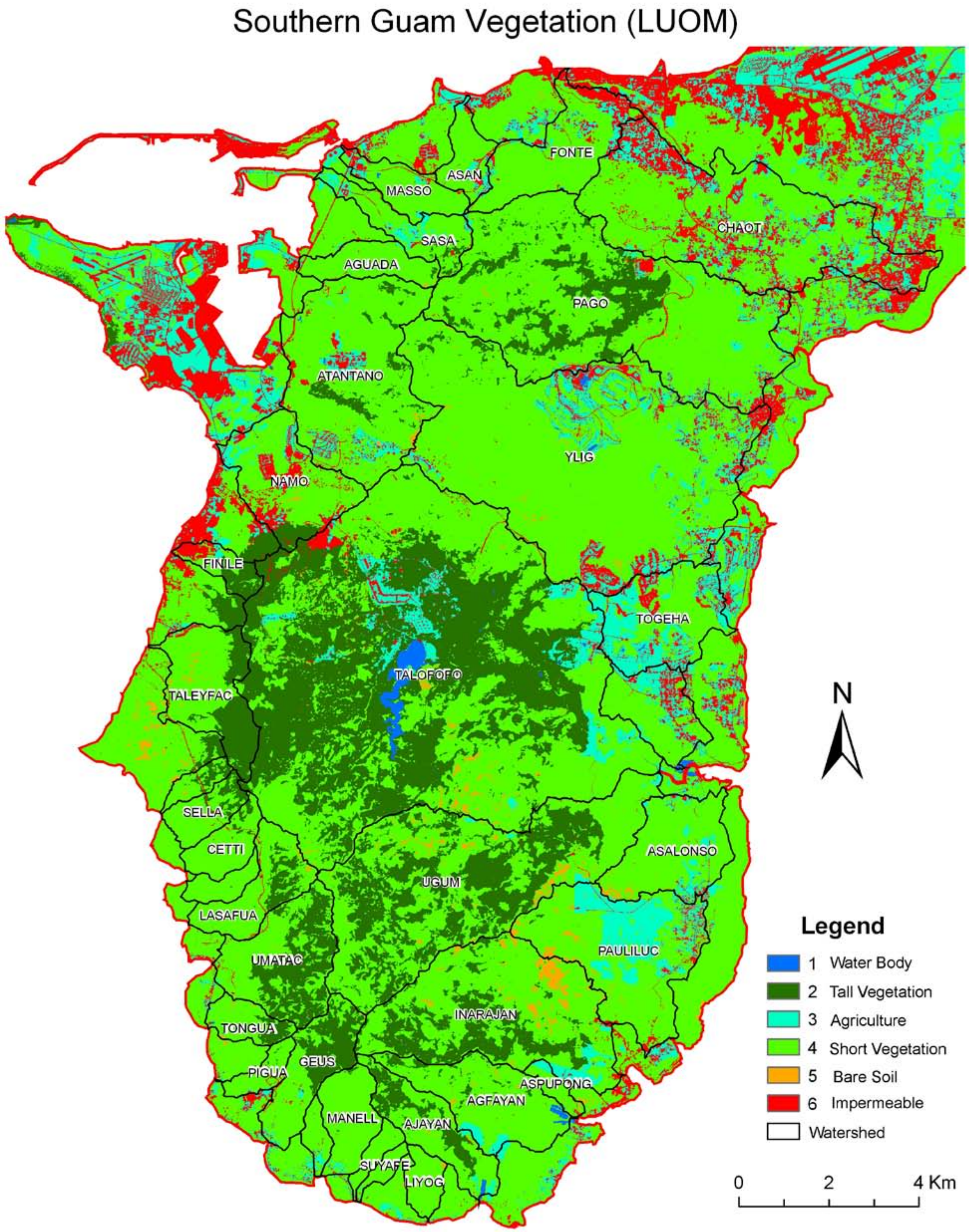


Figure 11. Vegetation distribution in Southern Guam (LUOM classification)

3.2.4 Soil data

Because of lack of soil test data, the soil GIS data are not directly used in the model simulation but used to help determine parameters such as initial soil moisture, saturate infiltration rates and hydraulic conductivity, which are critical in the infiltration model and the groundwater model. Table 4 shows the soil classification from the GIS shape file and Figure 12 shows the soil distribution in southern Guam.

Table 4. Soil classification

SOIL ID	Soil Name	SOIL ID	Soil Name
1	Agfayan clay, 15% to 30% slopes	31	Inarajan sandy clay loam, 0% to 3% slopes
2	Agfayan clay, 30% to 60% slopes	32	Inarajan Variant mucky clay, 0% to 3% slopes
3	Agfayan-Rock outcrop complex, 7% to 15% slopes	33	Pulantat clay, 3% to 7% slopes
4	Agfayan-Rock outcrop complex, 15% to 30% slopes	34	Pulantat clay, 7% to 15% slopes
5	Agfayan-Rock outcrop complex, 30% to 60% slopes	35	Pulantat clay, 15% to 30% slopes
6	Agfayan-Akina association, extremely steep	36	Pulantat clay, 30% to 60% slopes
7	Agfayan-Akina-Rock outcrop association, extremely	37	Pulantat-Chacha clays, undulating
8	Akina silty clay, 3% to 7% slopes	38	Pulantat-Chacha clays, rolling
9	Akina silty clay, 7% to 15% slopes	39	Pulantat-Kagman clays, 0% to 7% slopes
10	Akina silty clay, 15% to 30% slopes	40	Pulantat-Kagman clays, 7% to 15% slopes
11	Akina silty clay, 30% to 60% slopes	41	Pulantat-Urban land complex, 0% to 7% slopes
12	Akina-Agfayan association, steep	42	Pulantat-Urban land complex, 7% to 15% slopes
13	Akina-Atate silty clays, 0% to 7% slopes	43	Ritidian-Rock outcrop complex, 3% to 15% slopes
14	Akina-Atate silty clays, 7% to 15% slopes	44	Ritidian-Rock outcrop complex, 15% to 60% slopes
15	Akina-Atate silty clays, 15% to 30% slopes	45	Ritidian-Rock outcrop complex, 60% to 99% slopes
16	Akina-Atate silty clays, 30% to 60% slopes	46	Sasalaguan clay, 7% to 15% slopes
17	Akina-Atate association, steep	47	Shioya loamy sand, 0% to 5% slopes
18	Akina-Badland complex, 7% to 15% slopes	48	Togcha-Akina silty clays, 3% to 7% slopes
19	Akina-Badland complex, 15% to 30% slopes	49	Togcha-Akina silty clays, 7% to 15% slopes
20	Akina-Badland complex, 30% to 60% slopes	50	Togcha-Ylig complex, 3% to 7% slopes
21	Akina-Badland association, steep	51	Togcha-Ylig complex, 7% to 15% slopes
22	Akina-Urban land complex, 0% to 7% slopes	52	Troposaprists, 0% to 1% slopes
23	Chacha clay, 0% to 5% slopes	53	Ustorthents-Urban land complex, nearly level
24	Chacha Variant clay, 0% to 3% slopes	54	Ylig clay, 0% to 3% slopes
25	Guam cobbly clay loam, 3% to 7% slopes	55	Ylig clay, 3% to 7% slopes
26	Guam cobbly clay loam, 7% to 15% slopes	56	Water
27	Guam-Saipan complex, 0% to 7% slopes	99	No Data
28	Guam-Urban land complex, 0% to 3% slopes		
29	Guam-Yigo land complex, 0% to 7% slopes		
30	Inarajan clay, 0% to 4% slopes		

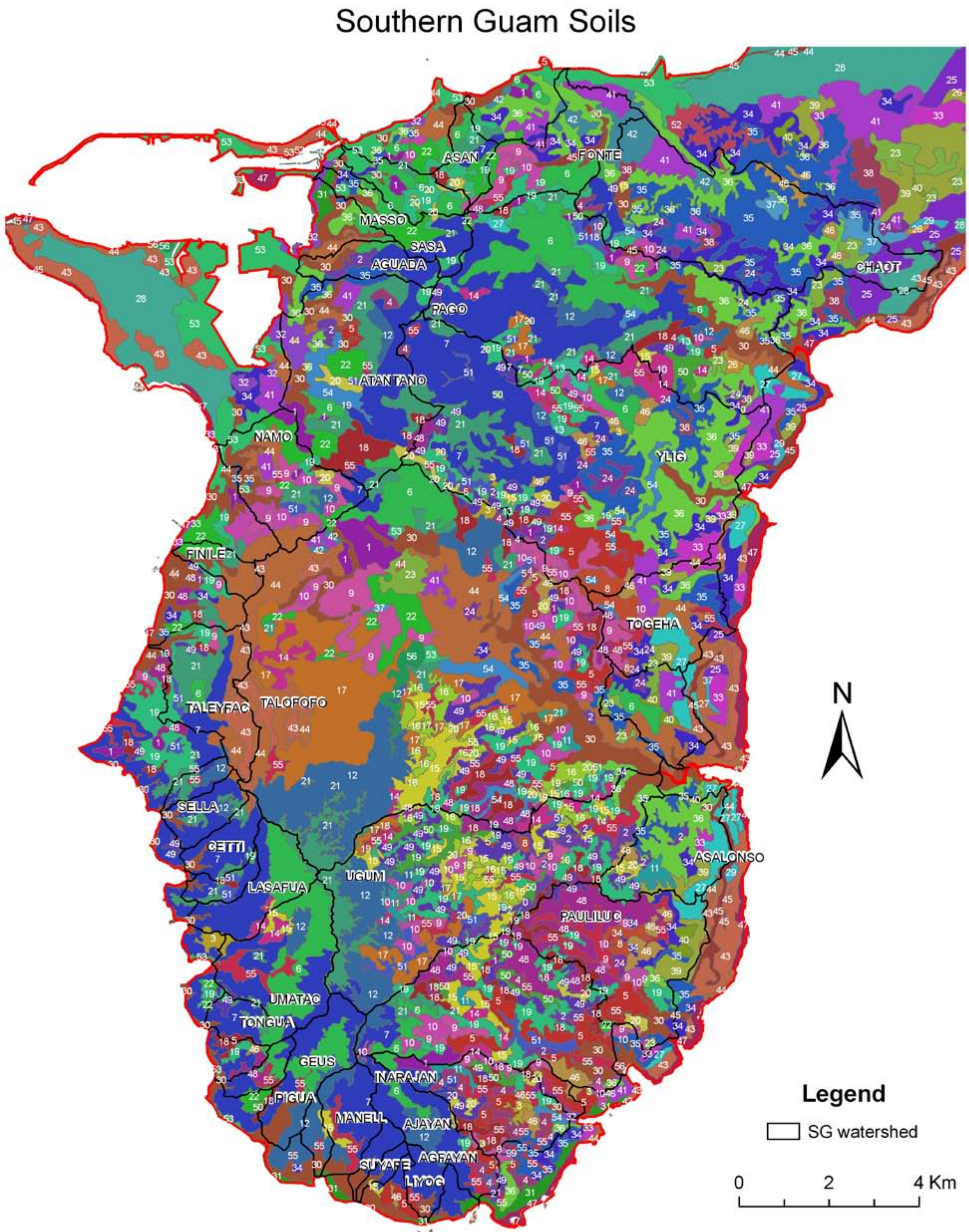


Figure 12. Soil distribution in southern Guam

(Numbers in the map are the classes defined in Table 4)

3.3 Process of climate data

The LUOM (Luo, 2007) requires the following climate data as model input, precipitation (rainfall), wind speed, sunshine time, and temperature. In order to generate long term hydrographs, long term time series of climate data are necessary in this study. Climate data in southern Guam are available from three sources, USGS, National Climate Data Center (NCDC), and Water and Environmental Research Institute (WERI) of the Western Pacific at University of Guam. There are a total of 16 rain gages (10 from USGS, 5 from NCDC and 1 from WERI) in Guam. Twelve (12) of them are located in southern Guam, 8 from USGS, which provide daily rainfall data only, 3 from NCDC, which provide hourly data, and 1 from WERI, which provides rainfall data in different time intervals (the shortest interval is 15 minutes). The daily rainfall data collected by USGS could be downloaded from their Pacific Islands Water Science Center website http://hi.water.usgs.gov/guam/guam_tab.htm, which is no longer available after January 2010 and has been replaced by http://wdr.water.usgs.gov/nwisgmap/?state=gu. Also some of the inactive streamflow and rain gages have been removed from the new website. Table 5 summarizes the available climate stations in southern Guam. Columns under "Data" in the table are the time spans of individual pieces of the consecutive data series at a station. The locations of all available rain gages in Guam are shown in Figures 8, Section 3.2, and the locations of those rain gages available in southern Guam are shown Figure 9, also Section 3.2.

Table 5. Available climate stations in southern Guam

No.	Station Name	ID	Source	Data *						Years of Data	Remark
				FROM	TO	FROM	TO	FROM	TO		
1	Almagosa	132105144405166	USGS	6/24/1992	9/30/1998	11/29/1999	8/13/2009			15	
2	Fena Filter Plant	132310144405766	USGS	5/1/1951	12/31/1983					32	Missing data
3	Fena Pump Station	132132144422366	USGS	10/6/1993	10/6/2009					16	Missing data
4	Fena Dam Spillway	132128144421201	USGS	10/1/2006	11/29/2009					2	Missing data
5	Mt. Chachao near Piti	132617144423366	USGS	10/6/1988	3/4/2009					20	Missing data
6	Mt. Jumullong Manglo	131921144401301	USGS	12/7/2000	2/20/2004					3	
7	Umatac	131729144393766	USGS	10/1/1988	10/14/2009					20	Missing data
8	Windward Hills Talofofo	132234144441966	USGS	2/1/1974	12/31/1983	10/1/1988	8/22/2004	2/28/2008	11/17/2009	27	Missing data
9	Fena Lake		NCDC	1/1/1980	12/31/2007					28	Missing data
10	Inarajan-NASA		NCDC	1/1/1979	12/31/2007					29	Missing data
11	Piti		NCDC	1/1/1978	12/31/2007					30	Missing data
12	Upper-Ugum		WERI	5/26/2005	10/9/2008					3	

* **Note:** Latest updated of data: December 2008 for WERI station, January 2008 for NCDC stations, and December 2009 for USGS stations.

Table 5 listed all the 8 USGS rain gages in southern Guam. The first station in Table 5, Almagosa (ID 132105144405166), has data records since June 24, 1992 until now, but there is more than a year of missing data from October 1, 1998 to November 28, 1999. Total available data from this station are about 15 years at the time when this project began in March 2009, but the consecutive data are separated into two series by the year of missing data (1998-1999) and the first series lasts only 5 years and the second lasts10 years. These lengths of consecutive data are poor for statistical hydrologic analysis. The second station in the table, Fena Filter Plant (ID 132310144405766) has 32 two years of data, in which there are many missing data. However, the last year of data at this station is 1983, which means that the station is no longer active and provides no data later than 1983. The third station, Fena at Pump Station (ID 132132144422366), has 16 years of consecutive data since 1993 till now, but also with many missing data. The fourth station, Fena Dam Spillway (ID 132128144421201), has only a couple of years of data since October 2006 with also missing data and do not help much in this study even though it has the latest data. The fifth station, Mt. Chachao near Piti (ID 132617144423366), probably is one of the two best active USGS stations that has 20 years of consecutive data since 1988 till now, also with missing data. The other best active USGS station is the seventh in Table 5, Umatac (ID 131729144393766). The sixth station, Mt. Jumullong Manglo (ID 131921144401301), has only 3 years of data since December 2000 to February 2004. This means that the station in no longer active and do not help much in the study. The number 8 station, Windward Hills Talofofo (ID 132234144441966), has inconsecutive data starting from 1974 till the current year (2009). However, there are two periods of several years of data gaps (huge missing data), the first gap is a 5-year one from 1983 to 1988, and the second gap is a 4-year one from 2004 to 2008. These data gaps or huge missing data make the data series little use in statistical hydrologic analysis.

There are 3 NCDC rain gages (Fena Lake, Inarajan-NASA and Piti) in southern Guam, and each of them has 28, 29 and 30 years of consecutive data, which were very helpful in this study. The latest year of data that WERI purchased is 2007. However, desperate missing data also exist in these data series.

Figure 13 shows examples of missing data in the rainfall data collected by a USGS rain gage and Figure 14 shows examples of missing data in the rainfall data collected at a NCDC climate station. The unpredictable times and irregular lengths of missing data make the treatment of missing data in the rainfall records very painful and sometimes even disastrous and very time consuming. In this study, the missing data were simply fed with the data from the adjacent stations of the same time as the missing data without any manipulation. If no adjacent station has data in the same periods of the missing data, the gaps were only filled in with 0 (no rainfall).

At the time when the project started, WERI's rain gage has only 3 years of data, which were very helpful in the model calibration in Ugum watershed. However, because that the data are recorded as rainfall accumulation in irregular time steps, it is very time consuming to rearrange the data into rainfall intensity in a regular time step, which is the usual process that most climate stations record the precipitation data and also required by most hydrologic models. And the LUOM also uses a regular time step. To treat these rainfall data, both manual rearrangement and computer programming were necessary.

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USGS	131729144393766	1990-11-03	0.04	A
USGS	131729144393766	1990-11-04	0.36	A
USGS	131729144393766	1990-11-05	0.98	A
USGS	131729144393766	1990-11-06	0.11	A
USGS	131729144393766	1990-11-07	0.12	A
USGS	131729144393766	1990-11-08	0.04	A
USGS	131729144393766	1990-11-09	0.10	A
USGS	131729144393766	1990-11-10	0.00	A
USGS	131729144393766	1990-11-11	0.13	A
USGS	131729144393766	1990-11-12	0.04	A
USGS	131729144393766	1990-11-13	0.80	A
USGS	131729144393766	1990-11-14	0.00	A
USGS	131729144393766	1990-11-15	1.98	A
USGS	131729144393766	1990-11-16	0.58	A
USGS	131729144393766	1990-11-17	0.10	A
USGS	131729144393766	1990-11-18	0.26	A
USGS	131729144393766	1990-11-19	0.13	A
USGS	131729144393766	1990-11-20	0.01	A
USGS	131729144393766	1990-11-21	0.26	A
USGS	131729144393766	1990-11-22	3.25	A
USGS	131729144393766	1990-11-23	6.46	A>
USGS	131729144393766	1990-11-24		
USGS	131729144393766	1990-11-25		
USGS	131729144393766	1990-11-26		
USGS	131729144393766	1990-11-27		
USGS	131729144393766	1990-11-28		
USGS	131729144393766	1990-11-29	0.00	A
USGS	131729144393766	1990-11-30	0.00	A
USGS	131729144393766	1990-12-01	0.00	A
USGS	131729144393766	1990-12-02	0.11	A
USGS	131729144393766	1990-12-03	0.00	A
USGS	131729144393766	1990-12-04	0.06	A
USGS	131729144393766	1990-12-05	0.14	A
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USGS	131729144393766	1990-12-07	0.48	A
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USGS	131729144393766	1990-12-12	0.06	A
USGS	131729144393766	1990-12-13	0.11	A>
USGS	131729144393766	1990-12-14		
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USGS	131729144393766	1990-12-16	0.00	A
USGS	131729144393766	1990-12-17	0.00	A
USGS	131729144393766	1990-12-18	0.00	A
USGS	131729144393766	1990-12-19	0.00	A
USGS	131729144393766	1990-12-20	1.51	A
USGS	131729144393766	1990-12-21	8.27	A>
USGS	131729144393766	1990-12-22		
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USGS	131729144393766	1990-12-24	0.00	A
USGS	131729144393766	1990-12-25	0.00	A
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USGS	131729144393766	1991-01-10	0.01	A
USGS	131729144393766	1991-01-11	0.11	A
USGS	131729144393766	1991-01-12	0.49	A
USGS	131729144393766	1991-01-13	0.11	A

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USGS	131729144393766	1989-02-19		
USGS	131729144393766	1989-02-20		
USGS	131729144393766	1989-02-21		
USGS	131729144393766	1989-02-22		
USGS	131729144393766	1989-02-23		
USGS	131729144393766	1989-02-24		
USGS	131729144393766	1989-02-25		
USGS	131729144393766	1989-02-26		
USGS	131729144393766	1989-02-27		
USGS	131729144393766	1989-02-28		
USGS	131729144393766	1989-03-01		
USGS	131729144393766	1989-03-02		
USGS	131729144393766	1989-03-03		
USGS	131729144393766	1989-03-04		
USGS	131729144393766	1989-03-05		
USGS	131729144393766	1989-03-06		
USGS	131729144393766	1989-03-07		
USGS	131729144393766	1989-03-08		
USGS	131729144393766	1989-03-09		
USGS	131729144393766	1989-03-10		
USGS	131729144393766	1989-03-11		
USGS	131729144393766	1989-03-12		
USGS	131729144393766	1989-03-13		
USGS	131729144393766	1989-03-14		
USGS	131729144393766	1989-03-15		
USGS	131729144393766	1989-03-16		
USGS	131729144393766	1989-03-17		
USGS	131729144393766	1989-03-18		
USGS	131729144393766	1989-03-19		
USGS	131729144393766	1989-03-20		
USGS	131729144393766	1989-03-21		
USGS	131729144393766	1989-03-22		
USGS	131729144393766	1989-03-23		
USGS	131729144393766	1989-03-24		
USGS	131729144393766	1989-03-25		
USGS	131729144393766	1989-03-26		
USGS	131729144393766	1989-03-27		
USGS	131729144393766	1989-03-28		
USGS	131729144393766	1989-03-29		
USGS	131729144393766	1989-03-30		
USGS	131729144393766	1989-03-31		
USGS	131729144393766	1989-04-01		
USGS	131729144393766	1989-04-02		
USGS	131729144393766	1989-04-03		
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USGS	131729144393766	1989-04-05		
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USGS	131729144393766	1989-04-07		
USGS	131729144393766	1989-04-08		
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USGS	131729144393766	1989-04-11		
USGS	131729144393766	1989-04-12		
USGS	131729144393766	1989-04-13		
USGS	131729144393766	1989-04-14		
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USGS	131729144393766	1989-04-16		
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USGS	131729144393766	1989-04-18		
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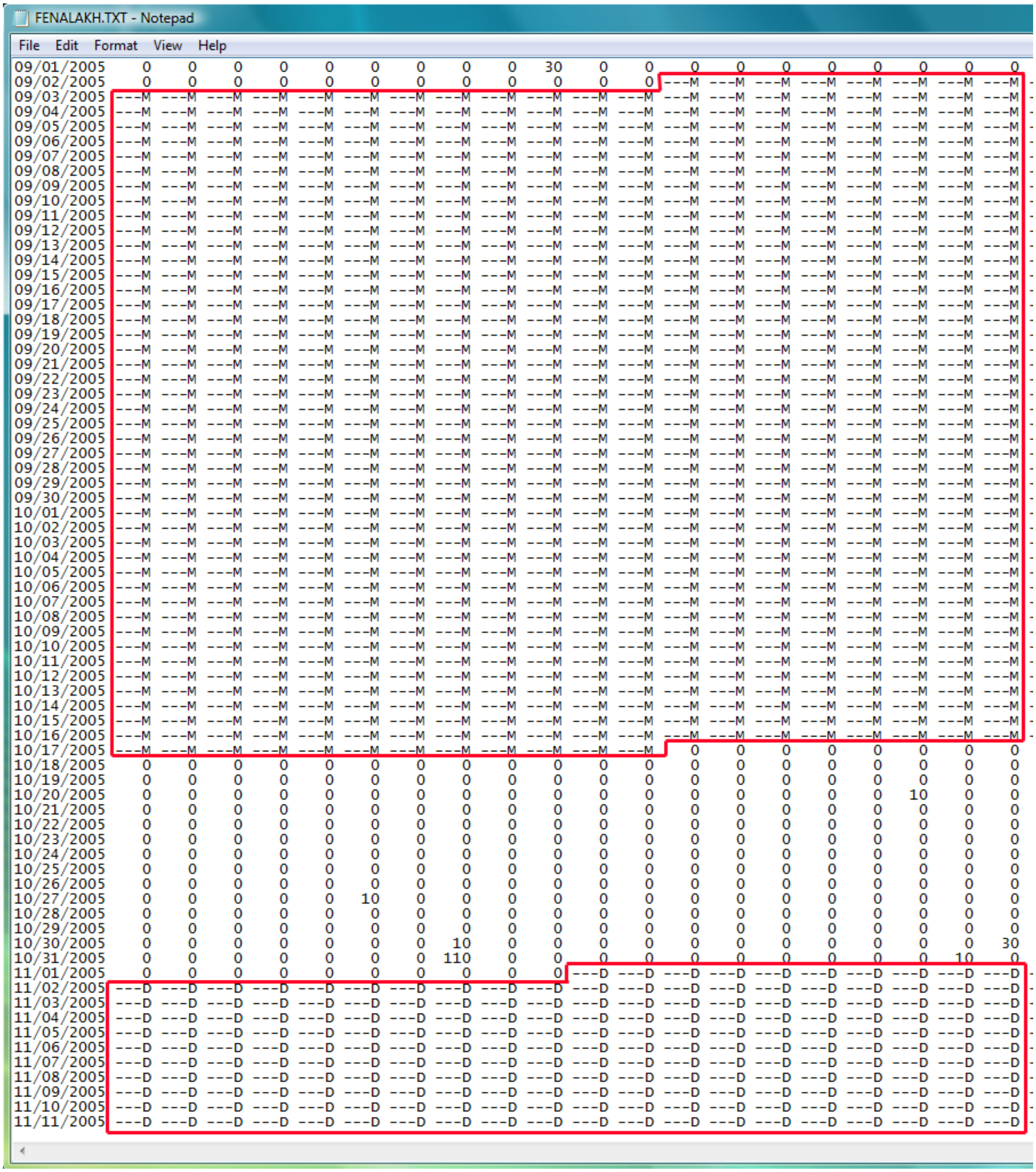
USGS	131729144393766	1989-04-20		
USGS	131729144393766	1989-04-21		
USGS	131729144393766	1989-04-22		
USGS	131729144393766	1989-04-23		
USGS	131729144393766	1989-04-24		
USGS	131729144393766	1989-04-25	0.23	A
USGS	131729144393766	1989-04-26	0.00	A
USGS	131729144393766	1989-04-27	0.73	A
USGS	131729144393766	1989-04-28	1.81	A
USGS	131729144393766	1989-04-29	0.05	A

Figure 13. Examples of missing data in the rainfall data collected by a USGS rain gage

(Station Umatac, ID 131729144393766)

(Red rectangles are the locations of missing data)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09/01/2005	0	0	0	0	0	0	0	0	0	30	0	0	0	0	0	0	0	0	0	0
09/02/2005	0	0	0	0	0	0	0	0	0	0	0	0	---M	---M	---M	---M	---M	---M	---M	---M
09/03/2005	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M
09/04/2005	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M
09/05/2005	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M
09/06/2005	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M
09/07/2005	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M
09/08/2005	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M
09/09/2005	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M
09/10/2005	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M
09/11/2005	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M
09/12/2005	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M
09/13/2005	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M
09/14/2005	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M
09/15/2005	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M
09/16/2005	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M
09/17/2005	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M
09/18/2005	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M
09/19/2005	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M
09/20/2005	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M
09/21/2005	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M
09/22/2005	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M
09/23/2005	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M
09/24/2005	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M
09/25/2005	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M
09/26/2005	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M
09/27/2005	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M
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10/02/2005	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M
10/03/2005	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M
10/04/2005	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M
10/05/2005	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M	---M
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10/18/2005	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10/19/2005	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10/20/2005	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0	0
10/21/2005	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10/22/2005	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10/23/2005	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10/24/2005	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10/25/2005	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10/26/2005	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10/27/2005	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10/28/2005	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10/29/2005	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10/30/2005	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	30
10/31/2005	0	0	0	0	0	0	0	110	0	0	0	0	0	0	0	0	0	0	10	0
11/01/2005	0	0	0	0	0	0	0	0	0	0	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D
11/02/2005	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D
11/03/2005	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D
11/04/2005	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D
11/05/2005	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D
11/06/2005	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D
11/07/2005	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D
11/08/2005	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D
11/09/2005	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D
11/10/2005	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D
11/11/2005	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D	---D

Figure 14. Examples of missing data in the rainfall data collected by a NCDC rain gage

(Station FENA LAKE)

(Patches surrounded by red lines are missing data)

None of the above rain gages provides climate data of temperature, wind speed, and sunshine time. But fortunately, the website of National Weather Service at National Oceanic and Atmospheric Administration (NOAA) of US Department of Commerce provides 24-hour summary of current climate conditions, which include time, temperature, dew point, pressure, wind direction and speed, and weather, at Agana Guam International Airport (http://weather.noaa.gov/weather/current/PGUM.html), even though no historical data are available. Table 6 lists the climate data for May 17, 2009 (EDT). The last column is Guam local time which is added by the authors of this report. These data were used as model input of annual averages of hourly temperature and wind speed. Other data shown in this table were not used in the model.

Table 6. NOAA 24-hour climate conditions at Agana International Airport (May 17, 2009)

Time						Temperature		Dew Point		Pressure		Wind		Weather	Guam Time
EDT (UTC)						F (C)		F (C)		Inches (hPa)		MPH			
Latest	11	PM	(3)	May	17	87.1	(30.6)	72	(22.2)	29.84	(1010)	E	15		13
	10	PM	(2)	May	17	88	(31.1)	70	(21.1)	29.85	(1010)	E	14		12
	9	PM	(1)	May	17	86	(30.0)	72	(22.2)	29.87	(1011)	E	14		11
	8	PM	0	May	17	86	(30.0)	73	(22.8)	29.88	(1011)	E	13		10
	7	PM	(23)	May	17	84.9	(29.4)	73	(22.8)	29.88	(1011)	ENE	8		9
	6	PM	(22)	May	17	82	(27.8)	73	(22.8)	29.87	(1011)	ENE	7		8
	5	PM	(21)	May	17	81	(27.2)	73	(22.8)	29.86	(1011)	ENE	7		7
	4	PM	(20)	May	17	79	(26.1)	72	(22.2)	29.85	(1010)	ENE	6		6
	3	PM	(19)	May	17	80.1	(26.7)	73	(22.8)	29.84	(1010)	ENE	6		5
	2	PM	(18)	May	17	80.1	(26.7)	73	(22.8)	29.84	(1010)	ENE	5		4
	1	PM	(17)	May	17	79	(26.1)	73.9	(23.3)	29.85	(1010)	NE	5		3
	Noon		(16)	May	17	80.1	(26.7)	73.9	(23.3)	29.86	(1011)	NE	5		2
	11	AM	(15)	May	17	79	(26.1)	73	(22.8)	29.88	(1011)	ENE	8		1
	10	AM	(14)	May	17	79	(26.1)	73	(22.8)	29.89	(1012)	E	5		0
	9	AM	(13)	May	17	77	(25.0)	73	(23.0)	29.91	(1012)	NE	8	light rain	23
	8	AM	(12)	May	17	78	(26.0)	73	(23.0)	29.92	(1013)	NE	16	heavy rain	22
	7	AM	(11)	May	17	82.9	(28.3)	72	(22.2)	29.89	(1012)	NE	6		21
	6	AM	(10)	May	17	82.9	(28.3)	73	(22.8)	29.86	(1011)	NE	8		20
	5	AM	(9)	May	17	82.9	(28.3)	72	(22.2)	29.84	(1010)	E	9		19
	4	AM	(8)	May	17	84.9	(29.4)	73	(22.8)	29.82	(1009)	E	9		18
	3	AM	(7)	May	17	84.9	(29.4)	72	(22.2)	29.8	(1009)	E	12		17
	2	AM	(6)	May	17	86	(30.0)	71.1	(21.7)	29.8	(1009)	E	13		16
	1	AM	(5)	May	17	88	(31.1)	72	(22.2)	29.81	(1009)	E	13		15
Oldest	Midnight		(4)	May	17	87.1	(30.6)	72	(22.2)	29.83	(1010)	E	14		14

There are no sunshine data available from the above sources, and the following assumptions were made to estimate the average sunshine time. On an average, sunshine in a day in tropical island Guam starts from 6 am and lasts until 6 pm. In the hour without rainfall, the sun shines for the whole hour, while in the hour with rainfall, the sunshine time is reduced proportionally to the intensity of rainfall.

3.4 Distribution of daily rainfall to hourly rainfall

LUOM (Luo, 2007) requires hourly climate data inputs (time step = 1 hour). However, rainfall data collected by USGS climate stations are daily data (time step = 24 hours), which the model is not able to use directly. Fortunately, the rainfall data collected by NCDC stations are hourly data. First, analysis of NCDC hourly data collected at Inarajan-NASA station was carried out; second, typical distributions of daily rainfalls of different intensities were picked out from the raw rainfall data; and finally, each of the hourly rainfalls was divided by the total rainfall in the day to obtain a ratio of each hourly rainfall to the total daily rainfall. The sum of the ratios of 24 hours is 1. Table 7 shows the ratios of typical distributions for nine different daily rainfall intensities: 0~10 mm, 11~30 mm, 31~50 mm, 51~70 mm, 71~90 mm, 91~110 mm, 111~130 mm, 131~180 mm, and 181 mm and more. When the daily rainfall collected at a USGS station is distributed, the distribution embracing this daily rainfall intensity is first selected, and then the daily rainfall is multiplied by each of the ratios of the 24 hours to generate the hourly rainfalls.

Figure 15 shows the bar charts of the ratios of daily rainfall distributions for all the 9 daily rainfall intensities. One can see from these bar charts that the daily rainfall is not distributed to all hours of the day because these distributions are selected from the actual daily rainfall events.

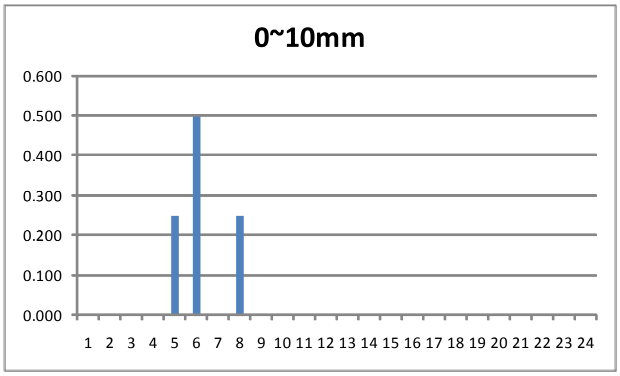
3.5 Process of streamflow data

Daily streamflow data at a few locations and in limited time spans are available from USGS streamflow gages. As described in Section 3.2, about 31 major stream networks and watersheds in southern Guam were delineated. However, as mentioned in Chapter 1, there are totally 21 streanflow gages in southern Guam installed and operated by USGS, but only 7 of these streamflow gages have been recording streamflow data until 2009, in which there are also many missing data similarly to the situation of the rainfall data. Table 1 in Chapter 1 shows the flow gages and their data time spans, and Figure 9 in Section 3.2 shows the locations of these stations. USGS streamflow data were downloaded from Pacific Islands Water Science Center website http://hi.water.usgs.gov/guam/guam_tab.htm, which is no longer available after January 2010 and has been replaced by http://wdr.water.usgs.gov/nwisgmap/?state=gu. Also some of the inactive streamflow and rain gages have been removed from the new website.

Since the flow data are used for model calibration and validation only, process of streamflow data is to screen the data to find a period that no missing data exist and coincidently there exist rainfall data in the same period for a specific watershed so that these streamflow data as the observed hydrograph could be used to compare with the simulated hydrograph form the model output.

Table 7. Ratios for daily rainfall distributions (daily to hourly)

Hour	Daily Rainfall								
	0~10mm	11~30mm	31~50mm	51~70mm	71~90mm	91~110mm	111~130mm	131~180mm	181mm~
1	0.000	0.000	0.000	0.000	0.118	0.158	0.021	0.016	0.012
2	0.000	0.000	0.000	0.000	0.206	0.026	0.000	0.016	0.037
3	0.000	0.000	0.000	0.000	0.265	0.079	0.000	0.065	0.012
4	0.000	0.000	0.000	0.000	0.029	0.105	0.043	0.000	0.025
5	0.250	0.000	0.000	0.000	0.206	0.079	0.149	0.000	0.012
6	0.500	0.000	0.000	0.000	0.059	0.000	0.000	0.081	0.037
7	0.000	0.000	0.059	0.000	0.000	0.026	0.128	0.016	0.037
8	0.250	0.125	0.000	0.000	0.029	0.053	0.064	0.032	0.012
9	0.000	0.000	0.000	0.000	0.088	0.079	0.064	0.016	0.000
10	0.000	0.125	0.000	0.000	0.000	0.053	0.106	0.065	0.000
11	0.000	0.000	0.000	0.000	0.000	0.026	0.106	0.145	0.000
12	0.000	0.250	0.059	0.000	0.000	0.105	0.043	0.161	0.000
13	0.000	0.375	0.411	0.000	0.000	0.026	0.064	0.113	0.025
14	0.000	0.000	0.059	0.000	0.000	0.053	0.043	0.065	0.235
15	0.000	0.000	0.059	0.240	0.000	0.053	0.106	0.048	0.063
16	0.000	0.125	0.235	0.120	0.000	0.079	0.000	0.032	0.000
17	0.000	0.000	0.059	0.040	0.000	0.000	0.000	0.032	0.074
18	0.000	0.000	0.000	0.040	0.000	0.000	0.000	0.000	0.235
19	0.000	0.000	0.000	0.280	0.000	0.000	0.000	0.000	0.012
20	0.000	0.000	0.000	0.200	0.000	0.000	0.043	0.000	0.111
21	0.000	0.000	0.059	0.040	0.000	0.000	0.020	0.000	0.037
22	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.081	0.012
23	0.000	0.000	0.000	0.040	0.000	0.000	0.000	0.016	0.000
24	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.012
Total	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000



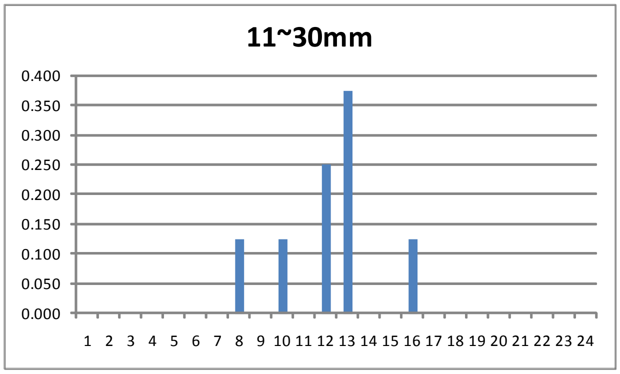
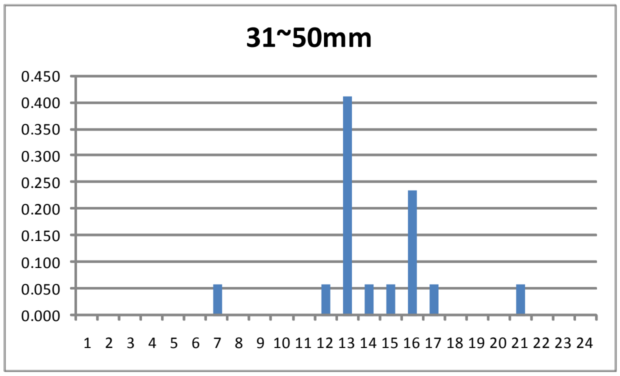
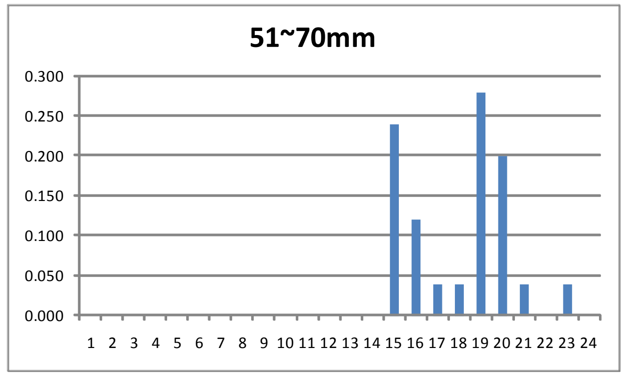
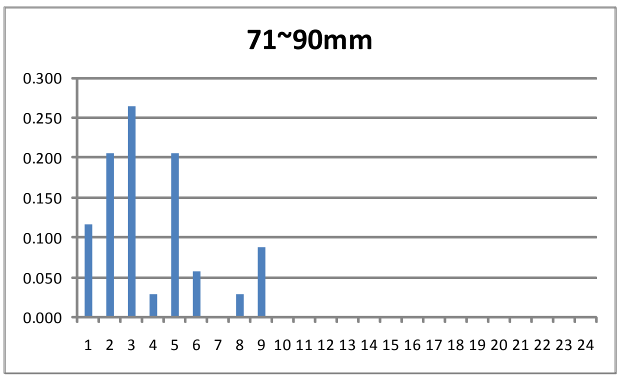


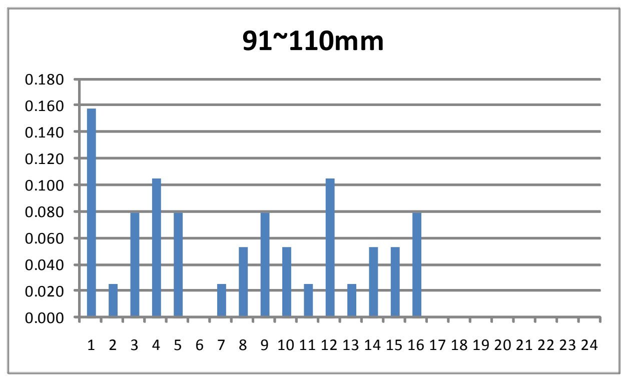
Figure 15. Bar charts of ratios for daily rainfall distributions (daily to hourly)

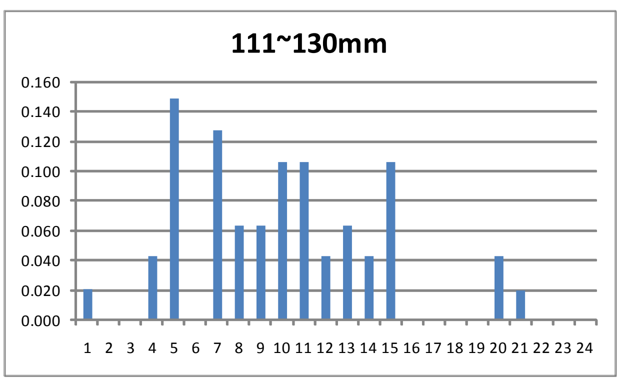
(Continued in next page)

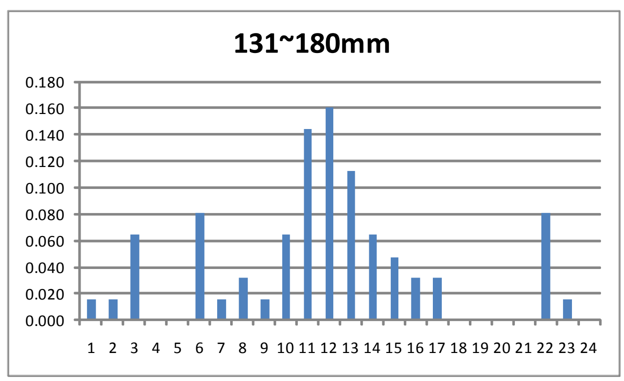












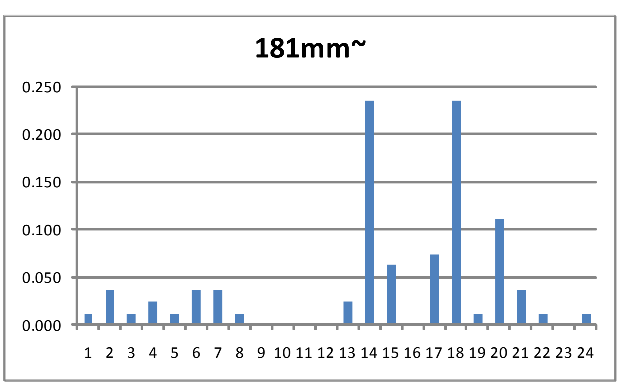


Figure 15 (Continued). **Bar charts of ratios for daily rainfall distributions (daily to hourly)**

Chapter 4. Model Calibration and Validation

4.1 Methodology for model calibration and validation

There are mainly three groups of parameters subjected to calibration. The first group is responsible for correct simulation of the base flow. Parameters belonging to this group are multipliers to the saturated hydraulic conductivity and the specific yield of the aquifer that are used in the groundwater model and the model for the water exchange between aquifers and channels. The second group guarantees correct simulation of the volume of the water yield. Parameters of this group are multipliers to the infiltration and evapotranspiration rates that are used in the infiltration and evapotranspiration models. The third group assures correct simulation of the timing of peak flows and the shape of the hydrograph, and the water yield volume as well. This group includes mainly one parameter – the Manning roughness coefficient for overland grid cells and channel grid cells.

Calibration of distributed parameters is a complicated and tedious procedure. In simple words, the parameters for grid cells in the drainage area of a specific station are adjusted so that the simulated hydrograph of this station eventually fits the observed one. Iteration in calibration is necessary. Another technique adopted in this study for calibration of distributed parameters such as Manning roughness coefficient is relating the parameters to the land use of each grid cell and then applying the same factor to the parameters for all grid cells of the same land use.

The performance of the model is evaluated visually and statistically. The visual criterion involves plotting and comparing the simulated and observed hydrographs to see if they fit each other. Visual evaluation could be subjective and numerically inaccurate, and therefore statistical evaluation was also carried out in this study. The statistical criteria involve the use of Nash and Sutcliffe (1970) coefficients of model efficiency (C_e) and model determination (C_d). The percentage difference of volume (DV) is another criterion. The coefficients of model efficiency describes how well the volume and timing of the simulated hydrograph compares to the observed one and is calculated by:

$$C_e = 1 - \frac{\sum_{i=1}^{n}\left(Q_{obs}^{i} - Q_{sim}^{i}\right)^2}{\sum_{i=1}^{n}\left(Q_{obs}^{i} - \bar{Q}_{obs}\right)^2} \tag{27}$$

where,

$$\bar{Q}_{obs} = \frac{\sum_{i=1}^{n} Q_{obs}^{i}}{n} \tag{28}$$

n is the number of time steps, $Q^i{}_{obs}$ is the observed flow at time step i, and $Q^i{}_{sim}$ is the calibrated flow at time step i. The coefficient of model determination, C_d, measures how well the shape of the simulated hydrograph reflects the observed hydrograph and depends solely on the timing of changes in the hydrograph and is given by (Nash and Sutcliffe, 1970):

$$C_d = 1 - \frac{\sum_{i=1}^{n}\left(Q_{obs}^i - \left(a \cdot Q_{sim}^i + b\right)\right)^2}{\sum_{i=1}^{n}\left(Q_{obs}^i - \overline{Q_{obs}}\right)^2} \tag{29}$$

where,

$$a = \frac{\sum_{i=1}^{n}\left(Q_{obs}^i \cdot Q_{sim}^i\right) - \frac{1}{n}\sum_{i=1}^{n} Q_{obs}^i \sum_{i=1}^{n} Q_{sim}^i}{\sum_{i=1}^{n}\left(Q_{sim}^i\right)^2 - \frac{1}{n}\left(\sum_{i=1}^{n} Q_{sim}^i\right)^2}, \text{ and } b = \frac{1}{n}\left(\sum_{i=1}^{n} Q_{obs}^i - a\sum_{i=1}^{n} Q_{sim}^i\right) \tag{30}$$

The closer to 1 the values of C_e and C_d are, the more successful the model calibration is and vice versa. And the closer to 0% the value of DV, the better the model behaves.

4.2 Determination of spatial and temporal steps

Considering modeling accuracy and computation time, a grid size of 50 meters (164 ft) was selected at the beginning of this study. The model was first calibrated in Ugum watershed, which is 19 km^2 (7.4 square miles). It has a total of 7,600 cells at this grid size. As introduced in Chapter 2, LUOM (Luo, 2007) is a fully physically based two-dimensional watershed model solving the two-dimensional diffusive wave equations iteratively. The solution is numerically steady and of high accuracy and is also time consuming. For the basic time step of 1 hour set in the model, computation of the hydrologic cycle of a year takes 24 hours (a day) in a personal computer of 2.5 GHz CUP. At this speed, a long term simulation of 50 years would need 50 days, which is too long. Meanwhile, LUOM (Luo, 2007) is a large-scale watershed model, in which a finer spatial step (grid size) requires a smaller temporal step so that the model is numerically convergent and generates high accuracy output. Decreasing in spatial and temporal steps would increase dramatically the computation time, which makes long term simulation (such as 50 years) practically infeasible. For example, if the model reduces its basic time step to half an hour (1800 seconds), the computation time for a period of 50 years would increase to 100 days (more than 3 months) in a personal computer of 2.5 GHz CUP. Simulation using a grid size of 50 meters has been actually carried out in Ugum watershed and other southern Guam watersheds, and the simulation results showed that the output accuracy was not satisfied. Therefore, a larger grid size of 100 meters is finally selected in this study. The basic temporal step was set to 1 hour and the model would automatically reduce the time step to as short as a couple of seconds based on the rainfall intensity when a rainfall event happens so that the model maintains numerical convergence during solving the two-dimensional diffusive wave equations for the surface flow.

4.3 Model calibration in Ugum watershed

The model was first calibrated in Ugum watershed, in which both rainfall and streamflow data are available. Figure 16 shows Ugum watershed and the rain gages and streamflow gages inside the watershed and in its vicinity.

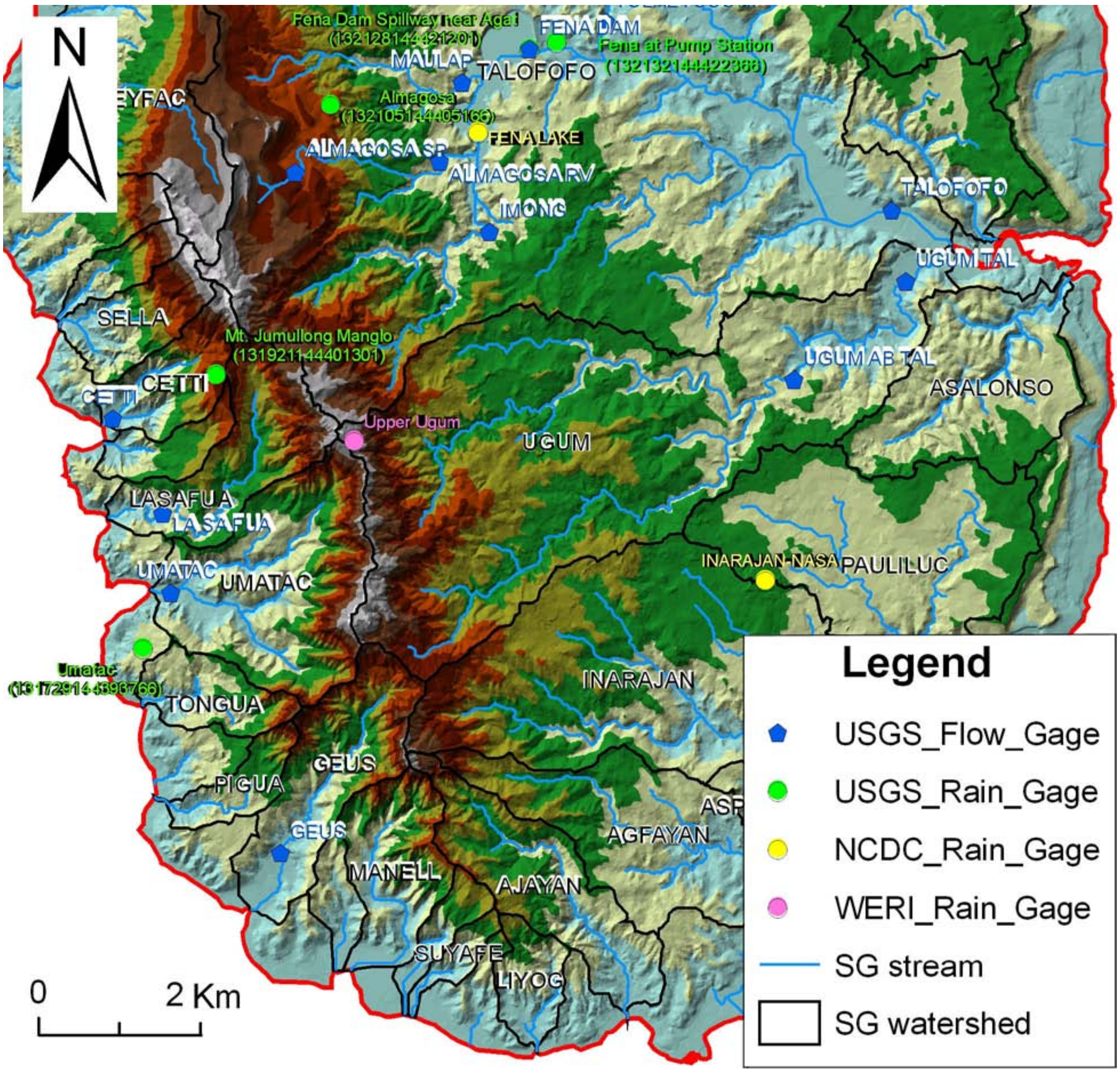


Figure 16. Ugum watershed and adjacent watersheds, climate stations and streamflow gages

Ugum watershed was selected as the first watershed for model calibration and validation because of its high availability of rainfall and streamflow data. There are a total of 7 rain gages and 2 streamflow gages located in the watershed and in its vicinity.

WERI rain gage Upper Ugum is located in it at the west end of the watershed, and 4 USGS rain gages (Umatac, Almagosa, Fena at Pump Station, and Mt. Jumullon Manglo) are also located in the western or its northern vicinity. Moreover, 2 additional NCDC rain gages are located in the adjacent areas to the north and south of the watershed. Rainfall data collected at these rain gages were used for model calibration and validation in three 2-year periods based the availability of rainfall data, and streamflow data as well.

There are two USGS streamflow gages located in Ugum watershed, Ugum near Talofofo, which is located at the watershed outlet, and Ugum above Talofofo, which is located at a point about 4 km (2.5 miles) upstream the watershed outlet and controls about 80% of the watershed area. However, station Ugum near Talofofo is inactive and the streamflow data collected are from June 19, 1952 to September 23, 1970. This time span of streamflow data does not overlap any of the available rainfall data collected at the climate stations inside the watershed or in its vicinity. This leaves the streamflow data collected at the station useless in the model calibration and validation. Therefore streamflow data collected at station Ugum above Talofofo, which is an active station having streamflow data until the current year, was used for model calibration and validation in this study.

Figure 17 in the next page shows a USGS rain gage – Mt. Jumullon Manglo (green cylinder) installed in the northwest vicinity of Ugum watershed. From this figure, one also can see that types of vegetation at a higher elevation (260m/853ft) in southern Guam are mainly grasses and other short vegetations.

4.3.1 The study watershed – Ugum watershed

Ugum watershed, 19 km^2 (7.3 square mile), is located to the southwest of Talofofo Bay, and most of the watershed (97%) is covered by vegetations of ravine forest and savanna complex as named in the USGS shape file or tall vegetation and short vegetation as named in LUOM (Figures 9 and 10 in Chapter 3). The rest 3% of the watershed is barren (badland) or bare soil. The soil types mainly include Ylig clay, Akina-Atate silty clay, Akina silty clay, Togcha-Akina silty clays, Pulantat clay, Akina-Badland complex, Agfayan clay, Sasalaguan clay, rock and urban land complex (USDA et al., 1988). The elevation ranges from 3 to 374 meters (10 to 1227 ft). Geologically, the watershed is situated on the layer of bolanos pyroclastic member (Miocene), which comprises of breccias, conglomerates, and sandstones consisting largely of fragmented andesite. This layer is laid on the top of facpi formation (Eocene), which comprises of basal portion consisting of high-Ca boninite pillow lavas interbedded with pillow breccias, hyaloclastites, and sandstones of the same lithology.

Figure 17. USGS rain gage – Mt. Jumullon Manglo (green cylinder) and types of vegetation

4.3.2 Digital data for the watershed

The two-dimensional, 100-meter (328-ft) grid size digital data of the watersheds, stream networks, vegetation and DEM are first output from the GIS raster files. Figure 18 in the next page shows the digital watershed of Ugum, in which there are totally 55 rows and 78 columns making up a total of 4290 cells. However, the Ugum watershed consists of only 1899 cells out of these 4290 cells. The yellow grids with value 1 are the watershed cells and the white cell with value 0 are grids outside the watershed, and the grids shaded with blue are grids of the stream network (rivers). The cell of row 2 and column 76 (right-hand top corner) is the watershed outlet. The digital stream network is in a separate sheet (not shown here), in which the river grid cells have value 1 while the non-river cells have value 0. The digital vegetation file contains one digit numbers of vegetation type. And the DEM file contains the elevation in float numbers. All these 2-dimensional digital data are converted into 1-dimensional data by a series of pretreatment programs. There are no detail data of river sections. These data are determined based on site investigation at one or two sections near the watershed outlet and map inspection. These data are important but do not affect much the results in watershed-scale hydrologic simulation.

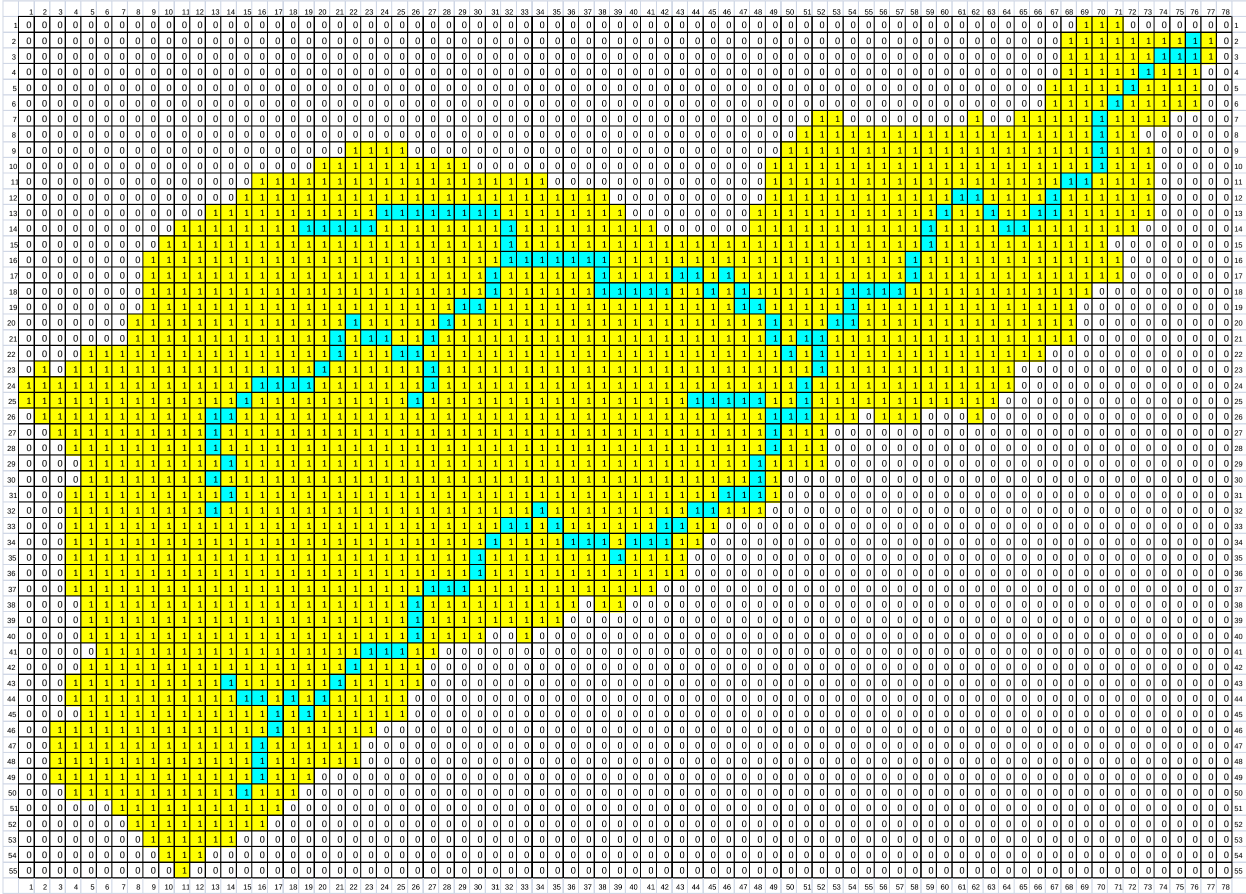
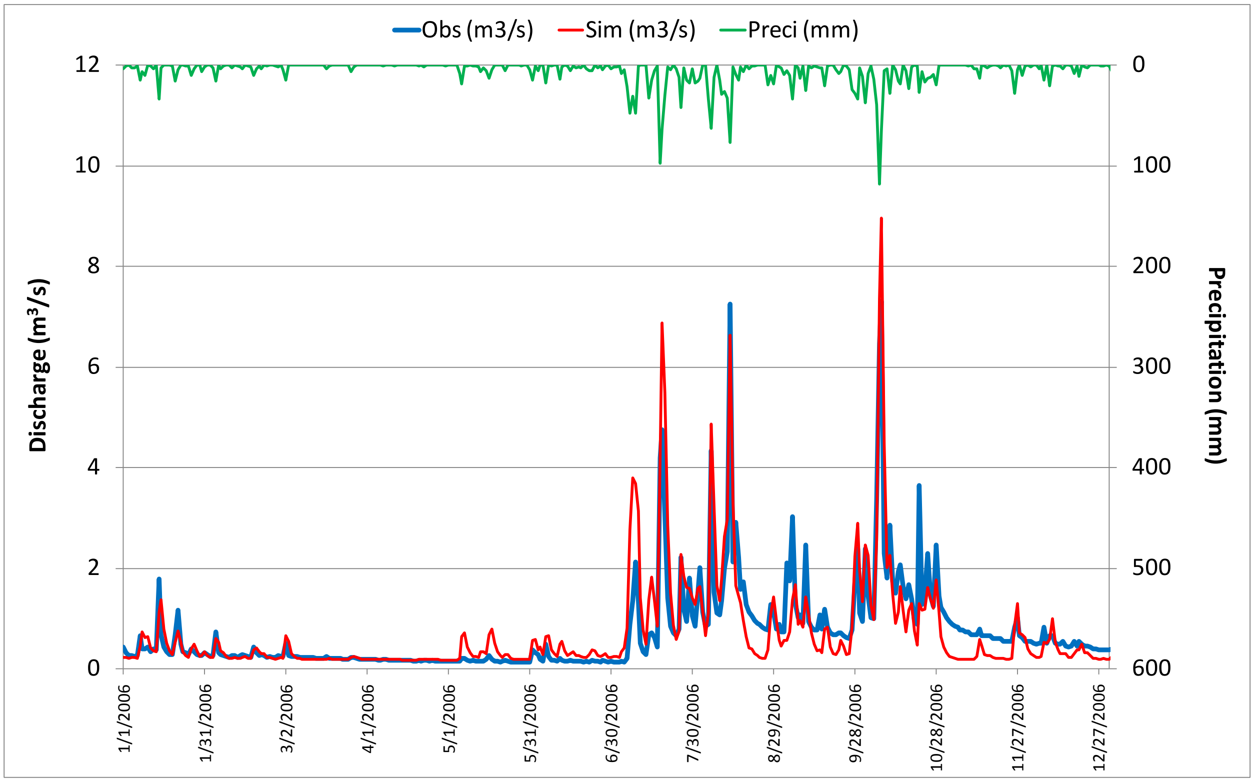


Figure 18. Digital watershed of Ugum

(1/yellow – watershed cells, 0/white – cells outside the watershed, blue -river cells)

4.3.3 Results of model calibration in 2006 and 2007

After studying the available streamflow and rainfall data, years of 2006 and 2007 were selected for the model calibration. Consecutive rainfall data are available at WERI Upper Ugum station, USGS Umatac station, and NCDC Inarajan-NASA station. And the other two periods, 2001-2002, in which consecutive rain fall data at two USGU stations, Umatac and Mt. Jumullong Manglo, and two NCDC stations, Fena Lake and Inarajan-NASA, are available even though streamflow data in this period are not complete, and 1981-1982, in which consecutive rainfall data at NCDC station Fena Lake and Inarajan-Nasa are available, were selected for model validation. All calibration and validation were carried out at the location of station Ugum above Talofofo. Figure 19 in the next page shows the hydrographs of model calibration in 2006 (upper) and 2007 (lower).



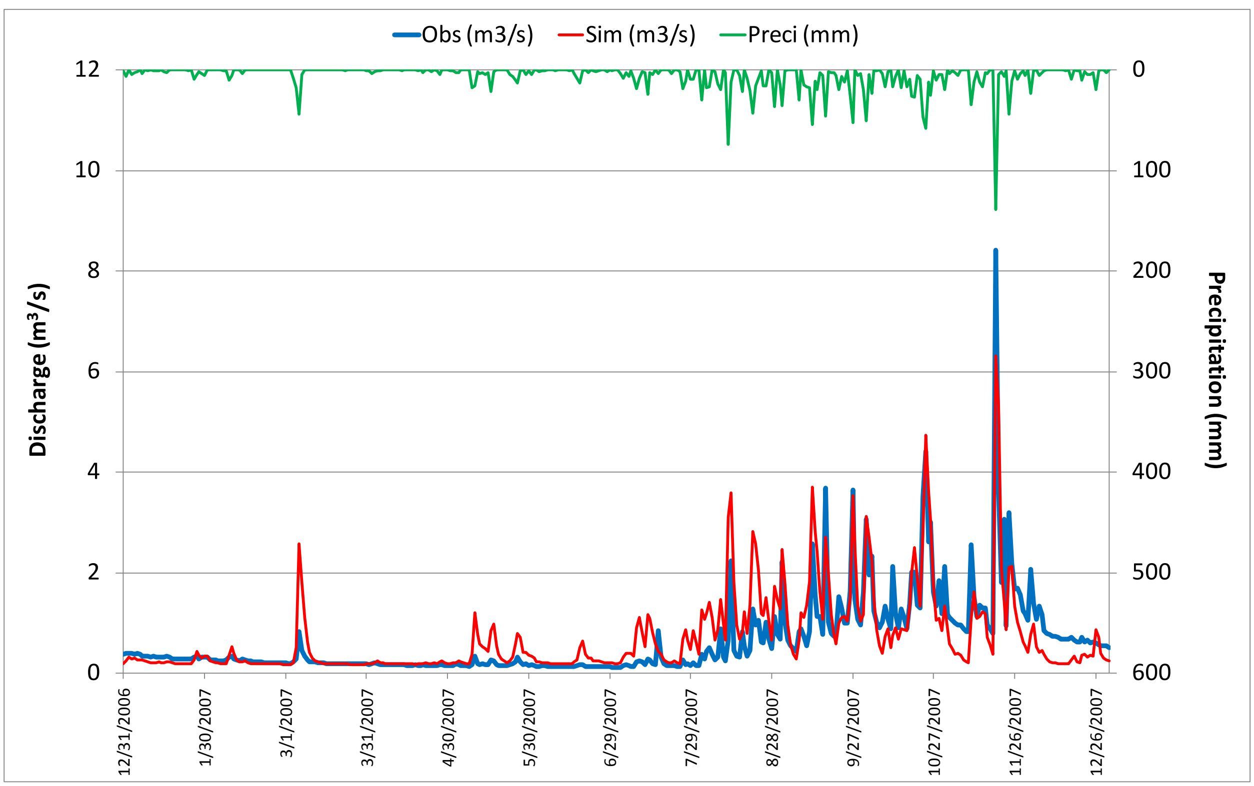


Figure 19. Comparison of hydrographs of model calibration in 2006 and 2007

(Upper-2006, lower-2007. Blue-observed flow, red-simulated flow, green-Precipitation or rainfall)

Visually from the figure, the simulated (red) and observed (blue) hydrographs fit each other quite well overall, even though the model overestimated the first three peaks and the fifth peak a little and underestimated the forth peak a bit, and underestimated part of the recession flows in 2006, and the model overestimated the smaller peaks and underestimated the largest peak in 2007. These overestimation and underestimation are closely related to the rainfall data and thus is not systematic. Taking the second and forth peaks in 2006 as an example, one can see that the second rainfall is larger than the forth, the simulation result correctly reflects this difference in the rainfalls. It is unreasonable to require the model to generate a larger peak of streamflow when the rainfall is smaller as the situation of the second and forth peaks in the hydrograph of 2006.

Statistically, the model efficiency coefficient (C_e), model determination coefficient (C_d) and percentage difference of volume (DV) for the two-year period of 2006 and 2007 are 0.68, 0.74 and 4.7%, respectively. The model efficiency coefficient and model determination coefficient are not very close to 1, but still good enough to demonstrate that the model behaves well. The DV shows only a very small overestimation (4.7%) of the water volume in this two-year period which is very strong evidence of the model’s performance. The model’s high accuracy in water volume simulation is important to water quantity related watershed management and planning.

4.3.4 Results of model validation in 2001 and 2002

The calibrated model was first validated in 2001 and 2002 in Ugum watershed without any changes of the model parameters. Figure 20 in the next page shows the comparison of simulated (red) and observed (blue) hydrographs. There are only 4 months of flow data in 2002 and therefore the second half of 2002 in the figure has only the red line (simulated hydrograph). The model overestimated the two early peaks slightly in 2001 and underestimated the third and forth peaks in 2001 and early 2002.

Looking at the rainfalls (green line on the top of the figure) and comparing the four large rainfall events (2001/07/13, 2001/08/14, 2001/11/17, and 2002/01/08) which were responsible for the four streamflow peaks, one can see that the values of the first (2001/07/13), third (2001/11/17) and fourth (2002/01/08) rainfalls are close to each other (94mm, 90mm, and 106mm, respectively), and therefore it is reasonable that the model generated similar responses of streamflow (5.8m^3/s, 6.0m^3/s, and 5.8m^3/s, respectively) to these rainfalls. This may suggest that the reason for the underestimation of the later two streamflow peaks (2001/11/17 and 2002/01/08) could be that the recorded rainfalls for these two streamflow peaks might not be as large as they were supposed to be. Or in other words, the model would generate expected streamflow peaks if the recorded rainfalls were large enough. There also could be other reasons for the underestimation of the streamflow peaks, such as errors in streamflow data reading.

Statistically, the model efficiency coefficient (C_e), model determination coefficient (C_d) and percentage difference of volume (DV) for 2001 are 0.71, 0.73, and 3.5%, respectively, which show a good agreement between the simulated and observed hydrographs in 2001.

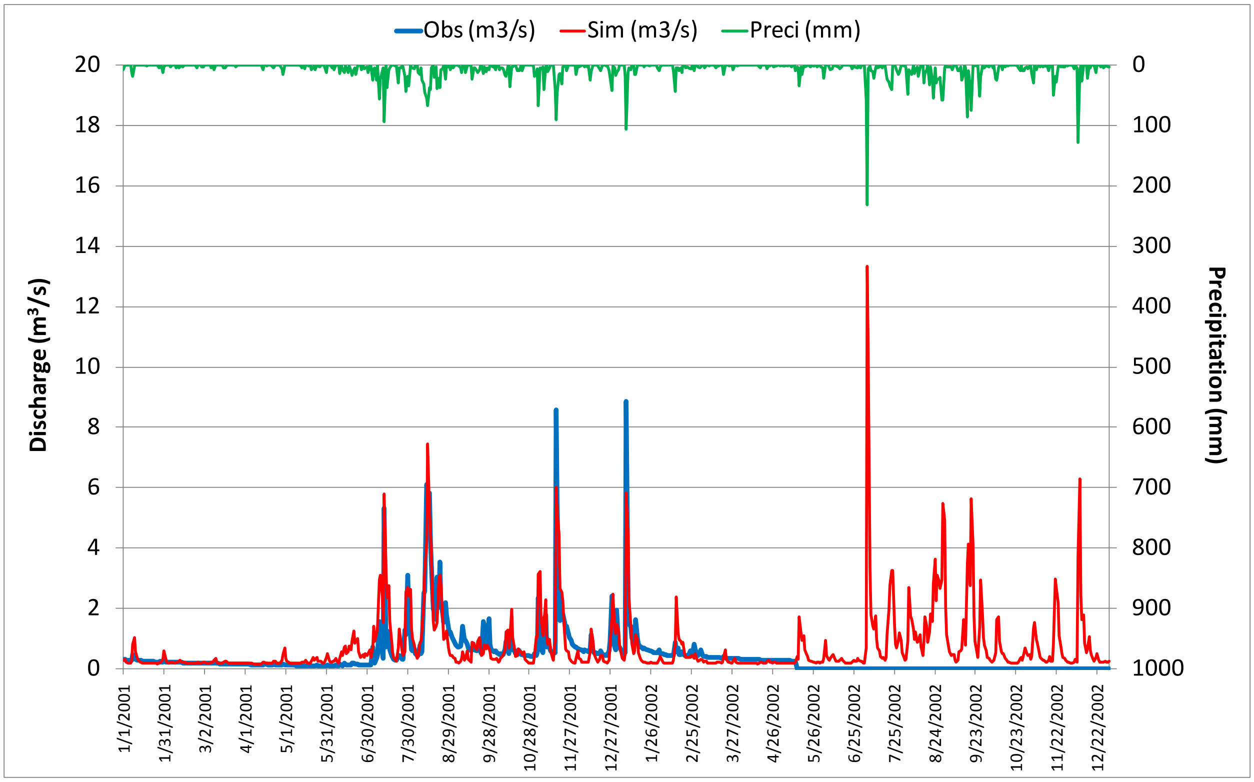


Figure 20. Comparison of hydrographs of model validation in 2001 and 2002

(Blue-observed flow, red-simulated flow, green-Precipitation or rainfall)

4.3.5 Results of model validation in 1981 and 1982

In order to test the calibrated model more extensively, the calibrated model was also validated in Ugum watershed for the period of 1981 to 1982. There is no change to the model parameters, and the only two NCDC stations, Fena Lake and Inarajan-NASA, have rainfall data for these two years. Figure 21 in the next page shows the comparison of the simulated and observed hydrographs. Visually, the model underestimated the largest peak and completely did not respond to the peak on September 18, 1981 because there was no record of rainfall on this day. Statistically, the model efficiency coefficient (C_e), model determination coefficient (C_d) and percentage difference of volume (DV) for these two years are 0.54, 0.61, and 6.7%, respectably. Model efficiency coefficient and model determination coefficient are not good enough, but considering the accuracy of rainfall data, this simulation result is still acceptable.

In summary, the model was calibrated in Ugum watershed for a two-year period of 2006 to 2007. Then the model was validated for two separate two-year periods, 2001 to 2002 and 1981 to 1982. Visual comparisons and statistical coefficients demonstrated that the model's performance of watershed modeling was good enough and acceptable in Ugum watershed.

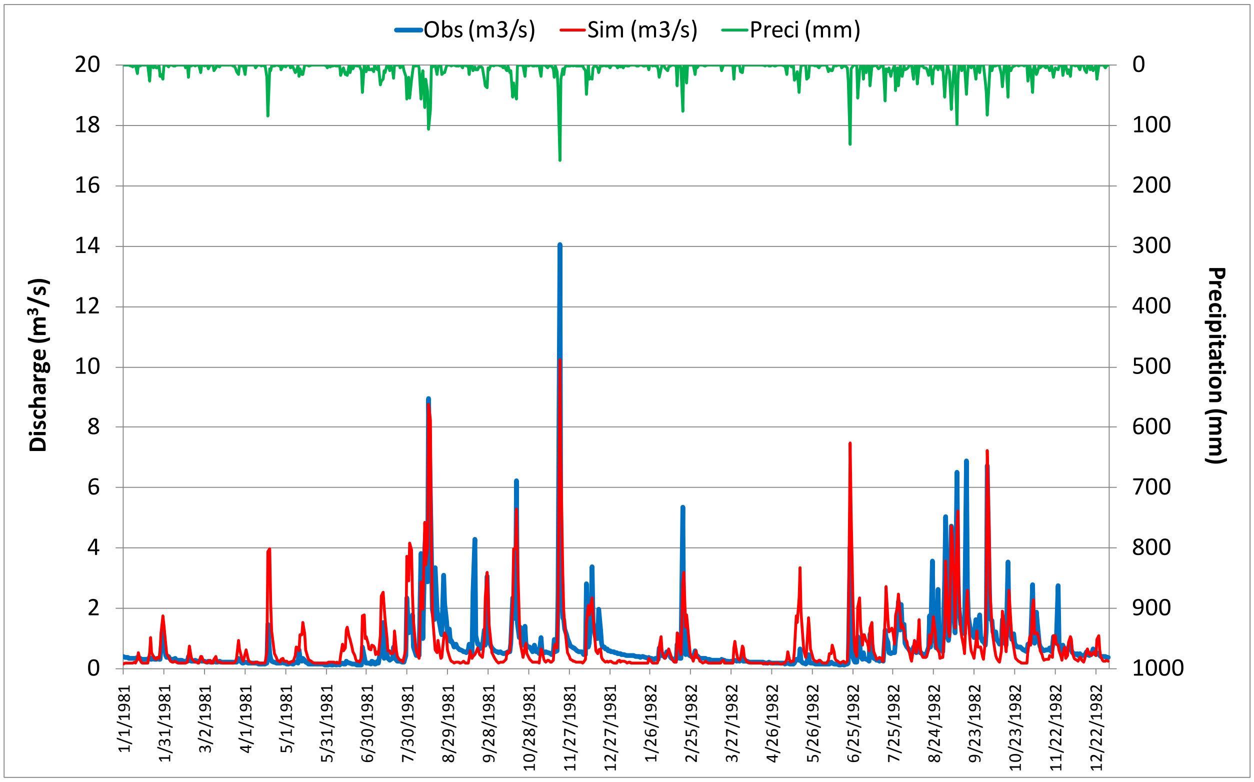


Figure 21. Comparison of hydrographs of model validation in 1981 and 1982

(Blue-observed flow, red-simulated flow, green-Precipitation or rainfall)

4.4 Model verification and recalibration in the adjacent four watersheds

In order to expand the application of the calibrated model to other southern Guam watersheds without a streamflow gage, further verification of the model's performance in other watersheds with streamflow data is necessary. Four immediately adjacent watersheds, Pauliluc (at Tinago station), Inarajan, Umatac and Lasafua were selected for this purpose. First, the calibrated model was verified in each of these watersheds without any change in the model parameters to see how well the simulated hydrographs fit the observed ones. Then, the model was recalibrated in all these four watersheds to obtain better agreements between the simulated and observed hydrographs.

4.4.1 Pauliluc watershed (at Tinago station)

Pauliluc watershed is located to the southeast of Ugum watershed. The watershed area is 8.84 km^2 (3.45 square miles) and 93.5% of the watershed is covered by short vegetation, agricultural fields and tall vegetation. The soil types, bedrocks and geologic deposits are similar to those in Ugum watershed. The elevation ranges from 2 meters (6 ft) to 127 meters (417 ft). There was a USGS streamflow gage (Tinago station) located in the immediate upstream reach of the conjunction of the Tinago River and the Pauliluc River. This station recorded flow data from November 1, 1952 to September 30, 1985, and the flow data in 1981 and 1982 were used for model verification and recalibration. The topographic characteristics of this watershed are shown in Figures 9 to 13, Chapter 3, and the location of the streamflow gage is shown in Figure 9, Chapter 3 and Figure 16, Chapter 4. Figure 22 shows the digital watershed of Pauliluc, in which the cell of row 35 and column 36 is the watershed outlet.

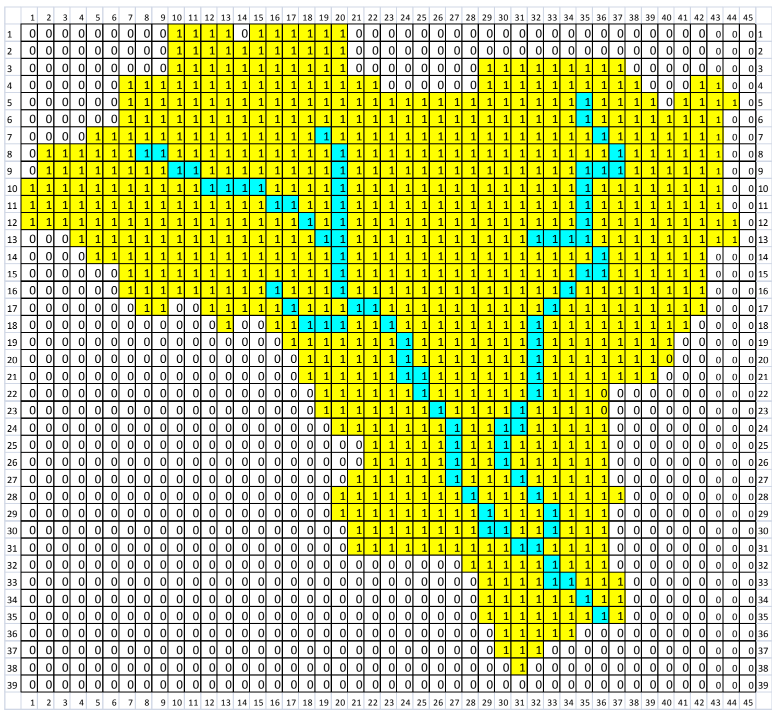


Figure 22. Digital watershed of Pauliluc

(1/yellow – watershed cells, 0/white – cells outside watershed, blue -river cells)

Figure 23 in the next page shows the result of model verification in Pauliluc watershed at Tinago station. Model verification means that there is no change in model parameters. And Figure 24 in the next page shows the result of model recalibration. From Figure 23, one can see that overall the simulated hydrograph fits the observed one well though the model overestimated the lower peaks and underestimated the higher peaks. However, statistically, the model efficiency coefficient (C_e), model determination coefficient (C_d) and percentage difference of volume (DV) for these two years are 0.48, 0.67, and 53.7%, respectively. The model efficiency coefficient and percentage volume difference are not good. After studying the rainfall data in the two years and the model responses, it can be seen that for some streamflow peaks recorded at Tinago station there was no correspondent rainfall events recorded at the rainfall stations. This may explain the low model efficiency coefficient. The model overestimating the small peaks is the reason of overestimation of the water volume. Two factors might cause this overestimation, more rainfalls recorded and model's over-response to small events.

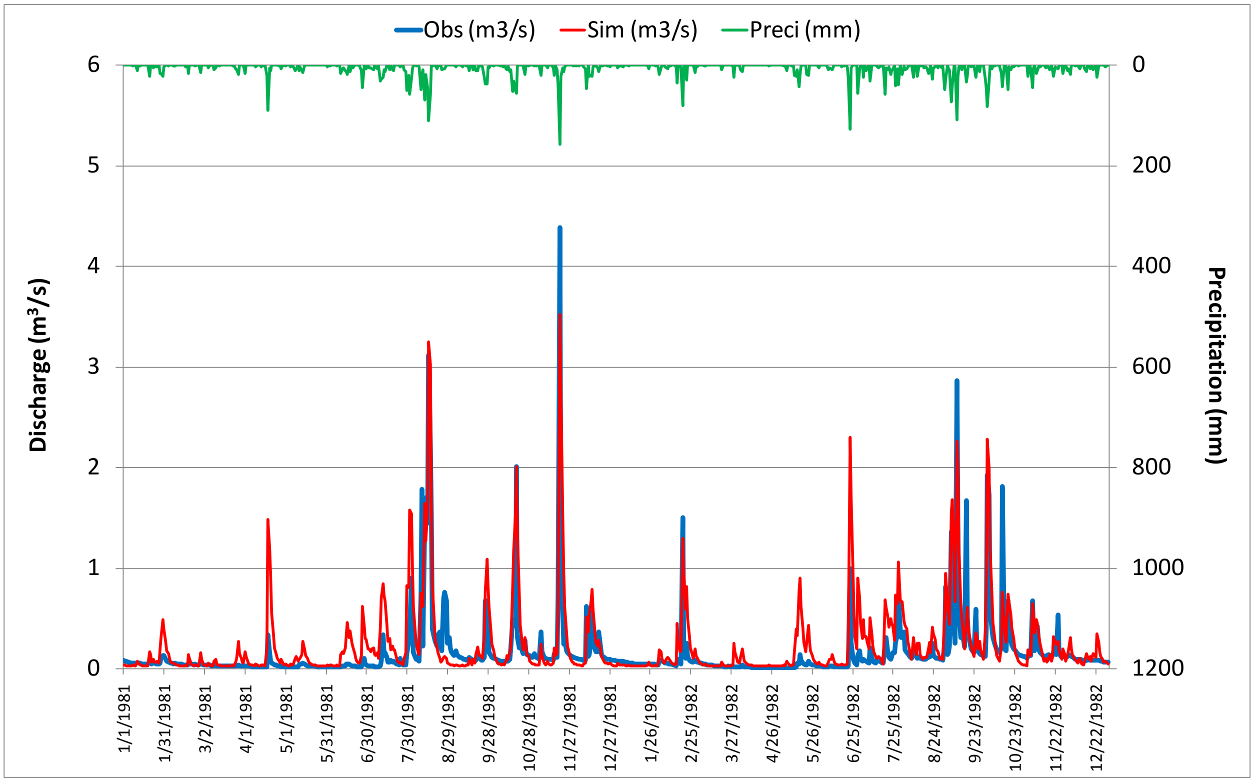


Figure 23. Result of model verification in Pauliluc watershed at Tinago station

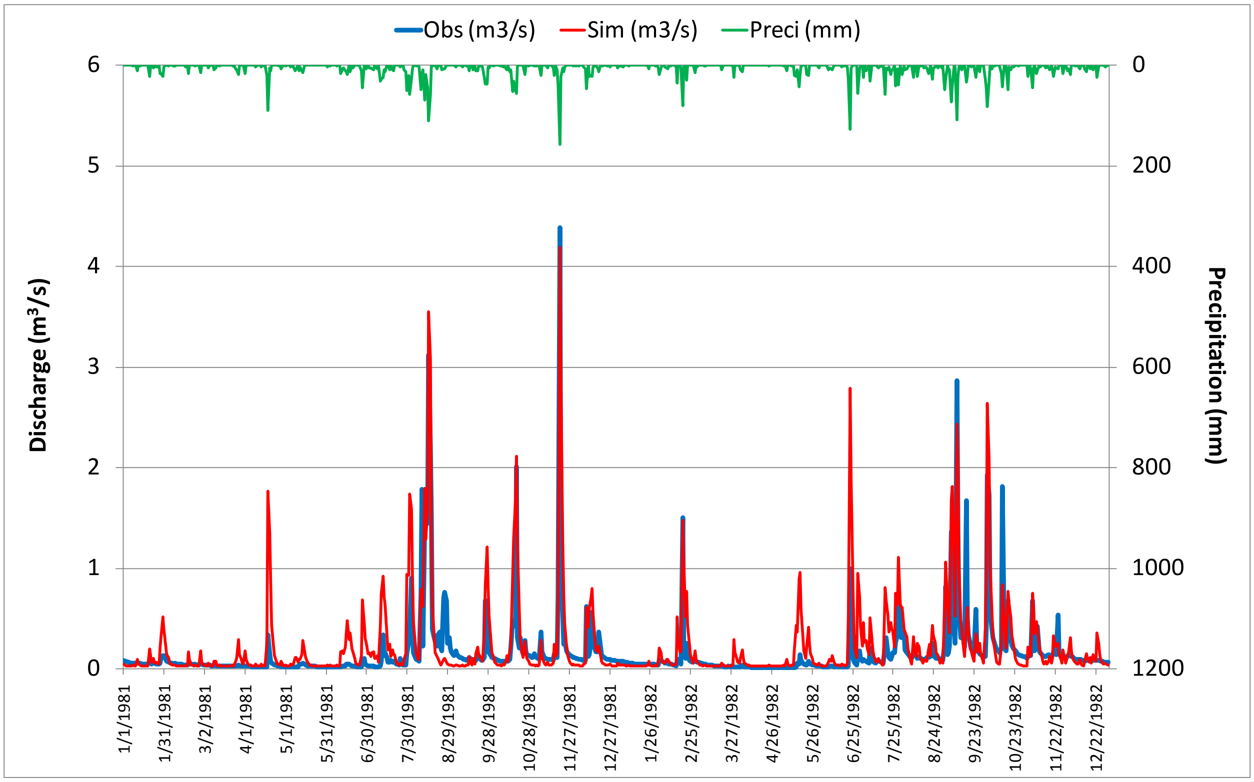


Figure 24. Result of model recalibration in Pauliluc watershed at Tinago station

The model was recalibrated in Pauliluc watershed at Tinago station. Figure 24 shows the result of model recalibration. By comparing Figures 23 and 24 visually, one can see that the peaks of the simulated hydrograph after recalibration are larger than the peaks of the simulated hydrograph before recalibration, and that the model response to small events became smaller. These are also reflected by the statistical coefficients C_e, C_d and DV, which are 0.46, 0.69, and 46.8%, respectively. The model determination coefficient and percentage volume difference are improved slightly, but the model efficiency coefficient deteriorates slightly. However, this is the best improved model in Pauliluc watershed.

4.4.2 Inarajan watershed

Inarajan watershed is located to the immediate south of Ugum watershed. The watershed area is 12.55 km^2 (4.9 square miles), one third smaller than that of Ugum watershed (19 km^2) and 94% of the watershed is covered by short vegetation, agricultural fields and tall vegetation. Figure 25 shows the digital watershed of Inarajan, in which the cell of row 32 and column 59 is the watershed outlet.

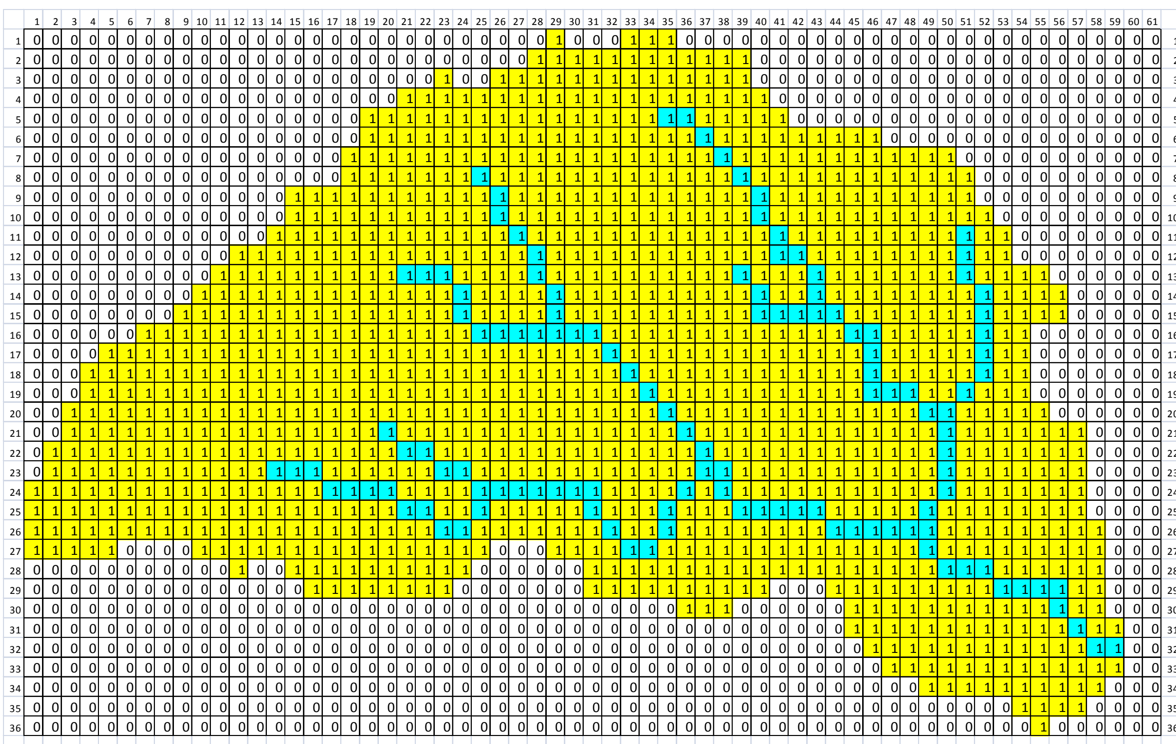


Figure 25. Digital watershed of Inarajan

(1/yellow – watershed cells, 0/white – cells outside watershed, blue -river cells)

The soil types, bedrocks and geologic deposits are similar to those in Ugum watershed. The elevation ranges from 1 meter (3 ft) to 316 meters (1037 ft). There was a USGS streamflow gage located 4 km upstream the watershed outlet. This station recorded flow data from October 1, 1952 to December 31, 1982, and the streamflow data in 1981 and 1982 are used for model verification and recalibration. The topographic characteristics of this watershed are shown in Figures 9 to 13, Chapter 3, and the location of the streamflow gage is shown in Figure 9, Chapter 3 and Figure 16, Chapter 4.

Figure 26 in the next page shows the result of model verification in Inarajan watershed. Model verification means that there is no change in the model parameters. From Figure 26, one can see that overall the simulated hydrograph fits the observed one well though the model overestimated the lower peaks and underestimate the higher peaks. However, statistically, the model efficiency coefficient (C_e), model determination coefficient (C_d) and percentage difference of volume (DV) for these two years are 0.63, 0.68, and 32.4%, respectively. The model efficiency coefficient and model determination coefficient are good and the percentage volume difference is acceptable though not good enough.

After studying the rainfall data in the two years and the model responses, it can be seen that, similar to Pauliluc watershed, for some flow peaks recorded at the flow station there was no correspondent rainfall event recorded at the rainfall stations. This may explain the low model efficiency coefficient. The model overestimating the small peaks is the reason of overestimation of the water volume. Two factors might be responsible for this overestimation, more rainfalls recorded and model over-response to small events.

The model was recalibrated in Inarajan watershed. Figure 27 in the next page shows the result of model recalibration. By comparing Figures 26 and 27 visually, one can see that the peaks of the simulated hydrograph after recalibration are larger than the peaks of the simulated hydrograph before recalibration, and that the model response to small events became smaller. These are also reflected by the statistical coefficients C_e, C_d and DV, which are 0.65, 0.69, and 20.1%, respectively. The model determination coefficient and model efficiency coefficient are improved slightly, and the percentage volume difference is improved considerably. This is the best improved model in Inarajan watershed.

The recalibration results of model efficiency coefficient and model determination coefficient in Inarajan watershed are close to those in Ugum watershed, though the percentage volume difference is larger than that in Ugum watershed.

4.4.3 Umatac watershed

Umatac watershed is located to the west of Ugum watershed. The watershed area is 5.54 km^2 (2.16 square miles) and 99% of the watershed is covered by short vegetation and tall vegetation. The soil types, bedrocks and geologic deposits are similar to those in Ugum watershed. The elevation ranges from 2.4 meters (8 ft) to 363 meters (1191 ft). There is a USGS flow gage located at the watershed outlet. This station recorded flow data from October 1, 1952 to the current year though many missing data in between, and the streamflow data in 2006 and 2007 were used for model verification and recalibration. The topographic characteristics of this watershed are shown in Figures 9 to 13, Chapter 3, and the location of the streamflow gage is shown in Figure 9, Chapter 3 and Figure 16, Chapter 4.

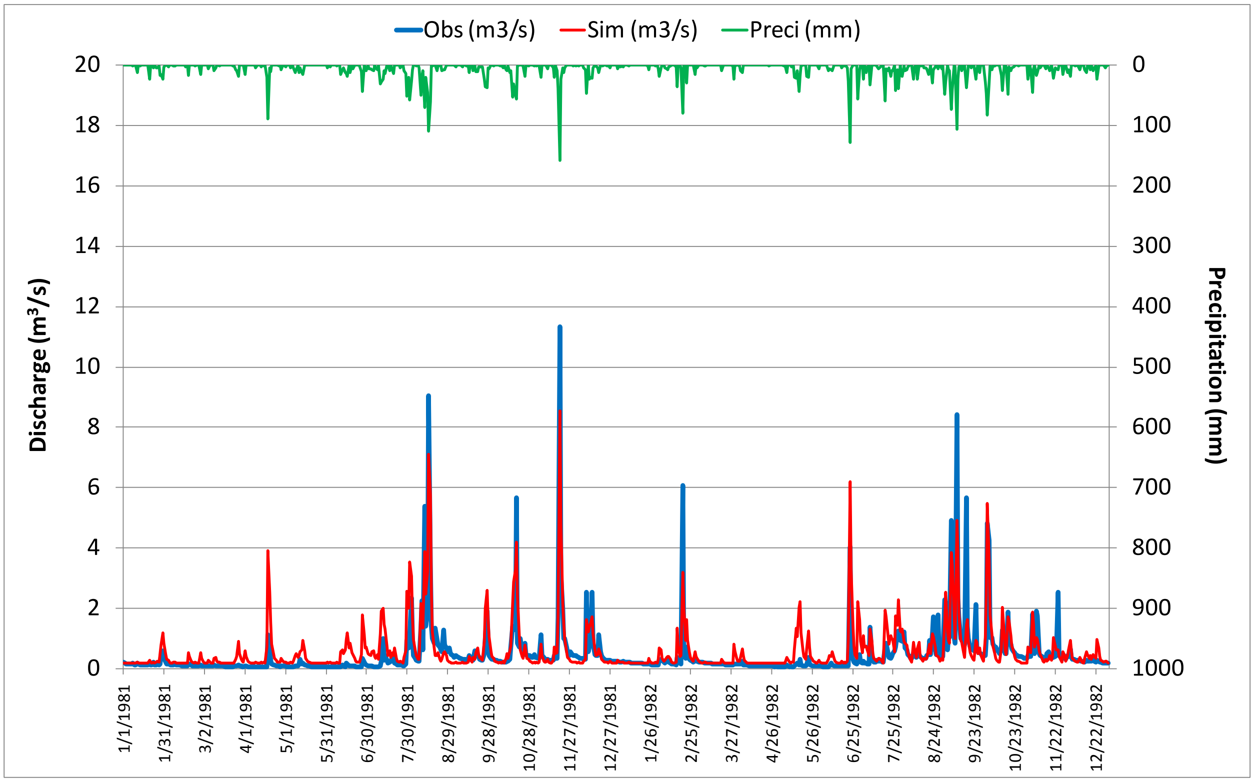


Figure 26. Result of model verification in Inarajan watershed

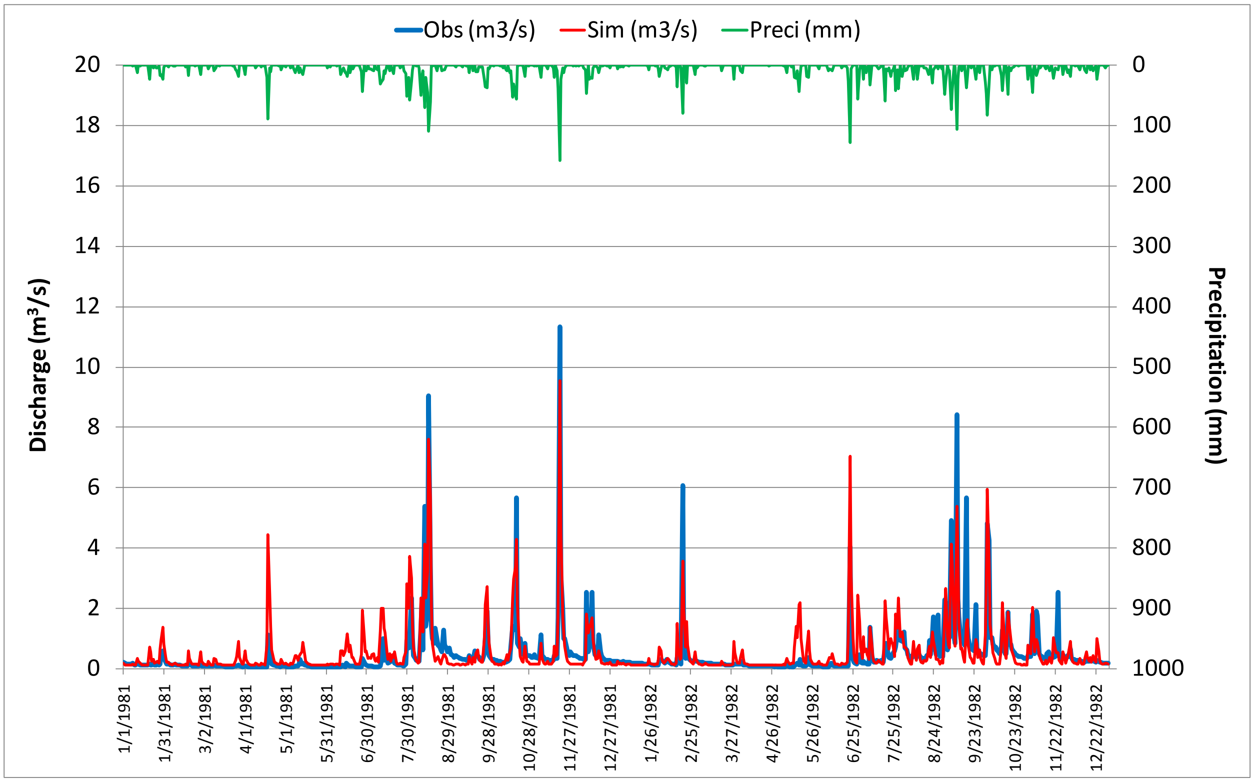


Figure 27. Result of model recalibration in Inarajan watershed

Figure 28 shows the digital watershed of Umatac, in which the cell of row 20 and column 1 is the watershed outlet. Figure 29 shows the image of the watershed outlet/estuary of the Umatac River. From this picture, one also can see the tall vegetation at the lower elevations.

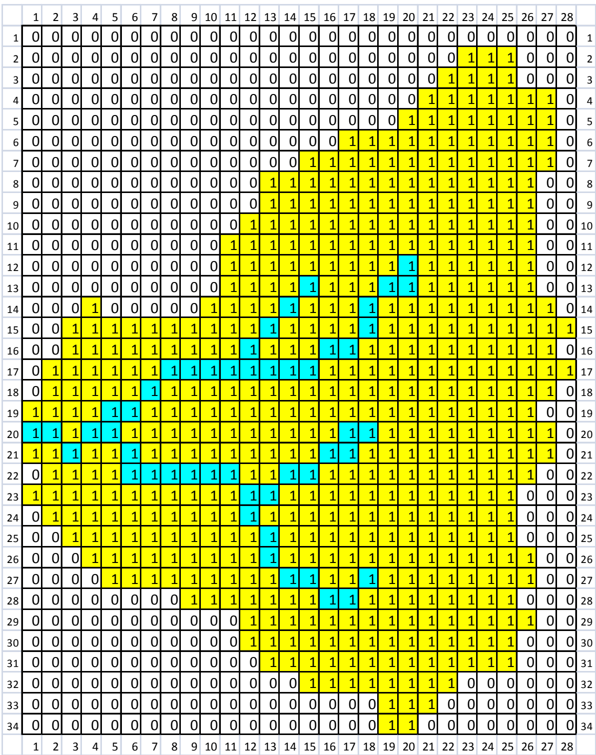


Figure 28. Digital watershed of Umatac

(1/yellow – watershed cells, 0/white – cells outside watershed, blue -river cells)

Figure 29. Estuary of the Umatac River

Figure 30 in the next page shows the result of model verification, and Figure 31 in the next page shows the result of model recalibration in Umatac watershed. Model verification means that there is no change in the model parameters. From Figure 30, one can see that overall the simulated hydrograph fits the observed one well though the model underestimated all the large peaks. Statistically, the model efficiency coefficient (C_e), model determination coefficient (C_d) and percentage difference of volume (DV) for these two years are 0.66, 0.78, and -22.2%, respectively. The model efficiency coefficient and model determination coefficient are pretty good and the percentage volume difference is acceptable though there is room for improvement.

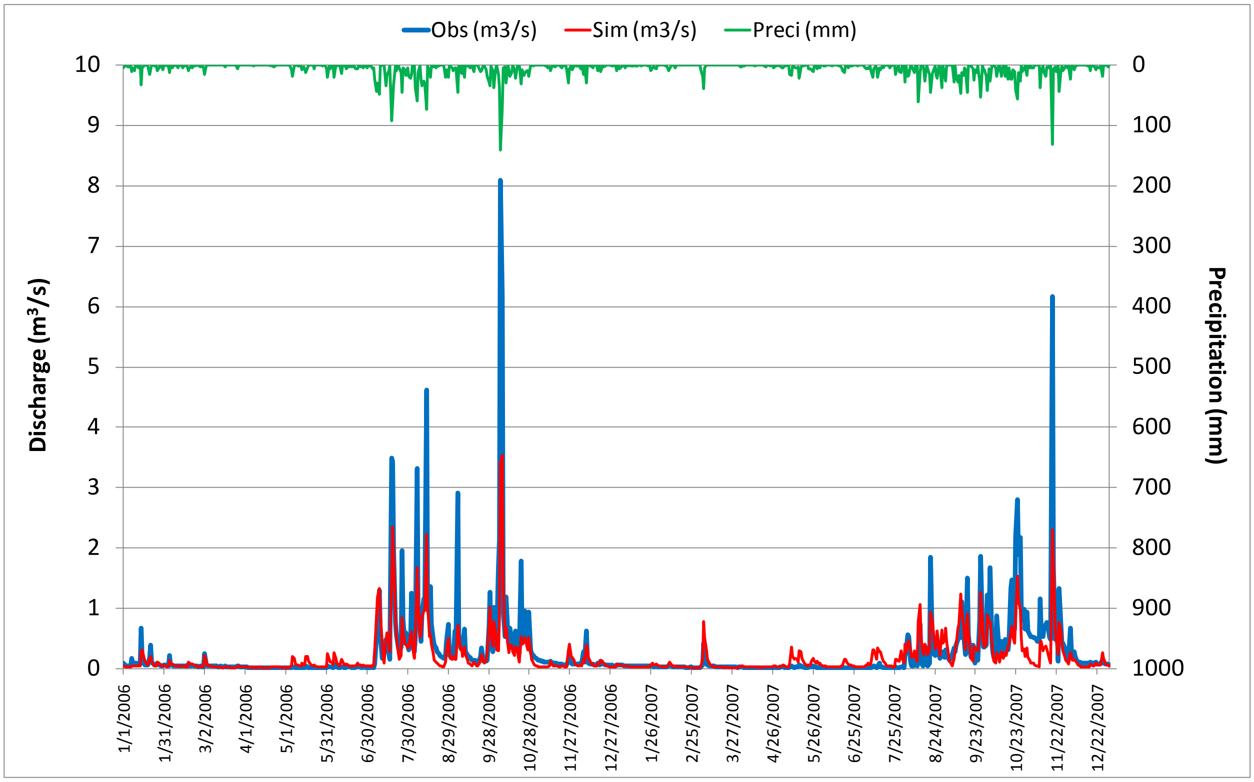


Figure 30. Result of model verification in Umatac watershed

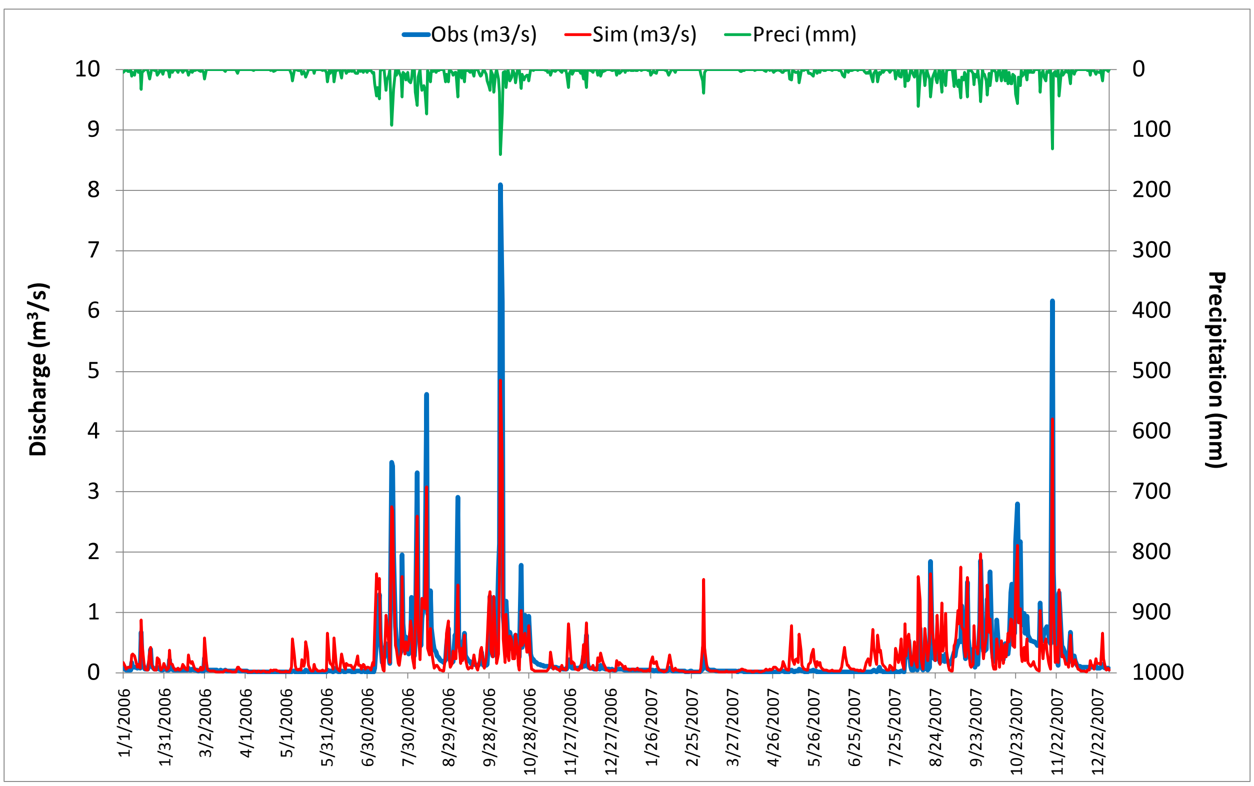


Figure 31. Result of model recalibration in Umatac watershed

By comparing Figures 30 and 31 visually, one can see that the peaks of the simulated hydrograph after recalibration are much closer to the observed peaks than before recalibration, though still having room for improvement especially for the big peaks. However, the statistical coefficients C_e , C_d and DV, especially C_d and DV, were improved considerably. The three coefficients are 0.76, 0.79, and 9%, respectively. The model efficiency coefficient and model determination coefficient are even better than those of the best calibrated model in Ugum watershed regardless the big underestimations of the large peaks in Umatac watershed. This tells that the numbers of coefficients sometimes are misleading and therefore the visual method of calibration is a supplementary method and always indispensable. Figure 31 shows the best improved model in Umatac watershed.

4.4.4 Lasafua watershed

Lasafua watershed is a small watershed located to the west of Ugum watershed. The watershed area is 3.15 km^2 (1.23 square miles), and 98% of the watershed is covered by short and tall vegetations. The soil types, bedrocks and geologic deposits are similar to those in Ugum watershed. The elevation ranges from 3 meter (10 ft) to 363 meters (1191 ft). There is a USGS flow gage located 3 km (1.9 miles) upstream the watershed outlet. This station recorded the steamflow from May 1, 1953 to the current year also with many missing data in between, and the streamflow data in 2001 and 2002 were used for model verification and recalibration. The topographic characteristics of this watershed are shown in Figures 9 to 13, Chapter 3, and the location of the flow gage is shown in Figure 9, Chapter 3 and Figure 16, Chapter 4. Figure 32 shows the digital watershed of Lasafua, in which the cell of row 24 and column 1 is the watershed outlet.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	1
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	2
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	3
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	4
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	5
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	6
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	7
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	8
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	9
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	10
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	11
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	12
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	13
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	14
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	15
16	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	16
17	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	17
18	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	18
19	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	19
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21	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	21
22	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	22
23	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	23
24	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	24
25	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	25
26	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	26
27	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	27
28	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	28
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	

Figure 32. Digital watershed of Lasafua

(1/yellow – watershed cells, 0/white – cells outside watershed, blue -river cells)

Figure 33 in the next page shows the result of model verification in Lasafua watershed. Model verification means that there is no change in the model parameters. From Figure 33, one can see that overall the simulated hydrograph fits the observed one well though the model underestimated most of the peaks. However, statistically, the model efficiency coefficient (C_e), model determination coefficient (C_d) and percentage difference of volume (DV) for these two years are 0.75, 0.80, and -2.6%, respectively, which are pretty good and even better than those in the model calibration in Ugum watershed.

In order to improve model behavior in simulation of peaks, the model was recalibrated in Lasafua watershed. Figure 34 in the next page shows the result of model recalibration. By comparing Figure 33 and 34 visually, one can see that the peaks of the simulated hydrograph after recalibration are much closer to the observed peaks than before recalibration. After recalibration, the statistical coefficients C_e, C_d and DV have been improved dramatically, and their values are 0.89, 0.90, and 1.6%, respectively. These values of model efficiency coefficient, model determination coefficient and percentage volume difference demonstrates that the model was very well calibrated even though visually one can see that the model still underestimated some of the peaks. This is the best calibrated model in the calibration in the five watersheds.

4.5 Summary

In this Chapter, model calibration and validation in Ugum watershed, in which both rainfall data and streamflow data are available, was described in detail. Based on the visual and statistical criteria, the calibrated model was good enough to be applied to Ugum watershed for long term simulation to generate time series of streamflow. However, the model will be not only applied to Ugum watershed, but also other watersheds without streamflow data; it is important to test the model performance in more adjacent watersheds, in which both rainfall data and streamflow data are available. The model was further verified in four other watersheds adjacent to Ugum watershed, Pauliluc (at Tinago station), Inarajan, Umatac and Lasafua. The verification shows that the model performance varies in these watersheds. However, the model performance is acceptable overall even before recalibration. In order to obtain the best application, the model was recalibrated in all these four watersheds to the best extent.

Until now, there are totally five calibrated models, which will be applied to the watersheds in which the models have been calibrated. And then, the calibrated models will be applied to other watersheds with or without a streamflow gage for long term simulation, either to fill in the missing data or “no-data” if the watershed has a streamflow gage in it, or to produce a long term time series of streamflow completely from the simulation output if there is no flow gage in the watershed.

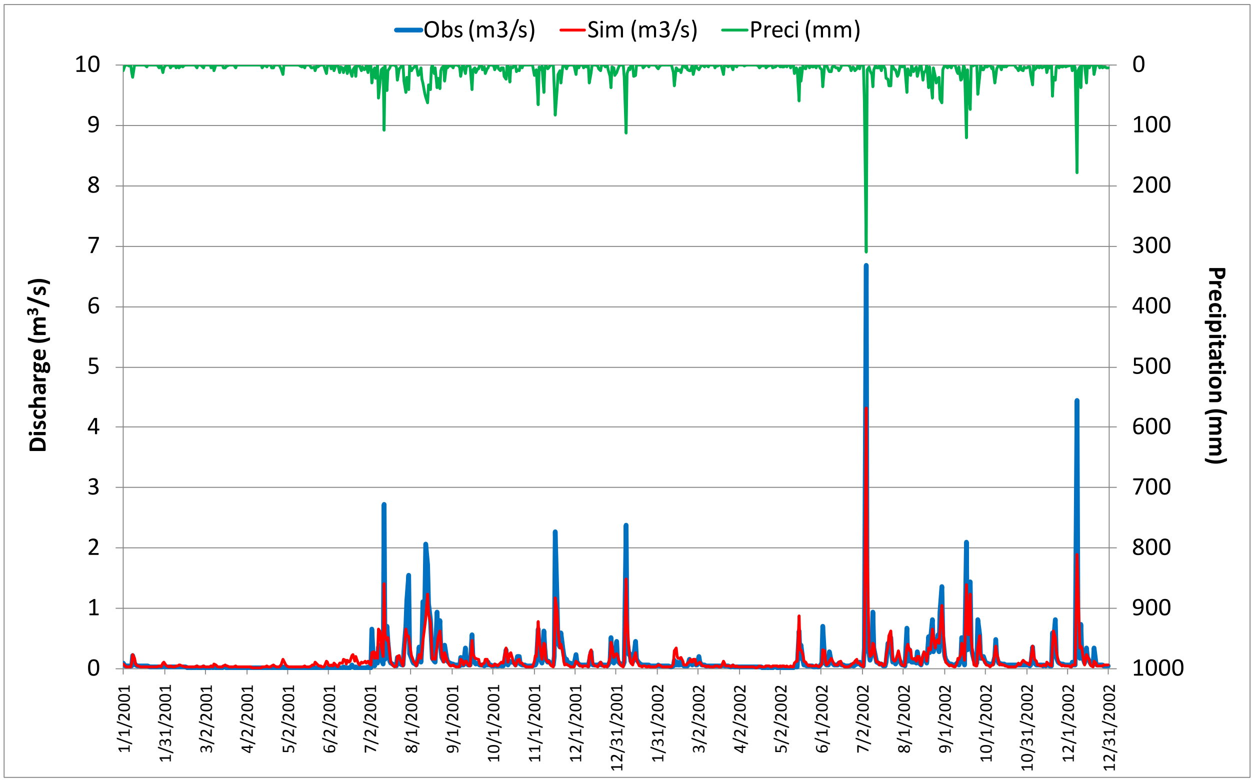

Figure 33. Result of model verification in Lasafua watershed

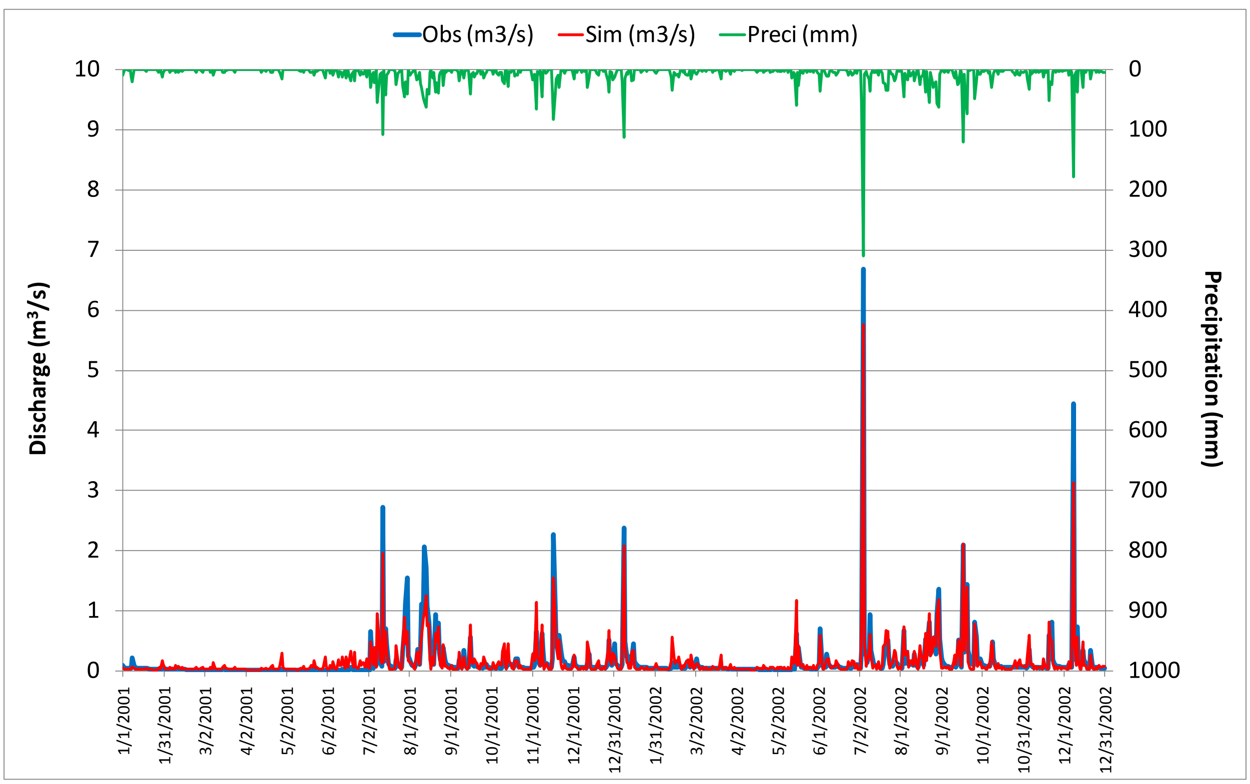

Figure 34. Result of model recalibration in Lasafua watershed

Chapter 5. Long Term Simulation in Twelve Southern Guam Watersheds

5.1 Description of simulated watersheds

The calibrated models were applied to 12 watersheds (applied watersheds) which are near around Ugum watershed and close to the other calibrated watersheds. Table 8 lists these watersheds and their geomorphologic characteristics.

Table 8. Geomorphologic characteristics of the applied watersheds

No.	Water-shed	Area (km^2)	Elevation (m)		Aspect	Vegetation (% forest)	Soils	Deposits and Bedrocks	Model calibrated	Model used
			Low	High						
1	Ugum	19	3	374	E	97.0	Ylig clay, Akina-Atate silty clay, etc.	Bolanos, sandstones, facpi formation, etc.	1	1
2	Inarajan	12.55	1	316	SE	94.0	As Ugum	As Ugum	2	2
3	Lasafua	3.15	3	363	SW	98.0	As Ugum	As Ugum	3	3
4	Pauliluc (Tinago)	8.84	2	127	SE	93.5	As Ugum	As Ugum	4	4
5	Umatac	5.54	2.4	363	W	99.0	As Ugum	As Ugum	5	5
6	Agfayan & Aspupong	5.72	1.4	286	SE	97.7	As Ugum	As Ugum		2
7	Anjayan	3.51	1	336	SE	99.4	As Ugum	As Ugum		3
8	Asalonso	4.83	4.5	97	NE	95.4	As Ugum	As Ugum		4
9	Cetti	2.64	1.7	385	SW	98.5	As Ugum	As Ugum		3
10	Geus	3.47	0.6	328	SW	98.3	As Ugum	As Ugum		5
11	Manell	3.22	1.2	294	S	98.8	As Ugum	As Ugum		3
12	Sella	2.41	1	400	SW	98.8	As Ugum	As Ugum		3

In the table above, the first 5 watersheds are the watersheds in which the model has been calibrated and validated, or verified and recalibrated. The rest 7 watersheds are the applied watersheds, to which one of the 5 calibrated models was applied. The calibrated models were applied to all these 12 watersheds to generate long term time series of steamflow. The watershed area ranges from 2.4 to 19 km^2 (0.9 to 7.4 square miles) the lowest elevation is about 1 meter (3 ft) and the highest elevation is 400 meters (1312 ft). The watersheds have all aspects (directions or facing) except north. Most of the areas (93.5% to 99%) of the watersheds are covered by tall and short forest. Soils and deposits and bedrocks are similar to those in Ugum watershed as described in Chapter 4 (4.3.1). Figure 35 shows the applied watersheds (filled with pink), to which the calibrated models were applied to simulate long term time series of streamflow. In the figure, those watersheds with their names underlined are the watersheds in which the model has been calibrated and validated or verified and recalibrated.

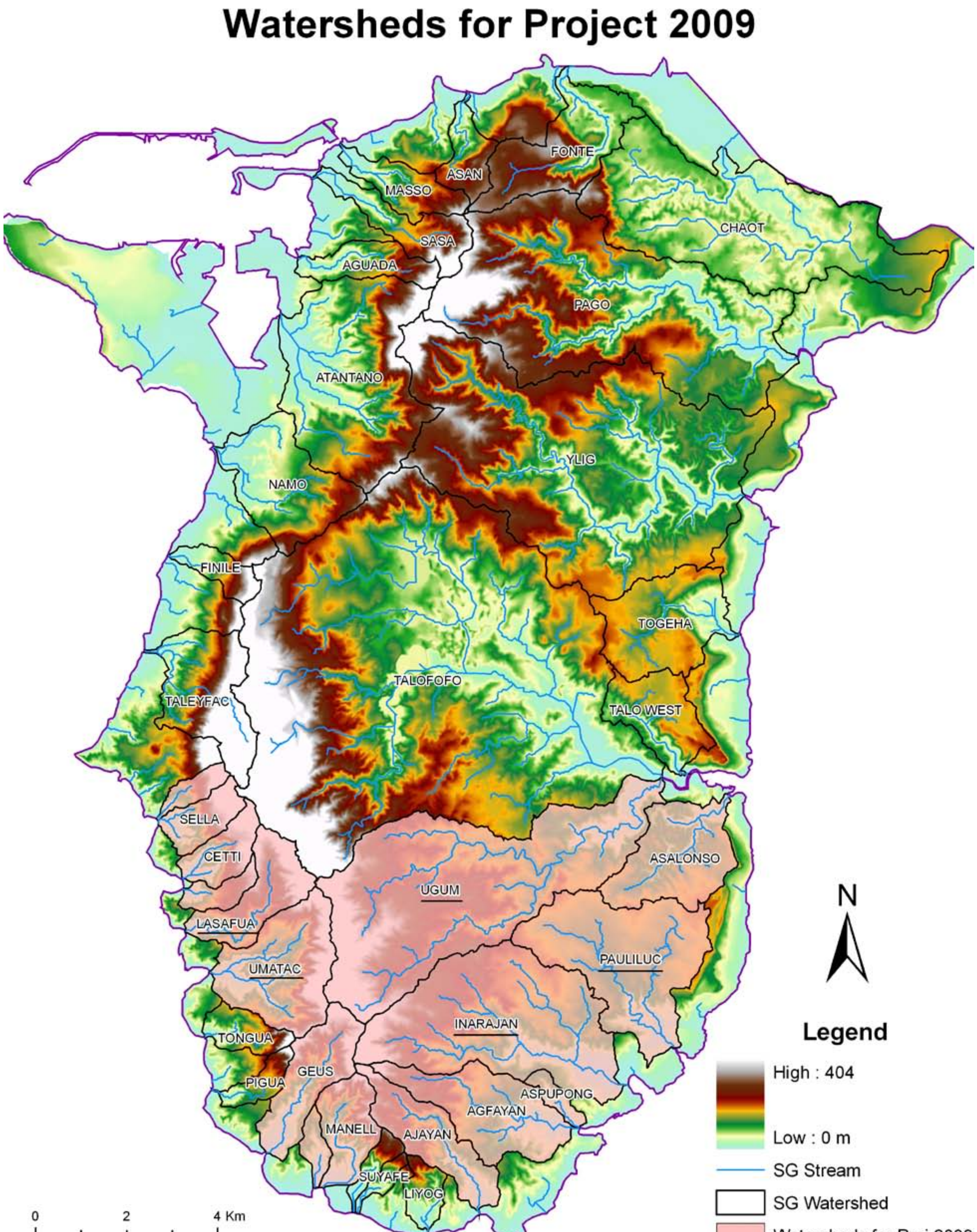

Figure 35. Watersheds (pink filled) simulated in Project 2009

5.2 Selection of calibrated models for applied watersheds

The model has been calibrated in 5 watersheds ("calibrated watersheds"), Ugum (calibrated model 1), Inarajan (calibrated model 2), Lasafua (calibrated model 3), Pauliluc at Tinago station (calibrated model 4) and Umatac (calibrated model 5), and therefore there are a total of 5 calibrated models. These calibrated models were applied to the 12 southern Guam watersheds ("applied watersheds") to generate long term time series of streamflow. When the model was applied to the applied watersheds, each applied watershed selected a model from the 5 calibrated models based on the criteria of geomorphologic similarity between the calibrated watershed and the applied watershed in area, elevation, aspect, slope, vegetation, soils, deposits and bedrocks. As the soils, deposits and bedrocks are pretty much the same in these watersheds, and the vegetation is a simulation factor in the model (the model has already taken the differences of vegetation into account), similarity of area, elevation, aspect or facing/direction, and slope plays an important role in the selection of the appropriate calibrated models for the applied watersheds. Figure 36 in the next page shows southern Guam slopes for selection of the calibrated models. The last column in Table 8 shows the selection of the calibrated models for all of the applied watersheds. For a calibrated watershed, the long term simulation used the model which was calibrated in the same watershed.

5.3 Composition of long term rainfall input data

As the model input, long term climate data are necessary for long term simulation. Table 5 in Chapter 3 shows that 9 of the 12 climate stations have 15 years of or longer rainfall data (except No. 4 – Fena Dame Spillway, which has 2 years of data; No. 6 – Mt. Jumullong Manglo, which has 3 years of data; and No. 12 – WERI station Upper-Ugum, which has 3 years of data). Table 9 shows the 9 climate stations which have 15 years of or longer rainfall data that are used to compose the long term rainfall time series as the input. Table 9 shows that USGS station – Fena Filter Plant has the earliest records of rainfall data since May 1, 1951. However, there are many missing data in these records from 1951 to 1954, and especially in 1954, there are about 2 months of missing data from September to October. This period (1951 to 1954) is earlier than the earliest year of data at any other climate stations in Guam and thus there is no way to fill in these massive missing data with the data recorded at an adjacent station. Therefore, the starting year for the long term rainfall data is 1955. Fifty four (54) years from 1955 to 2008 of long term rainfall data were composed for all these 9 stations. The methodology of "composition" of long term rainfall data is simply filling in the missing data or no-data using the data recorded at the closest adjacent stations without any manipulation of or changes in the observation data to avoid introducing unnecessary errors of treatment to the data. If a station has no record of data in a specific period, the station is said to have "missing data." But if the station simply does not have record of data earlier than certain time (before station installation) or after certain time (after the station stops functioning), the station is said to have "no-data."

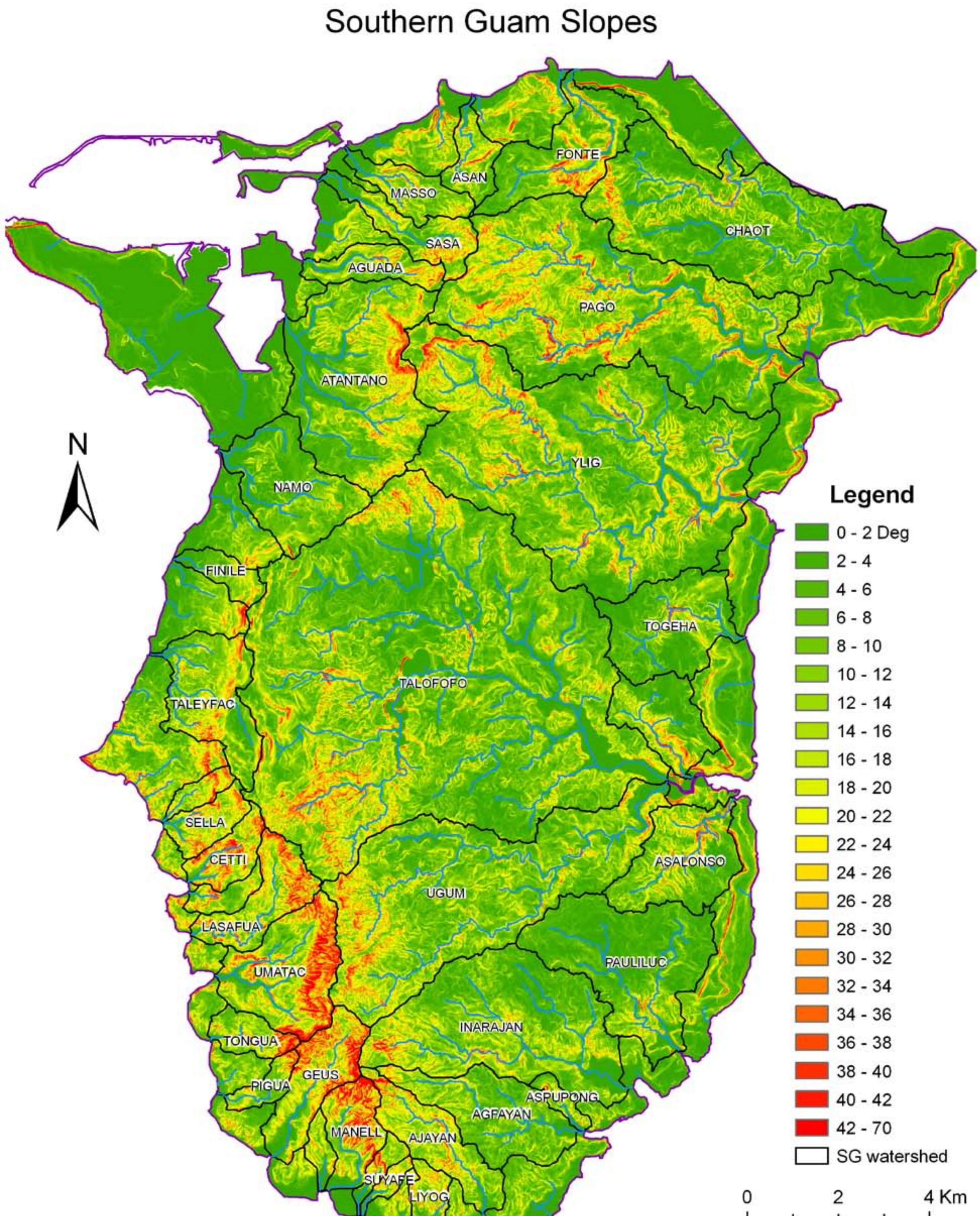

Figure 36. Southern Guam slopes as a criterion for selection of calibrated models

Table 9. Climate stations for composition of long term rainfall time series

No.	Station Name	ID	Source	Data *						Years of Data	Remark
				FROM	TO	FROM	TO	FROM	TO		
1	Almagosa	132105144405166	USGS	6/24/1992	9/30/1998	11/29/1999	8/13/2009			15	
2	Fena Filter Plant	132310144405766	USGS	5/1/1951	12/31/1983					32	Missing data
3	Fena Pump Station	132132144422366	USGS	10/6/1993	10/6/2009					16	Missing data
5	Mt. Chachao near Piti	132617144423366	USGS	10/6/1988	3/4/2009					20	Missing data
7	Umatac	131729144393766	USGS	10/1/1988	10/14/2009					20	Missing data
8	Windward Hills Talofofo	132234144441966	USGS	2/1/1974	12/31/1983	10/1/1988	8/22/2004	2/28/2008	11/17/2009	27	Missing data
9	Fena Lake		NCDC	1/1/1980	12/31/2007					28	Missing data
10	Inarajan-NASA		NCDC	1/1/1979	12/31/2007					29	Missing data
11	Piti		NCDC	1/1/1978	12/31/2007					30	Missing data

5.4 Long term simulation

Long term simulation (54 years) was carried out in all the 12 watersheds listed in Table 8 using the selected calibrated models with the long term input rainfall data described in the above section. The basic computation time step was 1 hour, which was reduced to several seconds automatically if a rainfall event occured to guarantee numerical convergence and higher output accuracy as related in Chapter 4. The long term simulation was time consuming and the computing time depends on the watershed area. Using a personal computer of 2.50-GHz CPU clock, the computation time range from 2 days (such as Sella watershed) to 20 days (such as Ugum watershed). The model outputted hourly and daily streamflows at two locations, the location of the USGS streamflow gage if there is one or a typical location a distance upstream the watershed outlet if there is no USGS streamflow gage, and the watershed outlet, but only daily outputs were used in this project because most original input rainfall data are daily data and the model was also calibrated on a base of a daily time step.

5.5 Output time series of long term streamflow

The output time series of long term streamflow for the watersheds without a streamflow gage are the same as the model output, which has 54 years of data. There are 5 such watersheds, which are Asalonso, Agfayan (and Aspupong), Ajayan, Manell, and Sella. The output time series of long term streamflow for the other watersheds in which there is a flow gage are different from the model output. There are 7 such watersheds, which are Ugum, Pauliluc (including Tinago), Inarajan, Umatac, Lasafua, Cetti, and Geus. In the latter case, in which streamflow gages were installed in the watersheds, the model outputs were used to fill in the missing data and/or “no-data.” This means that the observation data collected at the streamflow stations are the parts of the output time series in the same periods when observation data were collected, while the model output are the rest parts of the output time series of treamflow when observation data are not available. Figure 37 shows parts of the output time series in a text file for Ugum watershed.

```
UGUM_OUT_1953_2008.txt - Notepad
File  Edit  Format  View  Help
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!! WARNING !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
! The data you have obtained from this project, which was conducted at WERI,  !
! UOG and funded by USGS, are released on the condition that none of WERI,    !
! UOG or USGS may be held liable for any damages resulting from its use.      !
!.............................................................................!
! Q_STN: flow discharge at location of the USGS gage: UGUM ABOVE TALOFOFO.    !
! Q_OTL: flow discharge at the watershed outlet. When there are observed data !
! (SOURCE=USGS) Q_OTL=C*Q_STN, in which C=Q_OTL_simulated/Q_STN_simulated.    !
! SOURCE of USGS/LUOM: When there are observation data by USGS, the flow data !
! is from USGS, otherwise from simulation results using the LUOM (Luo, 2007). !
! Unit for flow discharge Q_STN and Q_OTL is: m3/s (cubic meter per second).  !
!.............................................................................!
!      WATERSHED: UGUM; DATA FROM JANUARY 1, 1953 TO DECEMBER 31, 2008        !
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

YYYY/MM/DD   Q_STN    Q_OTL  SOURCE
1953/01/01    .566     .877    USGS
1953/01/02    .439     .680    USGS
1953/01/03    .420     .651    USGS
1953/01/04    .384     .595    USGS
1953/01/05    .439     .680    USGS
1953/01/06    .402     .623    USGS
1953/01/07    .365     .566    USGS
1953/01/08    .347     .538    USGS
1953/01/09    .347     .538    USGS
1953/01/10    .329     .510    USGS
1953/01/11    .311     .482    USGS

1970/12/10    .430     .650    LUOM
1970/12/11    .650    1.010    LUOM
1970/12/12   1.050    1.640    LUOM
1970/12/13   1.240    1.940    LUOM
1970/12/14   1.940    2.950    LUOM
1970/12/15   1.740    2.790    LUOM
1970/12/16    .900    1.460    LUOM
1970/12/17    .610     .980    LUOM
1970/12/18    .840    1.260    LUOM
1970/12/19   1.150    1.860    LUOM
1970/12/20    .620    1.000    LUOM
1970/12/21    .400     .640    LUOM
1970/12/22    .290     .470    LUOM
1970/12/23    .240     .380    LUOM
```

Figure 37. Parts of the output file of long term time series of streamflow for Ugum watershed

In the output file, the title block explains the condition of use of this file, meanings of the symbols (locations of streamflow gages), unit (m^3/s – cubic meter per second), name of the watershed, and the period of data. In the data block, the first column is time (four digits of year, two digits of month and two digits of day), the second column is the streamflow at the location of the USGS gage if there is one, or at the location described in the title block if there is no USGS gage in the watershed, the third column is the streamflow at the watershed outlet or an location described in the title block if two smaller watersheds are simulated simultaneously, and the forth column is the data source, which is either "USGS" or "LUOM." Data source "USGS" means that the data are from observation data collected at a USGS streamflow gage installed at the same location, while data source "LUOM" means that the data are from the model output. For the watersheds without a USGS streamflow gage, the data source is always "LUOM." Table 10 summarizes the data characteristics of the output long term time series of streamflow.

Table 10. Data characteristics of output long term time series of streamflow

No.	Watershed	Area (km^2)	Calibrated	USGS Station	Data		
					From	To	Years
1	Ugum	19	Yes	2	1953	2008	56
2	Inarajan	12.55	Yes	1	1953	2008	56
3	Lasafua	3.15	Yes	1	1954	2008	55
4	Pauliluc (Tinago)	8.84	Yes	1	1953	2008	56
5	Umatac	5.54	Yes	1	1953	2008	56
6	Agfayan & Aspupong	5.72	No	0	1955	2008	54
7	Anjayan	3.51	No	0	1955	2008	54
8	Asalonso	4.83	No	0	1955	2008	54
9	Cetti	2.64	No	1	1955	2008	54
10	Geus	3.47	No	1	1954	2008	55
11	Manell	3.22	No	0	1955	2008	54
12	Sella	2.41	No	0	1955	2008	54

5.6 Summary

With the time scope of this project, the calibrated models have been applied to 12 southern Guam watersheds for long term simulation. Fifty four (54) years of rainfall data were composed based on rainfall data collected at the climate stations installed in southern Guam which have relative longer term of records (15 years or longer). Long term time series of streamflow were generated by combining the simulation results from the model output and observation streamflow data if available. The attached Appendix compiles the hydrographs for the latest 4 years of the output time series of streamflow for the watersheds in which observation data are not available, and comparisons of the measured and simulated hydrographs for the latest 4 years of the available observation streamflow data for the other watersheds in which observation data are available, in the sequence of Table 10.

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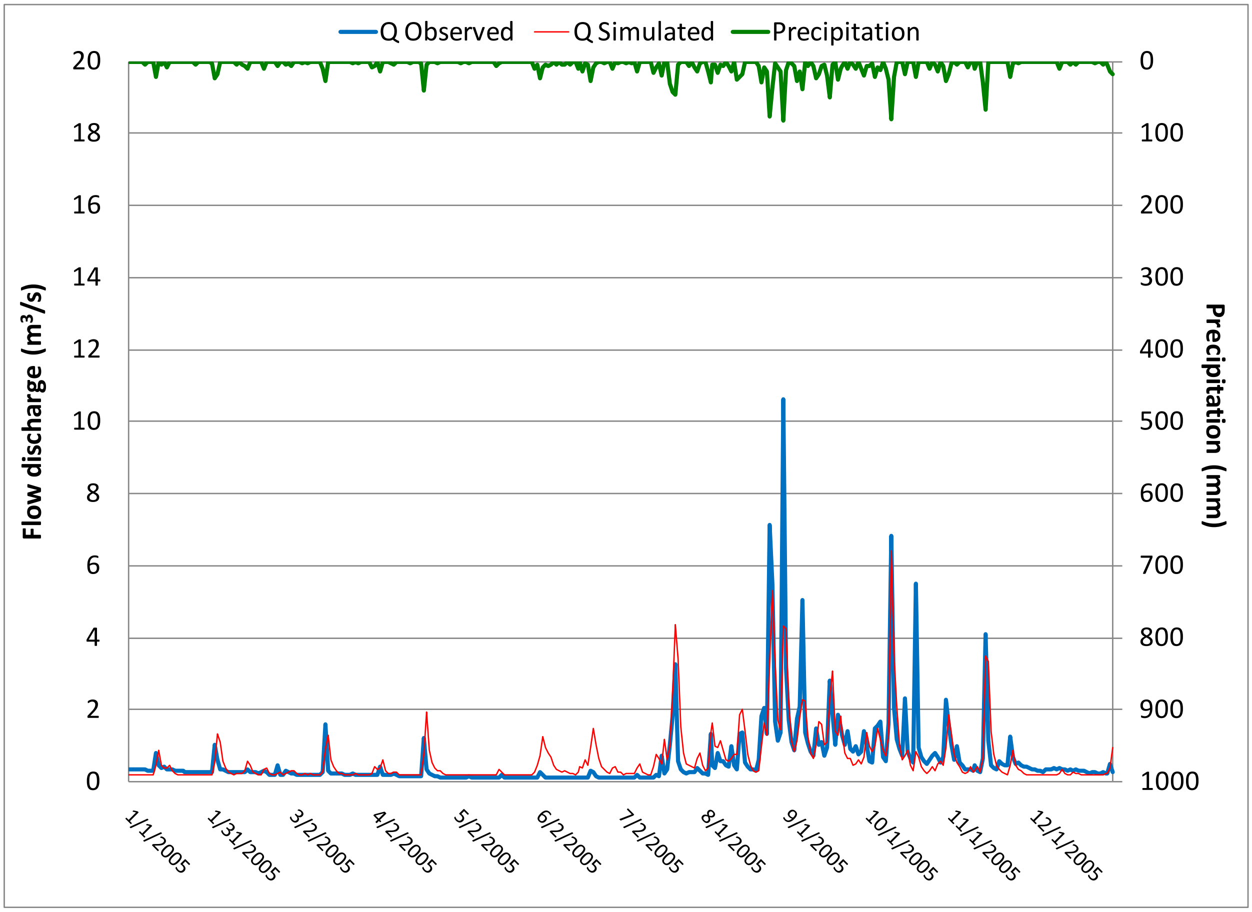
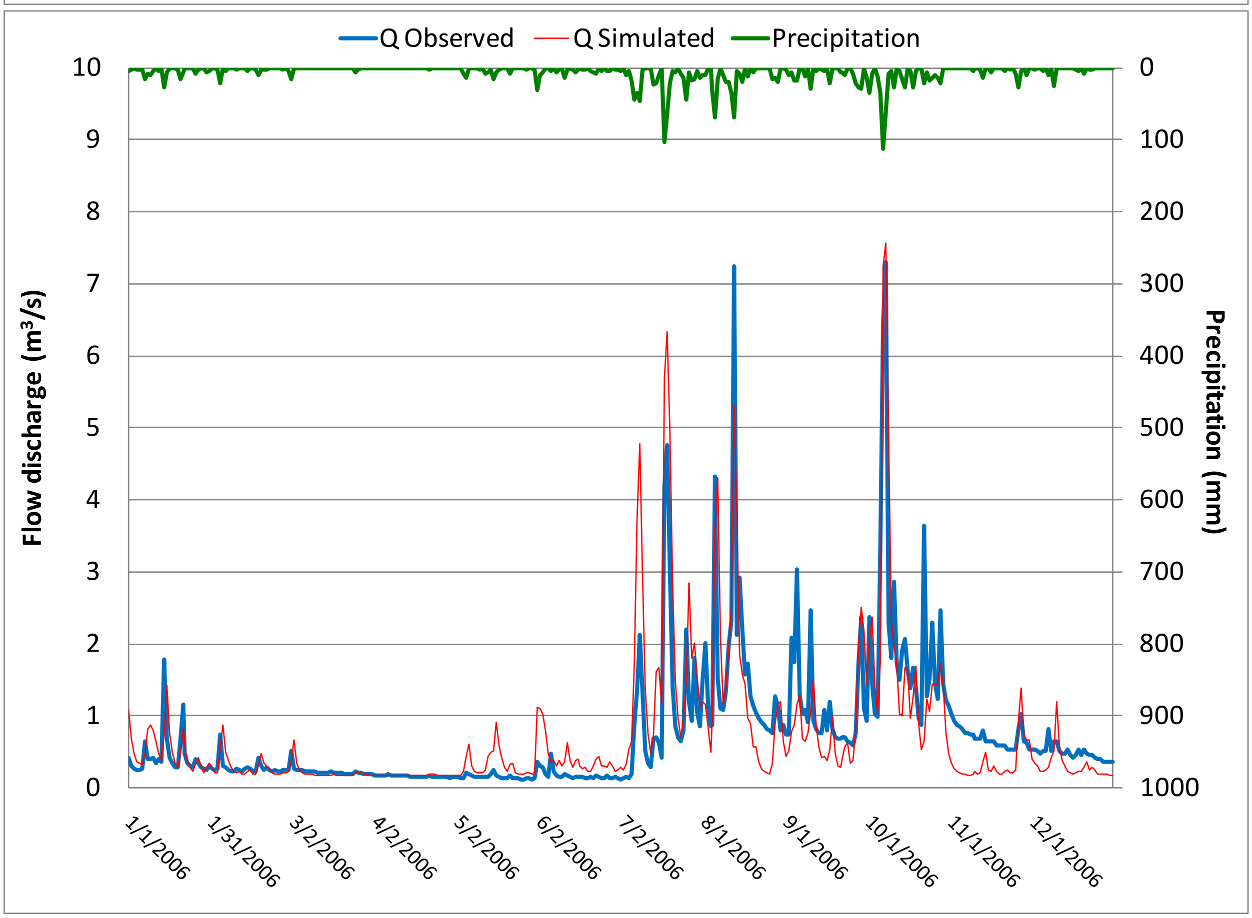
Appendix: Hydrographs and comparisons of hydrographs for the latest 4 years

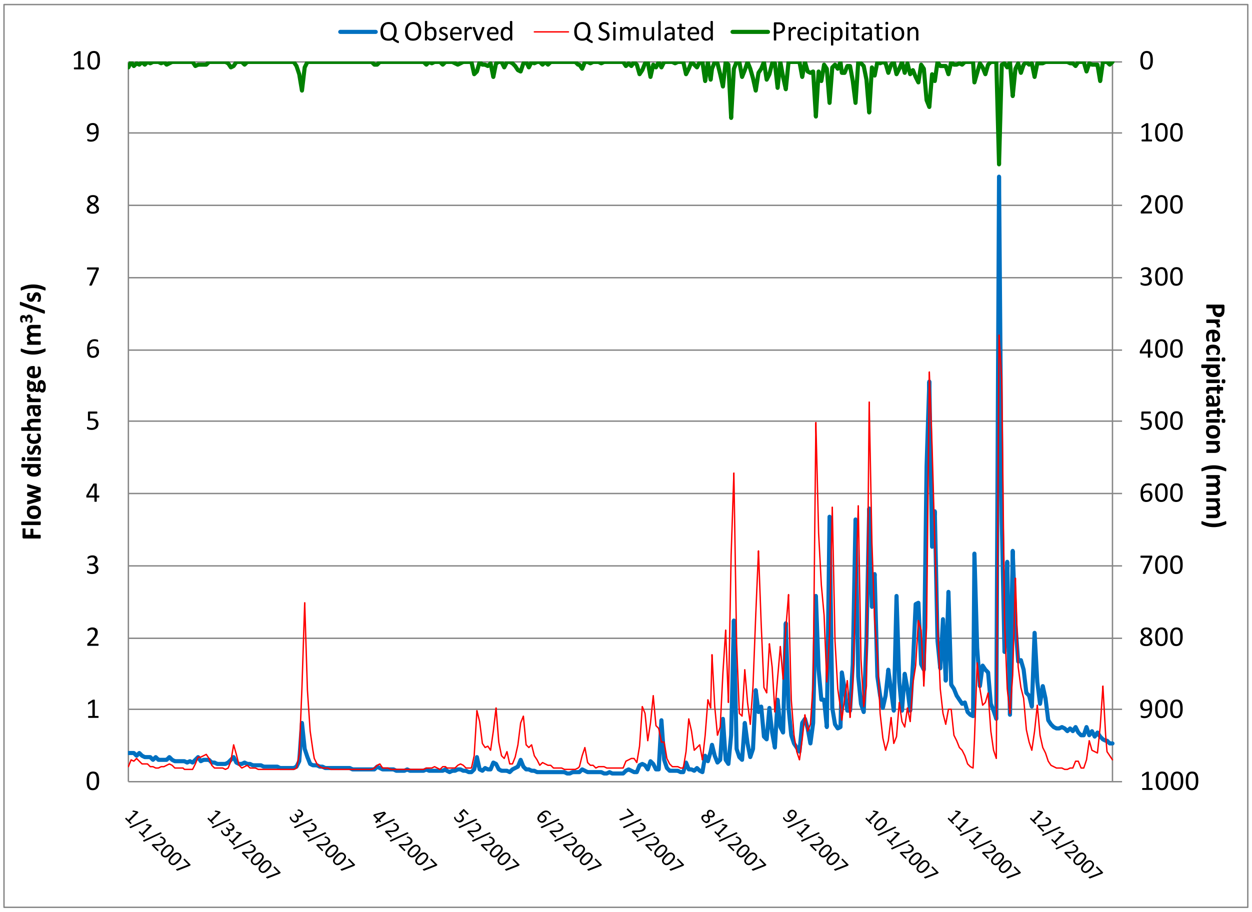
In this Appendix, the hydrographs for the latest 4 years of the output time series of streamflow for the watersheds in which observation data are not available (Agfayan, Anjayan, Asalonso, Manell and Sell), and comparisons of the measured and simulated hydrographs for the latest 4 years of the available observation streamflow data for the other watersheds in which observation data are available (Ugum, Inarajan, Lasafua, Pauliluc/Tinago, Umatac, Cetti, and Geus), are compiled in the sequence of Table 10, which is copied below.

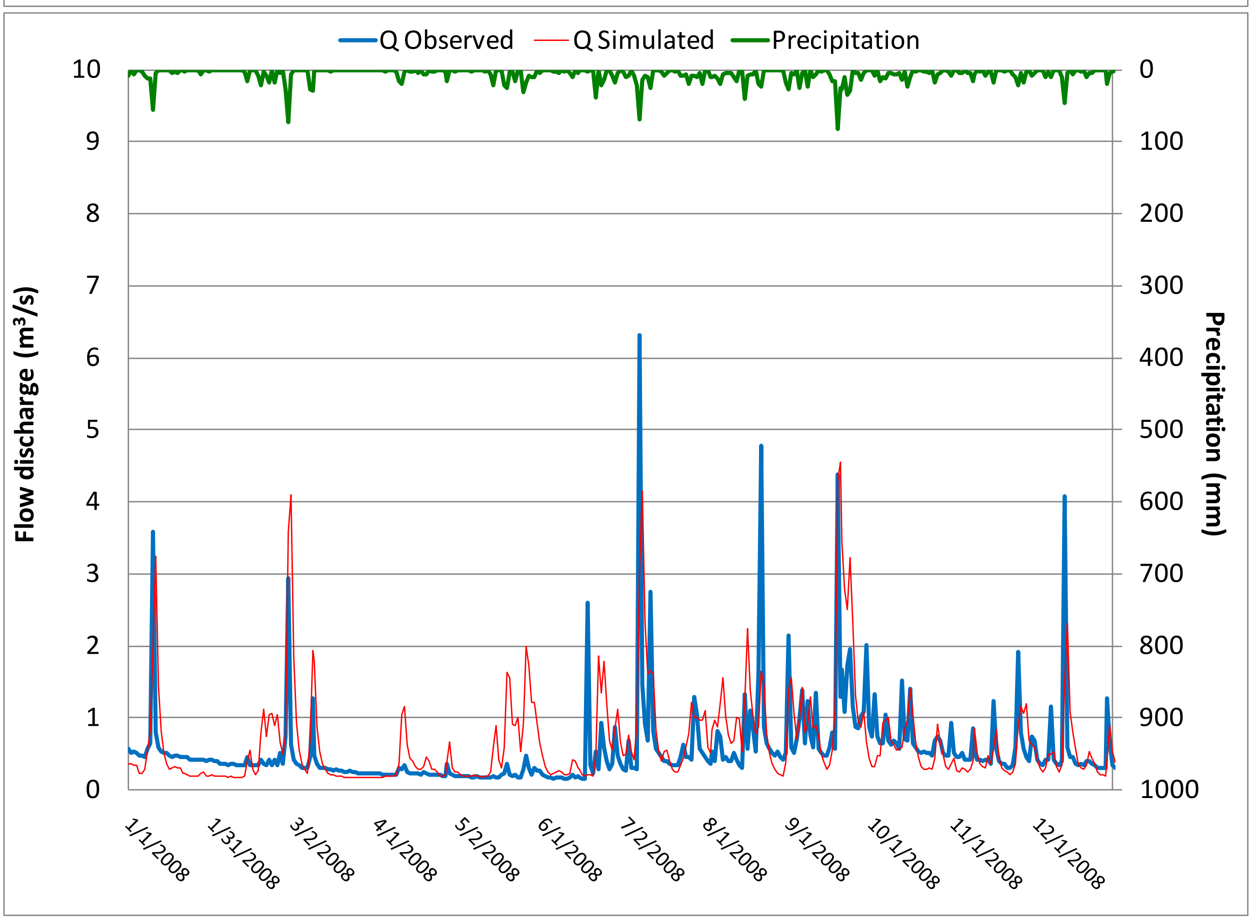
No.	Watershed	Area (km^2)	Calibrated	USGS Station	Data		
					From	To	Years
1	Ugum	19	Yes	2	1953	2008	56
2	Inarajan	12.55	Yes	1	1953	2008	56
3	Lasafua	3.15	Yes	1	1954	2008	55
4	Pauliluc (Tinago)	8.84	Yes	1	1953	2008	56
5	Umatac	5.54	Yes	1	1953	2008	56
6	Agfayan & Aspupong	5.72	No	0	1955	2008	54
7	Anjayan	3.51	No	0	1955	2008	54
8	Asalonso	4.83	No	0	1955	2008	54
9	Cetti	2.64	No	1	1955	2008	54
10	Geus	3.47	No	1	1954	2008	55
11	Manell	3.22	No	0	1955	2008	54
12	Sella	2.41	No	0	1955	2008	54



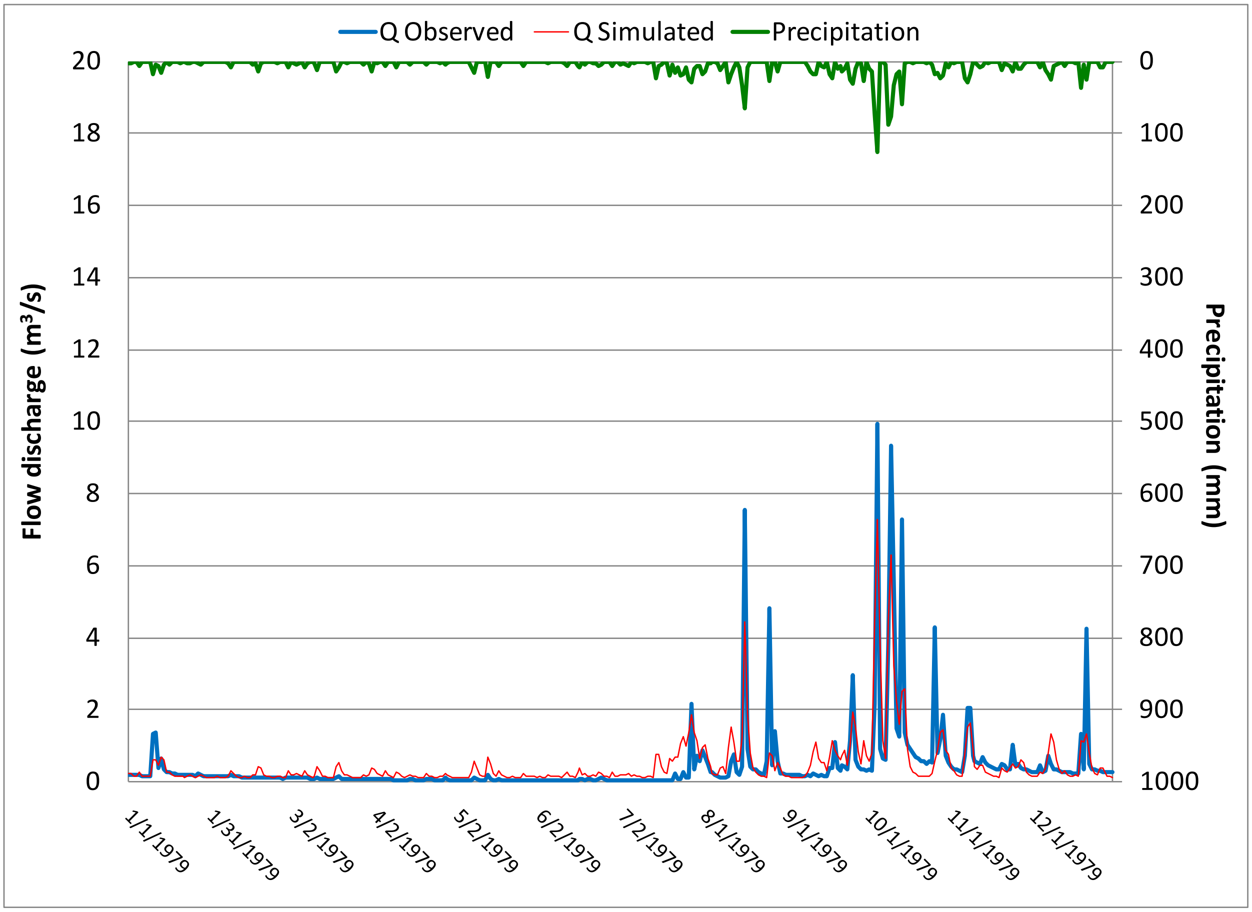


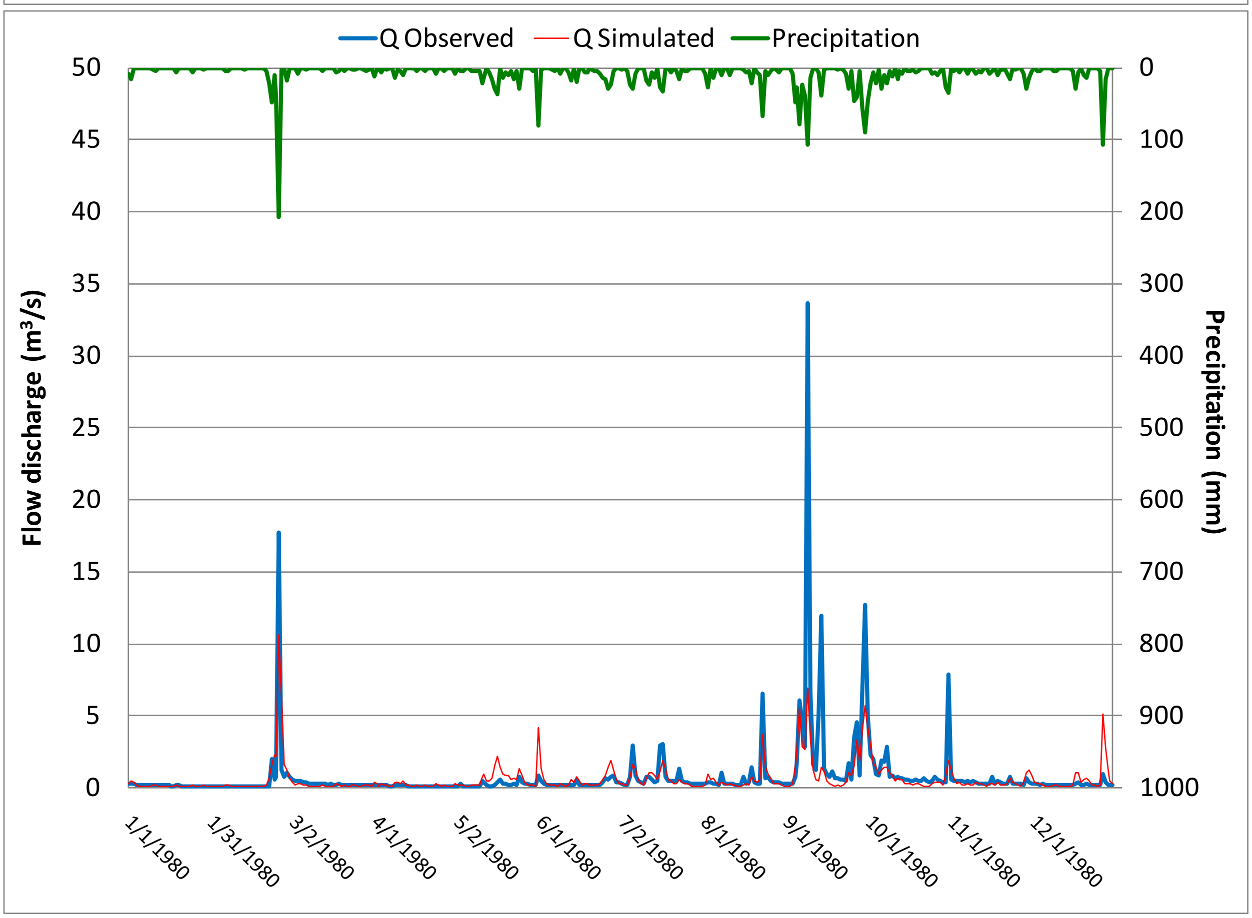
Ugum watershed (2005 and 2006)



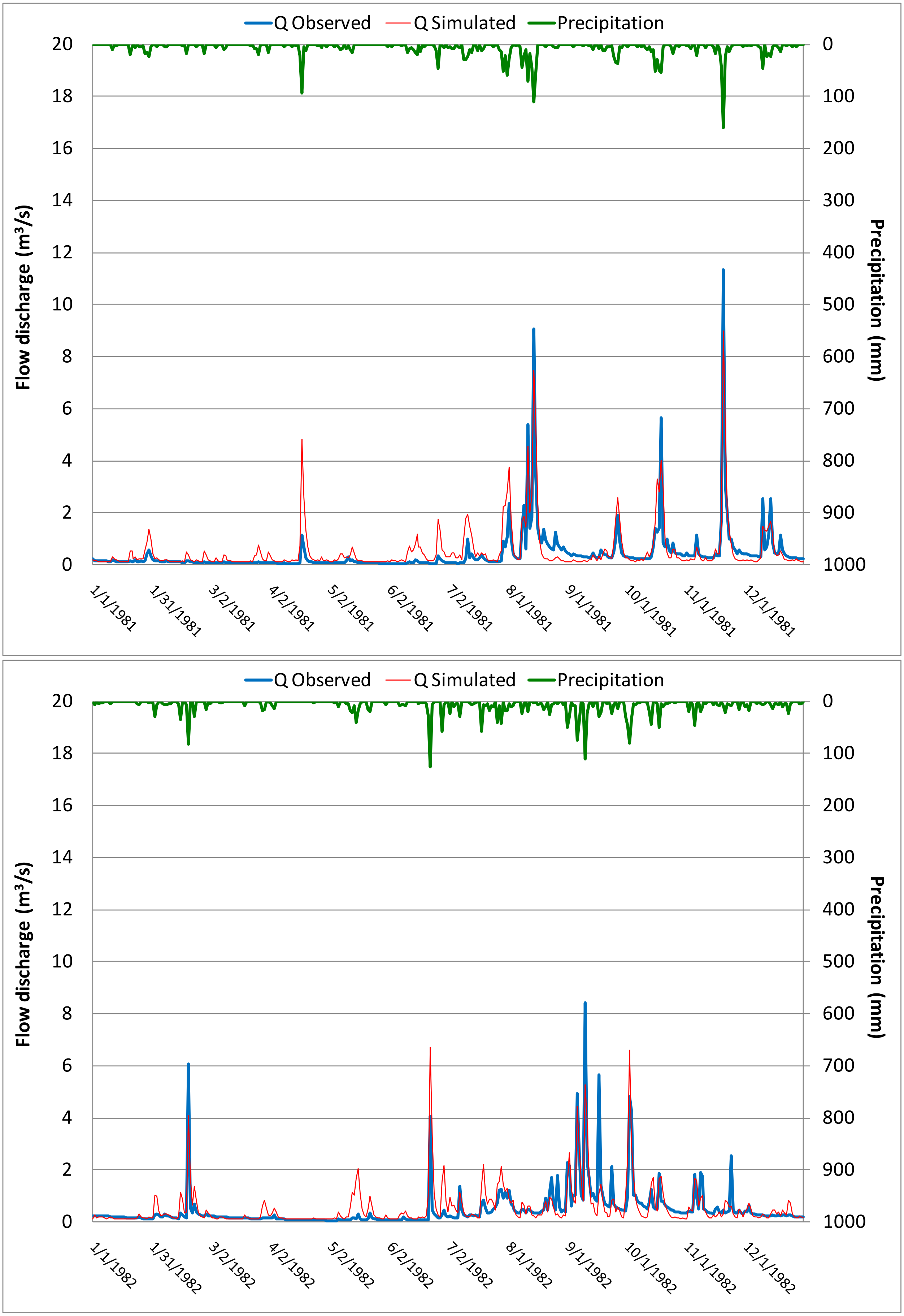


Ugum watershed (2007 and 2008)

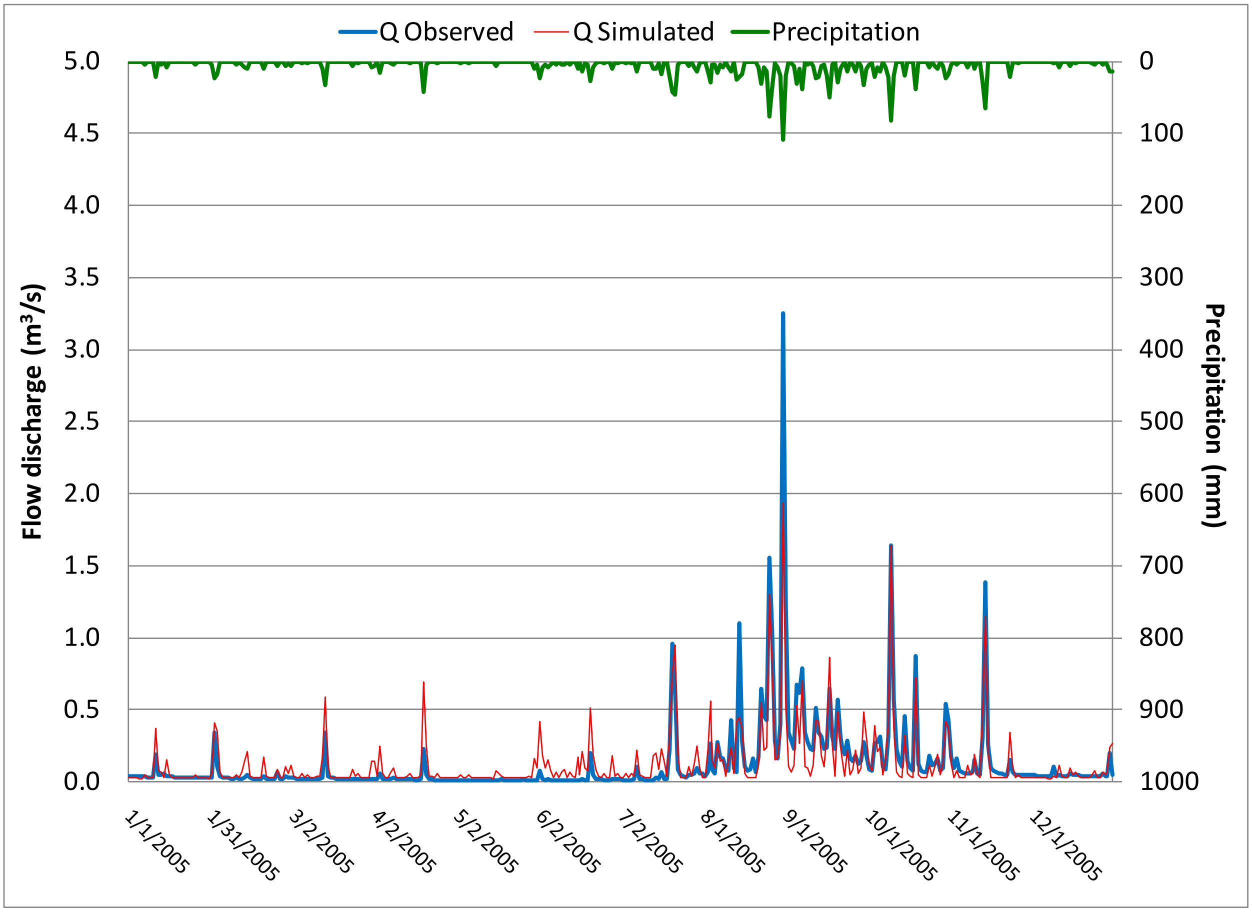


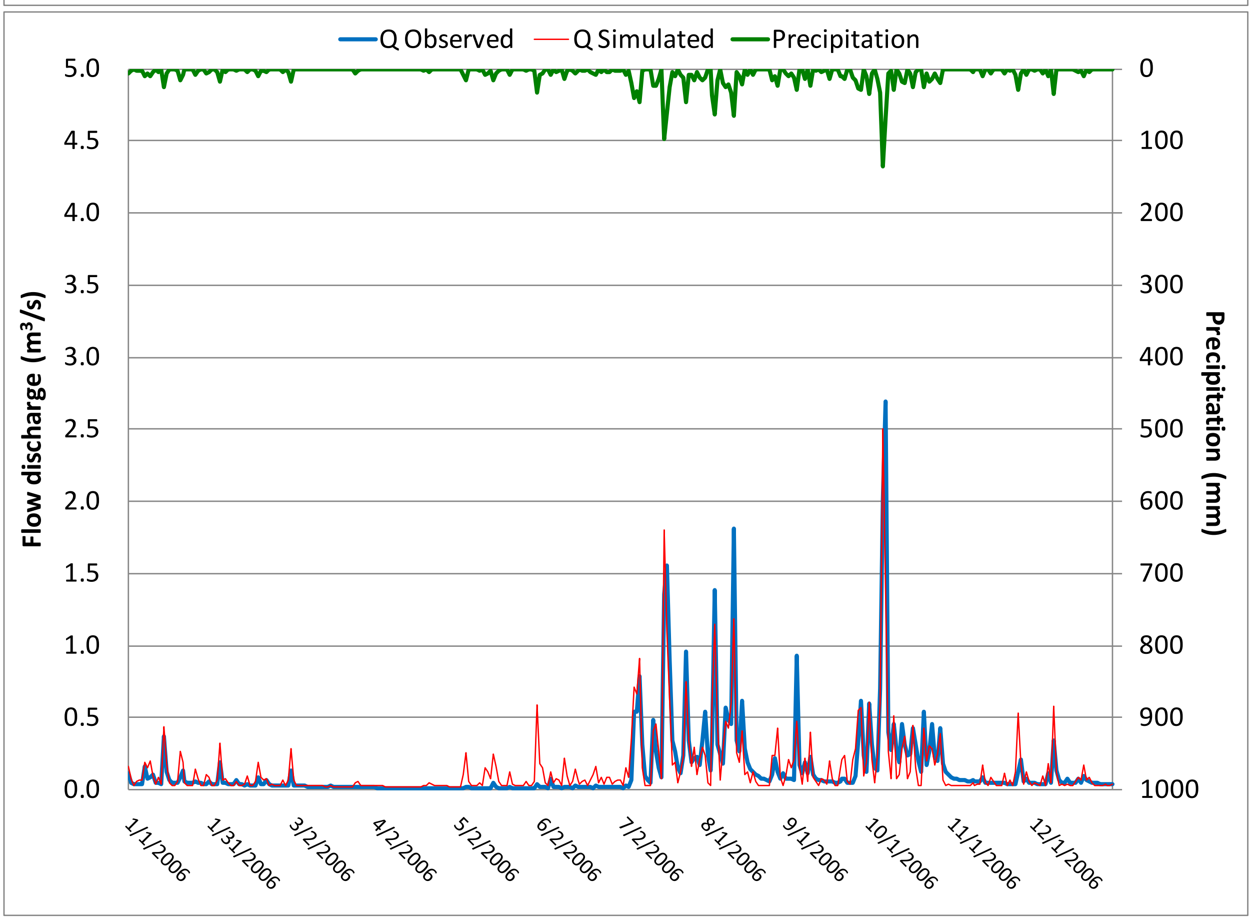


Inarajan watershed (1979 and 1980)

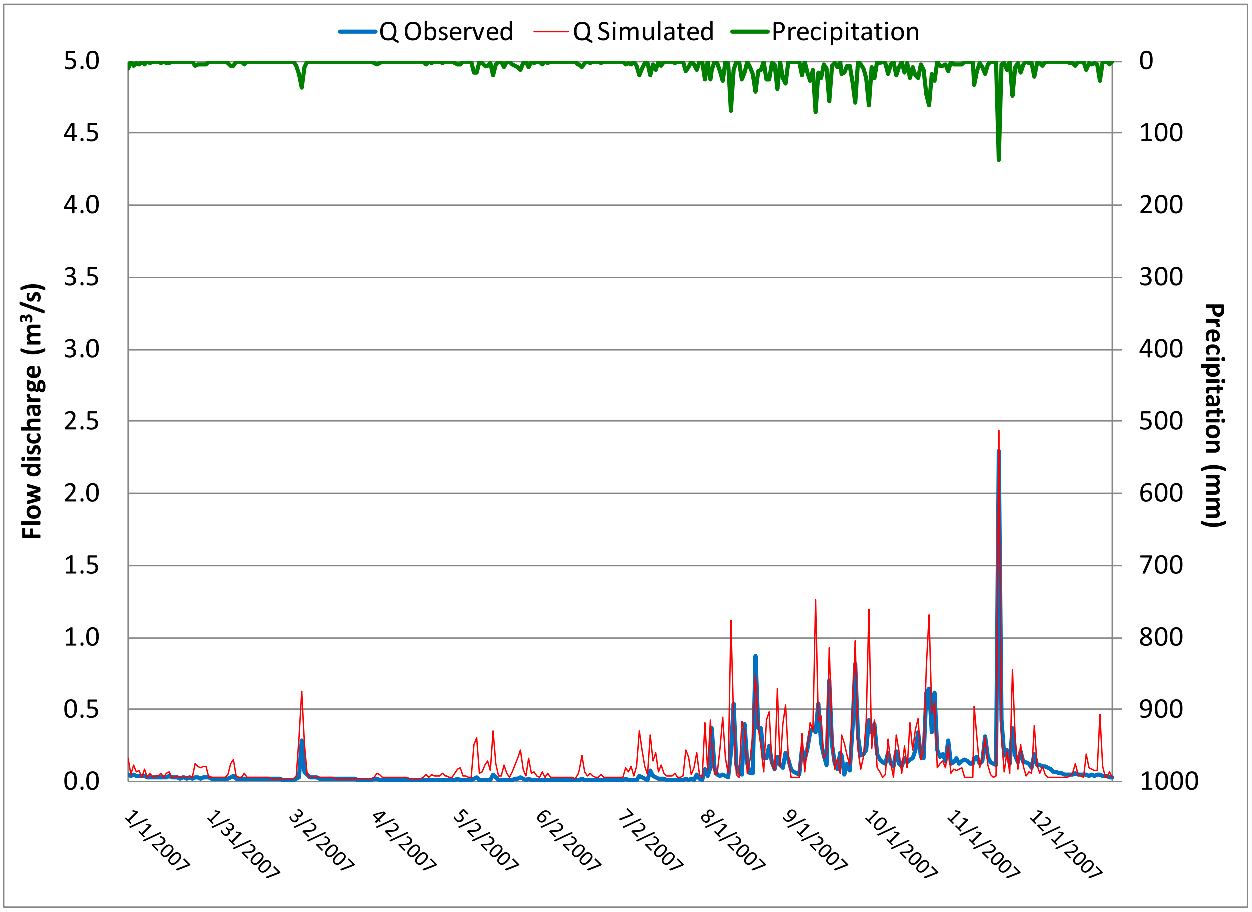


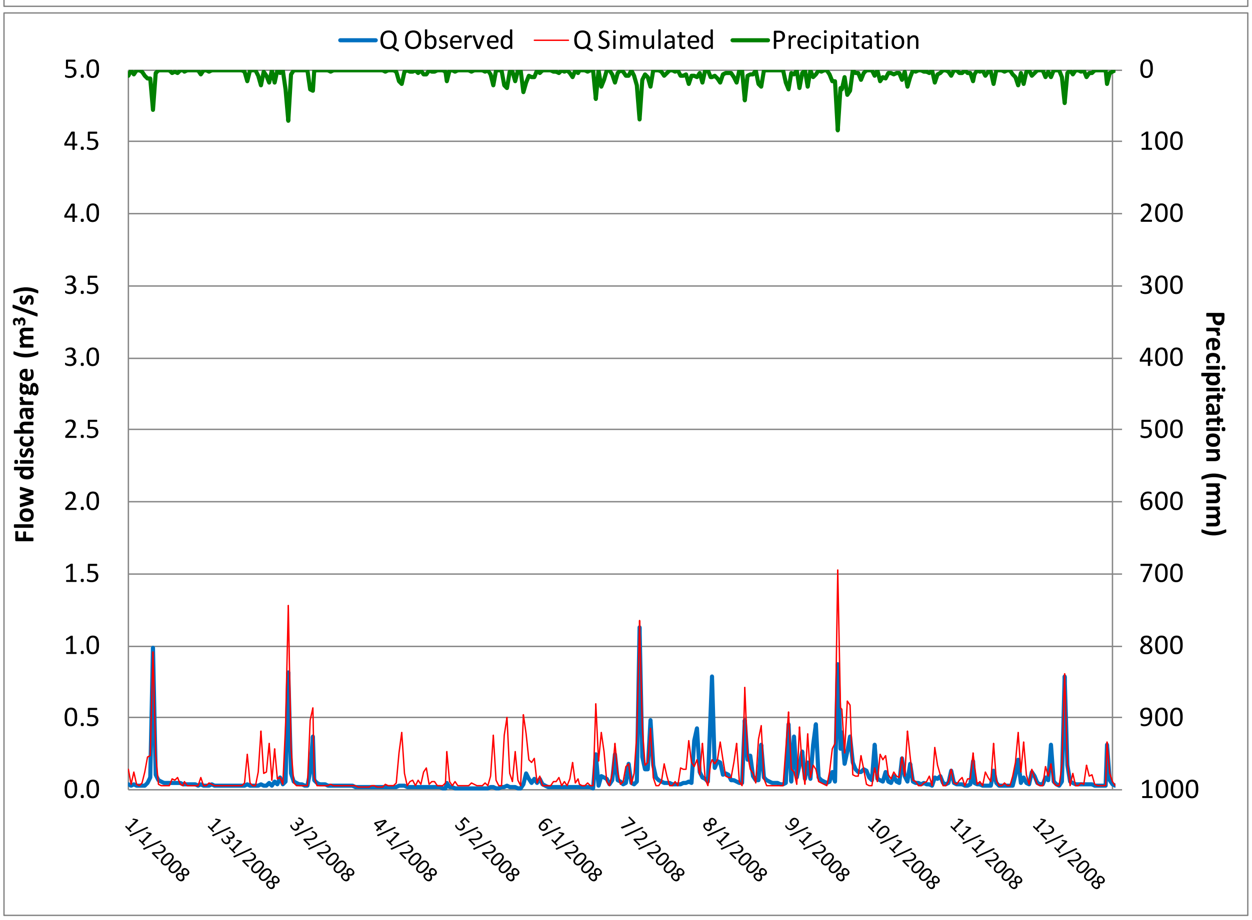
Inarajan watershed (1981 and 1982)



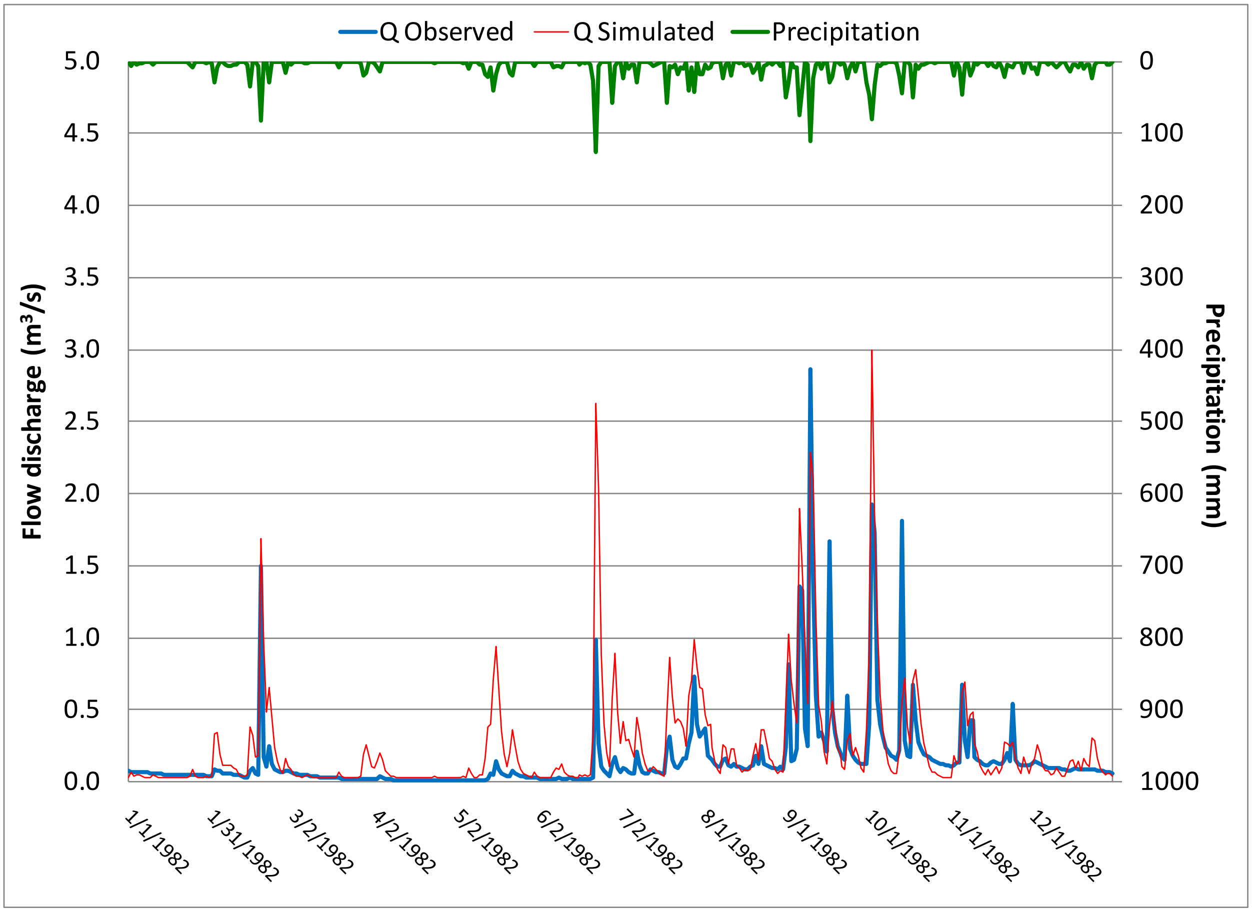


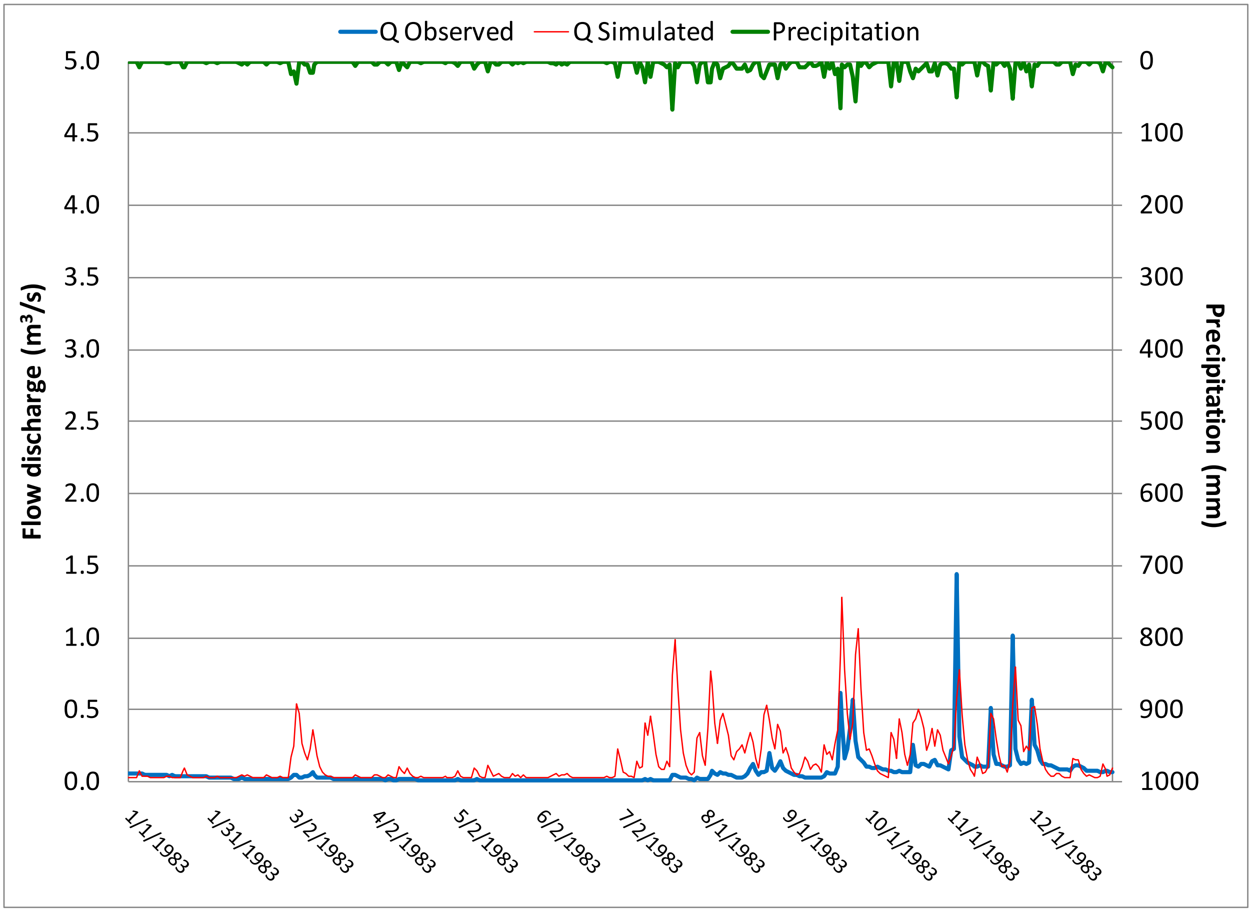
Lasafua watershed (2005 and 2006)



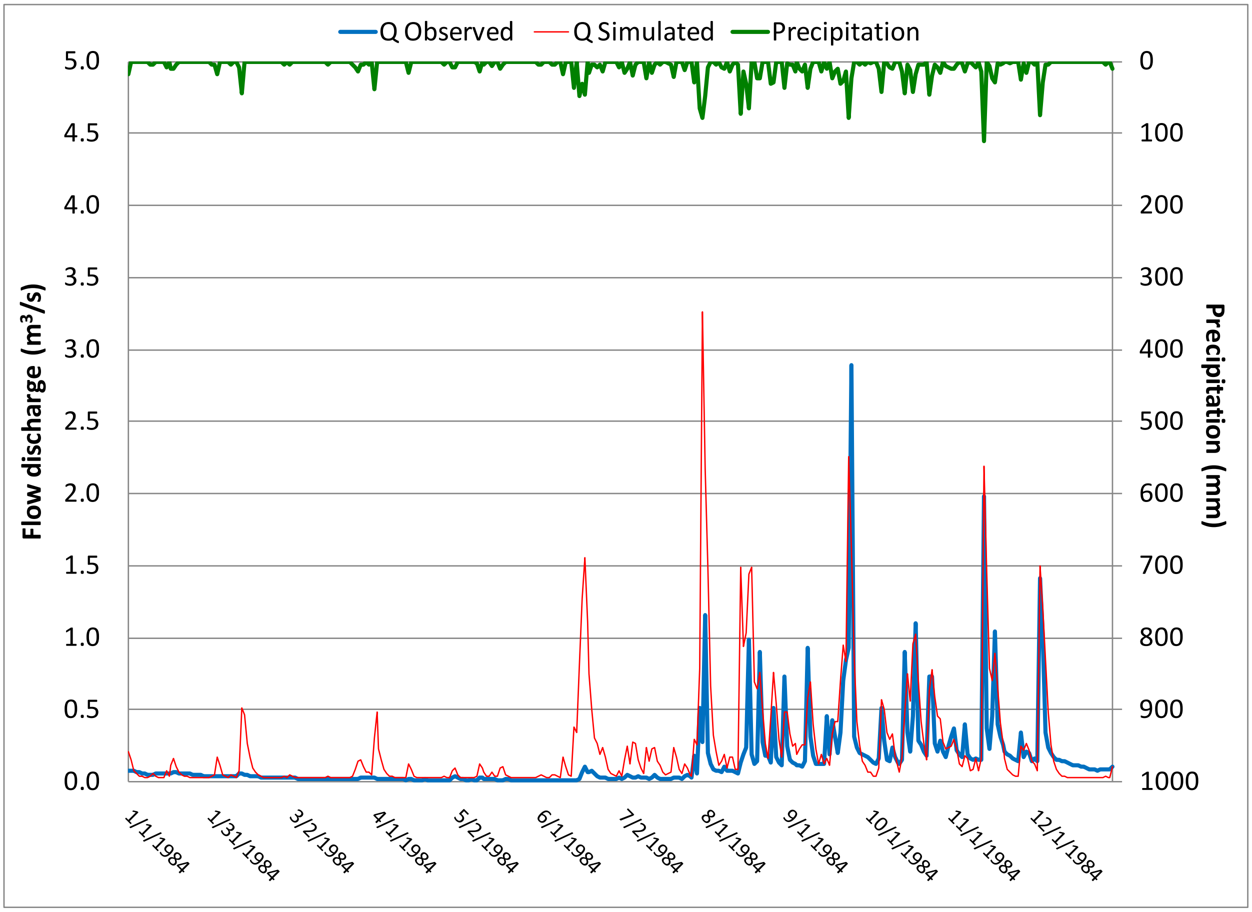


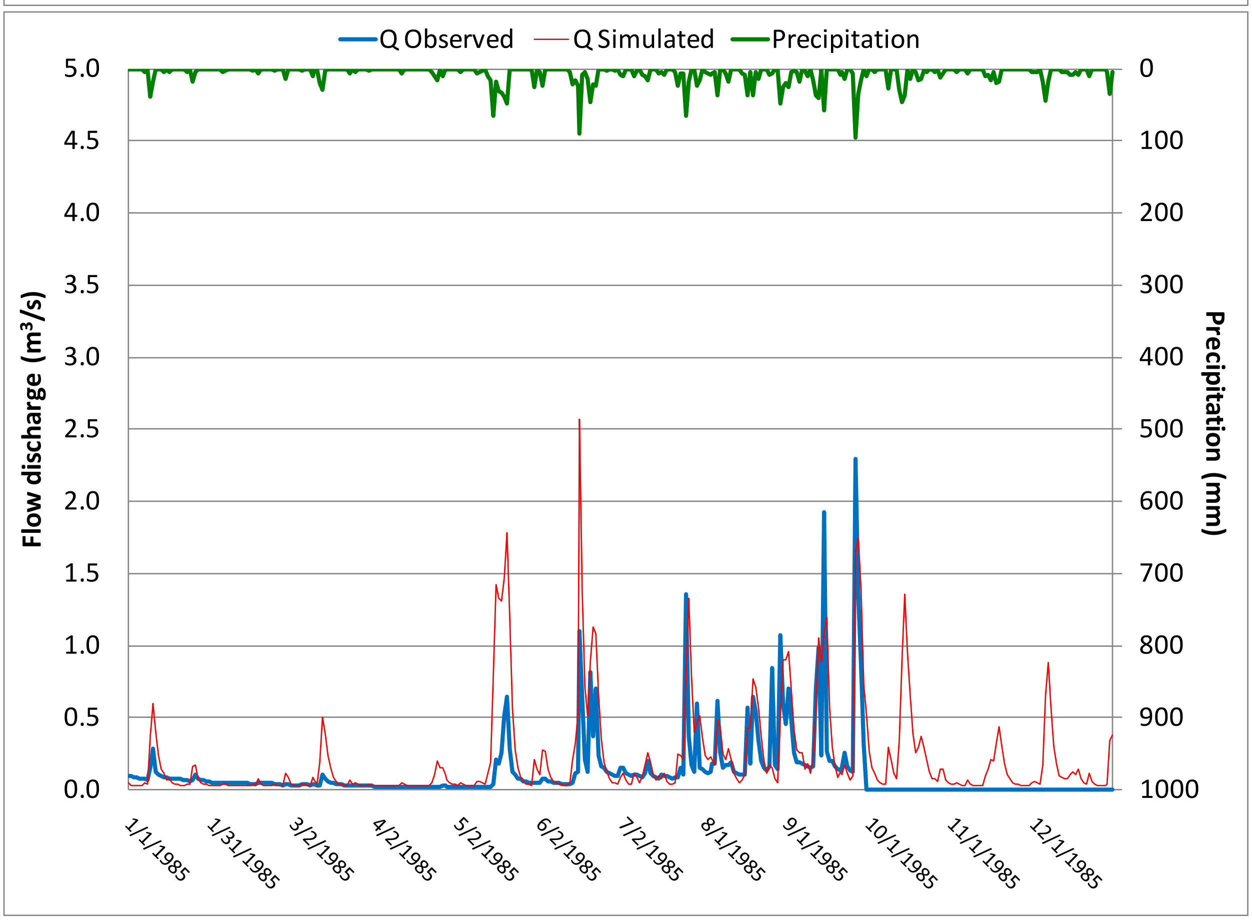
Lasafua watershed (2007 and 2008)



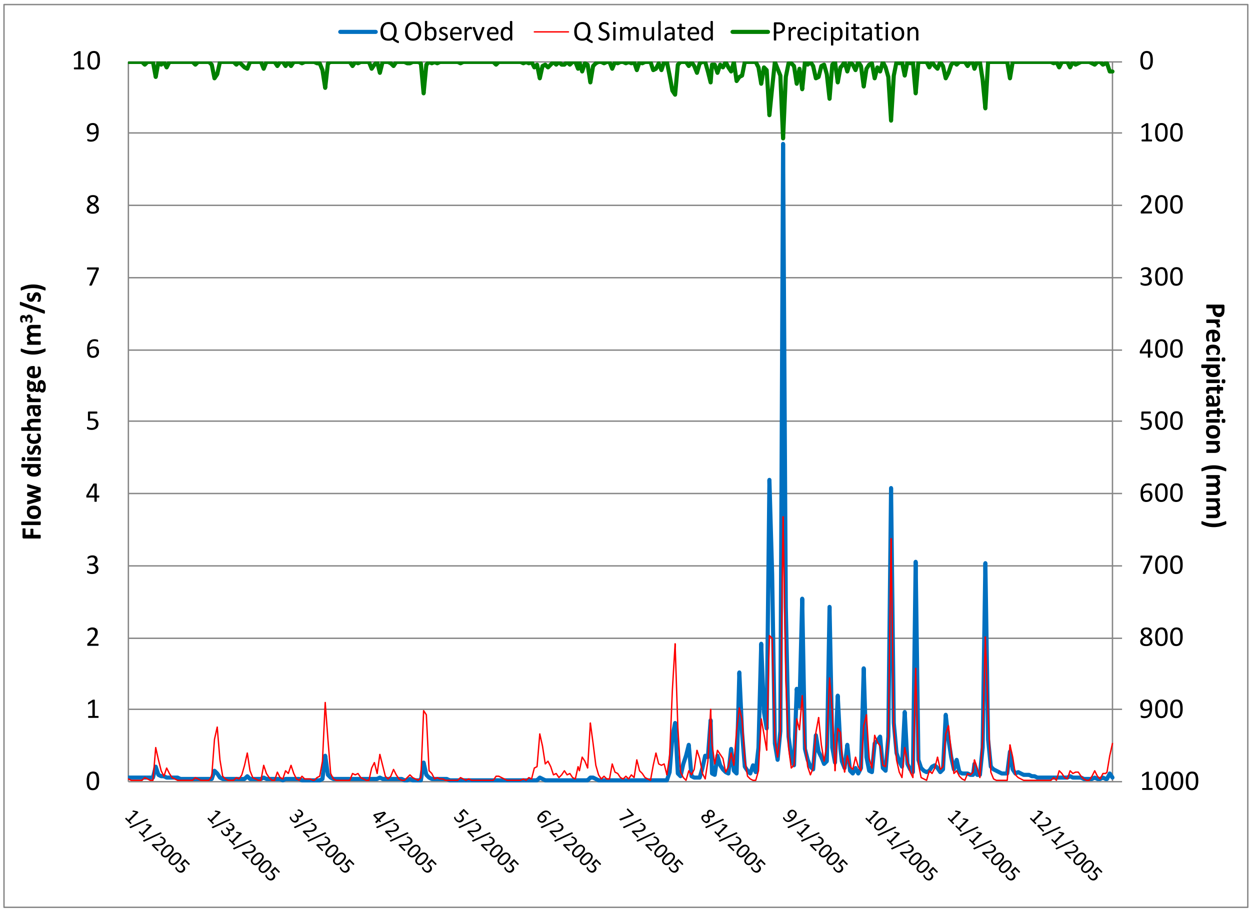


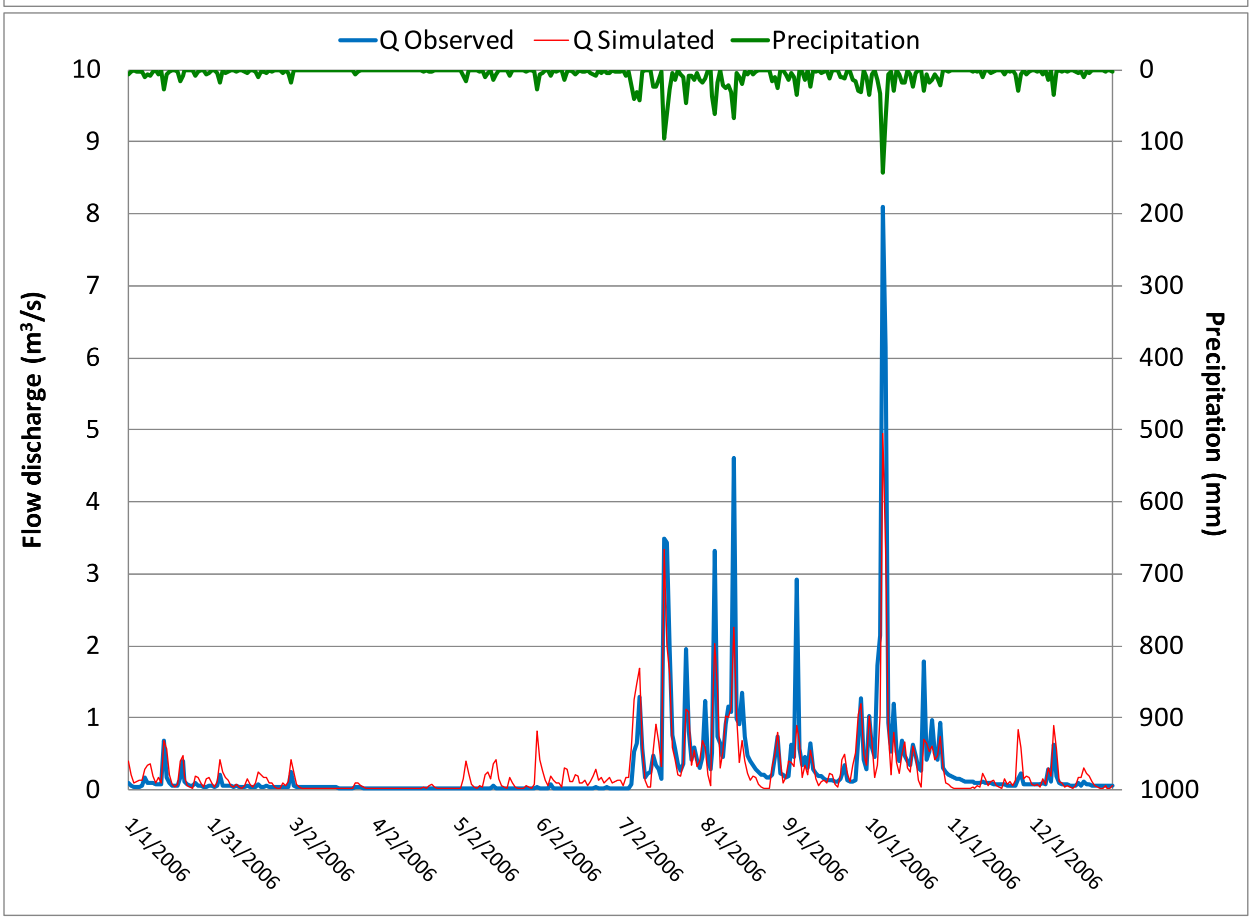
Pauliluc watershed (Tinago station) (1982 and 1983)



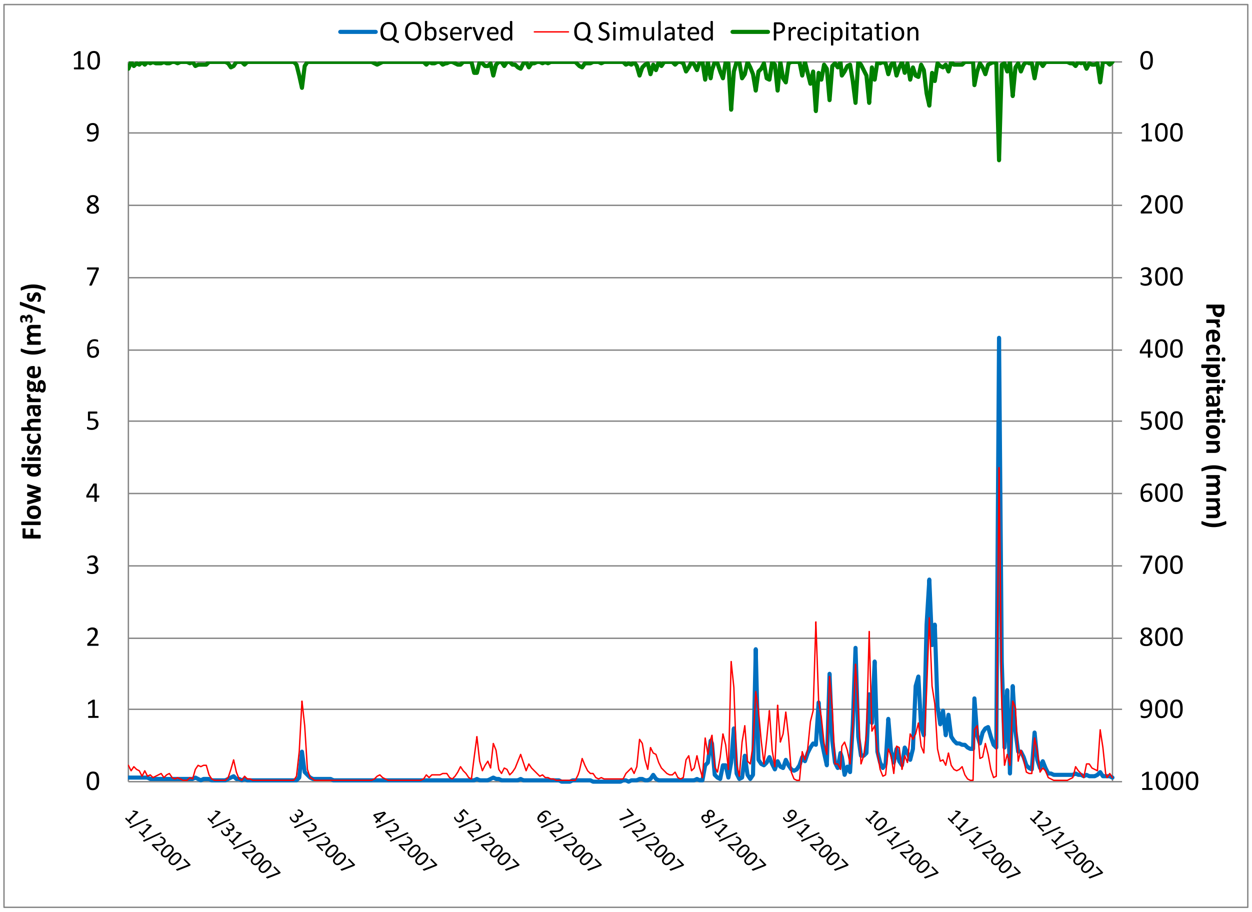


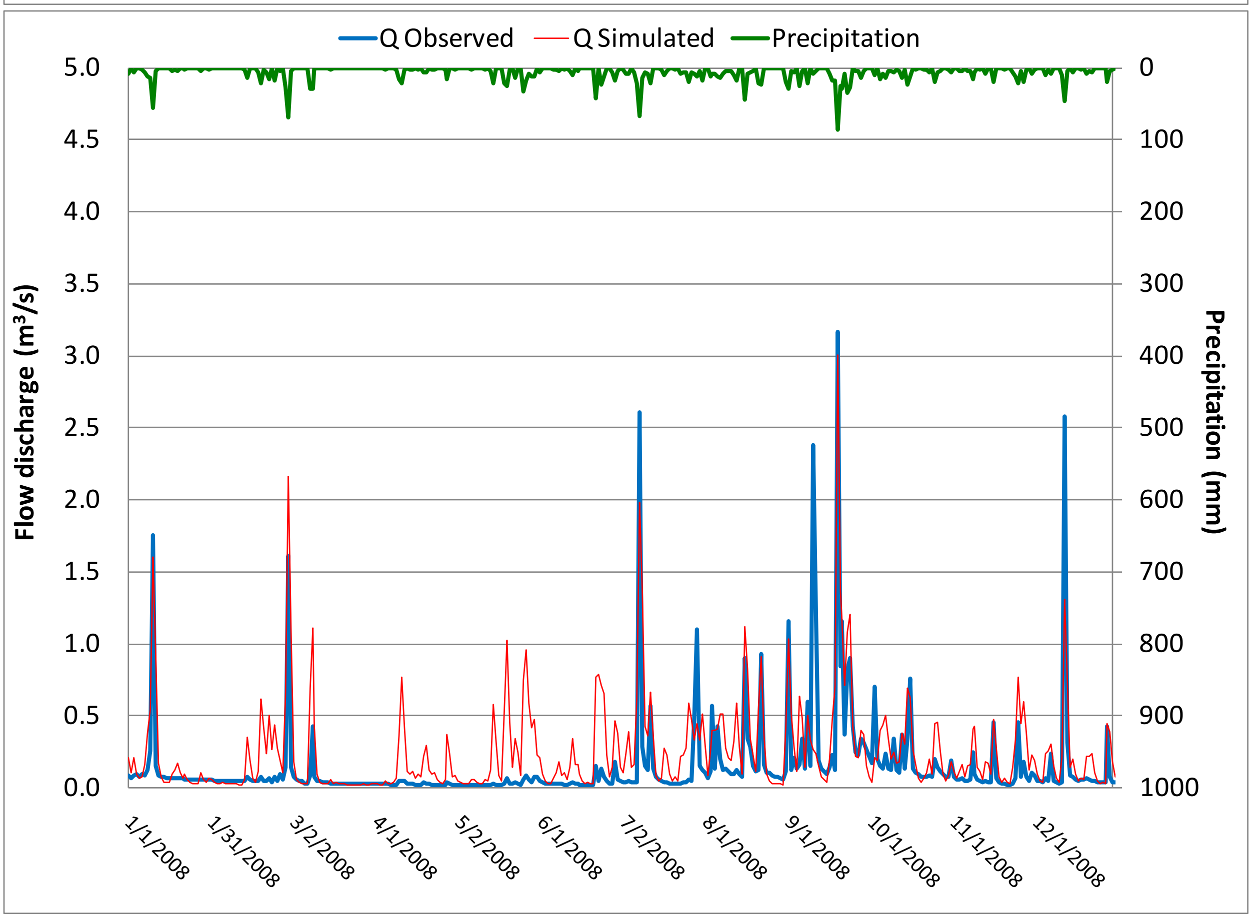
Pauliluc watershed (Tinago station) (1984 and 1985)



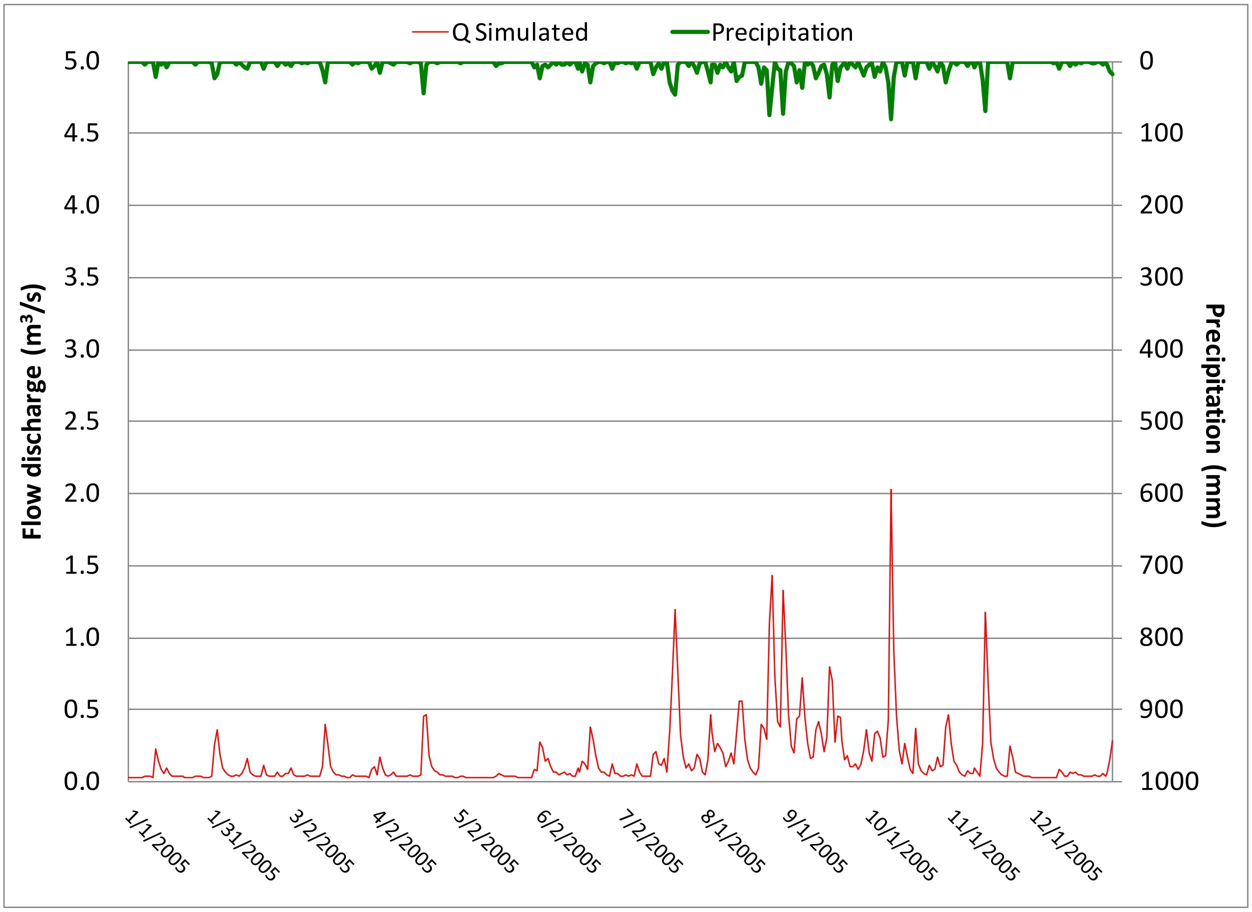


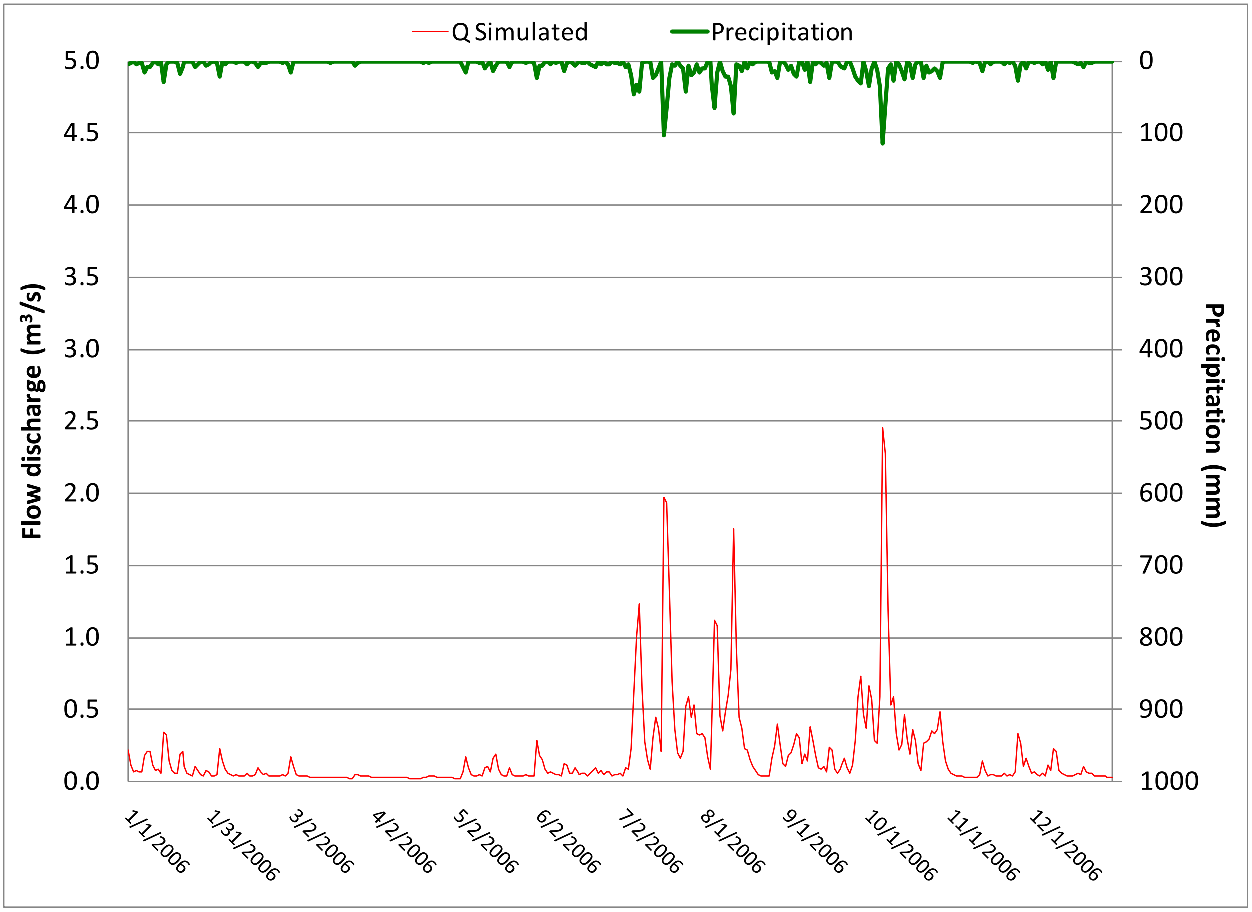
Umatac watershed (2005 and 2006)



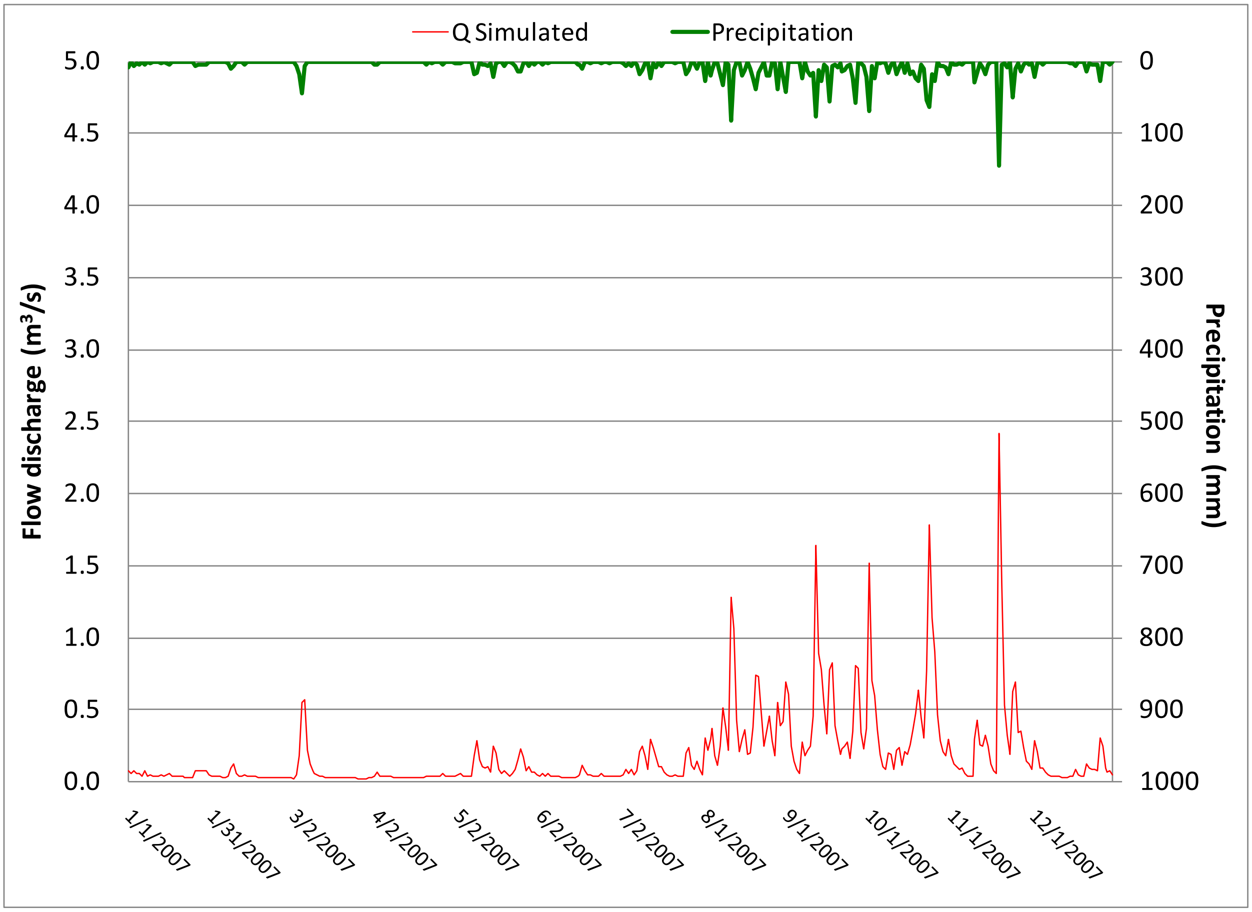


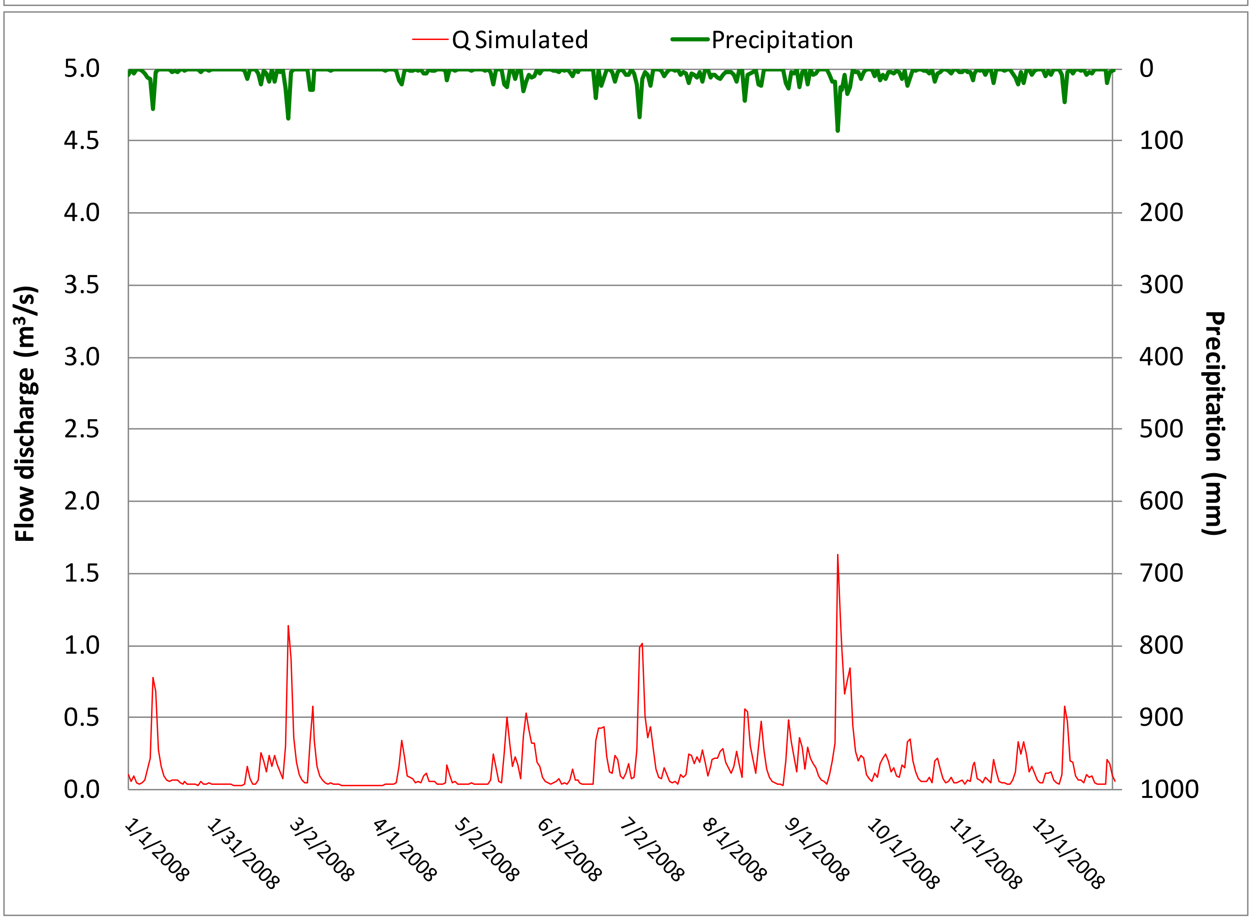
Umatac watershed (2007 and 2008)



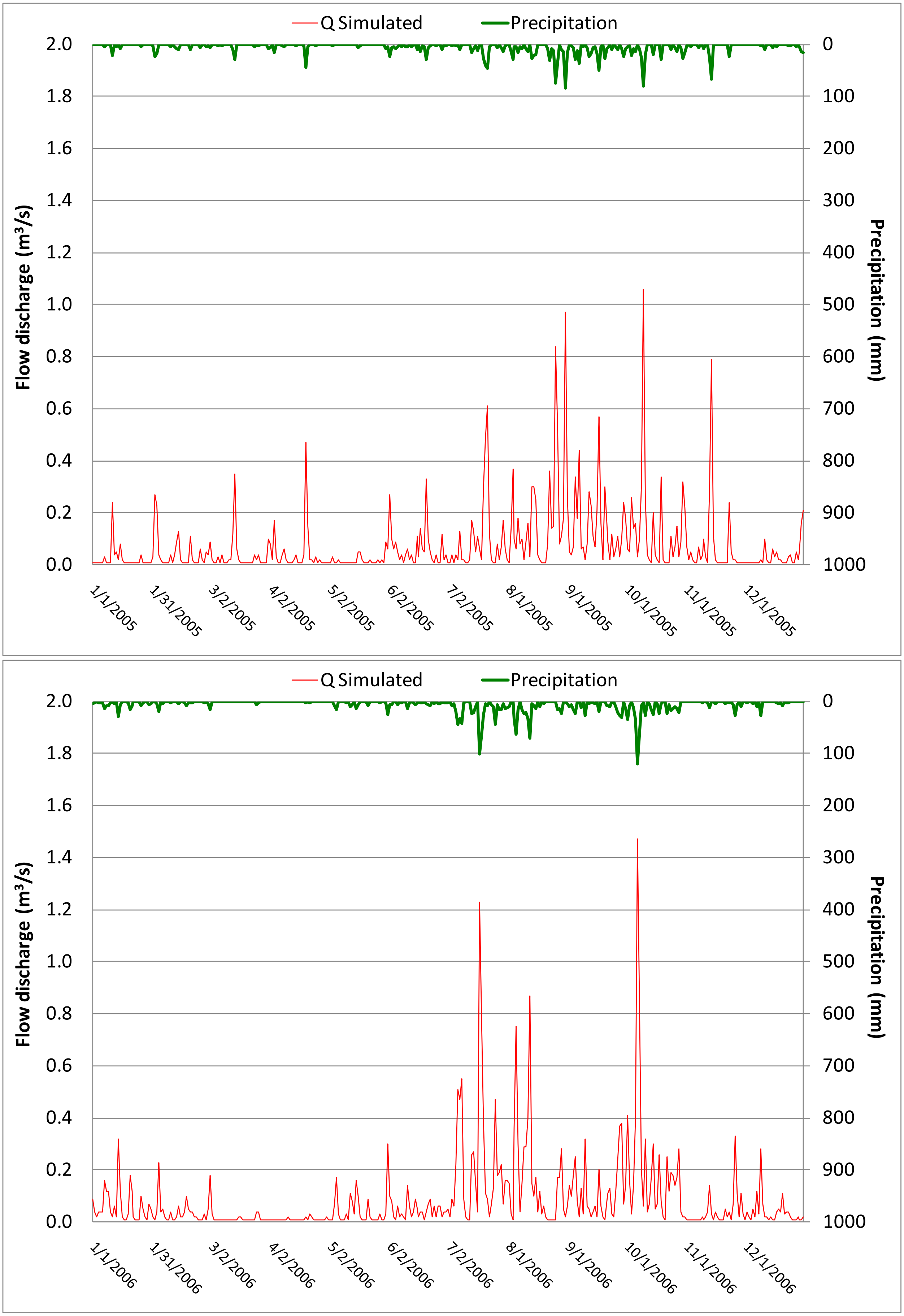


Agfayan watershed (2005 and 2006)

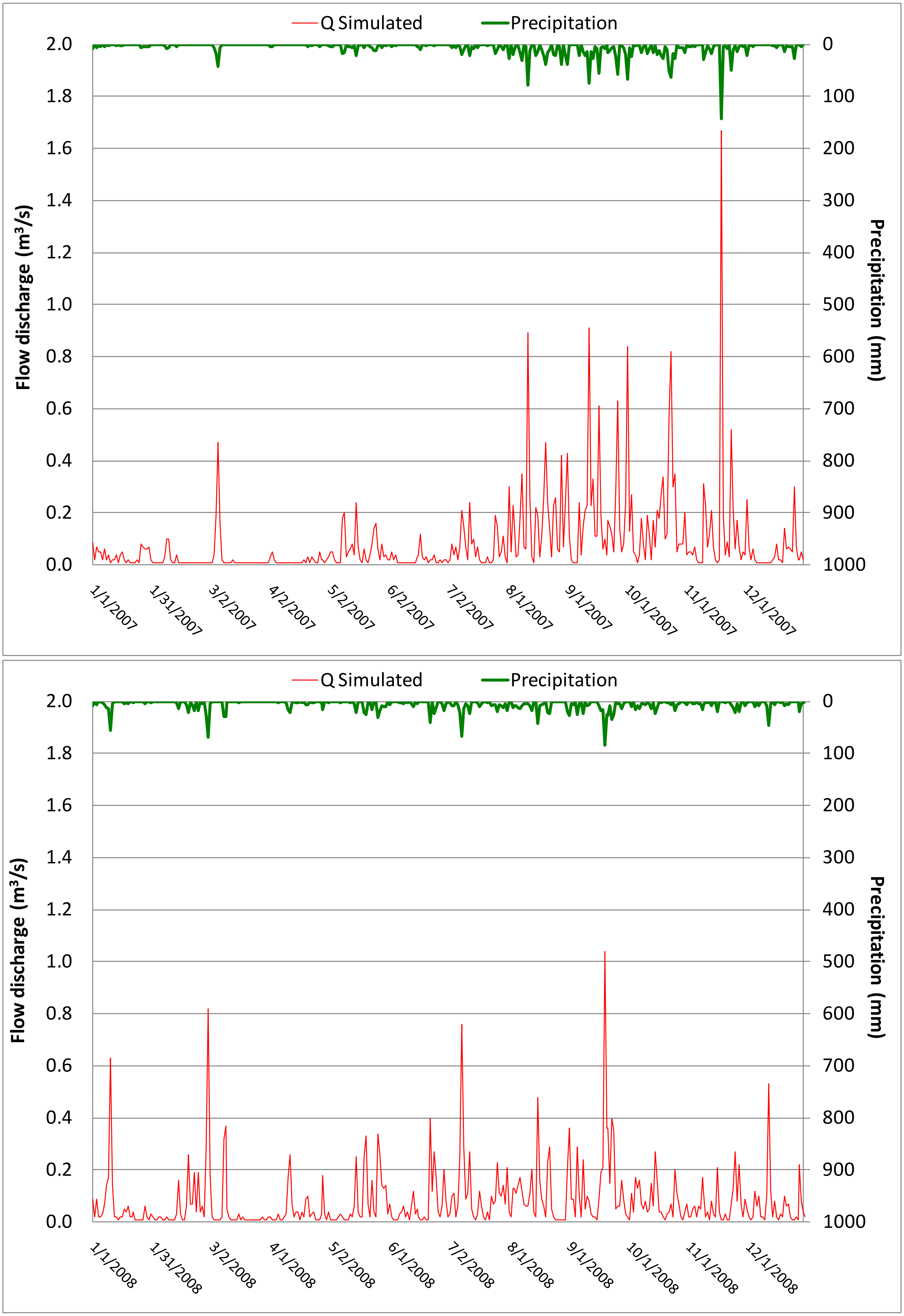




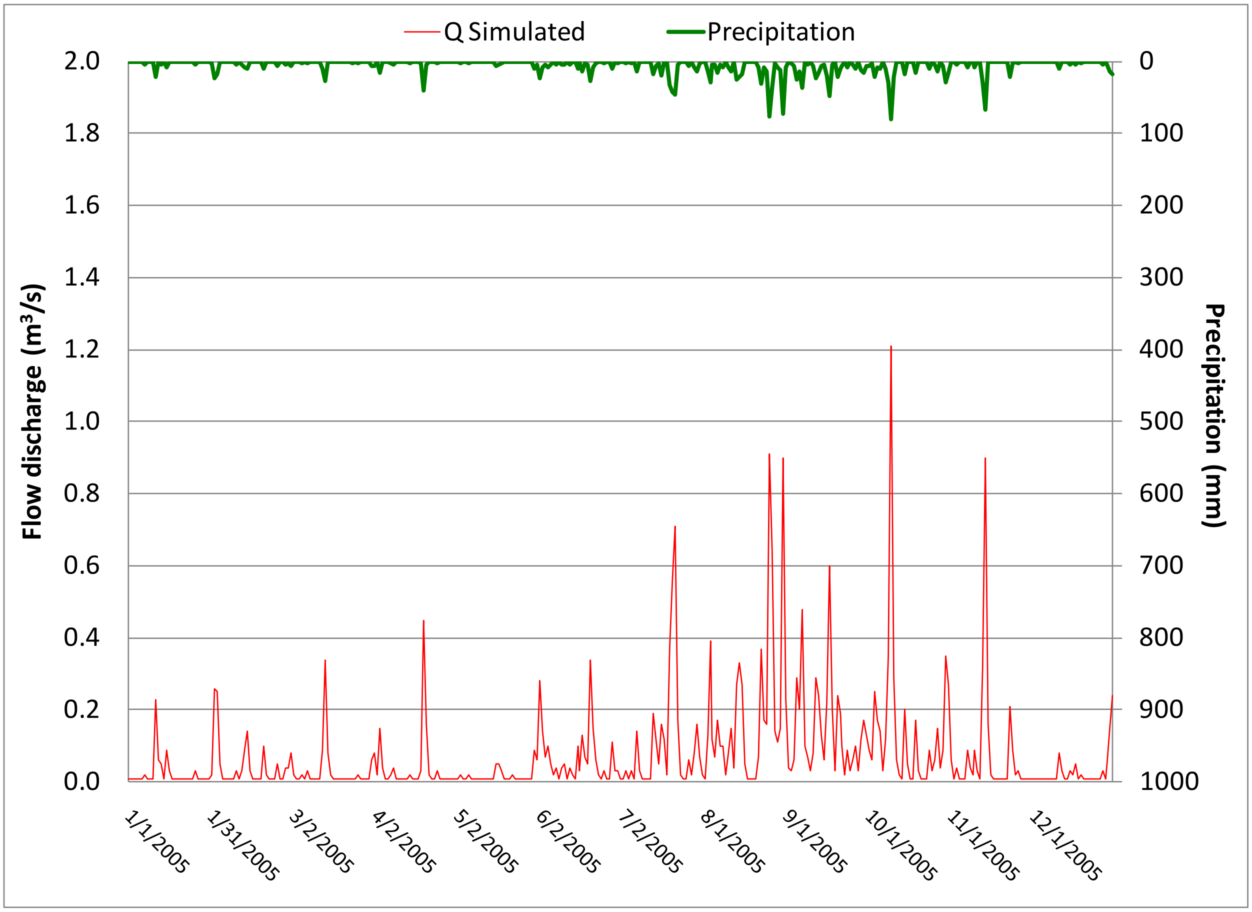
Agfayan watershed (2007 and 2008)

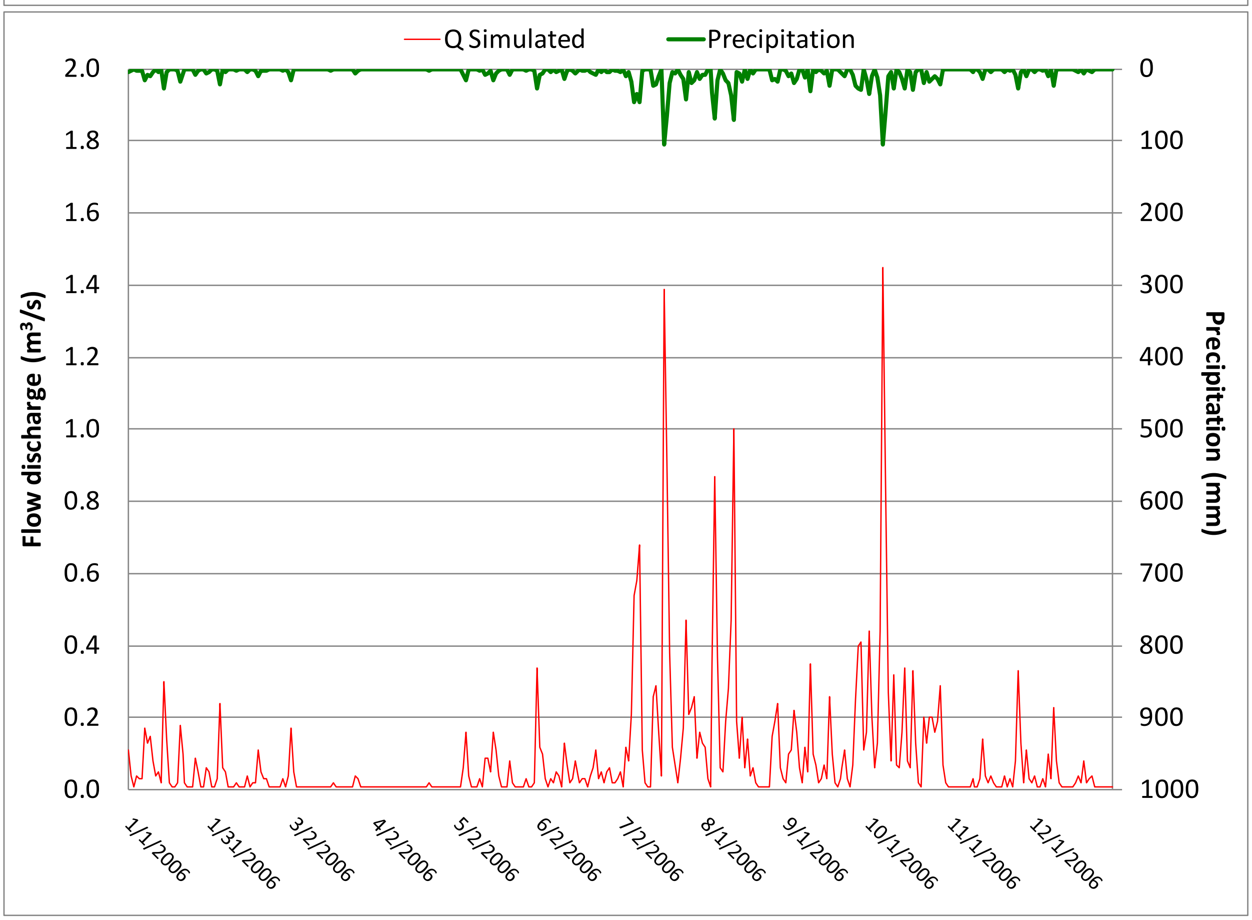


Anjayan watershed (2005 and 2006)

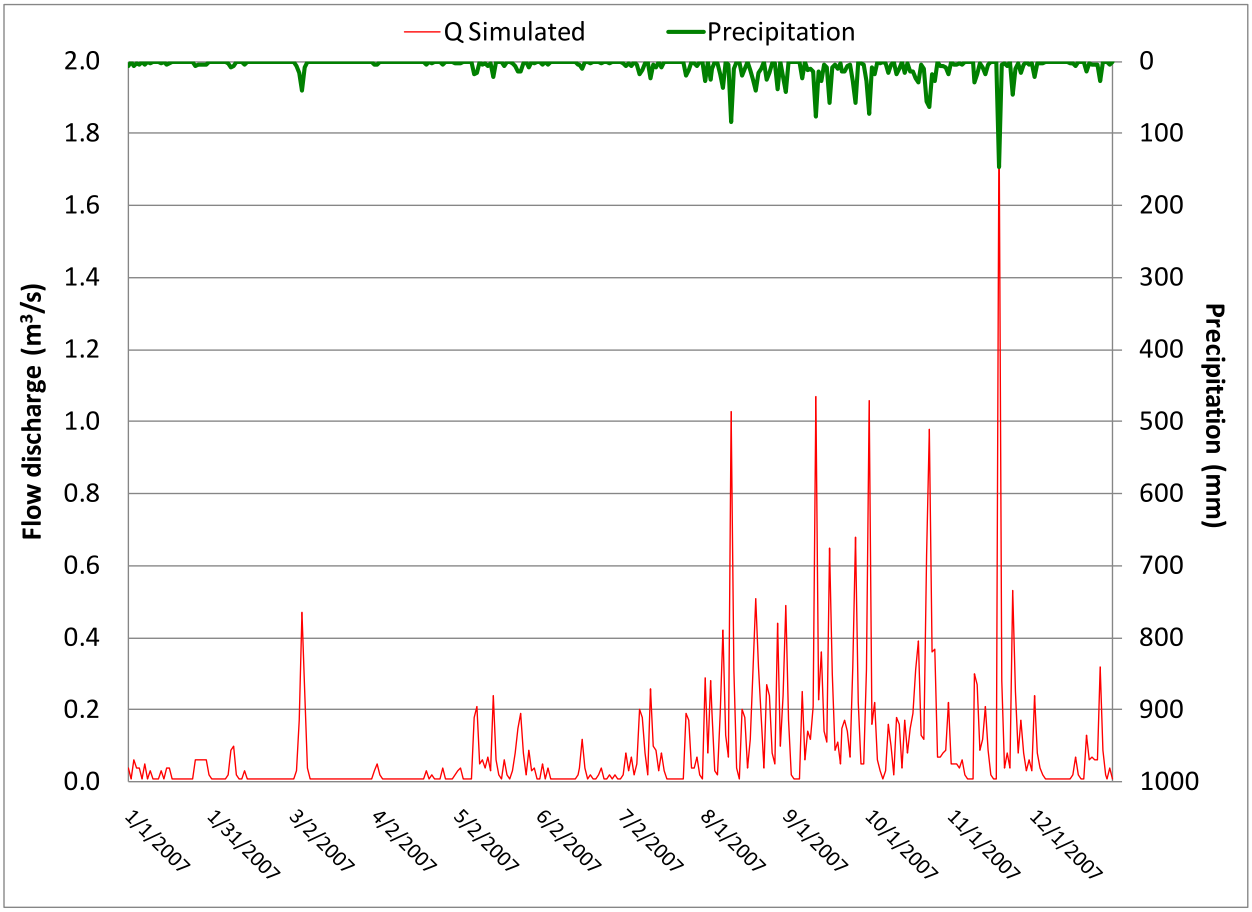


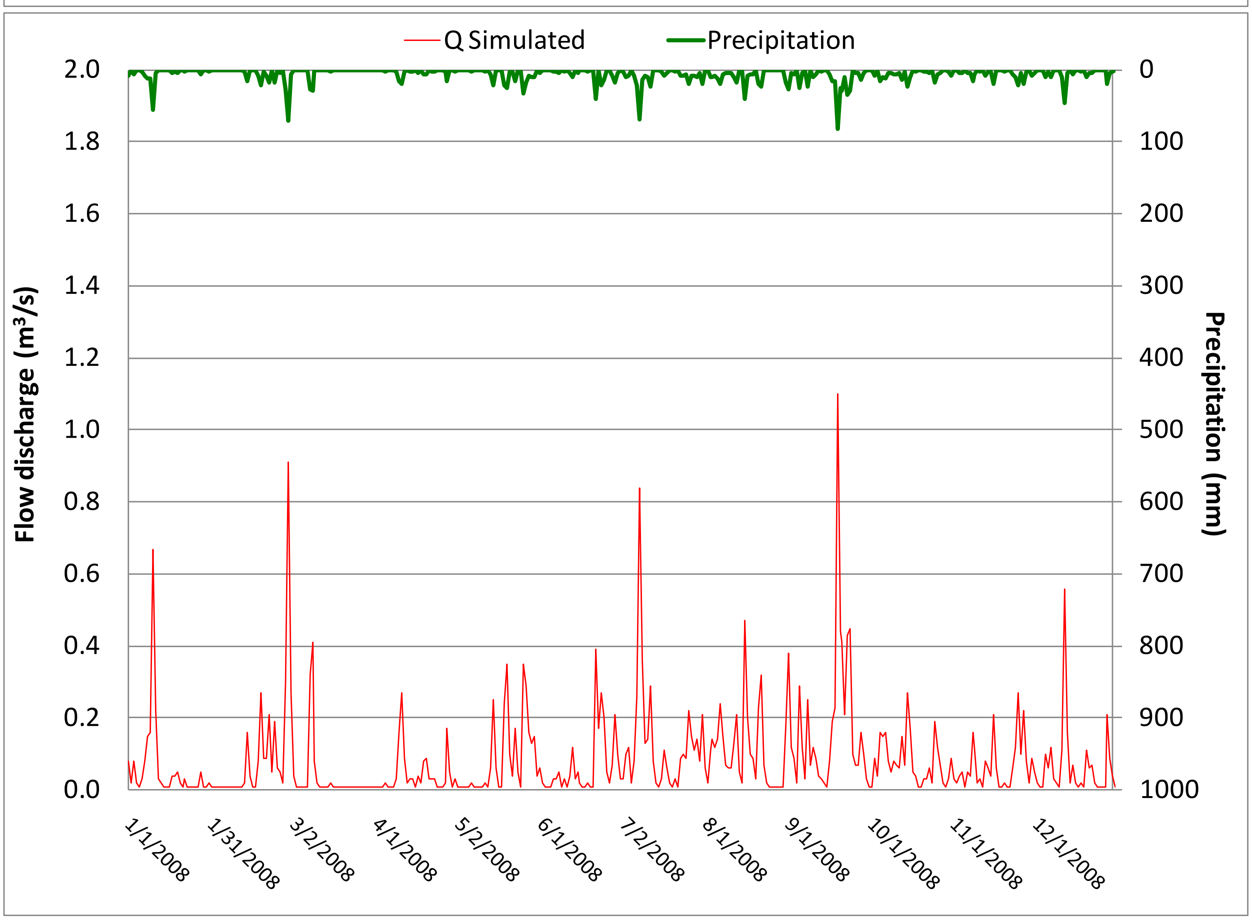
Anjayan watershed (2007 and 2008)



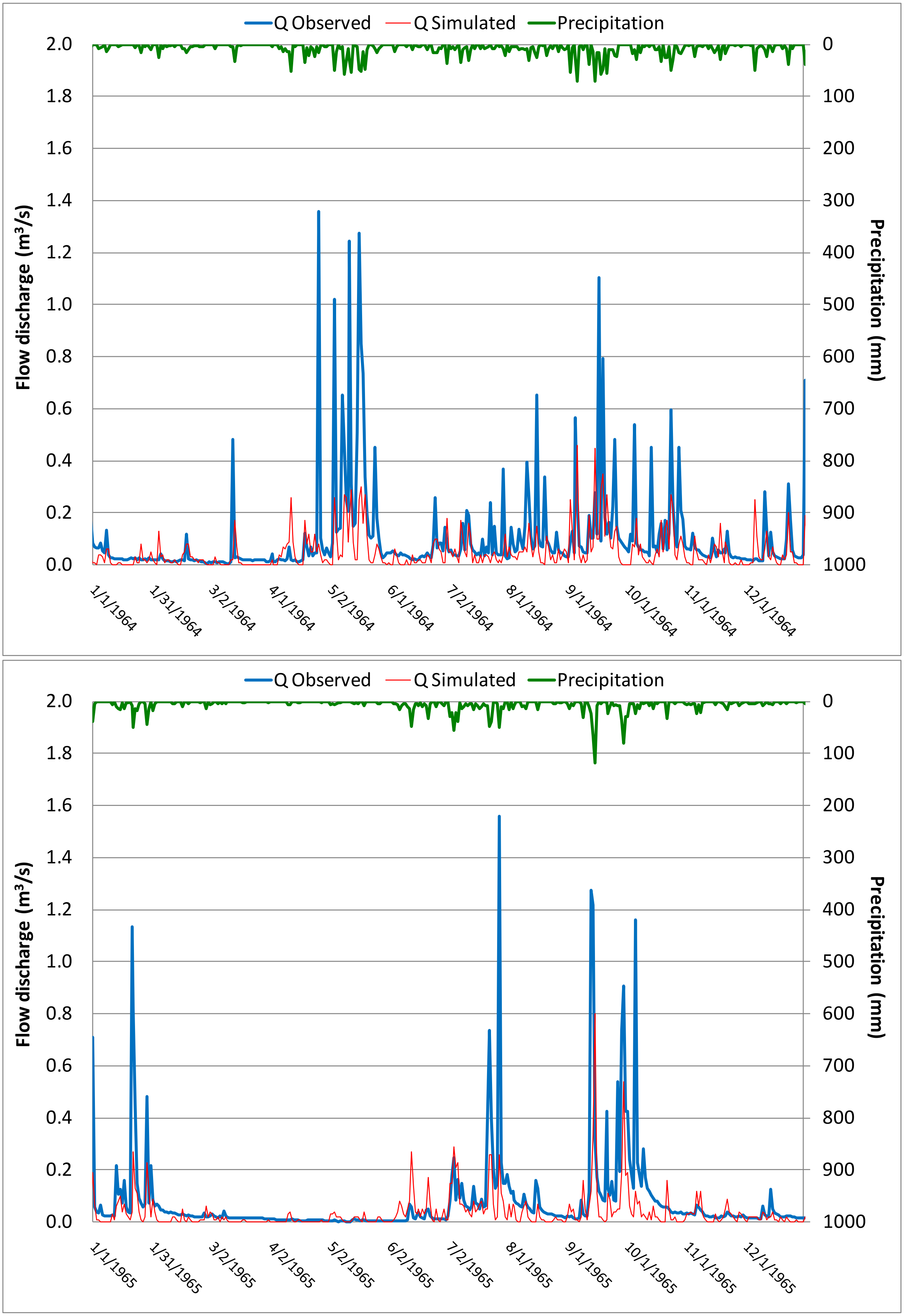


Asalonso watershed (2005 and 2006)

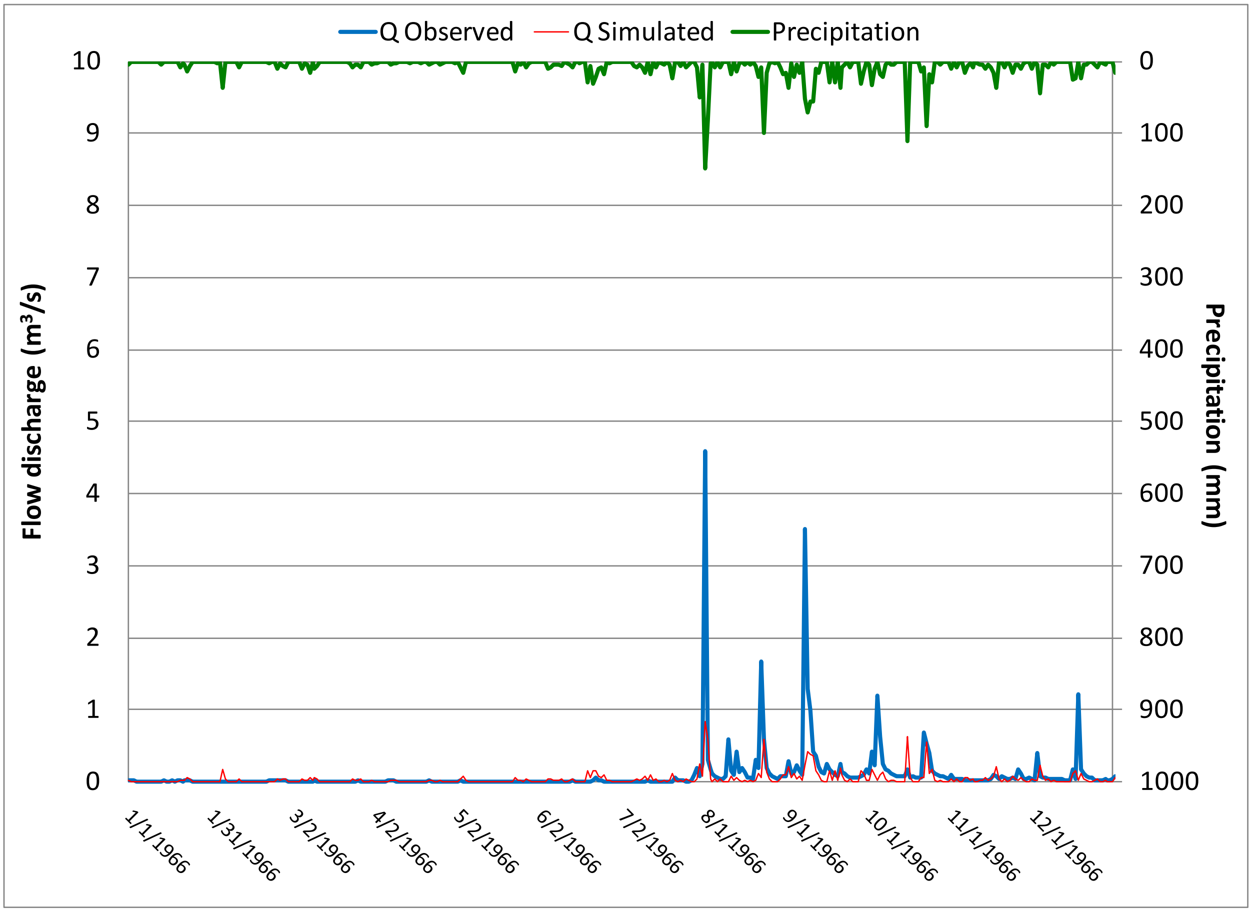


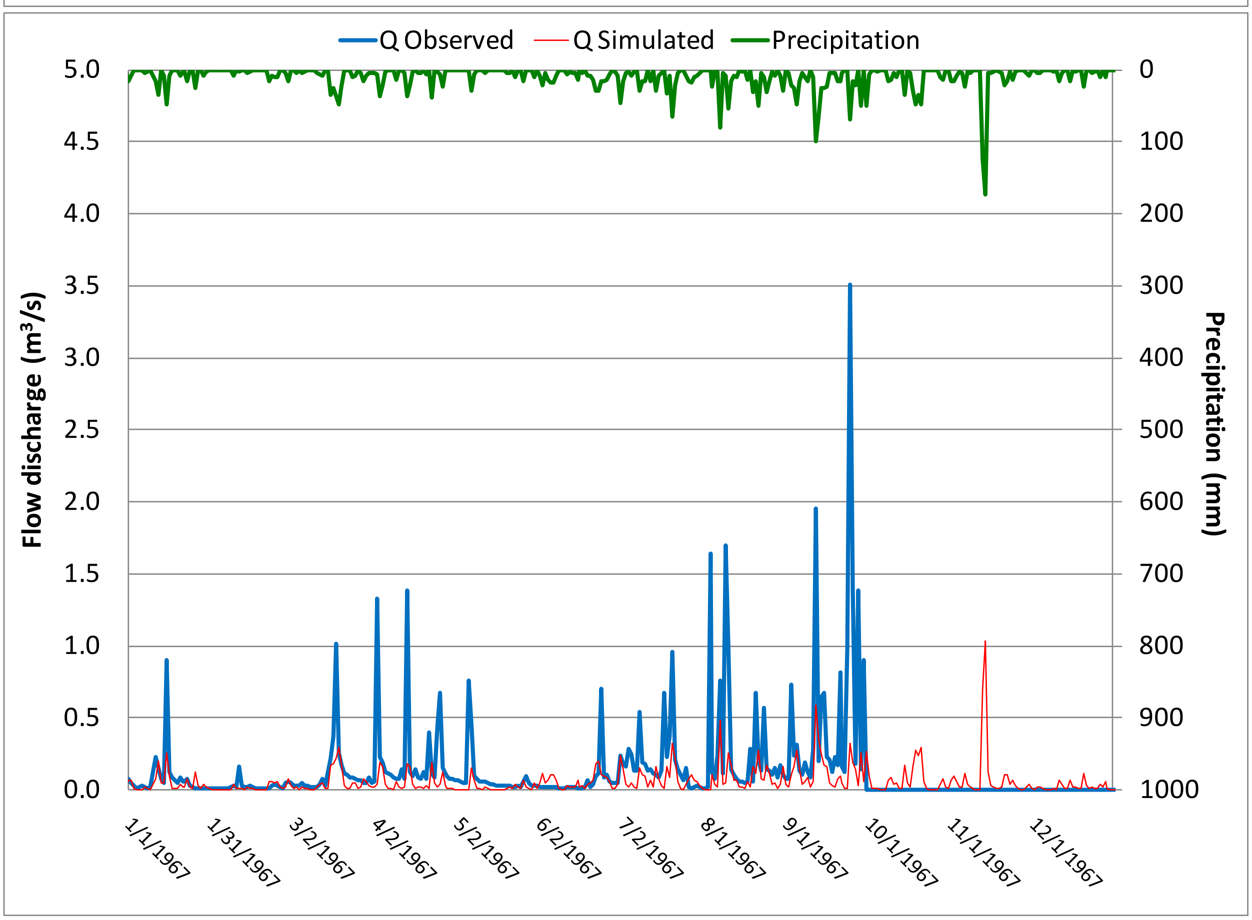


Asalonso watershed (2007 and 2008)

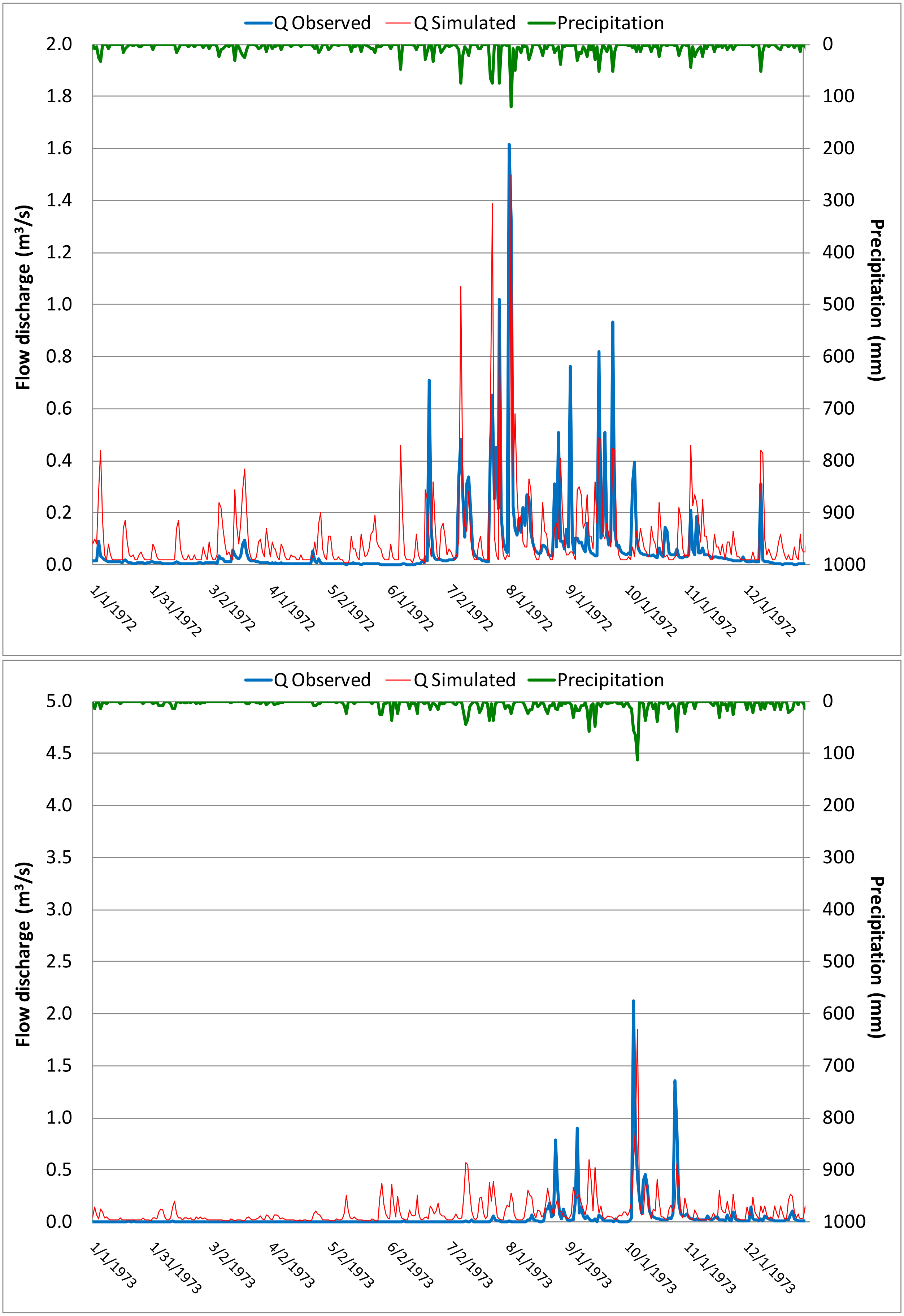


Cetti watershed (1964 and 1965)

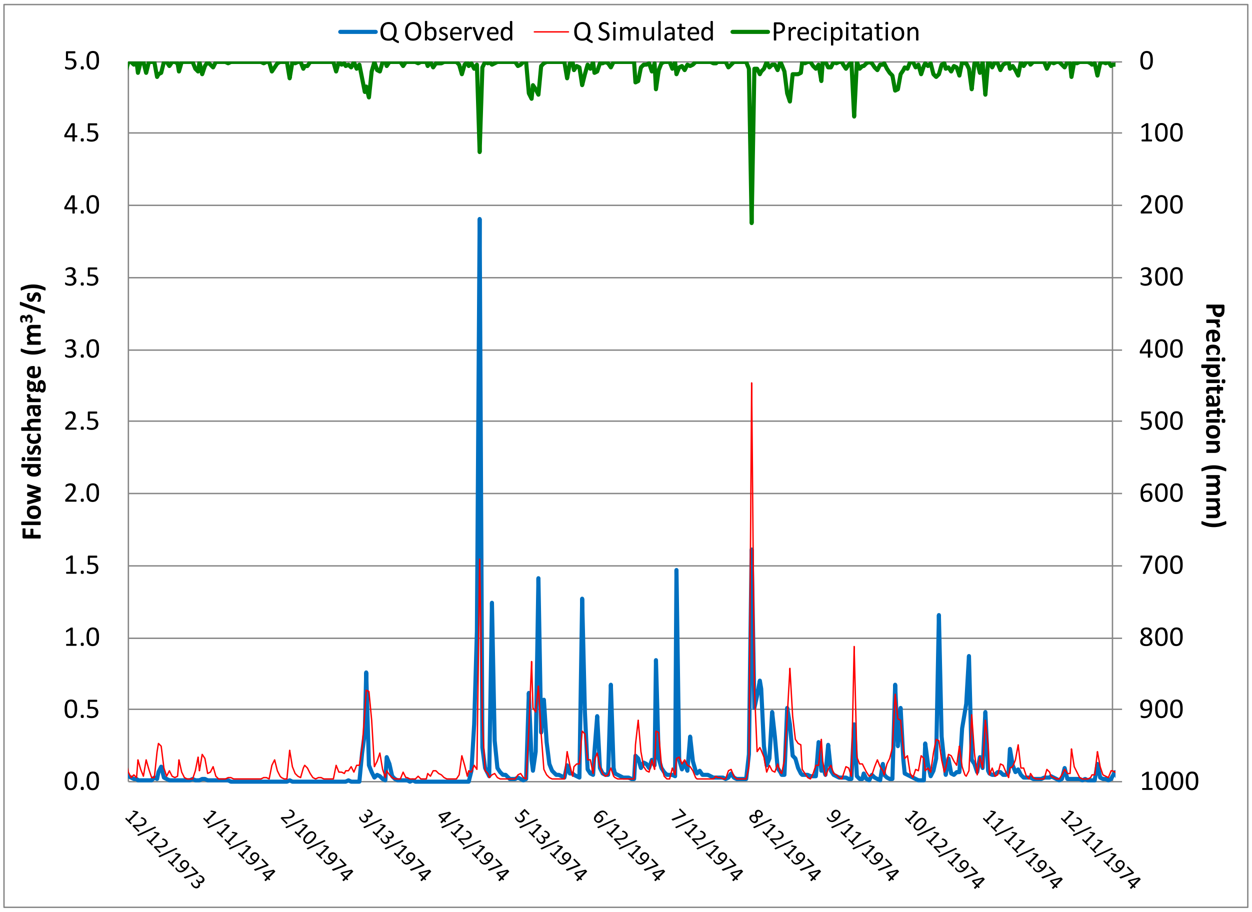


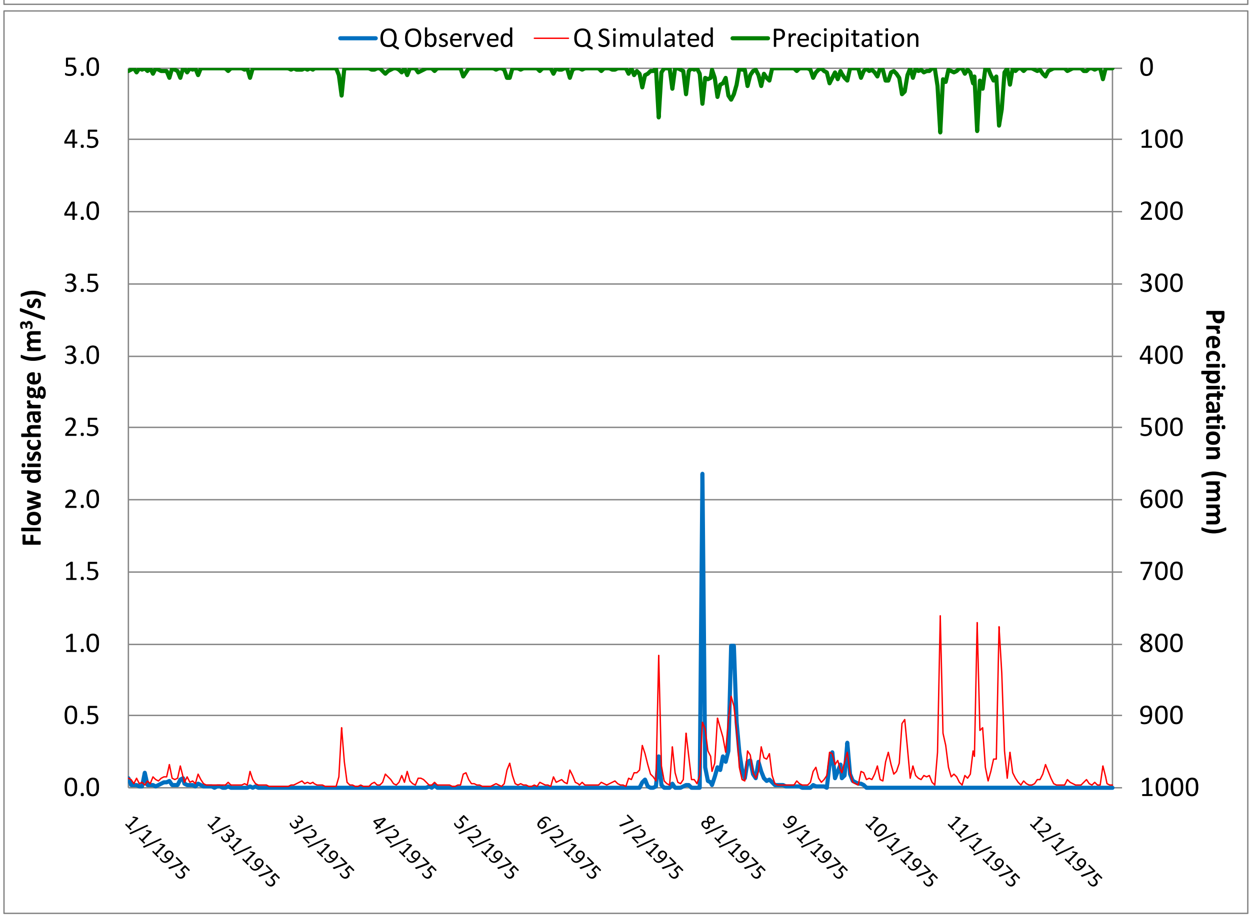


Cetti watershed (1966 and 1967)

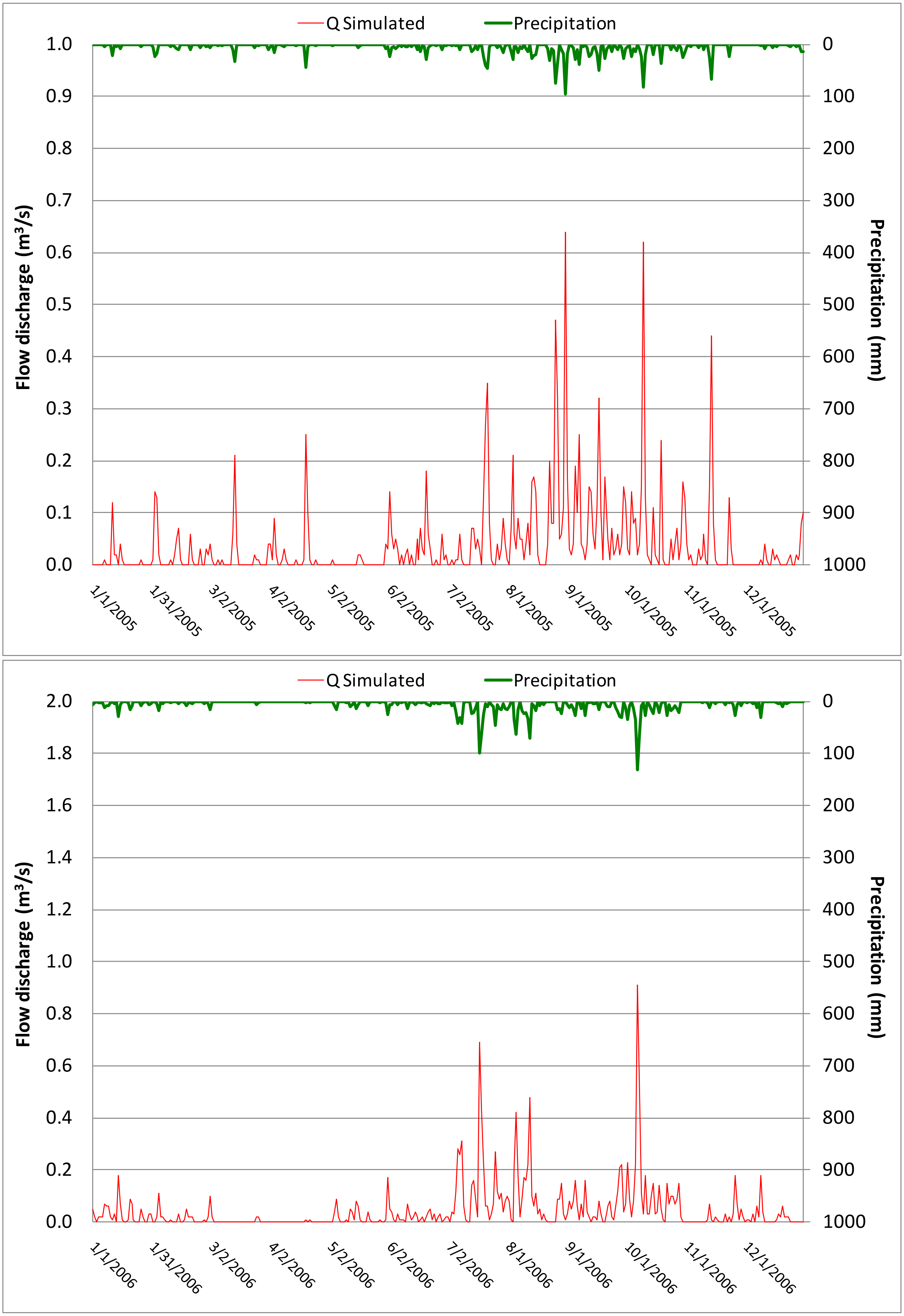


Geus watershed (1972 and 1973)

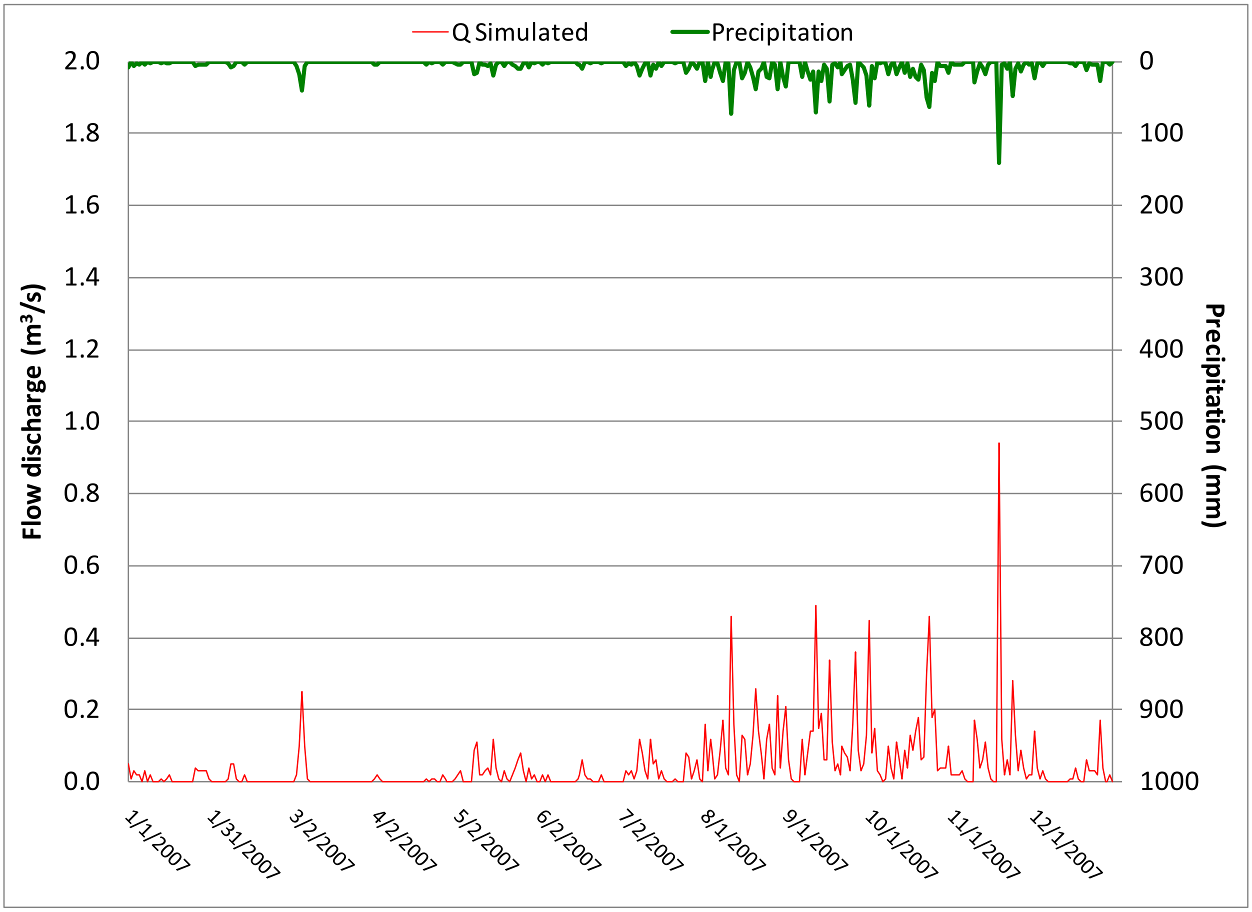


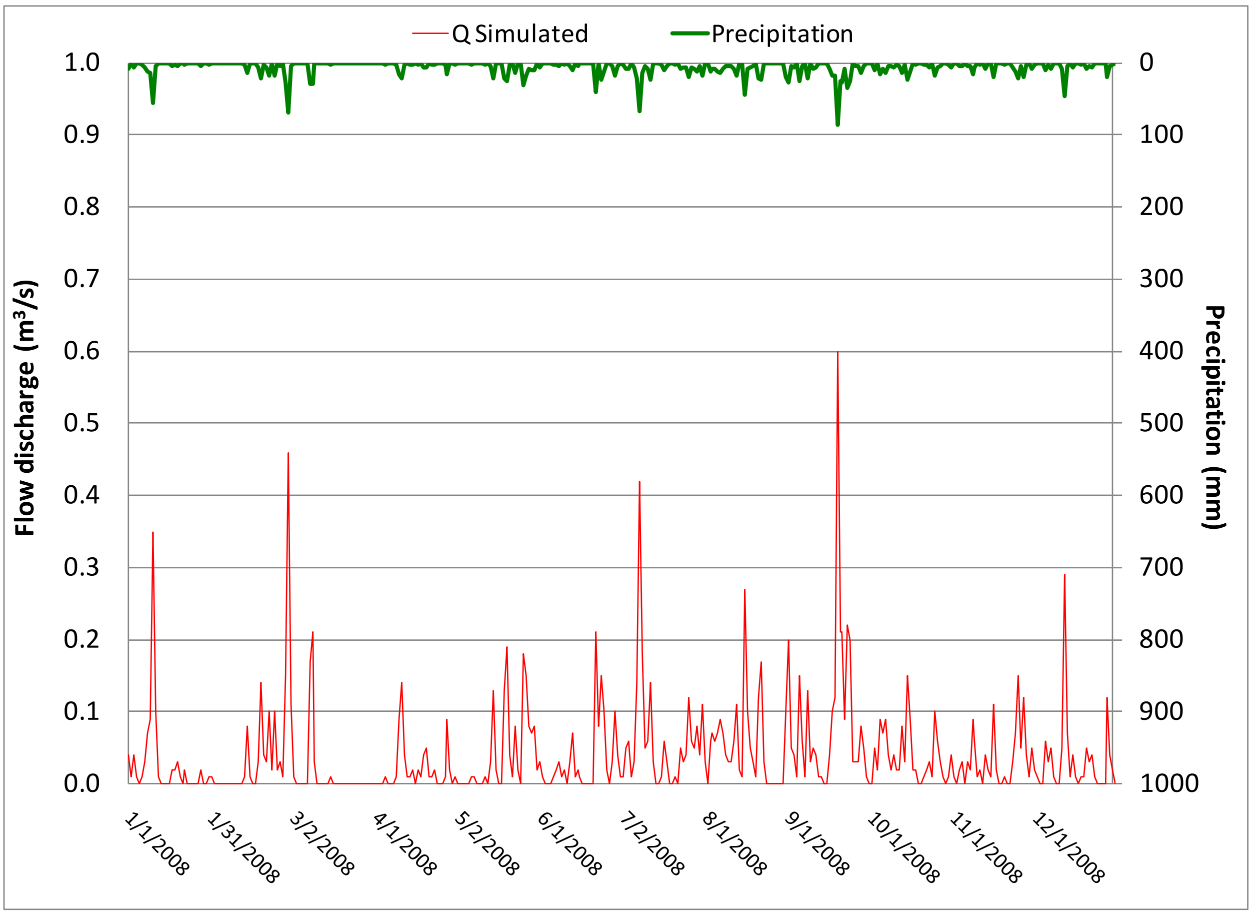


Geus watershed (1974 and 1975)

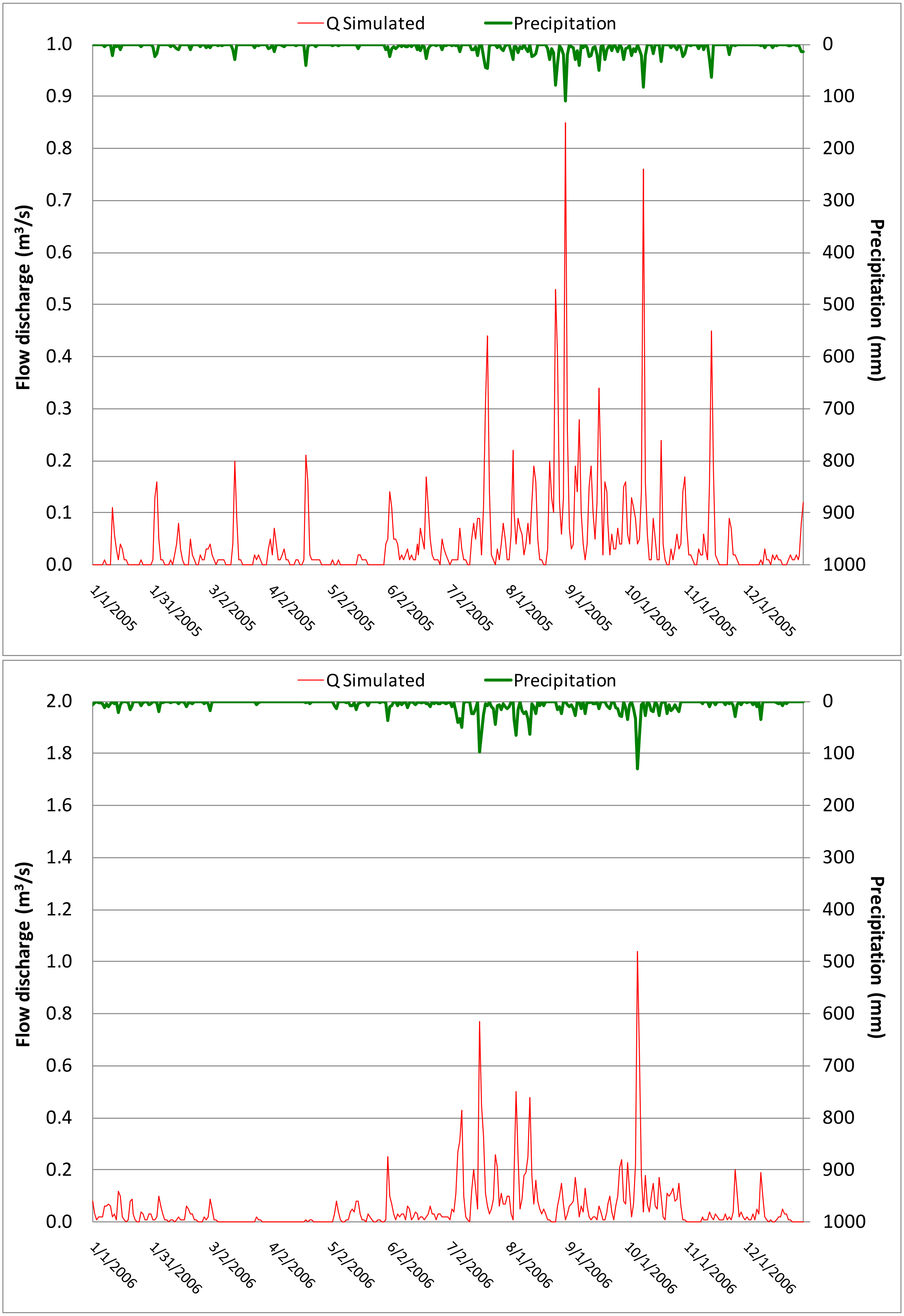


Manell watershed (2005 and 2006)

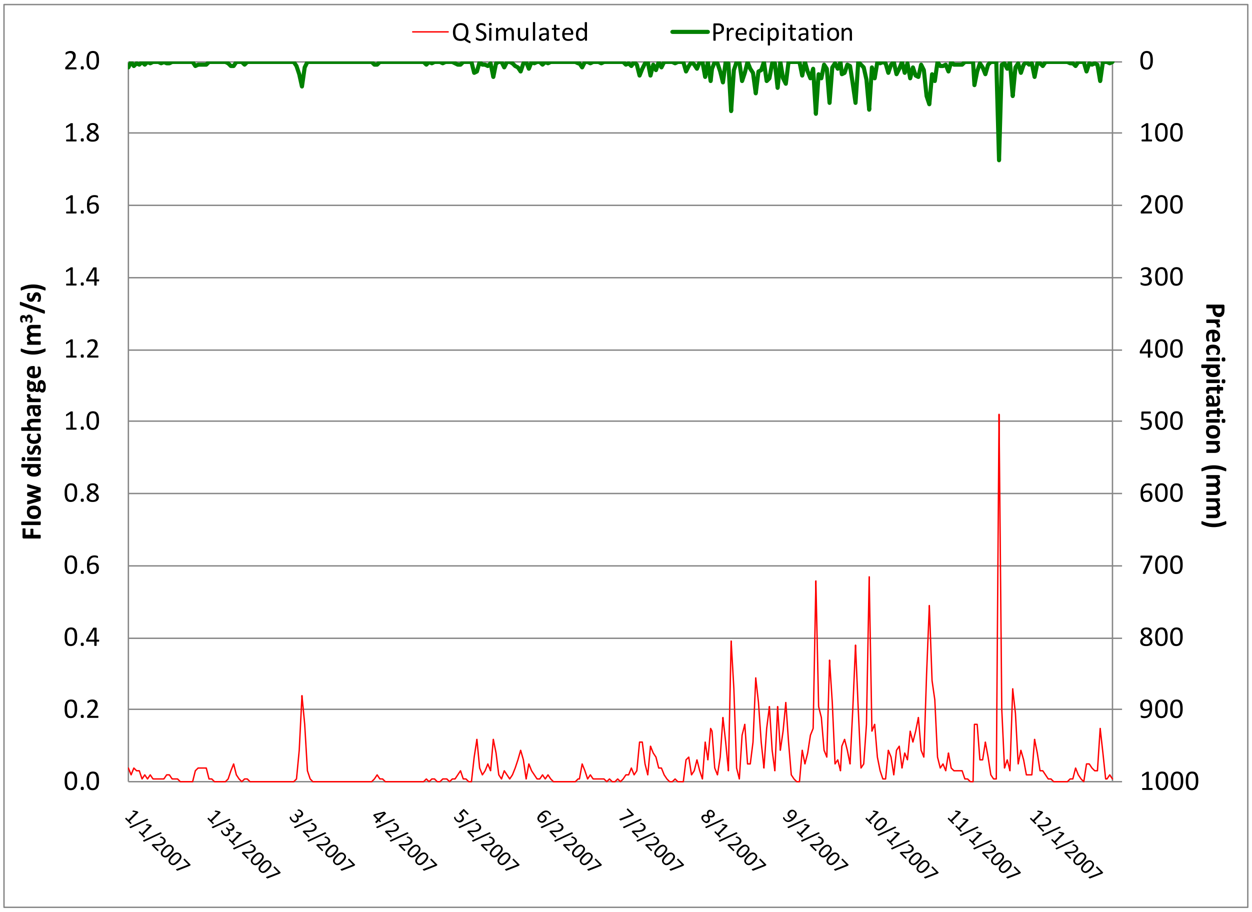


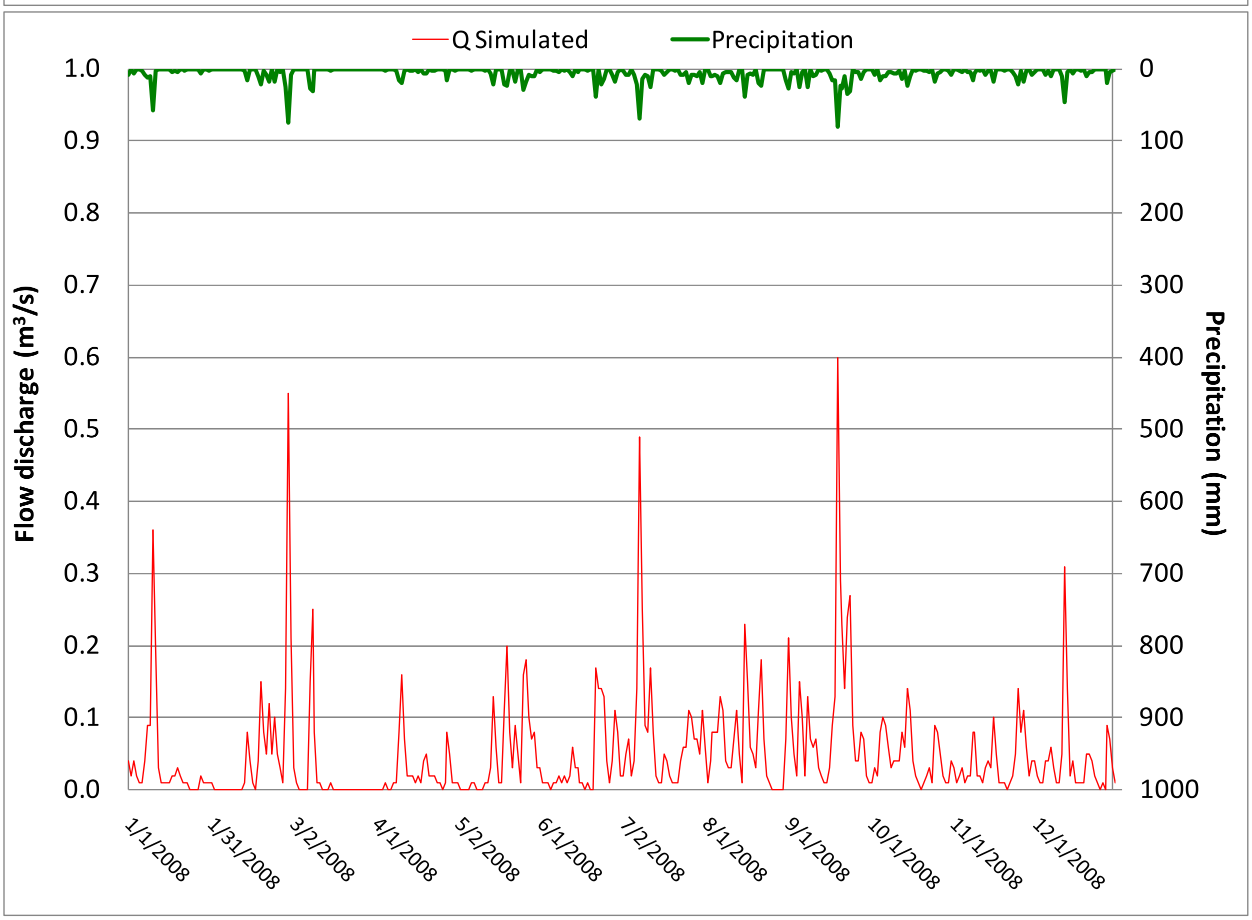


Manell watershed (2007 and 2008)



Sell watershed (2005 and 2006)





Sell watershed (2007 and 2008)