



**AIN SHAMS UNIVERSITY
FACULTY OF ENGINEERING**

Irrigation and Hydraulics Department

**A Spatially Variable Numerical Model for the Estimation
of Runoff Hydrographs**

A Thesis Submitted in Partial Fulfillment for the Requirements of the
Degree of Master of Science in Civil Engineering
(Irrigation and Hydraulics)

**Prepared By
Remah Farid Mohamed Ali Foda**

Bachelor of Science in Civil Engineering
(Structural Engineering)
Faculty of Engineering, Ain Shams University, 2007

Supervised By

Dr. Mohamed Abdel Hamid Gad
Irrigation and Hydraulics Department
Faculty of Engineering
Ain Shams University

Prof. Dr. Ayman George Awadallah
Civil Engineering Department
Faculty of Engineering
Fayoum University

Cairo – 2016



AIN SHAMS UNIVERSITY
FACULTY OF ENGINEERING

Irrigation and Hydraulics Department

Approval sheet

**A Spatially Variable Numerical Model for the
Estimation of Runoff Hydrographs**

By

REMAH FARID MOHAMED ALI FODA

B.Sc. Civil Engineering, Ain Shams University, 2003

This thesis for M.Sc. degree had been approved by:

Name

Signature

Prof. Dr. Abdel Mohsen Al-Mongy

Irrigation and Hydraulics Department,
Faculty of Engineering, Ain Shams University.

Prof. Dr. Abdallah Bazaraa

Irrigation and Hydraulics Department,
Faculty of Engineering, Cairo University.

Prof. Dr. Ayman George Awadallah

Civil Engineering Department,
Faculty of Engineering, Fayoum University.

Dr. Mohamed Abdel Hamid Gad

Irrigation and Hydraulics Department,
Faculty of Engineering, Ain Shams University.

Date: 16/01/2016

DEDICATION

I wish to dedicate this work to who patiently supported me
throughout all stages of preparing it,

TO

MY WIFE

STATEMENT

This dissertation is submitted to Ain Shams University, Faculty of Engineering for the degree of M.Sc. in Civil Engineering. The work included in this thesis was carried out by the author in the department of Irrigation and Hydraulics, Faculty of Engineering, Ain Shams University.

No part of the thesis has been submitted for a degree or qualification at any other University or Institution. The candidate confirms that the work submitted is his own and that appropriate credit has been given where reference has been made to the work of others.

Remah Farid Mohamed Ali Foda

Signature

Date: 16 January 2016

ACKNOWLEDGMENT

I'm deeply grateful to my supervisors **Dr. Mohamed Abdel Hamid Gad** and **Prof. Dr. Ayman George Awadallah**, for their guidance, faithful supervision, helpful suggestions, great support, cooperation and help in the model building and thesis preparation.

RESEARCHER DATA

Name	: Remah Farid Mohamed Ali Foda
Date of birth	: 25/03/1981
Place of birth	: Cairo - Egypt
Last academic degree	: Bachelor of Science
Field of specialization	: Civil Engineering
University issued the degree	: Ain Shams University
Date of issued degree	: June 2003
Current job	: Environmental Engineer at Dar Al Handasah Consultants

THESIS SUMMARY

Rainfall-runoff modeling is one of the most important engineering applications in hydrology, in which the process of transforming rainfall hyetograph into a runoff hydrograph is simulated.

The majority of commonly used rainfall-runoff models are not capable of incorporating spatially distributed rainfall and other hydrological data which became more available through satellite imaging and rainfall radar scan. Therefore, development of advanced hydrologic models adopting spatially variable input is considered highly desirable.

In this research, a GIS based rainfall-runoff model was developed with advanced capabilities including calculation of infiltration losses incorporating the spatiotemporal variability of it, implementing spatially distributed rainfall data (e.g. rainfall grids) as input to the model, performing the excess rainfall-runoff transformation using an advanced grid-based computation algorithm for spatially varied hydraulic radius calculation and implementation of flow path response functions for runoff flow routing, and the capability of simulating any number of watersheds simultaneously to reduce the hydrologic design time.

Previous research work in rainfall-runoff modeling was reviewed with special attention to the theories related to grid-based travel time calculations and runoff flow routing.

A custom Visual Basic (VB) code was developed under the environment of Esri ArcGIS software constituting four main modules

for a) geomorphologic analysis, b) rainfall input processing and precipitation loss calculation, c) grid-based flow velocity calculation, and d) runoff flow routing and hydrograph generation. The developed model included custom VB modules developed to perform hydrologic calculations by implementing various theoretical formulas adopted for use in the model, in addition to several standard functions already available in ArcGIS software.

The model was tested, calibrated, and validated using the recorded rainfall and runoff data of two case studies. The first was Walnut Gulch Experimental Watershed (WGEW) encompassing about 150 square kilometers in the semi-arid region of southeastern Arizona in USA ; and the second was Wadi Sudr Experimental Watershed (Egypt) of about 380 square kilometers.

The model was also applied in a hypothetical engineering design case, in eastern desert of Egypt, in order to present various model capabilities and test its performance.

Research conclusions were presented and recommendations were provided for future research work.

Key words:

rainfall - runoff - modelling - watershed - arid – GIS

Supervisors

Dr. Mohamed Abdel Hamid Gad

Prof. Dr. Ayman George Awadallah

TABLE OF CONTENTS

CHAPTER 1 – INTRODUCTION	1
1.1. General.....	1
1.2. Problem Statement	2
1.3. Research Objective	3
1.4. Thesis Layout.....	4
CHAPTER 2 – LITERATURE REVIEW	6
2.1. Introduction.....	6
2.2. Research Work.....	6
2.3. Summary	21
CHAPTER 3 – MODEL CONSTRUCTION	23
3.1. General.....	23
3.2. Model Schematic Flow Diagram	23
3.2.1. Geomorphologic Analysis Module	24
3.2.2. Precipitation Loss Calculation Module	33
3.2.3. Flow Velocity Calculation Module	44
3.2.4. Runoff Flow Routing and Hydrograph Generation Module	49
CHAPTER 4 – DATA COLLECTION AND PRE-PROCESSING	57
4.1. General.....	57
4.2. Study Area	57

4.3.	Watershed Instrumentation	59
4.4.	Watershed Topography	61
4.5.	Watershed Geology and Soils	62
4.6.	Watershed Vegetation	67
4.7.	Watershed Climate	70
4.8.	Precipitation Data	73
4.9.	Runoff Flow Data	81
CHAPTER 5 – MODEL CALIBRATION AND VALIDATION.....		87
5.1.	General	87
5.2.	Model Sensitivity Analysis	87
5.2.1.	Sensitivity to Dispersion Coefficient	87
5.2.2.	Sensitivity to Manning’s Roughness and Hydraulic Radius Calculation Method	92
5.2.3.	Sensitivity to Precipitation Loss Parameters	98
5.3.	Case Study 1: Walnut Gulch Experimental Watershed	102
5.3.1.	Model Calibration	102
5.3.2.	Model Validation	120
5.4.	Case Study 2: Wadi Sudr Experimental Watershed	137
CHAPTER 6 – MODEL APPLICATION.....		143
6.1.	General	143
6.2.	Model Application Case Study	143

**CHAPTER 7 – SUMMARY, CONCLUSIONS, AND
RECOMMENDATIONS..... 156**

7.1. General.....156

7.2. Research Summary156

7.3. Conclusions.....159

7.4. Recommendations.....162

REFERENCES..... 165

LIST OF FIGURES

Figure 3-1: General Workflow Diagram of the Model	24
Figure 3-2: Workflow Diagram of Geomorphologic Analysis Module	25
Figure 3-3: Typical Process of Sink Filling and Peak Removal in a DEM (Source: ArcGIS 9.1 Desktop Help)	26
Figure 3-4: Typical Flow direction Notation (Source: ArcGIS 9.1 Desktop Help)	27
Figure 3-5: Example of Flow Direction Grid Calculation	27
Figure 3-6: Example of Flow Accumulation Grid Calculation	28
Figure 3-7: Example of Watershed Grid Calculation	30
Figure 3-8: Example of Slope Grid Calculation	32
Figure 3-9: Workflow Diagram of Precipitation Loss Calculation Module	33
Figure 3-10: Example of Rainfall Grid Stack Input.....	36
Figure 3-11: Example of Total Depth Grid with Standard Rainfall Distribution Input.....	37
Figure 3-12: Example of Rainfall Hyetograph Input.....	38
Figure 3-13: Example of Total Depth Value Plus Standard Rainfall Distribution Input.....	39
Figure 3-14: Example of CN grid calculation from Input CN Polygons.....	42

Figure 3-15: Example of Excess Rainfall Calculation Process	43
Figure 3-16: Workflow Diagram of Flow Velocity Calculation Module	44
Figure 3-17: Example of Hydraulic Radius Calculation Process	47
Figure 3-18: Example of Velocity Grid Calculation Process	48
Figure 3-19: Workflow Diagram of Runoff Flow Routing and Hydrograph Generation Module	49
Figure 3-20: Example of “ T_i ” and “ Π_i ” Grids Calculation Process.....	53
Figure 3-21: Relationship between Impulse Response Timeline and Overall Watershed Response Timeline.....	55
Figure 3-22: Composition of Watershed Outflow Hydrograph.....	56
Figure 4-1: Location of Walnut Gulch Experimental Watershed (Source: SWRC & WGEW Brochure, 2007)	59
Figure 4-2: Walnut Gulch Watershed Instrumentation (Source: SWRC & WGEW Brochure, 2007)	60
Figure 4-3: Walnut Gulch Watershed 30m Resolution DEM.....	63
Figure 4-4: Walnut Gulch Watershed Calculated Slope Grid	64
Figure 4-5: Walnut Gulch Watershed Streamline Order (Source: SWRC & WGEW Brochure, 2007)	65
Figure 4-6: Walnut Gulch Watershed Geology (Source: Osterkamp, 2008).....	66
Figure 4-7: Walnut Gulch Watershed Soils (Source: Osterkamp, 2008)	67

Figure 4-8: Walnut Gulch Watershed Vegetation Map (Source: Vegetation data, Walnut Gulch Experimental Watershed, Arizona, United States, 2008).....	69
Figure 4-9: Climatic Characteristics of Walnut Gulch Watershed (Source: SWRC & WGEW Brochure, 2007)	71
Figure 4-10: Precipitation (mm) Storm Event August 27, 1982 (Source: SWRC & WGEW Brochure, 2007)	72
Figure 4-11: Total Precipitation (mm) of August 1982 (Source: SWRC & WGEW Brochure, 2007)	72
Figure 4-12: Rain Gauges in Walnut Gulch Watershed	74
Figure 4-13: Averaged Storm Hyetographs of the Two Selected Events.....	75
Figure 4-14: Sampled Rainfall Grids of First Event.....	77
Figure 4-15: Sampled Rainfall Grids of Second Event	79
Figure 4-16: Locations of the 11 Flumes on Large Watersheds of WGEW	83
Figure 4-17: Catchment Areas of the Selected Five Flumes	84
Figure 4-18: Recorded Runoff Hydrographs of the Selected Five Flumes in the First Event (July, 2012).....	85
Figure 4-19: Recorded Runoff Hydrographs of the Selected Five Flumes in the Second Event (August, 2000)	86
Figure 5-1: Calculated Outlet Hydrographs for Single Cell at Various Dispersion Coefficient Values	91

Figure 5-2: Calculated Outlet Hydrographs at Various “n” Values with Two-predictor Hydraulic Radius Formula.....	94
Figure 5-3: Calculated Outlet Hydrographs at Various “n” Values with Three-predictor Hydraulic Radius Formula.....	95
Figure 5-4: Calculated Peak Flow at Various “n” Values with Both Hydraulic Radius Formulas	96
Figure 5-5: Calculated Time to Peak at Various “n” Values with Both Hydraulic Radius Formulas.....	97
Figure 5-6: Calculated Outlet Hydrographs at Various “CN” Values with a “ λ ” Value of 0.15	99
Figure 5-7: Calculated Outlet Hydrographs at Various “CN” Values with a “ λ ” Value of 0.10	99
Figure 5-8: Calculated Outlet Hydrographs at Various “CN” Values with a “ λ ” Value of 0.15	100
Figure 5-9: Calculated Outlet Hydrographs at Various “CN” Values with a “ λ ” Value of 0.20	100
Figure 5-10: Calculated Total Runoff Volume at Various “CN” and “ λ ” Values	101
Figure 5-11: Calculated Peak Flow at Various “CN” and “ λ ” Values	101
Figure 5-12: Adopted CN Map of WGEW in the Calibration Event .	107
Figure 5-13: Calibration Analysis Grids of Flume FL001.....	108
Figure 5-14: Calibration Analysis Grids of Flume FL006.....	110