Advanced Technique for Rainfall-Runoff Simulation in Arid Catchments Sinai, Egypt

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Abstract

Egypt's Sinai Peninsula falls within an arid climatic belt that crosses northern Africa and southwestern Asia. Despite its aridity, Sinai is occasionally subjected to heavy rainfall causing flash floods, which are commonly characterized by sharp peak discharges with short durations. Several flash floods were recorded in south Sinai, which resulted in significant infrastructural damages, population displacement and, sometimes, loss of lives. Despite their hazardous effects, flash floods in Sinai, and other parts of southern Egypt, represent a potential for non-conventional fresh water sources. In order to mitigate flash flood damages and efficiently harvest the highly needed fresh water, it is crucially important to accurately predict the occurrence of flash floods in terms of both timing and magnitude. Rainfall-runoff numerical models have become widely recognized as tools for studying hydrological processes, predicting hydrologic impacts of human activities, and assessing available water resources. Several traditional studies have been implemented to develop hydrologic models for predicting flash floods in Sinai. In these studies, methodologies that are primarily conceptual, such as synthetic unit hydrographs, have shown little success at reproducing observed flood hydrographs. These approaches suffered from lack of accurate spatial representation of infiltration losses, rainfall distributions, and other hydrologic processes. Physically based distributed models provide an alternative approach that is based on physical understanding of hydrological processes, as well as improved spatial representation of rainfall input and watershed properties. In a new effort to provide accurate predictions of flash floods in Sinai, this study examines the utility of a physically-based distributed hydrologic model (Gridded Surface-Subsurface Hydrologic Analysis, GSSHA) to simulate rainfall-runoff response in a small and a mid-size catchment in Sinai. These experimental catchments were established by the Water Resources Research Institute (WRRI) in Sinai, as part of an extensive monitoring effort to improve the understanding of the hydrologic processes in Sinai's arid basins. GSSHA is a fully distributed-parameter, process-based hydrologic model that uses finite difference and finite volume methods to simulate different hydrologic processes such as rainfall distribution and interception, overland water retention, infiltration, evapotranspiration, two-dimensional overland flow, one dimensional channel routing, and different methods for modeling the soil moisture profile in the unsaturated zone. The Green and Ampt method (GA) was used to simulate infiltration losses into the unsaturated zone. The watershed topographic and hydrologic properties are represented using 90x90 m2 and 180x180 m2 Cartesian grids for the small and the mid-size catchments respectively. Channel dimensions were specified in the model based on field surveys using Global Positioning System (GPS). The rainfall data was collected and compiled from the available rain gauges in the study catchments. Overland hydraulic properties and soil hydraulic parameters were varied according to spatial combined classifications of soil type and land use maps. Field measurements of soil types and infiltration parameters were used to initially assign model parameters. The parameters were further adjusted through model calibration against available runoff measurements at each catchment outlet.

After performing calibration runs, sensitivity analyses were highly needed to evaluate the impact of the model parameters on the simulated hydrographs. The sensitivity analysis focused on the following parameters: Manning's coefficients for overland and channel flows; and infiltration parameters for overland flow such as porosity, capillary head and hydraulic conductivity. In addition, hydraulic conductivity and thickness of streambed material were assessed to examine the effect of channel transmission losses. The effect of the initial moisture content and the spatial variation in rainfall information were also considered. The analysis performed in this study yielded good agreement between GSSHA-simulated hydrographs and the corresponding stream-flow measurements, which indicated the ability of distributed models to better represent spatial variations in model input and parameters that affect rainfall-runoff processes in arid environments. However, the results also indicated significant sensitivity to the selection of model parameters and the representation of rainfall spatial variability due to the limited number of rainfall gauges in the catchments. Overall, the results of this study highlight the complexity of rainfall-runoff processes in arid regions especially under the constraints of limited information on rainfall variability and the significant heterogeneity in watershed properties and model parameters.

Keywords: Rainfall-Runoff Simulations, Arid and Semi-Arid Catchment, Distributed Hydrological Process; GSSHA Model; Rainfall Variability

Introduction

Egypt's Sinai Peninsula falls within an arid climatic belt that crosses northern Africa and southwestern Asia. Despite its aridity, Sinai is occasionally subject to heavy rainfall causing flash floods, which are commonly characterized by sharp peak discharges with short durations. Several flash floods were recorded in south Sinai, which resulted in significant infrastructural damages, population displacement and, sometimes, loss of lives. Despite their hazardous effects, flash floods in Sinai, and other parts of southern Egypt, represent a potential for non-conventional fresh water sources. In order to mitigate flash flood damages and efficiently harvest the highly needed fresh water, it is crucially important to accurately predict the occurrence of flash floods in terms of both timing and magnitude.

Rainfall-runoff numerical models have become widely recognized as tools for studying hydrological processes, predicting hydrologic impacts of human activities, and assessing available water resources. Several studies have been implemented to develop hydrologic models for predicting flash floods in Sinai. In these studies, methodologies that are primarily conceptual, such as synthetic unit hydrographs, have shown little success at reproducing observed flood hydrographs. These approaches suffered from lack of accurate spatial representation of infiltration losses, rainfall distributions, and other hydrologic processes.

Physically based distributed models provide an alternative approach that is based on physical understanding of hydrological processes, as well as improved spatial representation of rainfall input and watershed properties. In a new effort to provide accurate predictions of flash floods in Sinai, this study examines the utility of a physically-based distributed hydrologic model (Gridded Surface-Subsurface Hydrologic Analysis, GSSHA) to simulate rainfall-runoff response in a small and a mid-size experimental catchment in Sinai.

Study Area and Experimental Data

The current study focuses on two experimental catchments located in Sinai. These experimental catchments (Figure 1) were established by the Water Resources Research Institute (WRRI) in Sinai as an extensive monitoring effort to improve the understanding of the hydrologic processes in Sinai's arid basins. The experimental catchments are equipped with numerous rainfall and runoff gauges that have been in operation since 1989. Unlike wet environments, arid and semi-arid catchments are characterized with unique runoff generation processes that are usually controlled by:

(a) High rainfall variability: In general, high intensities, short durations, and low accumulations of infrequent rainstorms in arid regions, make rainfall patterns highly variable.

(b) Complex surface characteristics: Due to long dry periods, soil surface in Sinai's catchments and wadis (seasonal watercourses) are always bare at the onset of rainfall events.

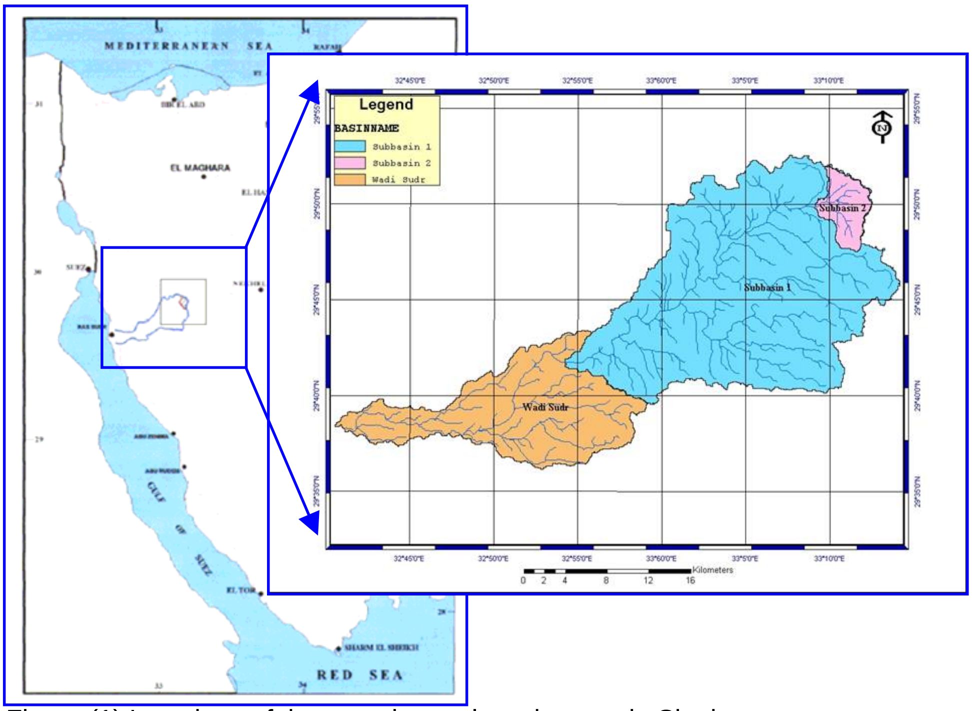

Figure (1) Locations of the experimental catchments in Sinai

1 Descriptions of the two watersheds

Wadi Sudr is one of south-west Sinai wadis which is located between latitudes 29° 35' and 29° 55', and longitudes 32° 40' and 33° 20'. Wadi Sudr covers a total area of about 600 km^2 and it drains directly in the Gulf of Suez at Sudr town. This wadi is instrumented by Water Resources Research Institute (WRRI) for Rainfall and runoff measurements since 1989. Two subbasins of Wadi Sudr are instrumented for runoff measurements, the first subbasin is of area about 450 km^2, and the second subbasin is of area about 26 km^2. Figure (1) illustrates the general layout of the catchment of wadi Sudr and its two subbasins. The criteria of selecting these experimental catchments are representativeness of hydrologic characteristics of the region, existence of high economic development interests, and accessibility for installation and maintaining the monitoring stations.

Over 95% of the land area is in the experimental catchments is desert. The elevation of the watershed varies from about 160 at the outlet to about 860 upstream the wadi. The watershed length is about 33.5 km. The land slope in the watershed is about 0.097 m/m. Various sources of spatial data were used for the study watersheds such as geographic maps, Digital Elevation Model (DEM), Figure (2) and satellite images.

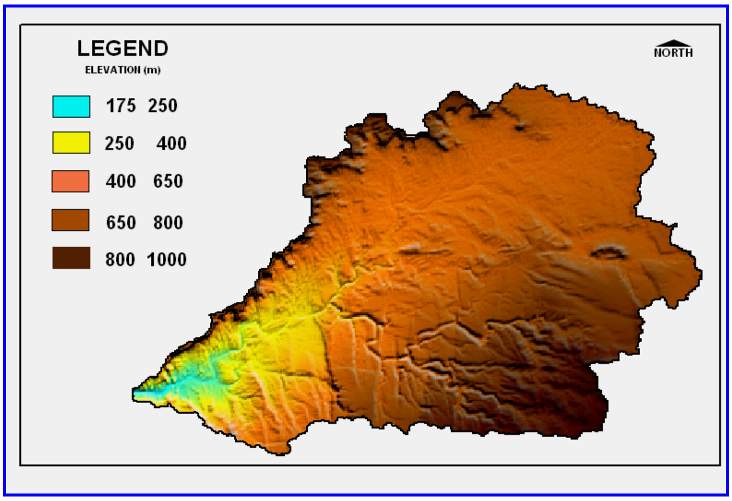

Figure (2) Digital Elevation Model of the experimental catchments area

2 Available Gauges and Data

Rainfall over the two watersheds is measured by means of several rain gauges. A network of rainfall equipments was installed in the watersheds in order to determine rainfall spatial and temporal distribution. The rainfall gauges within the watersheds are six recording gauges and many storage gauges. Recording gauges are used to measure rain intensities while storage gauges are used to provide accumulations of rainfall for periods of one day or more. There is also a runoff monitoring station with water level recorder located at the outlet of each watershed. Figure (3) shows the locations of all the rainfall gauges, weathering station, and the water level recorder.

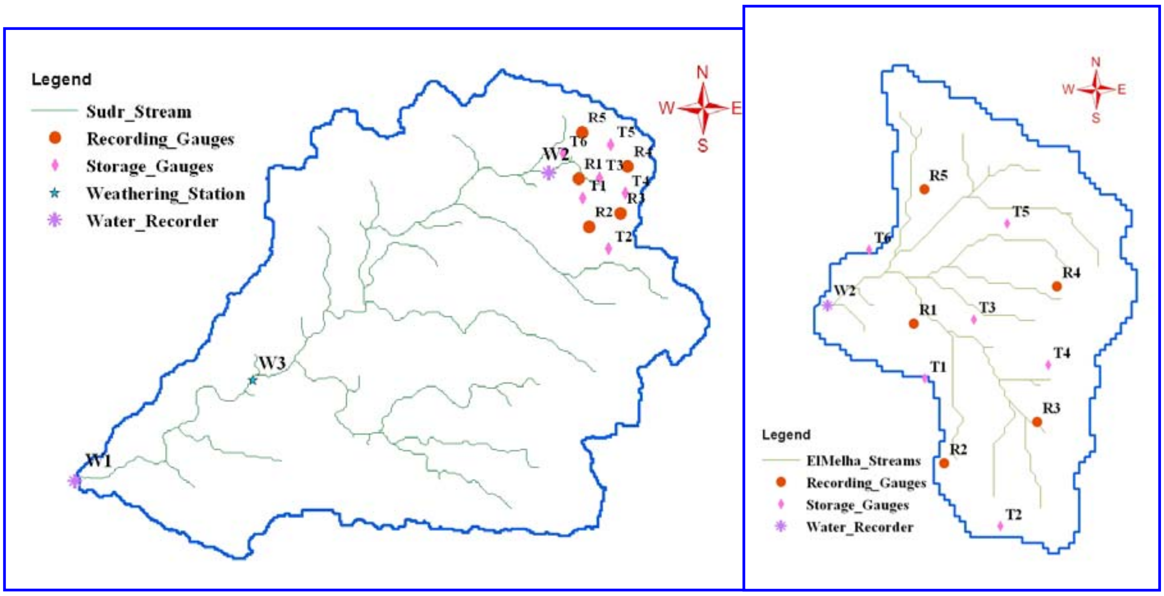

Figure (3) Locations of rain gauges in Sudr watershed (left) and in ElMelha watershed (right)

3 Additional Field Measurements

One of the most important model components is accurate specification of channel cross section dimensions. Therefore, several sites in the channels network were surveyed. Figure (4) shows the locations of the surveyed sections and examples of the surveyed channels. The criterion used in selecting these specific locations was to provide a reasonable coverage over the entire watershed and ensure representation of different stream orders (1st, 2nd order, etc.).

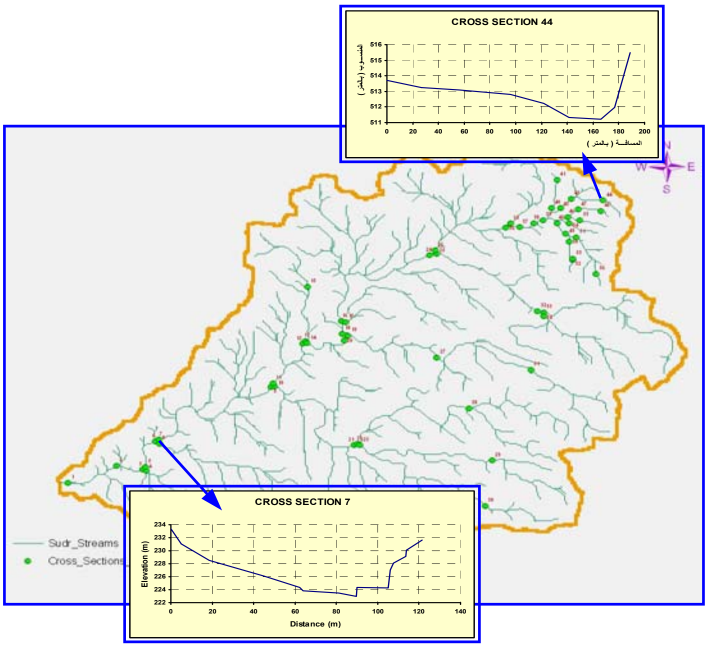

Figure (4) locations of the surveyed sections

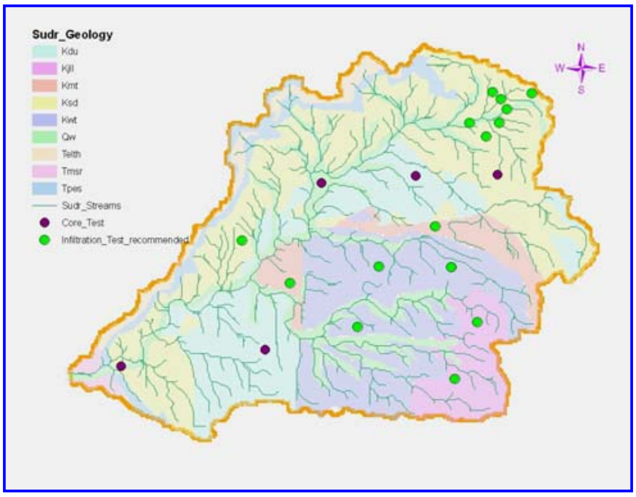

Figure (5) locations of the soil samples and Infiltration

Data on soil infiltration properties are collected. Figure (5) shows the locations of infiltration tests and soil samples. Criteria of selection soil samples are based on the watershed surface geology. Samples are taken at two different depths; 30 cm and 60 cm. Sieve analysis and soil classification are carried out for all samples. The infiltration data is analyzed to estimate Green and Ampt parameters to establish a preliminary model setup.

4 Available Rainfall-Runoff Events

Sinai receives a limited number of rainfall events with pronounced variability from one year to another, during any given year, and even during a single storm. Spatially, rainfall storms exhibit a strong variability especially during the heavy and localized thunderstorms. Only for the experimental catchments, high-resolution rainfall and runoff measurements are available. For the purposes of this study, the data from 1990 and 1991 were used. The criteria of selecting the storms of this study are isolated storm event, high rainfall and high peak flow rate.

A storm event was considered to be over when there was a period of at least 6 hours without rainfall. The storms included in this study were selected because they had significant rainfall amounts and observable runoff peaks. The above criteria resulted in five storm events for Sudr watershed and two storm events for ElMelha watershed.

Technical Approach and Methodology

Runoff generation in arid areas is spatially non-uniform and is mainly controlled by high intensity, short duration rainstorms and by soil surface conditions and its complex infiltration processes. Therefore, process-oriented models with distributed capabilities represent a promising tool for understanding and possibly modeling catchments with such hydrologic conditions. Once developed, these models can also help in the assessment and management of available water resources in arid environments.

1 Model Description (GSSHA)

In this study, the Gridded Surface Subsurface Hydrologic Analysis (GSSHA) system is used to develop a rainfall-runoff model for small and mid-size watersheds. GSSHA is a fully distributed-parameter, process-based hydrologic model (Downer and Ogden, 2004). It uses finite difference and finite volume methods to simulate different hydrologic processes such as rainfall distribution and interception, overland water retention, infiltration, evapotranspiration, two-dimensional overland flow, one dimensional channel routing, and different methods (e.g., Green and Ampt method, and Richards' equation) for modeling the soil moisture profile in the unsaturated zone. The model setup adopted in this study included the following options: two-dimensional diffusive wave approximation of the de Saint Venant equations for overland flow, one-dimensional explicit diffusive wave method for channel flow, Penman-Monteith equation for evapotranspiration calculations, and the Green and Ampt infiltration with redistribution (GAR) method for flow simulation in the unsaturated zone. The GAR method simulates the soil moisture redistribution during a runoff event, as well as the change in soil moisture due to evapotranspiration between rainfall events. This soil moisture accounting scheme allows for continuous-mode simulations that include both rainy and dry periods.

2 Model Setup

The watershed topographic and hydrologic properties are represented using 90x90 m^2 and 180x180 m^2 for the small and medium catchments, respectively Channel dimensions were specified in the model based on field surveys using Global Positioning System (GPS). The rainfall data was collected and compiled from the available rain gauges in the study catchments. Overland hydraulic properties (e.g., roughness parameters), soil hydraulic parameters (e.g., saturated hydraulic conductivity, soil suction head, effective porosity), and evapotranspiration parameters (e.g., vegetation transmission coefficients and root depths) were initially assigned based on spatial variations in the combined classifications of soil type and land use maps. The parameters were further adjusted through model calibration against available runoff measurements at each catchment outlet.

3 Model Calibration

To use the GSSHA model as an engineering modeling tool, it requires calibration to the historic flow conditions of the actual watershed system. The calibration procedure requires the adjustment of numerous parameters to optimize model results. The calibration was made manually and the obtained ranges of different parameters for both watersheds are summarized in table (1).

Table (1) ElMelha and Sudr watersheds parameters

Parameter	Value range
Overland Manning's coeff.	0.03-0.04
Channel Manning's coeff.	0.025-0.035
Porosity	0.05
Capillary head (cm)	1
Hydraulic Conductivity (cm/hr)	0.05-0.1 0.1-0.2
Initial Moisture	0.015-0.05
Rainfall Station	all stations
Channel Hydraulic Conductivity (cm/hr)	0.05-0.1
Thickness of Streambed Material (m)	0.5-1.0

4 Model Results

GSSHA model has been applied to two storms for the small catchment (ElMleha watershed). Figure (6) shows the simulated hydrographs for these storms including channel transmission losses. The first graph of figure (7) shows a comparison between the simulated and observed runoff for storm 25-2-1992 while the second graph shows storm 11-3-1994. The first graph shows lack of agreement between simulated and observed hydrographs due to error in the measurments. The second graph shows good agreement between simulated and observed hydrographs which proves the high capability of the distributed models.

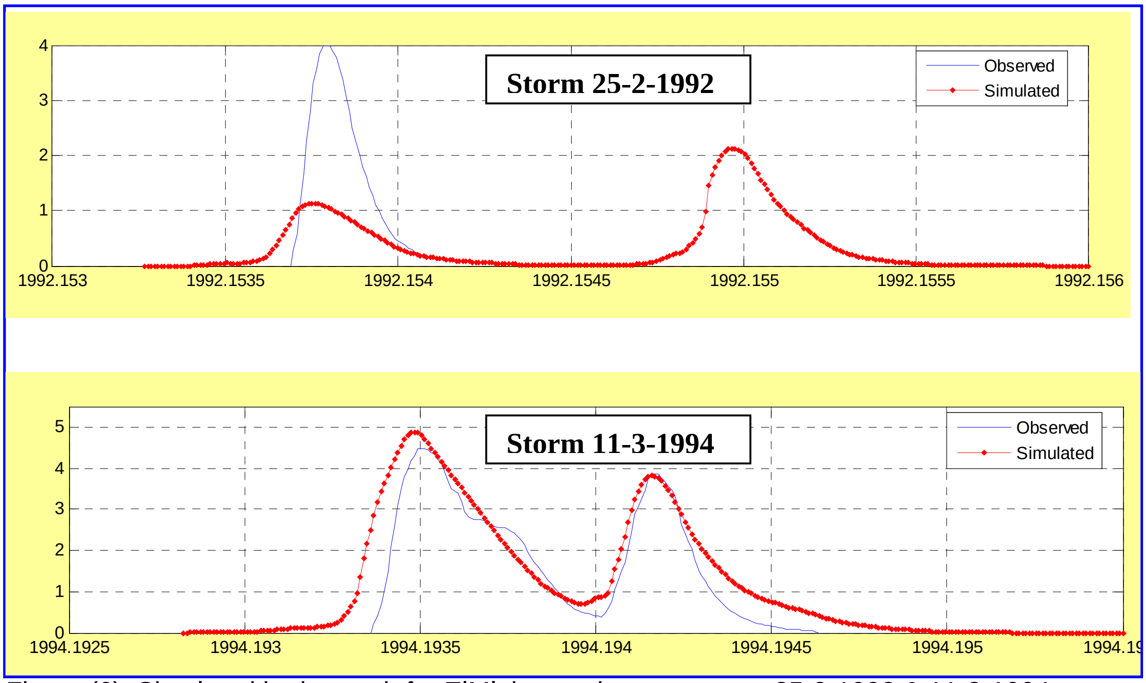

Figure (6): Simulated hydrograph for ElMleha catchment, storms 25-2-1992 & 11-3-1994

GSSHA model has been applied to five storms for the mid-size catchment (Sudr watershed). Figure (7) shows the simulated hydrographs for these studied storms including transmission losses for storms 26-1-1990, 4-2-1990, 6-3-1991, 22-3-1991 and 23-3-1991 respectivily. Some of the simulated hydrographs are in agreement with the observed in maximum flow rate, time to peak and hydrograph shape as in storms 22-3-1991 and 23-3-1991. Most of the simulated hydrographs are in agreement with the observed especially in reproducing the maximum flow rates.

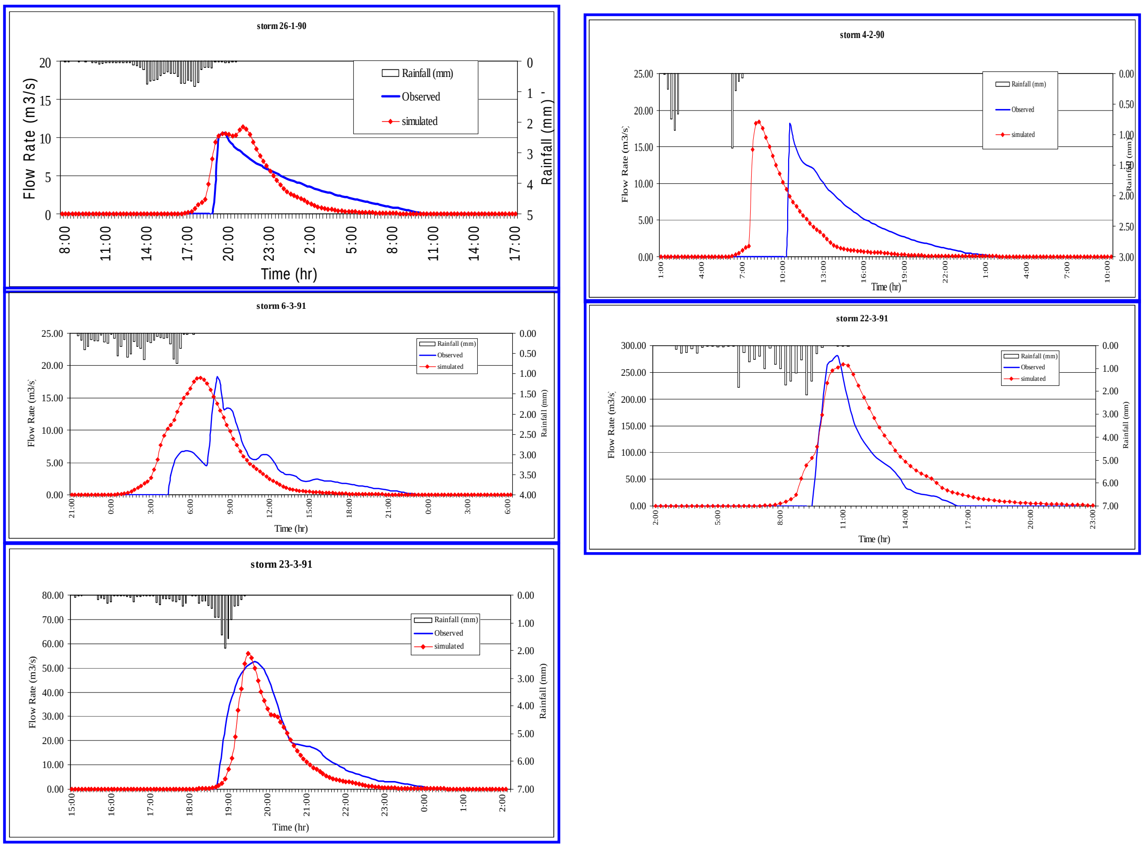

Figure (7): Simulated hydrograph for measured storms of Sudr catchment

Sensitivity Analysis of Model Simulations

Sensitivity analyses were highly needed to evaluate the impact of model parameters on the simulated hydrographs. Performing sensitivity analyses is a method to identify model parameters that have the biggest impact on model prediction.. Different model parameters were studied. As each parameter was allowed to vary, all others were held constant. The effect of the varying parameter was evaluated in terms of impacts on the peak flow rate, the time to peak and the overall hydrograph shape.

The sensitivity analysis focused on the following parameters: Manning's coefficients for overland and channel flows; and infiltration parameters for overland flow such as porosity, capillary head and hydraulic conductivity. In addition, hydraulic conductivity and thickness of streambed material were assessed to examine the effect of channel transmission losses. The effect of the initial moisture content and the spatial variation in rainfall information were also considered.

Two real storms were selected to perform the sensitivity analysis, Storm 11-3-1994 for ElMelha watershed and storm 22-3-1991 for Sudr watershed. The 'base' values that were used in this study were presented in Table (2) and all the parameters were investigated by multiplying their 'base' values by 0.5, 1.0, 1.5, and 2.0.

Table (2) Sensitivity analysis values for the watersheds

Parameter	Base Values	
	Sudr	ElMelha
Overland Manning's coeff.	0.03	0.04
Channel Manning's coeff.	0.025	0.028
Porosity	0.05	0.05
Capillary head (cm)	1	1
Hydraulic Conductivity (cm/hr)	0.05	0.1
	0.1	0.2
Initial Moisture	0.05	0.015
Channel Hydraulic Conductivity (cm/hr)	0.05	0.1
Thickness of Streambed Material (m)	1	0.5

Figures (8) & (9) summarize the impacts of the model parameters on the simulated hydrographs. It obvious from the figures that the estimates of the channel roughness had the high impact on both the peak flow rate and the time to peak flow rate prediction. While the estimates of overland roughness, hydraulic conductivity, channel hydraulic conductivity and thickness of streambed material had impact on the peak flow rate prediction only. The estimates of porosity, capillary head and initial moisture content had slight impact on peak flow rate prediction.

The sensitivity analysis of the rainfall as a spatially distributed parameter is studied by using the rainfall data of each gauge station separately. The results showed that the distribution of the rainfall over the watershed area had an impact on the resulting output hydrograph as can be noticed from the figures.

According to the results of these sensitivity analyses and to improve the model result, the estimates of watershed and rainfall parameters may need to be refined. Where there was a good deal of uncertainty in the estimation of these parameters. As example, a complete soil classification would improve the channel parameters estimates and accordingly the prediction of the hydrograph parameters.

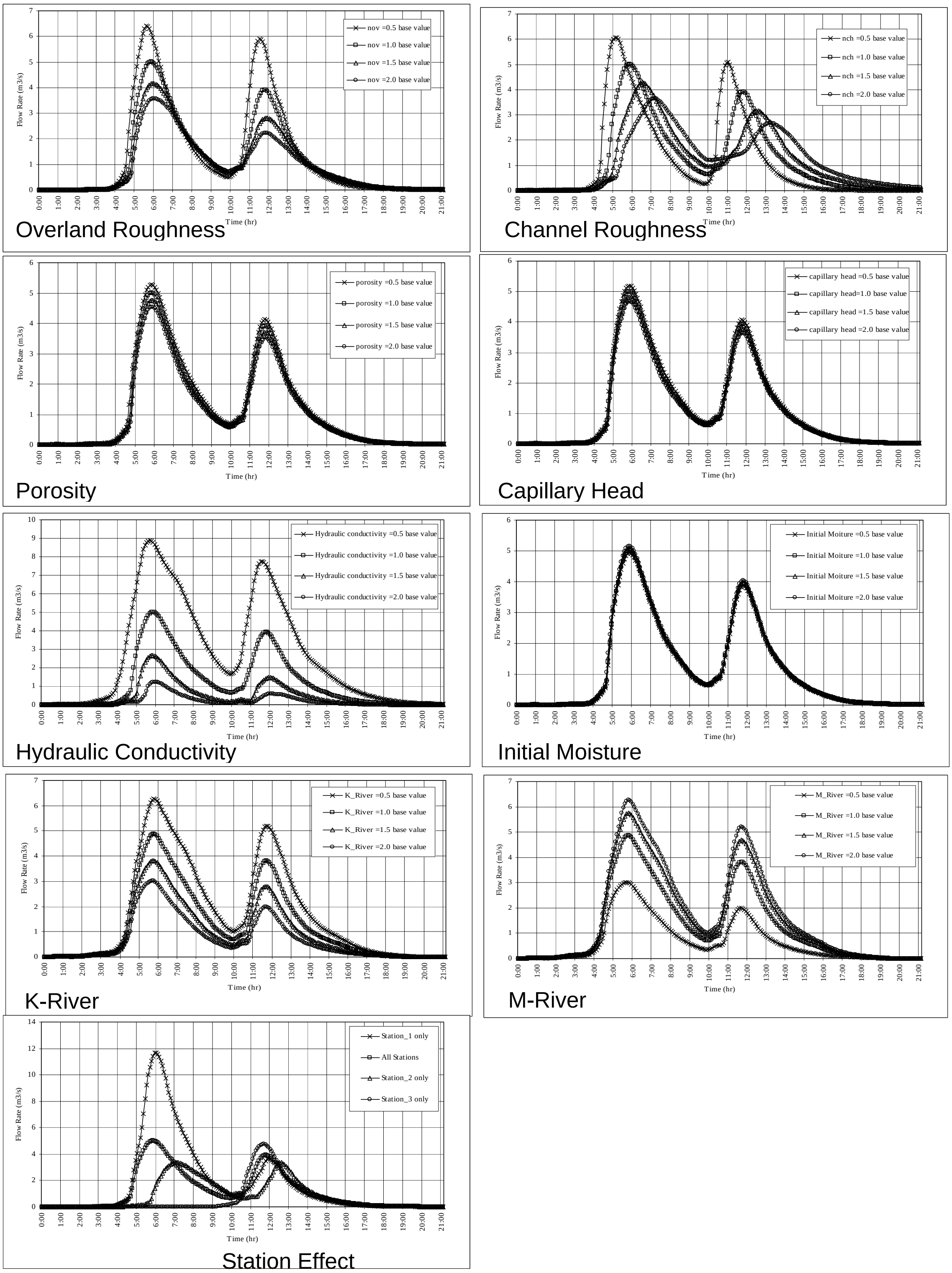

Figure (8) Sensitivity analysis results for the ElMelha watershed

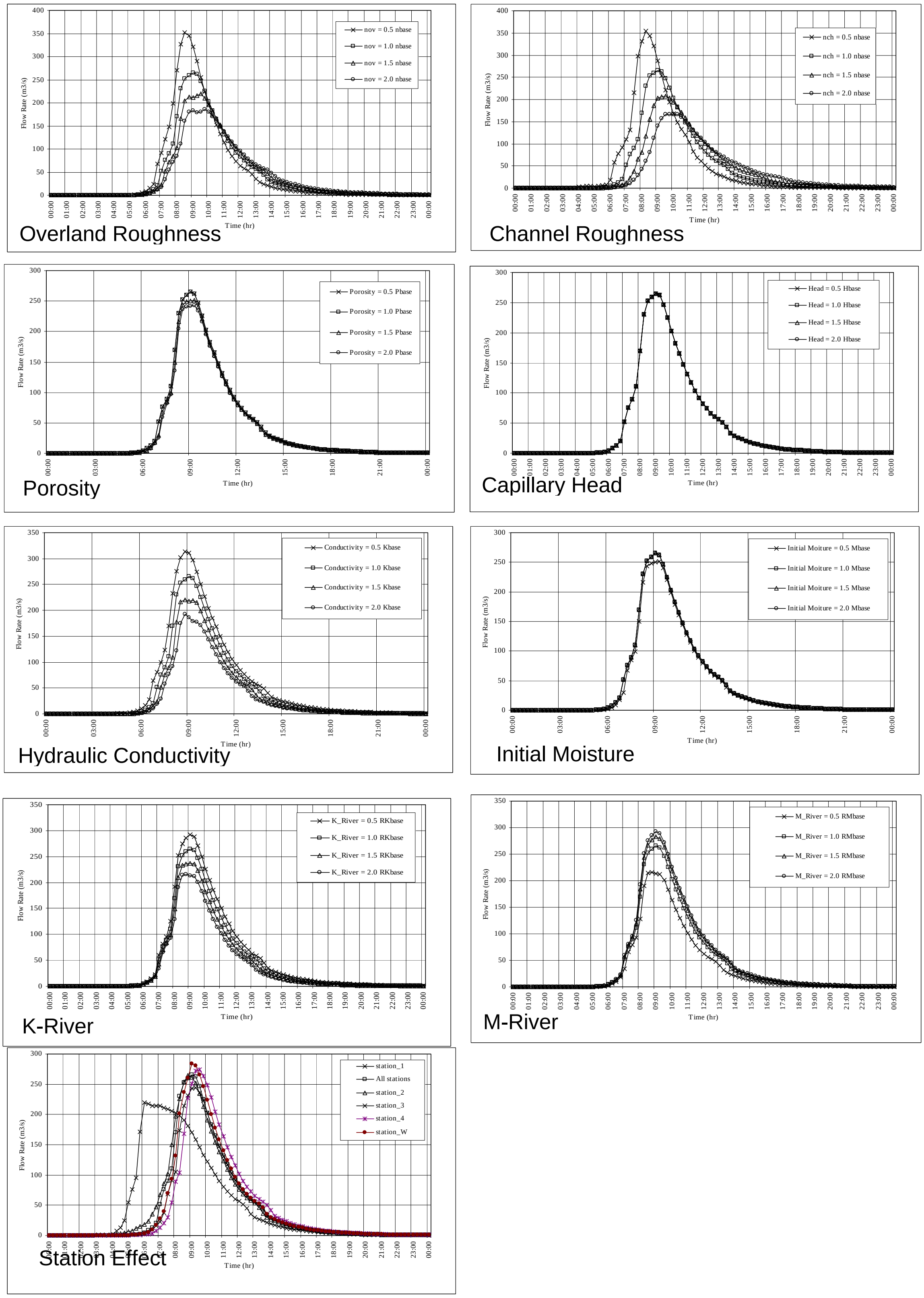

Figure (9) Sensitivity analysis results for the Sudr watershed

Summary and Conclusions

This study developed a physically-based distributed model for two arid sub-catchments in the Sinai Peninsula in Egypt. The model is based on the Gridded Surface and Subsurface Hydrologic Analysis (GSSHA) modeling system. The modeling analysis yielded a reasonably good agreement between GSSHA-simulated hydrographs and the corresponding stream-flow measurements, which indicated the ability of distributed models to better represent spatial variations in model input and parameters that affect rainfall-runoff processes in arid environments. However, the results also indicated significant sensitivity to the selection of model parameters and the representation of rainfall spatial variability due to the limited number of rainfall gauges in the catchments. Model results were most sensitive to channel routing, transmission parameters, and hydraulic conductivity. Overall, the results of this study highlight the complexity of rainfall-runoff processes in arid regions especially under the constraints of limited information on rainfall variability and the significant heterogeneity in watershed properties and model parameters. Lack of reliable and dense-enough rainfall data is the most challenging aspect of this type of analysis

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