INFORMATION TO USERS

This was produced from a copy of a document sent to us for microfilming. While the most advanced technological means to photograph and reproduce this document have been used, the quality is heavily dependent upon the quality of the material submitted.

The following explanation of techniques is provided to help you understand markings or notations which may appear on this reproduction.

1. The sign or "target" for pages apparently lacking from the document photographed is "Missing Page(s)". If it was possible to obtain the missing page(s) or section, they are spliced into the film along with adjacent pages. This may have necessitated cutting through an image and duplicating adjacent pages to assure you of complete continuity.

2. When an image on the film is obliterated with a round black mark it is an indication that the film inspector noticed either blurred copy because of movement during exposure, or duplicate copy. Unless we meant to delete copyrighted materials that should not have been filmed, you will find a good image of the page in the adjacent frame. If copyrighted materials were deleted you will find a target note listing the pages in the adjacent frame.

3. When a map, drawing or chart, etc., is part of the material being photographed the photographer has followed a definite method in "sectioning" the material. It is customary to begin filming at the upper left hand corner of a large sheet and to continue from left to right in equal sections with small overlaps. If necessary, sectioning is continued again—beginning below the first row and continuing on until complete.

4. For any illustrations that cannot be reproduced satisfactorily by xerography, photographic prints can be purchased at additional cost and tipped into your xerographic copy. Requests can be made to our Dissertations Customer Services Department.

5. Some pages in any document may have indistinct print. In all cases we have filmed the best available copy.
Mossaad, Mostafa El-Sayed

A STOCHASTIC MODEL FOR SOIL EROSION

The Ohio State University

Ph.D. 1981

University
Microfilms
International
300 N. Zeeb Road, Ann Arbor, MI 48106

Copyright 1982
by
Mossaad, Mostafa El-Sayed
All Rights Reserved
PLEASE NOTE:

In all cases this material has been filmed in the best possible way from the available copy.
Problems encountered with this document have been identified here with a check mark ✓.

1. Glossy photographs or pages
2. Colored illustrations, paper or print
3. Photographs with dark background
4. Illustrations are poor copy
5. Pages with black marks, not original copy
6. Print shows through as there is text on both sides of page
7. Indistinct, broken or small print on several pages
8. Print exceeds margin requirements
9. Tightly bound copy with print lost in spine
10. Computer printout pages with indistinct print ✓
11. Page(s) _________ lacking when material received, and not available from school or author.
12. Page(s) _________ seem to be missing in numbering only as text follows.
13. Two pages numbered __________. Text follows.
14. Curling and wrinkled pages
15. Other

University Microfilms International
A STOCHASTIC MODEL FOR SOIL EROSION

DISSERTATION

Presented in Partial Fulfillment of the Requirements for
the Degree Doctor of Philosophy in the Graduate
School of The Ohio State University

By

Mostafa El-Sayed Mossaad, B.Sc. (honors), M.A.Sc.

* * * * *

The Ohio State University

1981

Reading Committee:
T. H. Wu
V. T. Ricca
K. W. Bedford
W. E. Wolfe

Approved By

[Signature]
Adviser
Department of Civil Engineering
ACKNOWLEDGMENTS

This work would not have been possible but for the help and cooperation of many people.

I very gratefully and sincerely thank my adviser, Professor T.H. Wu for his constant encouragement and sound advice throughout the course of my doctoral study. His example of excellence and discipline shall always remain for me to follow.

I would like also to thank Professor K.W. Bedford for his suggestions regarding the use of Spectral Analysis, and for his generous supply of references. The invaluable comments of Professor V. Ricca on the hydraulic aspects of the study are most appreciated. The surface roughness data provided by Professor D. Van Doren, Jr. of the Ohio Agricultural Research and Development Center, Wooster, Ohio is gratefully acknowledged.

My gratitude to the Institute of Mining and Minerals Resources Research, at The Ohio State University, for granting me its Research Fellowship for the last two years of this study.

Special thanks is due to my friend Dr. Kamil Eren for offering me the privilege of using his own computer program of Spectral Analysis. Thanks are also due to my colleague, Dr. El-Fatih Ali for his valuable suggestions and ideas.

Finally, a word of appreciation is due to my wife, Dina, and my son Marwan for their patience and understanding during the course of my graduate work.
VITA

November 29, 1951

Born: Portsaïd, Egypt

1973

B.Sc. (honor), Faculty of Engineering, Cairo University, Egypt.

1975-1977

Teaching and Research Assistant, Civil Engineering Department, The University of Windsor, Windsor, Ontario, Canada.

1977

M.A.Sc. The University of Windsor, Windsor, Ontario, Canada

1977-1981

Graduate Research Associate, Civil Engineering Department, The Ohio State University, Columbus, Ohio

Publications


Fields of Study

Major Field: Civil Engineering

Studies in Geotechnical Engineering. Professors T.H. Wu, H. Gray, W. Wolfe, and J.T. Laba
Studies in Mechanics. Professors J.B. Kennedy, L. Fu.


TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Acknowledgments</th>
<th>ii</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vita</td>
<td>iii</td>
</tr>
<tr>
<td>List of Tables</td>
<td>ix</td>
</tr>
<tr>
<td>List of Figures</td>
<td>x</td>
</tr>
</tbody>
</table>

CHAPTER

I  INTRODUCTION ................................................. 1

II  REVIEW OF LITERATURE ................................. 6
   2.1 Empirical Models ................................. 6
   2.2 Analytical Models .................. 8
   2.3 Concept of Rill-Interrill Erosion .... 12
   2.4 Studies on Rill Patterns .......... 15
   2.5 Concluding Remarks .................... 17

III RANDOM SURFACE GENERATION ................. 19
   3.1 General Outline .......................... 19
   3.2 Analysis of Surface Roughness Data .... 20
      3.2.1 Method of Spectral Analysis ...... 21
      3.2.2 Important Assumptions and Considerations 23
      3.2.3 Observations from Spectral Analysis .. 25
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3</td>
<td>Procedure of Random Surface Generation</td>
<td>27</td>
</tr>
<tr>
<td>3.3.1</td>
<td>Analysis of the Data</td>
<td>27</td>
</tr>
<tr>
<td>3.3.2</td>
<td>Construction of the Random Surface</td>
<td>28</td>
</tr>
<tr>
<td>3.4</td>
<td>The Method of Zero-Crossing Analysis</td>
<td>29</td>
</tr>
<tr>
<td>3.4.1</td>
<td>Outline of the Method</td>
<td>30</td>
</tr>
<tr>
<td>3.4.2</td>
<td>Generation of Random Surface</td>
<td>32</td>
</tr>
<tr>
<td>3.5</td>
<td>Concluding Remarks</td>
<td>36</td>
</tr>
<tr>
<td>IV</td>
<td>EROSION MODEL</td>
<td>47</td>
</tr>
<tr>
<td>4.1</td>
<td>Rill Erosion Equation</td>
<td>48</td>
</tr>
<tr>
<td>4.2</td>
<td>Interrill Erosion Equation</td>
<td>54</td>
</tr>
<tr>
<td>4.3</td>
<td>Concluding Remarks</td>
<td>56</td>
</tr>
<tr>
<td>V</td>
<td>SIMULATION MODEL</td>
<td>61</td>
</tr>
<tr>
<td>5.1</td>
<td>Main Features of the Model</td>
<td>61</td>
</tr>
<tr>
<td>5.1.1</td>
<td>Routing of Water and Sediment</td>
<td>62</td>
</tr>
<tr>
<td>5.1.2</td>
<td>Erosion of the Surface</td>
<td>63</td>
</tr>
<tr>
<td>5.1.3</td>
<td>Temporal Change</td>
<td>64</td>
</tr>
<tr>
<td>5.2</td>
<td>Auxiliary Mechanisms</td>
<td>65</td>
</tr>
<tr>
<td>5.2.1</td>
<td>Ponding</td>
<td>65</td>
</tr>
<tr>
<td>5.2.2</td>
<td>Deposition Due to Ponding</td>
<td>66</td>
</tr>
<tr>
<td>5.2.3</td>
<td>Stability of Rill's Side Slopes</td>
<td>67</td>
</tr>
<tr>
<td>5.2.4</td>
<td>Low Humps</td>
<td>68</td>
</tr>
<tr>
<td>5.3</td>
<td>Structure of the Program</td>
<td>70</td>
</tr>
<tr>
<td>5.3.1</td>
<td>The Input Data</td>
<td>70</td>
</tr>
<tr>
<td>5.3.2</td>
<td>Analysis of Surface Roughness Data</td>
<td>71</td>
</tr>
<tr>
<td>5.3.3</td>
<td>Generation of the Random Surface</td>
<td>72</td>
</tr>
</tbody>
</table>
5.3.4 Computation of Overland Flow ............ 74
5.3.5 Erosion Computation ..................... 75

VI SENSITIVITY ANALYSIS OF THE MODEL ............ 85
6.1 Geometric Limitations ......................... 86
6.2 Sensitivity to Time Interval .................. 87
6.3 Sensitivity to Parameters in Erosion Equations . 89
   6.3.1 Coefficient n in Mannings Equation (N) . 89
   6.3.2 The Constant \( a_s \) for Rill Erosion (ASR) . 93
   6.3.3 The Constant \( a_{sh} \) for Interrill Erosion (ASH) 93
   6.3.4 The Exponent \( p \) ......................... 94
6.4 Sensitivity to Criterion of Side Slope Failure . 94
6.5 Effect of Randomness in Elevation ............ 95
6.6 Effect of Randomness in Rill Pattern ........... 97

VII NUMERICAL EXPERIMENTS ....................... 114
7.1 Comparison with Field Measurements .......... 115
7.2 Effect of Slope Gradient ..................... 118
7.3 Effect of Slope Length ....................... 119
7.4 Effect of Rainfall Intensity .................. 120
7.5 Evolution of Eroding Surfaces ................ 120

VIII SUMMARY, CONCLUSIONS AND RECOMMENDATIONS ...... 130
8.1 Summary and Conclusions ..................... 130
8.2 Recommendations for Further Research .......... 133
REFERENCES .......................................................... 135

APPENDIX A  Comparison of Rill Erosion Equation with Field Measurements  ........................................ 139

APPENDIX B  Listing and Sample Output of The Computer Program  .... 141
LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Results of Zero-Crossing Analysis</td>
</tr>
<tr>
<td>3.2</td>
<td>Directions of Random Component</td>
</tr>
<tr>
<td>6.1</td>
<td>Parameters used in sensitivity Analysis</td>
</tr>
<tr>
<td>A.1</td>
<td>Comparison between Measured and Computed Values of Rill Erosion</td>
</tr>
<tr>
<td>Figure</td>
<td>Title</td>
</tr>
<tr>
<td>--------</td>
<td>------------------------------------------------------------</td>
</tr>
<tr>
<td>3.1</td>
<td>Natural Surface Roughness</td>
</tr>
<tr>
<td>3.2</td>
<td>Elevation Trace</td>
</tr>
<tr>
<td>3.3</td>
<td>Measurement Plot</td>
</tr>
<tr>
<td>3.4</td>
<td>Spectral Density Function of Surface Roughness</td>
</tr>
<tr>
<td>3.5</td>
<td>Simulation of Surface Roughness</td>
</tr>
<tr>
<td>3.6</td>
<td>Isotropy in Square Rill Pattern</td>
</tr>
<tr>
<td>3.7</td>
<td>Isotropy in Hexagonal Rill Pattern</td>
</tr>
<tr>
<td>3.8</td>
<td>Parameters used in Zero-Crossing Analysis</td>
</tr>
<tr>
<td>3.9</td>
<td>Sequences Computed in Zero-Crossing Analysis</td>
</tr>
<tr>
<td>3.10</td>
<td>Average Wave used in Constructing a Hexagonal Rill Pattern</td>
</tr>
<tr>
<td>3.11</td>
<td>Uniform Rill Pattern</td>
</tr>
<tr>
<td>3.12</td>
<td>Random Rill Pattern</td>
</tr>
<tr>
<td>4.1</td>
<td>Surface Idealization</td>
</tr>
<tr>
<td>4.2</td>
<td>Rill Cross-Section</td>
</tr>
<tr>
<td>4.3</td>
<td>Flow Over Interrill Area</td>
</tr>
<tr>
<td>4.4</td>
<td>Geometrical Basis for Interrill Erosion Computation</td>
</tr>
<tr>
<td>5.1</td>
<td>Typical Routing of Rill and Interrill Flow</td>
</tr>
<tr>
<td>5.2</td>
<td>Change in Rill Geometry due to Rill Erosion</td>
</tr>
<tr>
<td>5.3</td>
<td>Ponding Conditions</td>
</tr>
<tr>
<td>5.4</td>
<td>Deposition due to Ponding</td>
</tr>
<tr>
<td>5.5</td>
<td>Mechanism of Side-Slope Failure</td>
</tr>
</tbody>
</table>
5.6 Segment with Positive Side Slopes .......................... 80
5.7 Segment with a Negative Side Slope ................. 80
5.8 Possible Cases associated with the low hump situation . 81
5.9 Computational Scheme ................................. 82
5.10 Construction of the Hexagonal Mesh .............. 83
5.11 Schematic Representation of Model Subroutines ... 84
6.1 ER vs T curve for a 20 x 50 mesh .................... 102
6.2 ER vs T curve for a 50 x 20 mesh ............... 102
6.3 Relationship between Erosion rate and time interval; short range .......... 103
6.4 Relationship between Erosion rate and time interval; long range ...... 103
6.5 Effect of Manning's Coeff. on erosion rate ....... 104
6.6 Effect of Manning's Coeff. on R/I Erosion ratio ... 104
6.7 R/I vs T curve for n = 0.04 for an 8-hr test ...... 105
6.8 Effect of the Constant ASR on Erosion rate ........ 106
6.9 Effect of the Constant ASR on R/I erosion ratio ... 106
6.10 Effect of the Constant ASH on Erosion rate ....... 107
6.11 Effect of the Constant ASH on R/I Erosion ratio ... 107
6.12 Effect of the Exponent p on Erosion rate ......... 108
6.13 Effect of the Exponent p on R/I erosion ratio ... 108
6.14 Effect of the factor SLIMIT on Erosion Rate ....... 109
6.15 Effect of the factor SLIMIT on R/I erosion ratio ... 109
6.16 Erosion on Uniform Surface ......................... 110
6.17 Test Samples from Uniform Rill Pattern .......... 111
6.18 Test Samples from Random Rill Pattern .......... 111
6.19 Effect of Rill Pattern Randomness on Flow; Test no. 1 . . 112
6.20 Effect of Rill Pattern Randomness on Flow; Test no. 2 . . 112
6.21 Irregularity in Generated surfaces ................. 113
7.1 Soil Loss from the Clay Site ....................... 122
7.2 Soil Loss from the Sandy Clay Site ............... 122
7.3 Effect of slope gradient on erosion rate ........... 123
7.4 Effect of time on the slope gradient - Erosion rate relation .................. 123
7.5 Effect of slope length on erosion rate .............. 124
7.6 Effect of slope length on R/I erosion ratio ....... 124
7.7 Effect of Rainfall intensity on erosion rate; RNL=50mm/hr 125
7.8 Effect of Rainfall intensity on erosion rate; RNL=25mm/hr 125
7.9 Effect of Rainfall intensity on erosion rate; RNL=12.5mm/hr 126
7.10 Relationship between Rainfall Intensity, Slope Gradient and Erosion Rate ....................... 126
7.11 Original Surface, t = 0 ............................ 127
7.12 Eroded surface, t = 200 minutes ................. 128
7.13 Eroded surface, t = 400 minutes ................. 129
CHAPTER I
INTRODUCTION

The problems of erosion and sedimentation have plagued man since those first days in ancient times when he began to alter the natural condition of the earth's surface for agricultural and other developmental activities. Millions of tons of soil are being eroded every year from agricultural fields, construction sites, and surface mining areas. Not only is the most productive surface soil being lost, but also serious environmental and economic problems are encountered due to sedimentation of this eroded soil in waterways and reservoirs.

Wise selection of land management practices to control erosion requires better estimation of erosion and sediment yield. Therefore, since the turn of the century, enormous efforts were made to develop better understanding and more accurate prediction of soil erosion.

The complexity of the process of soil erosion arises from the random nature of the natural factors that control erosion, which include rainfall characteristics, soil type, geology, and local topography. As described by Meyer et al. (25), the erosion process normally begins when raindrops strike a sloping soil surface. The impact of raindrops detaches soil particles from the soil mass. Conceptually, all rainfall is infiltrated so long as the infiltration capacity
exceeds the rainfall rate. The infiltration rate, however, decreases gradually due to the saturation of the surface soil, and due to the sealing of the surface voids by the raindrop impact. Once the rainfall rate exceeds the infiltration rate, some of the excess water may be ponded as surface storage in depressions, and the remainder becomes runoff by shallow overland flow. As the overland flow moves downslope, it increases in volume, and tends to concentrate into rills because of tillage marks and/or natural microtopography of the slope. The flow erodes soil and transports it downslope as suspension or as bedload or both. Successive rainstorms deepen the rills progressively until they become gullies.

The importance of the phenomenon of "rilling" has been addressed by many researchers (4, 24, 25, 46). Yet, existing erosion models either ignore the process of rilling, or include it as an empirical term without consideration of the process taking place in individual rills. This is, of course, due to the difficulty imposed by the complicated rill patterns, which change continuously with time.

The general objective of the present study is to develop an erosion model which can deal with the surface geometry on the small scale of individual rills, and which can describe the temporal evolution of the surface geometry as the erosion process accelerates. With the complexity of the erosion process in mind, it is obviously difficult to achieve a comprehensive model which accounts for all or most of the randomness involved in that process in a single study. Therefore, the model represents a first step along this line.
The present study considers the original surface irregularities, or microrelief, as a major factor contributing to the rilling process which is, in turn, an important feature of soil erosion. More specifically, the objective of this study is to develop a computer model which can perform the following:

1. Analyze the surface roughness data (microrelief measurements);

2. Based upon the statistical properties obtained from Item (1), the model should regenerate the slope surface in a fashion suitable for subsequent erosion computations;

3. Carry out erosion computations using a mathematical model which is based on the principles of erosion mechanics and hydraulics;

4. Account for temporal changes in the surface geometry, and its effect on subsequent erosion by an updating computational process.

The analysis of surface roughness data is carried out using the method of spectral analysis. For a given random surface generated by the model, the overland flow during any time interval is computed at every nodal point. During any time interval, the flow properties and the geometry are assumed to be constant. Material eroded from rills and from interrill areas is then computed. The change in
elevation due to erosion during any time interval is used to revise the surface elevations. This is used for computations of the following time interval.

The scope of this study is limited to cases in which rill patterns are developed in a random fashion, depending on the surface roughness conditions. It is important to mention that the tendency of rills to meander decreases as the slope steepens. In very steep slopes, the rill pattern develops into a number of almost straight gullies. In such cases, the randomness of the flow pattern is greatly eliminated, and the mechanism of the erosion process becomes different.

At the present stage, the model is designed for bare plane slopes with small scale irregularities. Deep tillage marks and local topographic variations are considered as large scale variations.

After reviewing the state of the art in Chapter II, the basic concepts and the model formulation are discussed in Chapters III and IV. Chapter V describes the computer model with the various mechanisms involved in the simulation process. The sensitivity of the model to different parameters and mechanisms is tested in Chapter VI. The model results are compared with the general features of the process of soil erosion through a number of numerical experiments described in Chapter VII. Chapter VIII summarizes the conclusions and recommendations for further work.

The work presented herein, although far from being ready for practical use, provides a new approach to the problem of soil erosion.
Further perfection of the techniques used can be valuable for the purpose of erosion prediction, and definitely improves the understanding of this phenomenon.
CHAPTER II
REVIEW OF LITERATURE

To design against erosion, researchers have continuously attempted to develop methods to estimate the amount of soil eroded from the land under different topographic and climatic conditions. Approaches found in the literature to tackle this problem can be classified into two main categories: empirical models based on large amounts of data collected over the years, and analytical models utilizing the improved knowledge of erosion mechanics and hydraulics.

2.1 **Empirical Models**

Earlier investigations indicated that the erosion rate and consequently the sediment yield are functions of: (i) direct rainfall or snowmelt; (ii) soil type and geology; (iii) catchment topography and geometry; and (iv) land use, including vegetative and mechanical treatment. Thus, for such a complex problem, the regression technique seemed to be an effective way to analyze the available data.

Since the late thirties, several correlation equations have been proposed. Zingg (47) published an empirical equation expressing soil loss as a function of slope length and steepness. Other researchers used this relation as a basis for developing erosion prediction
equations. Of those, we mention Musgrave (27), Wischmeier and Smith (40), Meyer and Kramer (22), and Young and Mutchler (45).

The most widely used correlation equation is the so-called Universal Soil Loss Equation (USLE), developed by Wischmeier and Smith (40), and Wischmeier (41). It includes greater detail in several aspects than the Musgrave (27) equation, or other predecessors. The USLE has the form:

\[ A = R K L S C P \]  \hspace{1cm} (2.1)

which identifies the average annual soil loss, \( A \), in terms of six major factors: rainfall erosiveness, \( R \); soil erodability, \( K \); slope length factor, \( L \); slope steepness factor, \( S \); cropping and management practices factor, \( C \); and the supporting conservation practice factor, \( P \). The mathematical relationships for the six factors were determined from statistical analysis of more than 10,000 plot years of data. The USLE was designed to estimate the long-term average annual soil losses for upland slopes where deposition is negligible. Erosion from gullies and stream channels or deposition on or below upland slopes is not considered in the USLE. The equation is applicable to seasonal periods with some increase in the margin of error, but it is least accurate for individual storms. Hence, for problems such as sediment control for construction sites, where soil loss estimates are needed for individual storm events, the computed estimates using the USLE may differ greatly from field observations (42). In addition, Frere et al. (10) indicated that some plant nutrients
and agricultural chemicals absorbed on sediments are also transported by overland flow. Evaluating the potential chemical yield requires the estimation of the amounts of sediment originating from the soil within the tillage layer. Generally, it is important to evaluate the amount of sediment coming from different locations along a slope. Unfortunately, these requirements are not fulfilled by the USLE.

2.2 Analytical Models

According to the previous section, the existing empirical equations do not meet the present need for a dynamic soil erosion model that can describe soil movement at different locations on a slope, at any time. This section reviews some of the important developments made along this line.

In the late sixties, researchers began developing soil erosion models based on concepts from erosion mechanics. An early effort in this field was made by Meyer and Wischmeier (23). Following the definition of soil erosion processes suggested by Ellison (5), they described soil erosion as a process of detachment and transportation of soil materials by the erosive agents: rainfall and runoff. Each agent has both a detaching and a transporting capacity, and Ellison suggested that these subprocesses must be studied separately. Similarly, the susceptibility of soil to erosion can be separated into its two components, susceptibility to detachment and susceptibility to transportation. In the same study, based upon some fundamentals of hydraulics and hydrology for steady
state conditions, Meyer and Wischmeier developed four equations describing the four subprocesses mentioned above. For the runoff, they adopted the principle of tractive force used in sediment transport mechanics, and derived equations to compute detachment capacity of the runoff, $D_F$, and the transport capacity of the runoff, $T_F$. Two other relations were derived to compute detachment capacity and transport capacity of rainfall ($D_R$ and $T_R$, respectively). In each of those four equations, parameters were introduced to describe related soil properties. Their simulation model divides the slope length into segments. On each segment, the four quantities, $D_F$, $T_F$, $D_R$ and $T_R$ are evaluated, and the actual soil loss is considered the lesser of the two summations, $(D_F + D_R)$ and $(T_F + T_R)$. This concept means that, on one hand, only particles that have been detached from the soil mass will be eroded, no matter how great the transport capacity. On the other hand, only particles that can be transported by the flow will be eroded, no matter how much is detached and available for transportation. The model, although primarily conceptual, contributes to the understanding of the soil erosion process. To proceed beyond the steady-state condition, the different parameters should be considered as time-dependent variables. Among those parameters are rainfall intensity, infiltration rate, and rill geometry as it affects the hydraulics of runoff.

In their attempt to improve the model, Foster and Meyer (8) studied experimentally the applicability of the sediment transport equations developed for rivers, to the shallow overland flow problem.
According to their study, Yalin's transport equation (43), which is based on the principle of tractive force, gives the best fit to experimental results. Their observations indicate that during simulated rain storms, a large fraction of aggregates detached from a cohesive soil mass moves by saltation and by rolling along the bottom of the small flow channels, the same type of grain motion assumed in Yalin's derivation.

Recently, Foster et al. (6) developed a field scale erosion model as a part of the comprehensive model for agricultural management systems called CREAMS. This is based upon the already-described Meyer and Wischmeier (23) model. A modified Yalin equation, to account for more than one soil particle diameter, is used to compute the transport capacity of the overland flow. The model allows for overland flow, channel flow, and impoundment. Computations are performed on a single storm basis.

Although these models deal with detachment and transport capacities separately, as suggested by Ellison (5), it is understood that the two quantities are interrelated (23). To define the interrelationship, Foster and Meyer (7) suggested the equation:

\[
\frac{\text{Detachment rate by flow}}{\text{Detachment capacity of flow}} + \frac{\text{Sediment load of flow}}{\text{Transport capacity of flow}} = 1 \quad (2.2)
\]

which was based upon some observations. Equation (2.2) agrees with Einstein's assumption that the rate of deposition is directly proportional to the difference between the actual sediment concentration in
the flow and the equilibrium concentration for the flow conditions. Based on Equation (2.2) and on the continuity of mass equation, Foster and Meyer derived a closed form solution for erosion and deposition rates on a slope of variable configurations. The model, however, assumes a steady state condition and a constant rill pattern on the slope.

Li et al. (11) considered the overland flow as a steady spatially-varied flow with the rainfall taken as lateral inflow. The shear stresses resulting from this flow were then used to compute the pick-up rate of sediment, on the basis of the following empirical relationship:

\[ P_S = a \tau_0^b \] (2.3)

where \( P_S \) is the sediment pick-up rate per unit area; \( \tau_0 \) is the boundary shear stress; and, \( a, b \) are constants.

This model considers only straight slopes with no deposition. Komura (17) modified the model of Li et al. (19) by using Kalinske's bed load function to determine the values of the constants \( a \) and \( b \) in Equation (2.3). The results of his computations agree with the results of some field measurements.

A more general analytical solution was presented by Smith (38). Unlike most of the preceding analytical models, Smith developed a numerical model that accounts for variable slope shape, length, and boundaries, for unsteady state conditions. The equation is solved
implicitly with a time-weighted four-point method at each time step. The structure of the model enables it to simulate the response from complex watershed shapes and serve as a framework within which alternative erosion and transport models can be compared. The process of development of rills with space and time is not considered in this model.

2.3 Concept of Rill - Interrill Erosion

As we recall from the description of the erosion process in Chapter I, the overland flow begins after the rainfall rate exceeds the soil infiltration rate. Then, as overland flow moves downslope, it tends to concentrate into rills. Realizing the important role of the rill pattern, researchers in the early seventies started to consider the erosion process as divided into two components: rill erosion, which results primarily from soil detached by concentrated runoff on a limited part of the land surface, and interrill erosion caused by raindrop impact and by a sheet flow over the remainder of the land surface.

All the models presented in Sections 2.1 and 2.2 combine rill and interrill erosion into a common effect. Consequently, they ignore the continuous change in the surface erodability due to the change in rill geometry with time and with distance downslope.

The importance of the rill-interrill erosion concept arises from the fact that the total amount of eroded soil depends greatly on the extent of "rilling" of a slope. This is due to the greater
transport capacity of rill flow than that of sheet flow (24). Moreover, the continuous change in rills geometry is clearly accompanied by a corresponding change in their hydraulic characteristics. Accordingly, their detachment and transport capacities vary with time and distance downslope. This, in turn, affects the total erosion rate from a slope. By separately evaluating a soil's susceptibility to rill erosion and to interrill erosion, we can improve our estimate of a soil's erodability, and the effect of variables such as slope length and initial microtopography.

In the same paper, Meyer et al. suggest that the four erosion subprocesses of soil detachment by rainfall, transport by rainfall, detachment by runoff, and transport by runoff can be recognized as operating on both rills and interrill areas of an eroding slope.

According to Meyer et al. (25), in their study of rill characteristics, there is a "critical" flow rate below which rill erosion does not begin. They suggest that the process of rill erosion is a complex combination of head cuts, detachment of soil by flow shear stresses, and slumping of undercut sideslopes with subsequent removal of slumped material by flow.

The idea of dividing the erosion computation into several components based on different susceptibility to erosion was utilized by David and Beer (4) in their simulation model. The daily sediment yield of a watershed is considered as the sum of soil quantities lost by splash, by erosion of impervious surfaces, by erosion of loose particles, by rill erosion, and by channel bed and bank scour. The
model computes the depth of overland flow using the Stanford Watershed Model based on daily precipitation data. Although the model realizes rill erosion as a separate component, the variation in rilling pattern is not accounted for. Also, the computational equations are only valid when the rill size is very small.

Meyer, Foster and Romkens (25) studied the effect of several factors such as soil susceptibility to rilling, slope length, slope steepness, and other factors, on the rill and interrill erosion. Their results indicate that the extent of rilling affects both the total quantity of eroded soil and the location on the slope where the soil is eroded. The slope length is another important factor since runoff increases with distance downslope. The increased flow will increase rill erosion at lower parts of the slope, whereas erosion from interrill areas is not influenced much by slope length. For this reason, rill erosion vanishes at the top of a slope, where all sediment is from interrill erosion, and increases downslope. The interrill contribution to the total upland erosion may then vary from nearly 100% on short slopes where rilling is negligible, to a small percentage for longer slopes where rill erosion is predominant (26).

Based on the concept of rill and interrill erosion, Foster and Meyer (9) presented a model for slope erosion. In the interrill areas, raindrop impact is a dominant factor in detaching soil particles. Transport capacity of interrill flow is expressed in terms of the slope geometry, rainfall rate, and the soil transportability.
For the rill erosion, Foster and Meyer used Yalin's equation to compute both detachment and transport capacities of rill flow. However, the variables of rill flow at all locations along every rill must be known to apply the Yalin's equation directly. These variables include the hydraulic radius, slope of the energy line, discharge, average velocity, roughness coefficient, and particle size. Unfortunately, little information concerning the frequency of rills or their cross-sectional geometry is available until after the rills have formed and measurements have been taken. To overcome this difficulty, Foster and Meyer (9) approximated the flow in each rill by imposing the average overland flow depth onto the microrelief profile.

From the review of research done toward utilizing this concept of rill and interrill erosion, it appears that an important need is a methodology to deal with rill patterns on an adequately detailed level.

2.4 Studies on Rill Patterns

Apparently, the first attempt to rationally predict the rill pattern on an eroding slope was presented by Leopold and Langbein (18). Their mechanism of drainage is a process that begins when the water first falls as precipitation on an uplifted land mass. The movement of a water drop downslope molds a path that will be taken by succeeding particles of water. There are, however, many possible paths for a water droplet and its sediment load. According to Leopold and Langbein, the path of this first water droplet can be
simulated by a random walk process. Random walks of different water droplets then will form a possible drainage network or a rilling pattern for the slope. The randomness postulated in this model is supported by observations of Horton (14). Horton suggests that the direction and micropiracy of incipient rills is a matter of chance until the rills deepen sufficiently to become master rills. It is then realized that the random walk simulation is suitable only in the early stage of the erosion process.

Based on the previous conceptual model, Schenck (33) developed a computer program to simulate drainage-basin networks. The model divides the slope area into many elementary areas with random directions of drainage. He used the Monte Carlo method of simulation to generate the random walk process. The geometrical properties of the simulated networks were found to be in agreement with those observed from natural drainage networks. A similar but more comprehensive study was done by Smart et al. (36).

Schneidegger (32) also used the random walk model to simulate drainage patterns of watersheds with different boundary conditions. His results agreed with some field observations.

An alternative approach to the problem of predicting a drainage pattern is presented by Seginer (34). His "random roughness" model utilizes the same matrix of elementary areas, squares. However, they are not assigned random directions. Rather, they are assigned random elevations which, in turn, control the drainage pattern. The construction of this model thus contains two links:
the first, which generates the elevations, essentially random, and the second, which produces a unique drainage network for any given topography, deterministic.

Merva et al. (21) emphasized the importance of the consideration of the random nature of drainage surfaces in studying drainage and erosion characteristics. In their paper, they explained the need for an adequate and feasible description of surface irregularities based on its statistical characteristics, and suggested that the spectral density function be used to describe the microrelief.

It is clear that the multitude of studies on drainage patterns and on surface irregularities contributed significantly to the understanding of the phenomenon of slope erosion. However, the link between studies on drainage patterns in general, or rill patterns in particular, and the actual application of these principles to obtain a value for the erosion rate does not exist.

2.5 Concluding Remark

Based on the previous review of literature, one can identify two main directions. The first direction is represented by the increasing appreciation of the random nature of the erosion process. The most important factor contributing to this randomness is probably the slope surface irregularities. Other factors such as rainfall characteristics and soil properties are also generally random in nature, and contribute to the overall random behavior. The second direction is seen in the tendency to deal with the mechanics of the problem on
more rational and less empirical bases. The principles of mechanics of sediment transport, although essentially derived for flow in rivers, provide a starting point for the present state of knowledge.
3.1 General Outline

The model proposed for this research builds on the two major trends of research described in Section 2.5. It attempts to combine the random factors that control erosion with the principles of hydraulics and sediment transport.

Essentially, the model consists of two major submodels. First, the random surface model which performs statistical analysis of the surface roughness data obtained from field measurements. Based on the results of this analysis, the model generates a random surface in the form of an array of points with different elevations. Second, an erosion model which describes the movement of water from one point on the generated surface to another, and computes the resulting erosion at every point. The erosion equations are based on principles of hydraulics and mechanics of transport, as explained in Chapter IV.

Evolution of the erosion process with time is obtained by computation for discrete time intervals. Flow and erosion computations for the first time interval are based on the geometrical configurations of the initial random surface. During this and subsequent intervals, the flow properties and the geometry
are assumed to be constant, i.e., a steady state condition is assumed. The change in elevation due to erosion during the first time interval is used to revise the surface geometry which is then used for computations of the second time interval.

Generation of one random surface and then operating on it with the erosion mechanism for the required number of time intervals represents only one realization of the stochastic process. From this realization, we obtain one value of the total soil loss and the change in surface geometry due to the specified storm. By repeating the whole process and generating many random surfaces and subjecting them to erosion, we obtain a sample. This sample can then be used to study the probabilistic properties of the erosion process.

3.2 Analysis of Surface Roughness Data

The surface irregularities of a soil slope can generally be considered as consisting of a large number of small "humps" of irregular shapes and arrangements. When overland flow begins to move downslope, the water moves in the meandering depressions or paths, as shown in Figure 3.1.

The function of the random surface model is to generate, numerically, a random surface which has characteristics representative of the real surface. The similarity between real and generated surfaces depends on two factors. On the one hand, it is desirable that the statistical properties of the generated surface be as close as possible to those of the original surface. On the
other hand, the numerical representation of the surface must be suitable for subsequent erosion computations. The trade-off between those two conditions is the main consideration in the formulation of the random surface model.

3.2.1 Method of Spectral Analysis

Consider an elevation trace along any line on a slope surface, as shown in Figure 3.2. The spacing between measurements, $\Delta x$, must be small enough to reveal the necessary details, namely, rills and humps.

This profile can be considered as a continuous function, $f(x)$, with the distance, $x$, as the independent variable. Fourier analysis can then be used to express this function as a sum of an infinite number of sinusoidal terms. This is just the process of fitting to the data a trigonometric polynomial in the least square sense.

According to Fourier theorem (2), a periodic function, $x(t)$, having a fundamental period, $T$, and satisfying the conditions known as Dirichlet's conditions (2), can be represented by an infinite Fourier series,

$$x(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} (a_n \cos n \omega_0 t + b_n \sin n \omega_0 t)$$  \hspace{1cm} (3.1)

where $\omega_0 = 2\pi/T$ is the fundamental angular frequency, $a_n$ and $b_n$ are Fourier coefficients.
The previous expression is equivalent to decomposing the periodic function, $x(t)$, into an infinite number of harmonic components. That is, we are transforming the function from time (or space) domain to frequency domain. Transformation of a data record to frequency domain means determining its spectrum. Thus, spectral analysis is the process of calculating and interpreting a spectrum.

The frequency and/or wavenumber, which is the reciprocal of frequency, is in many respects a more significant and more useful variable to use than the time (or space) function. It should be noted that transforming a data vector, $x(t)$, into frequency domain does not mean the addition of anything new, but merely a rearrangement of the given data record according to frequency instead of time sequence. In many fields, the spectral analysis yields a better understanding of data as well as the systems which produced those data. The latter property has been very useful in geophysical applications (2, 29).

In practice, a data record must be expressed in the form of a finite number of sinusoidal waves. Each wave has its own contribution to the total variance of the record. This contribution depends on the value of the coefficients, $a_n$ and $b_n$, associated with this wave. An alternative terminology for the total variance is the total power.

The detailed mathematical background for the application of the method of spectral analysis as well as the interpretation of its results may be found in Rayner (29) and Bath (2).
3.2.2 Important Assumptions and Considerations

The procedure used to apply the spectral analysis method and the assumptions associated with it are explained below.

The field measurements of the surface roughness are usually carried out by measuring the elevation of a number of equidistant points along a certain line. A measurement plot is composed of several profiles or elevation traces as shown, e.g., in Figure 3.3.

The surface roughness as represented by the random variations of elevation with distance can be regarded as a stochastic process. Each one of the elevation traces can be assumed as a realization of the same stochastic process, if the irregularity of the land surface is "homogeneous," a term introduced by Merva et al. (21). A surface is homogeneous if the nature of the irregularity does not change from location to location. This condition is usually fulfilled in cases where mechanical treatment of the surface is the same at all locations.

If each elevation trace represented a realization, then the group of traces in a measurement plot is considered as an ensemble (See Figure 3.3). The properties of the stochastic process are better represented in an ensemble than in a single realization. It is therefore preferable to include the whole ensemble in the spectral analysis.
The classical method of analyzing an ensemble in time domain is to compute the autocorrelation function of each realization, then the overall autocorrelation function is calculated by averaging values of autocorrelation functions at each time lag (28). In spectral analysis, however, the spectrum of a process contains the same information given by the autocorrelation function, but in frequency domain. Accordingly, the overall spectrum of a process can be computed by averaging Fourier coefficients of the same harmonic component for all realizations, then the average harmonic components are composed together to produce the spectrum.

According to Merva et al. (21), a surface is called isotropic if the statistical properties, estimated by measurements taken along two orthogonal traces, are identical. It is clear that such a condition cannot be met in plowed surfaces, or in surfaces which have experienced considerable erosion.

When field measurements are made along parallel traces, they represent elevation variation only in one direction. When the analysis of this data is used to generate a surface, the assumption of isotropy of the surface irregularities is then implied.

It is important to mention that the method of spectral analysis can be used to study the data in two-dimensional form directly. That is, the data of all points on a plot are treated as one data record (29). In fact, Shinozuka and Jan (35) described the procedure to use two-dimensional spectral analysis in generating a random surface. The generated surface in this case would
probably be a better representation of the original one, but would impose greater difficulties on the operation of erosion mechanisms. Therefore, in the present simplified model, the random surface is generated using one-dimensional analysis only.

3.2.3 Observations from Spectral Analysis

The present research utilizes a computer program for one-dimensional spectral analysis (16), as a subroutine in the model. For any data of an elevation trace, the program mainly computes the coefficients, a and b, of every harmonic component. This provides enough information to compute the amplitude, phase, and the contribution of any component to the total variance of the original function.

The data used for spectral analysis consists of elevation measurements from plots of the dimensions shown in Figure 3.3. The data was a part of a study conducted by Van Ooren (39) at Wooster, Ohio. Analysis was done for the plots which were plowed and then disked four times. Other plots were disked fewer times, and would probably exhibit less isotropy due to deeper tillage marks.

The results of spectral analysis are presented in the form of a curve showing the relationship between different harmonic components and the corresponding contributions to the total variance, or power. This curve is usually called the spectral density function. Interpretation of the spectral density function is very
useful in understanding the system which generated the given data. A peak at any wave length generally indicates that this particular wave contributes more to the variance of the function than other waves of comparable length.

The spectral density function of the plot used in this study is shown in Figure 3.4. This curve is computed using the averaging procedure explained in Section 3.2.2. The spectrum is composed of 50 harmonic components with wavelengths ranging from 198 cm to 3.96 cm. The corresponding wavenumber, as shown in Figure 3.4, ranges from 1 to 50.

The overall spectrum is divided into two types of roughness: the macro-roughness, which is the part composed of waves with lengths greater than 30 cm; and the micro-roughness, which is the part composed of waves with lengths less than or equal to 30 cm. The rill pattern, being formed of small-scale surface irregularities, is considered to be represented by the micro-roughness. Therefore, the wave with the highest peak, in the micro-roughness range of the spectral density function, is assumed to be the "basic" wave.

Figure 3.4 indicates that some of the waves in the macro-roughness range may have the greatest contribution to the variance of the surface. Those large waves are attributed to local topographic variations combined with the effect of tilling. Such waves have little effect on the formulation of the elementary rill pattern on the surface, and are ignored.
3.3 Procedure of Random Surface Generation

In light of the assumptions and the observations discussed previously, it is now possible to lay out the procedure followed in this model for generating a random surface on the basis of spectral analysis. The procedure is composed of two major steps. The first step is the spectral analysis of the roughness data. The second step is the numerical generation of the surface, based on the characteristics obtained from the first step.

3.3.1 Analysis of the Data

This step is carried out in the following sequence:

1. Conduct spectral analysis on each one of the elevation traces obtained from the measurement plot. This means that each trace will be subjected to Fourier analysis and will be decomposed into a number of harmonic components with different wave lengths and coefficients, a and b.

2. Compute the average harmonic components by averaging the coefficients a and b from all elevation traces. The resulting composition of harmonic components is regarded as the spectrum of the measurement plot, and is presented in a form similar to that shown in Figure 3.4.
3. From within the range of micro-roughness, pick up the wave component with the highest contribution to variance. This is the basic wave.

4. Deduct the basic wave from each of the original elevation traces in order to obtain what is called the residual data. The residual data is treated as a random component and is represented by a normal distribution.

5. Compute the mean and standard deviation of the residual data from each trace. Then compute the average values which are the mean and the standard deviation for the whole plot.

The final outcome of this step is the length and amplitude of the basic wave, the mean, and the standard deviation of the residual data.

3.3.2 Construction of the Random Surface

The random surface is generated by superposing a matrix of circular humps, which represent the basic wave, on a plane surface, which has a slope equal to the average slope of the actual surface. As shown in Figure 3.5, the centerlines of
the low zones around the humps form a hexagonal mesh. At each nodal point, as well as at hump centers, a random component drawn from the distribution of the residual data is added.

The selection of a hexagonal mesh to simulate the elementary rill pattern is based on several considerations. In a rectangular grid, there is a possibility of three streams merging at a single point, since we have four branches connected together at each nodal point. This situation is seldom met in nature (34). With three members only meeting at each nodal point, the possibility of three streams merging at one point is much less. Accordingly, a hexagonal mesh provides a more realistic representation of a stream network in general. A hexagonal mesh is also a closer simulation of the actually curved rills. Moreover, a square mesh provides isotropy in two directions only, as shown in Figure 3.6, whereas a hexagonal mesh provides three directions of isotropy, as shown in Figure 3.7.

3.4 The Method of Zero-Crossing Analysis

The method of zero-crossing analysis is another method for analyzing surface roughness data. This section briefly discusses the outlines of this method of analysis and its application in our case. More details on the mathematical formulation and the computer program can be found in Reference (20).
3.4.1 Outline of the Method

A zero crossing is defined as the intersection of the continuous function, \( x(t) \), with its mean line (Figure 3.8). Each point at which the function \( x(t) \) ceases to decline and starts to rise, or ceases to rise and starts to decline, is called a turning point. A turning point is a peak when it is a relative maximum and a trough when it is a relative minimum. The longitudinal distance along the mean line between successive zero crossings is the zero crossing distance. The number of turning points between any two zero crossings is odd. If there is more than one turning point in a zero crossing distance, the peak (or trough) with the largest departure from the mean line will be considered the only peak (or trough) in this distance. With these considerations, there will be only one peak or one trough between two adjacent zero crossings.

The vertical distance between a peak and the mean line is the positive amplitude, \( a_+ \), and between a trough and mean line is the negative amplitude, \( a_- \). Finally, the sum of the positive and negative amplitudes \( a_+ + a_- \) is the wave height and also the sum of two adjacent zero crossing distances is the wave length.

For short records, the zero-crossing analysis can be done by manual computations, while long records are analyzed by means of a computer program. The first step, in either case, is to
identify the mean line. This can be done by the following procedure. The record is divided into \( q \) equal segments, such that each segment contains about 2 to 5 waves. For each part, the mean surface level is calculated and considered as a point at the center of the segment. Now there are \( q \) points, at the center of the \( q \) segments, and each point represents the mean surface level within that part. The problem is to pass an appropriate curve through these \( q \) points such that it can be considered as the mean line of the record. A third degree polynomial is selected for this purpose, in order that not only the profile is unique and continuous, but also its first and second derivatives representing slope and curvature.

When the profile of the mean line is defined, the problem of determination of the crossings with the mean line can be reduced to the determination of the crossings of the mean-removed data with the horizontal axis. For example, the number of zero crossings of the mean-removed data is equal to the number of its sign changes.

In addition to the number of zero crossings, four other sequences are obtained from zero-crossing analysis. These are the sequences of wavelength, positive amplitude, negative amplitude, and waveheight. Each of those sequences is considered as a sample from which the statistical properties of the random variable of interest can be inferred.
3.4.2 Generation of Random Surfaces

According to the definitions explained in Section 3.4.1, the sequence of wavelengths in any elevation trace, as shown in Figure 3.9, is represented by \( \omega L_1, \omega L_2, \ldots \). The computer program for zero-crossing analysis (20) provides the mean, the standard deviation, and the statistical distribution of the random variables representing wavelength, \( \omega L \); positive amplitude, \( A \); and negative amplitude, \( B \).

Following the procedure described in Section 3.3.2, we can use the results of zero-crossing analysis to generate the random surface. In this case, the basic wave will have length equal to \( \omega L_{av} \), and an amplitude equal to the average of \( A_{av} \) and \( B_{av} \). The distribution of the residual data can then be computed as explained in Section 3.3.1. A sample random surface is shown in Figure 3.10.

The zero-crossing analysis was conducted using the same roughness data obtained from Wooster, Ohio. First, each one of the elevation traces was analyzed separately. Then, all of the traces were considered and analyzed as one record. The results are shown in Table 3.1. The average values for the wavelength and the waveheight are 17 cm and 29.5 mm, respectively.

The method of zero-crossing analysis can be more useful in studying the variation of the hump size. Such a study can be used to generate a random surface with a random rill pattern.
Consider the elevation trace shown in Figure 3.9. The sequence of wavelengths can be expressed as follows:

\[
\omega L_1 = \omega L_{av} + \omega X_1 + \omega X_2
\]

\[
\omega L_2 = \omega L_{av} + \omega X_1 + \omega X_2
\]

\[
\vdots
\]

\[
\omega L_n = \omega L_{av} + \omega X_1 + \omega X_2
\]

where \(X_1^i\) and \(X_2^i\) are two random components applied at the two ends of the distance, \(\omega L_{av}\), in Figure 3.10.

It is reasonable to assume that \(X_1^i\) and \(X_2^i\) are two realizations of the same random variable, \(X\). This variable is assumed to have a uniform distribution. The problem is then reduced to finding the parameters of this distribution. This can be simply done by computing, for each element, \(\omega L_i\), of the wavelength sequence. The corresponding value of \(X_i\) is as follows:

\[
X_i = \frac{1}{2} (\omega L_i - \omega L_{av})
\]

Then the mean and the standard deviation of \(X\) can be computed.

On the basis of the assumptions of homogeneity and isotropy, we can use the same random variable, \(X\), in the two directions, across and along the slope surface.
<table>
<thead>
<tr>
<th>Elevation trace</th>
<th>(\omega_L) (cm)</th>
<th>+ Amp. (mm)</th>
<th>- Amp. (mm)</th>
<th>waveheight (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>11.04</td>
<td>9.60</td>
<td>12.99</td>
<td>22.59</td>
</tr>
<tr>
<td>2</td>
<td>13.54</td>
<td>14.50</td>
<td>15.14</td>
<td>29.64</td>
</tr>
<tr>
<td>3</td>
<td>12.89</td>
<td>12.16</td>
<td>17.96</td>
<td>30.12</td>
</tr>
<tr>
<td>4</td>
<td>12.23</td>
<td>12.34</td>
<td>12.86</td>
<td>25.20</td>
</tr>
<tr>
<td>5</td>
<td>11.28</td>
<td>13.19</td>
<td>14.92</td>
<td>28.11</td>
</tr>
<tr>
<td>6</td>
<td>27.72</td>
<td>14.68</td>
<td>22.45</td>
<td>37.13</td>
</tr>
<tr>
<td>7</td>
<td>19.53</td>
<td>14.19</td>
<td>18.56</td>
<td>32.75</td>
</tr>
<tr>
<td>Combined</td>
<td>13.96</td>
<td>13.52</td>
<td>15.23</td>
<td>28.75</td>
</tr>
</tbody>
</table>
The procedure to generate the surface with random rill pattern consists of the following steps:

1. Using \( wL_{av} \) as the hexagon width, generate a regular hexagonal mesh.

2. From the uniform distribution of the continuous interval, \((0,1)\), draw a random number for each nodal point. This number is used to determine the direction in which the random component of \( X \) will be applied. This is done according to the rule given in Table 3.2 below.

<table>
<thead>
<tr>
<th>Value of Random Number Drawn from ( U(0,1) )</th>
<th>Direction of Random Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 0.0 \leq r &lt; 0.25 )</td>
<td>upward</td>
</tr>
<tr>
<td>( 0.25 \leq r &lt; 0.50 )</td>
<td>downward</td>
</tr>
<tr>
<td>( 0.50 \leq r &lt; 0.75 )</td>
<td>left</td>
</tr>
<tr>
<td>( 0.75 \leq r &lt; 1.00 )</td>
<td>right</td>
</tr>
</tbody>
</table>

3. From the uniform distribution of \( X \), draw a random number for each nodal point. This number specifies the magnitude of the shift in the direction determined in Step (2).
5. Use the distribution of the residual data to generate a random component for the elevation of every nodal point.

Figures 3.11 and 3.12 show the rill patterns generated using hexagonal and random mesh, respectively.

3.5 Concluding Remarks

The use of the zero-crossing analysis in generating an irregular rill pattern may represent a better approximation of the surface. However, this irregularity imposes great difficulties in the coding of the flow-routing, and erosion mechanisms. Therefore, the present erosion model uses the hexagonal mesh as a rill pattern.

While the zero crossing analysis offers advantages, the present model uses the spectral analysis for analysis of the roughness data. The main reason for this is that spectral analysis allows us to recognize the relative importance of large-scale and small-scale surface irregularities. Therefore, we can define the part of the data which contributes most to the formation of the rill pattern. Moreover, the method of spectral analysis, although not fully utilized in this model, provides greater potential for improvement of surface roughness modeling.
The mechanism of selecting only one wave component of the spectrum as the basic wave created a problem in the simulation process. This is because the amplitude of this wave alone is not large enough to represent the humps. We note that the average wavelength and wave height obtained by using the zero-crossing analysis are about 17 cm and 29.5 mm, respectively (See Table 3.1). That is, the average amplitude can be taken as about 15 mm. On the other hand, the length and amplitude of the basic wave as determined by spectral analysis of the same data are 18 cm and 3.7 mm, respectively. If we use the amplitude of the basic wave to generate the surface, the top of the hump may become lower than some nodal points of the hexagon surrounding it. This creates rill segments with negative side slopes. If this condition occurs at all or most of the rill segments, the rill pattern, as a drainage network, would lose its function, and the rill-interrill characteristics of the surface would vanish.

To avoid this problem, the following simplified solution is used. For a basic wave of length $\omega L$, the length of the hexagon's side is equal to $\omega L/\sqrt{3}$. If the surface is inclined with an angle of $\theta$, then each hump center is raised by the amount $\frac{\omega L}{\sqrt{3}} \sin \theta$. For a slope of $20^\circ$, which is the slope used in this analysis, the additional increment, $\frac{\omega L}{\sqrt{3}} \sin \theta$, is equal to 35 mm, about twice the average amplitude computed using zero-crossing analysis. This value is equal to 18.1 mm.
for a ten-degree-slope. Hence, we can see that the simplified approach described above is a reasonable approximation as compared with the results of zero crossing analysis. Prior to superposing the basic wave or the random component, the elevation of the hump center is equal to the elevation of the highest nodal point around it. Then the basic wave and the random increments in elevation are added. Due to this randomness, some of the humps could still be lower than some of the surrounding nodal points. Our model allows for some rill segments to be eliminated, depending upon the original roughness data.
b) Profile A-A

Figure 3.1 Natural Surface Roughness
Figure 3.2 Elevation Trace

Figure 3.3 Measurement Plot
Figure 3.4 Spectral Density Function of Surface Roughness
Figure 3.5 Simulation of Surface Roughness
Figure 3.6 Isotropy in Square Rill Pattern

Figure 3.7 Isotropy in Hexagonal Rill Pattern
Figure 3.8 Parameters used in Zero-Crossing Analysis
Source: Ref (20)
Figure 3.9 Sequences Computed in Zero-Crossing Analysis

Figure 3.10 Average Wave used in Constructing a Hexagonal Rill Pattern
Figure 3.11 Uniform Rill Pattern

Figure 3.12 Random Rill Pattern
CHAPTER IV
EROSION MODEL

The subject of this chapter is the model for computation of erosion in rills and over interrill areas. Emphasis is placed on the development of computational procedures which are suitable for the surface model and are based on principles of hydraulics and sediment transport mechanics.

The present analysis considers only erosion of soil particles by the shearing action of flow in rills and over interrill areas. In other words, the direct detachment and transport process due to rainfall splash is not accounted for. The rainfall impact is only considered as an agent that detaches particles of surface soil and causes the soil aggregates of a cohesive mass to move in a fashion similar to that of cohesionless soil particles (8). For this reason, transport equations derived for cohesionless soils are usually applied on slopes of cohesive material (8, 6, 9).

Based on the description given in Chapter III, the random surface is composed of a matrix of higher points, humps, surrounded by small channels, rills, connecting the lower points. For the purpose of erosion computation, the geometrical configurations of the surface are simplified. The humps are assumed to be in the form of hexagonal pyramids with a different slope for each of the six sides,
depending on the random outcome of surface generation. Rills are assumed to be formed of channels with triangular cross sections with the side slopes of the adjacent humps forming its boundaries, as shown in Figure 4.1. A channel between two nodal points is termed a "rill segment." In the remaining sections of this chapter, the equations of erosion of rills and of humps are derived.

4.1 Rill Erosion Equation

Consider a rill segment, ab, as shown in Figure 4.1(a); let \( q_1 \) be the rate of water flow received from upslope at point a, and \( q_2 \) be the flow at b. \( q_2 \) is greater than \( q_1 \) by the amount of water drained from the two adjacent humps. The flow in the rill segment, ab, is actually a spatially-varied flow with the rainfall acting as a lateral inflow. Researchers such as Yoon and Wenzel (44), Li et al. (19), and Komura (17), considered the overland flow as a spatially-varied flow. However, since the present model deals with the erosion problem at a significantly smaller scale, equations of uniform flow are used to describe flow in a rill segment.

Erosion due to rill flow is based on the concept of tractive force which is generated by the shearing stresses between the flow and the boundaries. This criterion is used in the derivation of many sediment transport equations (12).

Consider the triangular cross-section of any rill segment, as shown in Figure 4.2. The average value of the tractive force per unit wetted area, i.e., the unit tractive force, \( \tau_0 \), is given by:
\( \tau_0 = \gamma R S_f \) \hspace{1cm} (4.1)

where

\( \gamma \) = unit weight of water;
\( R \) = hydraulic radius of the channel: \( R = \text{Area/wetted perimeter}; \)
and,
\( S_f \) = slope of the energy grade line.

Henderson (13) indicates that the slope of the energy line, \( S_f \), can be approximated by the bed slope, \( S_0 \), for a mountain type channel. Using this approximation, Equation (4.1) becomes:

\( \tau_0 = \gamma R S_0 \) \hspace{1cm} (4.2)

According to Chow (3), the unit tractive force in channels, except for wide open channels, is not uniformly distributed along the wetted perimeter. Therefore, it is more appropriate to use the tractive force per unit length of the rill as expressed by the following equation:

\[ F_0 = \tau_0 \times P = \gamma A S \] \hspace{1cm} (4.3)

where

\( P \) = wetted perimeter; and
\( A \) = cross-sectional area of the flow.

In terms of the geometrical features of the triangular cross-section, as given in Figure 4.2, we have:
Neglecting the variation of $S_0$ along the segment ab, the value of $F_0$ is then dependent upon $h$ at any point. The values of $h_1$ at a and $h_2$ at b depend on the corresponding values, $q_1$ and $q_2$. Turbulence intensity measurements by Yoon and Wenzel (44) indicated that the flow under the influence of rainfall was turbulent. Therefore, to obtain the flow depth, $h$, at any point we can use Manning equation (3),

$$V = \frac{1}{n} R^{2/3} S_f^{1/2}$$

(4.5)

where

- $V$ = the mean velocity in meter/sec;
- $R$ = the hydraulic radius in meters;
- $S_f$ = the slope of the energy line; and,
- $n$ = the coefficient of roughness, specifically known as Manning's $n$.

Using the approximation $S_f = S_0$, and the relation $q = V \cdot A$, we get:

$$q = \frac{A}{n} R^{2/3} S_0^{1/2}$$

(4.6)

which can be expressed in terms of $h$ as:

$$q = \left(\frac{1}{2} \frac{c_1 h^2}{n} \right) \left(\frac{1}{2} c_3 h \right)^{2/3} S_0^{1/2}$$

(4.7)

Therefore,

$$h = \frac{2^{5/3} n q}{c_1 c_3 S_0^{1/2}}$$

(4.8)

where $c_1$ and $c_3$ are defined in Figure 4.2.
The flow in rills has been so far treated as open channel flow. The flow characteristics are then used to compute the amount of soil eroded. This scheme implies that the effect of sediment already carried in the flow is not considered. That is, the concentration of sediment is assumed small enough so that the equation of motion for sediment-laden water can be approximated by the equation of motion for water only.

According to Li et al. (19), the continuity equation for sediment can be expressed as:

$$\frac{d q_s}{dx} = p_s$$  \hspace{1cm} (4.9)

where

$q_s$ = the sediment discharge per unit width of channel, and

$p_s$ = the fine-sediment pick-up rate per unit area.

$q_s$ is a function of the flow characteristics and specifically, the flow tractive or shearing force. The bed load equation derived by Kalinske (12) is used to obtain $q_s$. It is expressed in the nondimensional form as:

$$\frac{q_s}{U_* D} = a_s \left[ \frac{U_*^2}{\rho_s \left( \frac{\rho_s}{\rho_w} - 1 \right) g D} \right]^p$$  \hspace{1cm} (4.10)

where

$q_s$ = the sediment discharge including suspended sediment in volume of material per unit time and unit width;
$U_*$ is the friction velocity; 
$D$ is the mean sediment size; 
$\rho_s$ and $\rho_w$ are densities of sediment and water, respectively; 
g is the gravity acceleration; 
$a_s$ is a constant; and 
p is a dimensionless exponent.

The reasons for using Kalinske's equation are discussed in the last section of this chapter.

Substituting for $U_*$ by $\tau_0/\omega > \rho_s$ can be expressed as:

$$q_s = \frac{B_1}{\rho_w (1+2p)/2} \tau_0^{(1+2p)/2}$$  \hspace{1cm} (4.11)

in which $\tau_0$ is the unit tractive force and

$$B_1 = \frac{a_s}{(\frac{\rho_s}{\rho_w} - 1) g \omega^p D^{p-1}}$$  \hspace{1cm} (4.12)

Assuming that a similar relation exists between the "total" sediment discharge per unit length of the channel, $Q_s$, and the corresponding tractive force per unit length, $F_0$, Equation (4.11) can be rewritten in the form:

$$Q_s = \frac{B_1}{\rho_w (1+2p)/2} F_0^{(1+2p)/2}$$  \hspace{1cm} (4.13)
It should be noticed that the Kalinske's equation is derived for a two-dimensional flow condition. This implies that the hydrodynamic forces exerted on any soil particle is assumed to be acting in the longitudinal direction only, and no lateral forces (in the cross-sectional direction) exist. Such condition can be represented by the flow over interrill areas. For the rill flow, however, the triangular cross-section gives rise to a lateral gravity component acting on soil particles resting on the side slope of the rill. The transition from Equation 4.11 to Equation 4.13 is therefore an approximation in which the effect of this lateral gravity component is not considered.

The continuity equation for sediment, given by Equation (4.9), can also be modified as:

$$\frac{dQ_s}{dx} = P_s$$  \hspace{1cm} (4.14)

in which $P_s$ is the fine-sediment pickup rate per unit length of the channel.

For a long slope, the average erosion rate per unit area is defined by Li et al. (19) as the average pickup rate along the slope and is expressed as:

$$E = \frac{1}{L} \int_L P_s \, dx$$  \hspace{1cm} (4.15)

where $L$ is the length of the slope in the x-direction. But for the short segments considered in our case, $E$ is taken as directly equal to $P_s$. Accordingly, the erosion rate in volume per unit length of the channel, $E_v$, is given by:

$$E_v = \frac{dQ_s}{dx}$$  \hspace{1cm} (4.16)
Taking the derivative of Equation (4.13), we obtain:

\[ E_v = \frac{1}{2} \frac{(1+2p) B}{\rho_w (1+2p)/2} F_0 \frac{d F_0}{d x} F_0^{(2p-1)/2} \]  

(4.17)

in which \( F_0 \) at any point is obtained from Equations (4.4) and (4.8), in terms of the water discharge.

Considering, again, the size of the channel, the term \( \frac{d F_0}{d x} \) can be rewritten in difference form. That is, for the rill segment of length \( L \), the erosion rate of rills, in volume per unit time, \( E_v \), can be expressed as:

\[ E_r = \frac{1}{2} \frac{(1+2p) B}{\rho_w (1+2p)/2} \frac{F_{02} - F_{01}}{L} \left( \frac{F_{01} + F_{02}}{2} \right)^{\frac{2p-1}{2}} \times \Delta L \]

and the final computational form for \( E_r \) becomes:

\[ E_r = \frac{1}{2} \frac{(1+2p) B}{\rho_w (1+2p)/2} \left( F_{02} - F_{01} \right) \left( \frac{F_{01} + F_{02}}{2} \right)^{\frac{2p-1}{2}} \]  

(4.18)

where \( \beta \) is given by Equation (4.12) and \( F_{01} \) and \( F_{02} \) are computed from Equations (4.4) and (4.8).

4.2 Intermill Erosion Equation

A similar approach is used to express the erosion rate of intermill areas in terms of the flow characteristics, which differ somewhat from those of rill flows. The flow in this case is approximated by a sheet flow with \( q_1 = 0 \) at the top and \( q_2 \) at the bottom, with an amount depending on the area between different rills.

Consider a surface with slope \( S_0 \) and length \( L \), as shown in Figure 4.3. Assume that the flow depth increases linearly downslope from \( y_1 = 0 \) at the top to \( y_2 \) at length \( L \). The unit tractive force
resulting from this flow at points a and b, respectively, is given by:

\[ \tau_{01} = \gamma y_1 S_0 = 0 \quad (4.19) \]

and

\[ \tau_{02} = \gamma y_2 S_0 \quad (4.20) \]

in which the wide-channel approximation, \( R = y \), has been applied.

The flow depth is also determined using Manning's equation which gives, for this case:

\[ q = \frac{1}{n} y^{2/3} S_0^{1/2} \quad (4.21) \]

The flow depth at any point is given in terms of the flow rate as,

\[ y = \left( \frac{\sqrt{S_0}}{n q} \right)^{3/5} \quad (4.22) \]

Based on the continuity equation for sediment (Equation 4.9), in conjunction with Kalinske's bed load formula, an expression for erosion rate of interrill areas can be written as:

\[ E_i = \frac{1}{2} \frac{\beta L (1+2p)}{\rho_w} L \times \frac{2p+1}{\tau_{02}^2} \quad (4.23) \]

where

- \( E_i \) = erosion rate of interrill areas in volume per unit area per unit time;
- \( E_i \) as given in Equation (4.12); and,
- \( \tau_{02} \) = the unit tractive force, or shear stresses, at distance \( L \) downslope, and is computed from Equations (4.22) and (4.20).
Although the water flows over the humps in a more or less radial fashion, the present analysis assumes a one-dimensional flow in the direction of the centerline of each one of the six sides of the hexagonal pyramid. Furthermore, the total amount of erosion from each (triangular) side is computed for the equivalent rectangle, as shown in Figure 4.4.

4.3 Concluding Remarks

It is important to notice that the derived erosion equations do not compare the transport capacity of the flow with its detachment capacity, as explained in Chapter II. The model, for simplicity, assumes that the slope surface will always provide the overland flow with a sediment load which is adequate to its transport capacity. This assumption, in fact, depends on the effect of rainfall impact on loosening the surface soil and detaching a sufficient amount of soil aggregates. In other words, the erosion equations by themselves do not account for the possibility of deposition. Nevertheless, the process of deposition is being, partly, considered in this model through the use of computational mechanisms as explained in Section 5.2.2.

The use of Kalinske's bed load equation in the mathematical model for erosion computation is the subject of the remaining part of this discussion. Essentially, all sediment transport equations are derived for the simplified case of two-dimensional flow (43).
which approximates flow in wide rivers. Nevertheless, no single
equation has been found to hold for all situations. For the special
case of overland flow, on the basis of the present knowledge, there is
no compelling theoretical reason to choose any of the existing sedi-
ment transport equations over any other.

The choice of Kalinke's equation for this study is primarily
empirical. It has been actually used by Komura (17) in developing
a mathematical model for slope erosion by overland flow. The study
is especially useful in defining the range of values for some constants
in the equation, when applied to overland flow.

We have also compared the results of some field measurements
of rill erosion (25) with the corresponding values computed by
Equation (4.18) (See Appendix A). We used the value of 0.2 mm as the
soil aggregate diameter, .025 for Manning's coefficient, and the
values suggested by Komura (17) for the remaining parameters. The
agreement of the results further supports the use of Kalinke's
equation in our model.
Figure 4.1 Surface Idealization

a) Plan

b) Section A-A
\[ C_1 = \frac{1}{s_1} + \frac{1}{s_2} \]
\[ C_2 = \frac{1}{s_1} + \frac{1}{s_{1.2}} \]
\[ C_3 = C_1 / C_2 \]

\[ A = \frac{1}{2} h^2 \left( \frac{1}{s_1} + \frac{1}{s_2} \right) \]
\[ = \frac{1}{2} h^2 C_1 \]
\[ P = h \left( \frac{1}{s_{1.1}} + \frac{1}{s_{1.2}} \right) \]
\[ = h C_2 \]
\[ R = \frac{1}{2} h C_3 \]

Figure 4.2 Rill Cross-section

Figure 4.3 Flow Over Interrill Area
Figure 4.4 Geometrical Basis for Interrill Erosion Computation
CHAPTER V
SIMULATION MODEL

Based upon the theoretical and practical considerations discussed in Chapters III and IV, a computation scheme is constructed to simulate the process of slope erosion by rainfall. A random surface is first generated on the basis of the statistical properties of the original surface, as explained in Chapter III. The overland flow is assumed to move downslope following the rill pattern created by a hexagonal mesh. The resulting erosion in rills and over inter-rill areas is then computed for the specified number of time intervals.

The details of the simulation model are described in the following sections. The listing of the computer program with a sample output is presented in Appendix B.

5.1 Main Features of the Model

In this section, the computation schemes for simulating the main features of the model are described. Those are the routing of the overland flow and the sediment load over the surface, the topographical changes due to erosion, and the changes in the process with successive time intervals. There are, however, a number of auxiliary mechanisms which are very important; these will be discussed in the next section.
5.1.1 Routing of Water and Sediment

Part of the rain falling on the test area is assumed to infiltrate through the surface layer. The rate of infiltration is known to decay with time. However, for simplicity, the model assumes a constant runoff coefficient, RNF (which is the fraction of rainfall that becomes runoff). This part is divided between the rills, which occupy a limited area of the surface, and the interrills, or the humps, which occupy most of the surface area. However, the water falling on the interrill areas, in excess of infiltration, is drained to the surrounding rill segments (as had been stated earlier), as shown in Figure 5.1.

The rate of flow and the sediment load at any nodal point of the hexagonal mesh depends on its position in the mesh, as well as the random elevation. The hexagonal mesh allows for two types of nodal points, as represented by points a and b in Figure 5.1. Point a receives flow from two branches and discharges it in only one direction downslope. Whereas point b has only one inflow branch, then the flow routed downslope is divided between two branches.

The flow in rills moves forward only if the bed slope of the rill segment is positive, i.e., inclined downwards. If the bed slope is either zero or negative, the flow routing of this rill is terminated at this point, and no further movement downslope is permitted. The rill flow is thus not allowed to move upslope even if the random elevations of the nodal points created such a situation.

At points such as a in Figure 5.1, the flow merging from the
two inflow branches is automatically directed to the third, outflow, branch. But for points such as b, the incoming water is divided between the outflow branches according to the ratio of the square root of the two bed slopes, i.e., \( (S_{01}/S_{02})^{1/2} \). This procedure complies with the slope exponent in Manning's formula as shown in Equation (4.6). As for the sediment load, we use the ratio of \( (S_{01}/S_{02})^{5/16(2p+1)} \) which is obtained from Equations (4.18) and (4.4), in which \( p \) is the exponent of Kalinske's bed load equation.

5.1.2 Erosion of the Surface

Erosion of a rill segment affects its geometry in both cross-sectional and longitudinal directions. The amount of soil eroded by rill flow for one time interval is computed from Equation (4.18). This amount is then removed from the rill cross-section in the manner indicated by the shaded area in Figure 5.2. The bed level is then lowered by the distance, \( DE \).

Interrill erosion is computed from Equation (4.23) for the area of the side slopes which is above the water level. Interrill erosion is supposed to steepen the side slopes gradually. To account for this action in a simplistic manner, the new side slopes, \( S_1 \) and \( S_2 \), to be considered for the next interval, are assumed to be represented by the dashed lines on Figure 5.2. This is an approximation of the actual condition which results in different side slopes below and above the water. However, this approximation eliminates a considerable computational difficulty. Moreover, the water depth in
rills increases downslope, where rills are more important. Thus, the error due to this approximation also decreases downslope.

In the longitudinal direction, the rill segment is assumed to be eroded uniformly. But since more than one rill segment always meet at each nodal point, the final decrease in the elevation of this nodal point is taken to be the average of the three values of DE computed for each branch.

5.1.3 Temporal Change

The time-dependent nature of the erosion process is accounted for by using a number of steady state time intervals. That is, during each time interval, the elevations of all nodal points and humps remain constant. The changes in the surface geometry due to erosion are then computed at the end of the interval, and the new elevations of all points are used for the next time interval. The effect of the time interval length on the model results is discussed later in Section 6.2.

The water flow at any nodal point, during a time interval, is the sum of the rill flow arriving from upslope and the water drained from the adjacent humps. The same mechanism applies for sediment load at any point. The total amount of sediment yield produced during any time interval is computed as the sum of sediment load at the nodal points at the bottom of the slope.

It has been mentioned earlier that runoff actually starts at different points on the surface after the rainfall rate has exceeded
the infiltration rate. It is important to notice, however, that the computations begin at the time when the runoff initiated at the top of the slope has reached the bottom. The amount of sediment eroded before that time is neglected.

5.2 Auxiliary Mechanisms

Beside the main computational schemes previously described, there is a number of auxiliary mechanisms which are very important for the development of the simulation of the erosion process, and provide the model with more realistic features.

5.2.1 Ponding

Recalling the mechanism of flow routing discussed in Section 5.1.1, the flow in any rill segment moves forward only if the bed slope of the rill is positive, i.e., inclined downward. When the bed slope is either zero or negative, the model assumes that the water ponds and that the flow velocity becomes zero along this segment.

At the nodal points, where three segments are connected, the ponding mechanism is as follows. For a point such as a in Figure 5.3, ponding occurs when the branch ai has a slope less than or equal to zero. The inflow (received from upslope) in segments ij and ik is then equal to zero. Such rill segments will only receive water that is drained from adjacent humps. At a point such as b in Figure 5.3, complete ponding occurs only if both bi and bj have
slopes less than or equal to zero. When only one of the two branches is ponded, then the flow is automatically routed through the other branch.

According to Manning's equation (Equation 4.6), the flow velocity, and consequently erosion, vanishes when the bed slope is equal to zero. This is, indeed, true when the equation is applied to an isolated channel. In our case, however, the small channels representing rill segments are connected with each other at nodal points. It is easy to realize that the water can flow, at least to some distance, in a channel with a zero or negative bed slope if the momentum of the upstream flow is sufficient. In other words, the present model maintains the condition of mass continuity at nodal points, whereas continuity of momentum (or energy) is not considered at this stage.

5.2.2 Deposition Due to Ponding

When ponding occurs, the flow is assumed to have reached a zero velocity, and therefore deposition becomes certain at ponded areas. The presence of ponding also influences the velocity of flow at points some distance upstream, and causes a reduction in the erosion rate at these points. This model uses a simplified mechanism to simulate the effect of ponding on deposition, as well as on reducing erosion at locations upslope.

Consider the case when ponding occurs at point 1 in Figure 5.4. This means that the bedslope of the lower branches is less than or equal to zero, and there is no other possibility for routing
the flow. The flow in the segment 2-1 is assumed to approach a zero velocity at point 1. The total sediment load arriving at point 1 is then deposited on the bottom of several rill segments upstream and downstream of point 1. The pattern of depositing the sediment load is also shown in Figure 5.4. The final change in the elevation of any point is the net difference between this deposition and erosion as computed from Equations (4.18) and (4.23). It is clear that the deposition mechanism is simple and, to some extent, arbitrary. Nevertheless, it serves the purpose of incorporating deposition in the model.

5.2.3 Stability of Rills' Side Slopes

As described in Section 2.3, the process of rill development is a combination of erosion, slumping of undercut side slopes, and head cuts. Since the progression of rill and inter-rill erosion steepen the side slopes, it is important to define a criterion with which we can check the stability of the side slopes at any time during the erosion process. On the other hand, this criterion must be simple so that it may be incorporated in the model.

The stability criterion used in this model consists, simply, of an arbitrarily chosen value of the limiting gradient, SLIMIT, that a side slope can withstand. When the gradient exceeds SLIMIT, the slope fails and assumes a new, arbitrary, flatter gradient, SSTART. The side slopes are assumed to remain plane, before and
after failure. The values of the two limits can be estimated from experience with the type of soil in question.

When a side slope fails, the top of the slope, which is the center of the hump, is lowered by a certain distance, as shown in Figure 5.5. Some of the sides of the hump may fail while others may still be stable. Therefore, in computations, each side has its own elevation at its top. At the end of the test period, and for the purpose of plotting only, the final elevation of the hump center is computed as the average of the top elevation of the six sides.

The soil mass removed after each slope failure should be added to the sediment load of the rill segment in which failure occurred. Usually, such masses cannot be directly carried by the transport capacity of the flow, and they require a more complicated account of deposition over the length of the rill. Therefore, these masses are presently ignored in the computation of the total sediment load. Due to this approximation, the model may be underestimating the total sediment yield.

5.2.4 Low Humps

In this model, the elevation of a hump is usually greater than the elevations of all six nodal points of the surrounding hexagon. However, if, due to the random designation of elevations, one or more of the six points become higher than the hump center, then this hump is called here a "low" hump. For example, in Figure 5.5, if point a is higher than both points i and j, then the cross-section of the rill segment ij would have the
configurations shown in Figure 5.6. In this case, the two side slopes are positive. On the other hand, if point a happens to be lower than the average elevation of ij which is represented by point b, then the rill would have the cross-section shown in Figure 5.7. Such a condition prevents the development of a rill in the first place, and the flow routing is altered.

To illustrate the various possibilities that are associated with a low hump, the rill segment ij in Figure 5.5 is assumed to have the cross-section shown in Figure 5.7. Consider the whole cross-section passing through points c, b, a, and d. Differentiation between various possibilities depends on two factors, namely, the bed slope, $S_0$, of ij, and the side slope, $S_p$, of the opposite rill segment, ml. The bed slope, $S_0$, must be, in the first place, positive so that the flow at point i can move forward. However, the flow will move in either the direction of ij or the direction ba, depending upon the difference in the absolute value of $S_0$, and $S_2$ in Figure 5.7. That is, the flow is routed in the direction of maximum slope. On the other hand, the sign of $S_p$ determines whether the flow passing over the negative slope, $S_2$, would continue over slope $S_p$ and join the rill flow in segment ml, or would just pond at a. Figure 5.8 illustrates the possible cases and the corresponding routing considered in each case. It should be mentioned that there is always a need to make some modifications to different mechanisms when applied at points on the boundaries of the test area. Details of those modifications are not presented herein. They are, rather, indicated within the computer program algorithm.
5.3 **Structure of the Program**

The computer program developed for the simulation model is composed of five main consecutive steps, as shown in Figure 5.9. This section presents the outlines of each computational step with the selected computer subroutines.

5.3.1 **The Input Data**

The input data is divided into the three groups described below:

(a) **Surface Roughness Data:** This consists of the measured elevation traces of the original surface. The data variables of this group are:

- \( YYP \) = a vector variable describing the elevation at all points on all elevation traces in sequence;
- \( NPF \) = number of elevation traces;
- \( NP \) = number of measurements on each trace;
- \( DX \) = spacing between measurements;
- \( TLEN \) = total length of the elevation trace.

(b) **Physical Parameters:** These are the variables describing the physical properties of the problem, used in erosion computations, namely:

- \( UWT \) = unit weight of the soil, in \( N/m^3 \);
- \( DMLM \) = representative diameter of soil particles, in mm;
- \( RN \) = Manning's roughness coefficient;
G = gravity acceleration, in m/sec^2;
SG = soil specific weight;
RO = water density, kg/m^3;
p = exponent of Kalinske's equation; see Equation (4.10);
ASR = soil constant, a_s, in erosion equation; see Equations (4.18) and (4.12); and,
ASH = soil constant, a_S, in interrill erosion equation; see Equations (4.23) and (4.12).

(c) Storm and Slope Data

NX = number of nodal points in the cross-direction of the underlying rectangular mesh, see Section 5.3.3;
NY = number of nodal points in the longitudinal direction of the underlying rectangular mesh;
SLOPE = the average slope of the test area, in degrees;
RNL = rainfall intensity in mm/hr;
RNF = runoff coefficient, see Section 5.1.1;
TI = length of time interval, in minutes;
NTI = number of time intervals; and,
NRS = number of random surfaces to be generated. A sample of size = NRS can then be used in any further statistical analysis.

5.3.2 Analysis of Surface Roughness Data

The input to this step is the surface roughness data. The analysis is conducted in the following sequence:
1. For each of the elevation traces, remove the mean (Subroutine FILTER), then compute Fourier coefficients (Subroutine POWER). Fourier coefficients are computed using the method of Fast Fourier Transform, which is documented in the computer package called IMSL (15), and is called by Subroutine POWER.

2. Compute the average coefficients for each wave component (Subroutine C W A V E ).

3. From the range of waves of length $\leq 30$ cm, pick up the wave component with maximum contribution to total variance. Then compute the residuals from each trace (Subroutine C W A V E ).

4. Compute the mean and the standard deviation of the residuals from each trace (Subroutine RESDL).

5. Compute the average mean and standard deviation for all traces (Subroutine C W A V E ).

5.3.3 Generation of the Random Surface

The input to this step is the amplitude, AMP, and the wavelength, WL, of the basic wave, plus the mean and the standard deviation of the residual data.
The computational procedure for generating a random surface is described as follows:

1. Compute the nodal coordinates of a rectangular mesh \( NX \times NY \) with the mesh size as indicated in Figure 5.10 (Subroutine HXMESH).

2. Assign codes to nodal points according to their location in the mesh. Points such as \( b \) are assigned code = 2, whereas points such as \( a \) are assigned code = 1. The remaining points of the rectangular mesh, such as \( c \), are given code = 0. The hexagonal mesh is formed when points of code = 0 are eliminated, as shown by the solid lines in Figure 5.10.

3. Compute the elevations of the plane surface at nodal points using the value of SLOPE for the surface gradient (Subroutine ELEVTN).

4. Superimpose the basic wave on the plane surface according to the given values of amplitude.

5. Using Subroutines RANORM and RANDU, draw a random number for each nodal point and add it to the elevations obtained by Subroutine ELEVTN.
6. Draw another group of random numbers to randomize the elevations of the humps (Subroutine HUMP).

7. Check the stability of side slopes of all rill segments (Subroutine SFAILR). Criterion and mechanisms for this procedure are discussed in Section 5.2.3.

These steps generate the initial random surface, which is then subjected to overland flow and erosion.

5.3.4 Computation of Overland Flow

Based on the considerations described in Sections 5.1 and 5.2, the routing of overland flow is carried out for each time interval as follows:

1. Survey all rill segments to check for ponding along any path, on the basis of the mechanisms explained in Section 5.2.1 (Subroutine POND).

2. Compute the flow at each nodal point (Subroutine FLOW).

3. When low humps exist, revise flow computations on the basis of the mechanism explained in Section 5.2.4 (Subroutine RDISTB).
5.3.5 Erosion Computation

Given the elevation and the overland flow at every nodal point, the erosion in rill segments and over adjacent humps are computed. Rill segments whose upstream nodal point has code = 1 are dealt with in Subroutine ERSN1. Rills whose upstream node has code = 2 are processed through Subroutine ERSN2. Computations for every rill segment are conducted in the following order:

1. For any rill segment, identify the surrounding humps which form its side slopes (Subroutine IDHMP).

2. Compute new values of bed slope and side slopes (Subroutine ERSN1, or ERSN1).

3. Determine flow depth and width in rill segment (Subroutine CSEC).

4. Compute erosion on side slopes of humps, or interrill erosion (Subroutine HERSN).

5. Compute rill erosion and the corresponding change in rill geometry on the basis of the mechanism explained in Section 5.1.2 (Subroutine RERSN).
6. Compute the total amount of soil eroded, and transported by the flow above a nodal point (Subroutine ERSN1 or ERSN2). If ponding exists along a rill path, the deposition mechanism described in Section 5.2.2 is applied.

7. Revise the distribution of sediment load at nodal points in order to account for the presence of low humps (Subroutine SNEGTV). The mechanism used in this step is explained in Section 5.2.4.

8. Calculate and store the total amount of sediment load received at nodal points at the bottom of the slope. This quantity represents the total sediment yield in a specific time interval.

9. Elevation of nodal points and humps are revised to account for erosion during the preceding time interval. Arrays of flow and erosion are initialized, in preparation for the new values of the next time interval.

The computation steps explained in Sections 5.3.4 and 5.3.5 are repeated for successive time intervals until the end of
6. Compute the total amount of soil eroded, and transported by the flow above a nodal point (Subroutine ERSN1 or ERSN2). If ponding exists along a rill path, the deposition mechanism described in Section 5.2.2 is applied.

7. Revise the distribution of sediment load at nodal points in order to account for the presence of low humps (Subroutine SNEGTV). The mechanism used in this step is explained in Section 5.2.4.

8. Calculate and store the total amount of sediment load received at nodal points at the bottom of the slope. This quantity represents the total sediment yield in a specific time interval.

9. Elevation of nodal points and humps are revised to account for erosion during the preceding time interval. Arrays of flow and erosion are initialized, in preparation for the new values of the next time interval.

The computation steps explained in Sections 5.3.4 and 5.3.5 are repeated for successive time intervals until the end of
the test period. Figure 5.11 shows a schematic representation of the relation between different subroutines.
Figure 5.1 Typical Routing of Rill and Interrill Flow

Figure 5.2 Change in Rill Geometry due to Rill Erosion
Figure 5.3 Ponding Conditions

a) Segments affected by ponding

b) Deposition pattern

Figure 5.4 Deposition due to Ponding
Figure 5.5 Mechanism of Side-Slope Failure

Figure 5.6 Segment with Positive Side Slopes

Figure 5.7 Segment with a negative side slope
Figure 5.8 Possible Cases associated with the low hump situation

\( S_0 = \text{bed slope} \)

**Computational mechanism**

\[ S_0 > S_2, \quad (W_1 + h_1) + (W_2) = j \]

\[ (W_3 + h_3) = m_1 \]

\[ (W_1 + h_1) + (W_2) + (W_3 + h_3) = m_1 \]

**Notations**

- \( W_1 \): water flowing on side slope CD
- \( h_1 \): hump erosion from side slope ab
- \( W_2 \): water flowing in rill ij
- \( h_3 \): hump erosion from side slope bc
- \( W_3 \): water flowing in side slope ba

\[ (W_0 + h_1)^{(W_0 + h_2)} (W_2) (W_3 + h_3)^{W_0 + h_2} a; \text{ (ponding)} \]

\[ (W_0 + h_1) + (W_2) + (W_3 + h_3)^{(W_0 + h_2)} a; \text{ (ponding)} \]
Subroutines associated with different steps:

- CWAVE
- FILTER
- POWER
- HXMSH
- ELEVTN
- HUMP
- RANDU
- POND
- FLOW
- RDISTB
- ERSN1
- ERSN1
- IDHMP
- CSEC
- TERPI
- RESD
- RANORM
- SFAILR
- ACJNT
- HERSN
- RERSN
- SNEGTV

Figure 5.9 Computational Scheme
Figure 5.10 Construction of the Hexagonal Mesh
Figure 5.11 Schematic Representation of Model Subroutines
CHAPTER VI
SENSITIVITY ANALYSIS OF THE MODEL

The discussion presented in this chapter investigates the sensitivity of the model to variations in different parameters and factors considered in its development.

The computational procedure of the computer program is long, and thus requires a preliminary study to determine reasonable limits of time and space for which the model can be applied. Accordingly, the first part of the sensitivity analysis is devoted to investigating the effect of some factors such as the length of time interval, and the configurations of the test area on the performance of the model.

The second part of this analysis examines the sensitivity of the model to the important parameters in erosion equations. Those parameters are $n$, $a_s$, and $p$, which appear in Equations (4.8) and (4.12).

The last part of this chapter investigates the sensitivity of the model to randomness in coordinates of surface points. This includes the effect of the rill pattern on the performance of the model. Specifically, we studied the case in which the uniform hexagonal rill pattern is distorted by a random component in the plane of the slope.
In most of the cases studied, the criterion for judging the performance of the model is the shape of the curve relating the soil Erosion Rate, in kg/m²/hr, to time (ER vs. T). When relevant, we also use the relation between Rill-Interrill Erosion Ratio and time, (R/I vs. T).

6.1 Geometric Limitations

As described in Section 6.3.1, the model computes the time-dependent erosion in increments of time. During each time interval, the flow passing by any point is assumed at steady state, the resulting erosion is computed for that time interval. The elevations of mesh points are then revised at the end of each time interval.

The width of the hexagonal mesh element is determined from the results of the spectral analysis of the surface roughness (length of the basic wave). For a given mesh size, we can try to control the length of time interval, and the size of the test area.

A preliminary test was conducted using a rectangular area covered by a 20 x 50 mesh (i.e., NX = 20 and NY = 50, as defined in Section 5.3.1). The results, shown in Figure 6.1, indicate strong fluctuations in the ER vs. T curve.

A closer study of the numerical scheme indicated that this phenomenon is related to the shape of the test area. In
rill segments, such as ab in Figure 5.1, if \( b \) becomes higher than \( a \), due to difference in erosion rates, the water and sediment reaching point \( a \) is ponded at \( a \). Therefore, the total amount of sediment collected at the bottom of the slope is decreased by the same amount. If the width of the test area is small, then the number of segments such as \( ab \) across the width is also small. Accordingly, if ponding occurs at any segment, especially the ones near the bottom of the slope, the ER vs. T curve will experience a significant drop. Then, in subsequent intervals, when deposition elevates point \( a \) above \( b \), the ponding situation disappears, and the amount of sediment reaching the bottom rises again. The drop and rise lead to fluctuations in the ER vs. T curve.

When the test area is wide enough, the ER vs. T curve for exactly the same conditions has smaller fluctuations. Figure 6.2 shows the results when using a 50 x 20 mesh.

The program's capacity is presently limited to a maximum number of nodal points of 2000. Therefore, subsequent runs are conducted using a 65 x 30 mesh.

6.2 Sensitivity to Time Interval

The study of the effect of the length of time interval is important in dynamic simulation models. Figures 6.3 and 6.4 show the variation of the model performance with time intervals ranging from 2.0 to 360 minutes. The results indicate a significant change in the shape of the ER vs. T curve with increasing
time interval. For short time intervals, the erosion rate generally increases with time. However, the value of the erosion rate at a specific time is larger for shorter intervals. Moreover, the erosion rate of the first time interval is the same in all cases.

In the erosion mechanism explained in Section 5.1.2, we find that with the progress of rill erosion, the side slopes become steeper and steeper until they reach the failure limit, (SLIMIT). Thereafter, the failed side slope assumes a new value, (SSTART). The subsequent interrill erosion on that sideslope will have a lower rate. Consequently, during a long time interval, more sideslopes will reach failure limit, and the interrill erosion of the next interval will be more significantly reduced. Furthermore, the fact that the soil masses which fail are not accounted for in the sediment yield also reduces the computed erosion (see Section 5.2.3).

Another factor influencing the model's behavior is the effect of updating the elevations after each time interval. In shorter time intervals, the updating process takes place more frequently, and therefore, the erosion process accelerates with a faster rate, and vice versa in longer time intervals.

On the basis of the above understanding, and to avoid excessive computation costs, a time interval of 10 minutes is used in the rest of the study.
6.3 Sensitivity to Parameters in Erosion Equations

The erosion model approximates the flow in rills and over interrill areas by a uniform flow, as expressed by the Manning equation (Equation 4.5). Therefore, it is important to investigate the effect of Manning's coefficient on the results of the model.

Other important parameters in the erosion models are the exponent, $P$, and the constant, $a_s$, in Kalinske's bed load equation (Equation 4.10). However, $a_s$ for rill erosion may be considerably different from $a_s$ for interrill erosion. Therefore, ASR is used to denote $a_s$ in the rill erosion equation, Equation (4.18) and ASH is used in interrill erosion equation, Equation (4.23).

Table 6.1 indicates the values adopted for different parameters in the sensitivity analysis.

6.3.1 Coefficient $n$ in Manning's Equation (N)

The value of $n$ is strongly dependent on the roughness of the surface over which water flows. Values of $n$, for a variety of cases, are reported by Chow (3). However, because of the small scale at which the erosion problem is analyzed, it is very difficult to choose the appropriate values of $n$. To test the model, arbitrary values of 0.02, 0.03, 0.04 and 0.05 were used for $n$. As shown in Table 6.1, when other parameters were tested, $n$ took on the value of 0.04.
<table>
<thead>
<tr>
<th>Parameters Fixed During the Analysis</th>
<th>Parameters Varied During the Analysis*</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N X \times NY = 65 \times 30$</td>
<td>$N = 0.02, 0.03, (0.04), 0.05$</td>
</tr>
<tr>
<td>$R NL = 64 , mm/hr$</td>
<td>$ASR = 200, 300, (400), 500$</td>
</tr>
<tr>
<td>$R NF = 0.5$</td>
<td>$ASH = 10, (20), 30, 40$</td>
</tr>
<tr>
<td>$TTIME = 6 , hours$</td>
<td>$P = (1.5), 1.75, 2, 2.5$</td>
</tr>
<tr>
<td>$TI = 10 , min.$</td>
<td>$SLIMIT = 1.1, 1.2, 1.3, (1.4)$</td>
</tr>
<tr>
<td>$D = 0.01 , mm$</td>
<td></td>
</tr>
<tr>
<td>$SLOPE = 20^0 \approx 37%$</td>
<td></td>
</tr>
<tr>
<td>$SSTART = 1.1$</td>
<td></td>
</tr>
</tbody>
</table>

* Values in parentheses are used when testing other parameters.
The ER vs. T curves for different values of n are shown in Figure 6.5. In general, the erosion rate increases with the increase of n. Although a higher value of n decreases the flow velocity, yet it increases the flow depth and consequently, the shear stresses, which controls erosion in this model (Equations 4.3 and 4.4).

It can also be seen that the fluctuation of the ER vs. T curve increases with n. This can be attributed to the effect of the ponding mechanism, since with higher erosion rate, associated with increasing n, the flow carries more sediment. Thus, the drops and rises in ER vs T curve are due to increased frequency of ponding.

The effect of Manning's coefficient on the rill-interrill erosion characteristics is shown in Figure 6.6. This effect varies with time during the test period. At late times, when erosion is sufficiently accelerated, higher values of n result in higher rill-interrill erosion ratio. The reason for this is explained below.

The erosion mechanism as described in Section 5.1.2 directly relates the erosion of the bed of a rill with the erosion from its sides. That is, if a rill bed is lowered by a certain distance, the slopes of the sides are increased by a corresponding amount. But the increase in the slope of the bed is less than that of the sides because erosion lowers both ends of the rill segment, although by different amounts. Therefore, the rill erosion
actually increases the interrill erosion of adjacent humps more than the rill erosion in the segment itself. Realizing that rills comprise only a small fraction of the surface, we can see why the progress of erosion results in a continuous reduction in the rill-interrill erosion ratio.

The increase of interrill erosion causes the side slopes to reach failure limit (SLIMIT) at a faster rate. Subsequent interrill erosion will be significantly reduced, causing the rill-interrill erosion ratio to increase for the rill segment in question. This is the reason for the fluctuations in the R/I vs. T curve.

From the previous explanation, we can see that the overall R/I ratio will decrease with time until side slope failure begins to affect a large enough number of humps in every time interval. At this point, interrill erosion ceases to increase, while the rill erosion continues to increase, and the trend of the R/I vs. T curve is reversed. The time at which the R/I ratio begins to increase depends on parameters which control erosion. In this test, higher values of n result in greater erosion rates, and shorten the time to reach this point. We can see from Figure 6.6 that the R/I ratio begins to increase at 240 minutes where n = 0.05. When the test period is extended for the case of n = 0.04, as shown in Figure 6.7, the R/I ratio begins to increase after about 380 minutes.
In summary, we find that, within the tested range, i.e., 0.02 to 0.05, the model is sensitive to Manning's coefficient. Its value affects both the total erosion rate, and the rill-interrill characteristics.

6.3.2 The Constant $a_s$ for Rill Erosion (ASR)

According to Komura (17), the value of $a_s$ when rills and gullies exist (denoted by ASR), is about 300. For interrill erosion, $a_s$ (denoted by ASH) takes on a value of about 30.

The sensitivity to ASR was tested for values equal to 200, 300, 400 and 500. When other parameters were tested, ASR took on the value of 400.

The effect of ASR on the erosion rate is shown in Figure 6.8. It can be seen that the model is not very sensitive to the value of ASR. However, this parameter has more influence on the rill-interrill characteristics. Figure 6.9 indicates that higher values of ASR result in larger R/I ratio. An increase in ASR clearly accelerates rill erosion. Therefore, the R/I vs. $T$ curve for the case of ASR = 500 begins to reverse its trend before other cases.

6.3.3 The Constant $a_s$ for Interrill Erosion (ASH)

The test was conducted using ASH values of 10, 20, 30 and 40. When other parameters were tested, ASH was given a value of 20.
As shown in Figure 6.10, the erosion rate generally increases with the increase of ASH. The maximum erosion rate of the case ASH = 40 is about three times that of the case, ASH = 10. The erosion rate is clearly more sensitive to ASH than to ASR.

In terms of the rill-interrill characteristics, as expected, R/I erosion ratio decreases with the increase of ASH, as shown in Figure 6.11.

6.3.4 The Exponent \( p \)

The parameter \( p \) is an empirical exponent in the Kalinske equation, as shown in Equation (4.10). For open channels, Kalinske and Brown (see Rouse (14)) suggest a value of 2 for \( p \).

To investigate the effect of \( p \) on the model, erosion is computed for \( p \) values of 1.5, 1.75, 2.0, and 2.5. Figure 6.12 shows the effect of \( p \) on the erosion rate. Smaller values of \( p \) result in higher rates of erosion. The erosion rate is sensitive to \( p \), and the sensitivity increases for smaller values of \( p \). The R/I ratio is less sensitive but generally, smaller values of \( p \) produce higher rill-interrill erosion ratio. For example, at the end of the test, R/I ratio for \( p = 1.5 \) is twice as much as that for \( p = 2.5 \), as shown in Figure 6.13.

6.4 Sensitivity to Criterion of Side Slope Failure

The mechanism of side slope failure, although simple, is very important in erosion simulation over longer time periods.
The two controlling factors are the upper and lower limits of the slopes, SLIMIT and SSTART, respectively.

The purpose of this test is to study the behavior of this model under different values of the quantity (SLIMIT - SSTART). To do so, SSTART is assigned a fixed value of 1.1, whereas SLIMIT varies from 1.1 to 1.4.

The influence of this factor on the erosion rate is shown in Figure 6.14. The sensitivity of the model to the quantity (SLIMIT - SSTART) is generally low, but it increases somewhat as the erosion progresses.

For an individual rill segment, a larger value of (SLIMIT - SSTART) allows for steeper side slopes. Therefore, we can expect higher rate of interrill erosion, and higher total erosion. But for the multitude of rill segments of the random surface, the combined effect of slope steepening and failure reduces the difference in results between different values of (SLIMIT - SSTART). The same low level of sensitivity is also noticed from the R/I vs. T curves shown in Figure 6.15.

6.5 Effect of Randomness in Elevation

This part of the analysis is aimed at studying the sensitivity of the model to the randomness in elevations of nodal points on humps. Therefore, a comparison is made between the model results when randomness is included and when it is omitted in the slope surface.
The case when randomness is included can be represented by the results in Figure 6.14, described in the previous section. The test is repeated under the same conditions, except with the random component set equal to zero. The latter scheme results in a surface with identical humps. Furthermore, all rill segments emerging out of a nodal point of code = 1 (e.g., point a in Figure 5.1), will have a bed slope equal to the average slope. Rill segments emerging out of nodal points of code = 2 (e.g., point b in Figure 5.1), will have identical bed slope which is less than the average slope.

Figure 6.16 shows the relationship between the erosion rate and time for the uniform surface. In comparison with the results in Figure 6.14, we can see that the uniform surface produces higher rates of erosion at all times. The erosion rate increases nearly uniformly with time, with little or no fluctuation, depending on the value of SLIMIT.

It seems obvious that the non-random case presents a surface with less "obstacles," and with no possibility of ponding along rill paths. Thus, water flows downslope in identical channels, resulting in uniform erosion of the surface. It is therefore possible to conclude that the randomness in elevations of the surface points has a considerable effect on the results of the model.

Further examination of the shape of the erosion rate curve provides better understanding of the way the mechanism of side
slope failure operates. Figure 6.16 represents the results of four identical surfaces, but with different limits for the side slope failure. In the case of SLIMIT = 1.1, the erosion rate increases uniformly with time for a period of about 160 minutes. At this point, the side slopes of all rill segments reached the limit (SLIMIT), and the rate of interrill erosion remains the same with time. The total erosion rate, however, continues to increase, with a lower rate, due to the increase in rill erosion.

It is easy to see that the reduction in the erosion rate takes place in all the cases, but with different magnitudes, and at different times. The larger the value of SLIMIT (i.e., larger SLIMIT - SSTART), the more the time needed to reach the failure limit, and the greater the drop in erosion rate due to side slope failures.

6.6 Effect of Randomness in Rill Pattern

As described in Section 3.2, the surface of a new soil slope consists of many humps and depressions, as shown in Figure 3.1. The actual path of overland flow is quite irregular, at least in the early stages of erosion, before well-defined master rills are formed (See Horton (14)).

The uniform hexagonal mesh used in this model, as an elementary rill pattern, is an important simplification. As part of the sensitivity analysis, an attempt is made in this
section to compare the performance of the model with the results of a simplified model using a random rill pattern.

The random rill pattern is generated according to the procedure described in Section 3.4.2, using the results of zero-crossing analysis. The amount of soil eroded at any point is directly dependent on the flow characteristics at this point. Therefore, instead of comparing amounts of soil eroded, we can use the flow as a basis for comparison. Consequently, the problem is reduced to a comparison between water quantities from humps, and flowing in different rill segments. Such comparison is far from being complete, yet it serves as an indication to the potential effect of the rill pattern.

The random surface used in the comparison covers an area of NX = 15 and NY = 8, with an average slope of 20 degrees. For the random rill pattern, the surface is generated according to the procedure described in Section 3.4.2. For simplicity, we assume a unit amount of water to be drained into each rill segment from adjacent humps. At nodal points, the flow is also divided between different segments according to the rules described in Section 5.1.1. Flow computations are done manually. For this reason, the comparison is made using a relatively small area (15 x 8). For the hexagonal rill pattern, results are directly obtained from the model (output of Subroutine FLOW).

Because the rill flow increases downslope, we must compare the flow of rill segments at approximately the same relative
position on the slope. Two samples in each surface are selected to make the comparison. The first sample consists of the rill segments of the 4th "row" from the top. The second sample consists of rill segments in the 6th "row". The location of samples are shown in Figures 6.17 and 6.18. Each sample contained 14 segments.

Figures 6.19 and 6.20 show the empirical distributions of the flow obtained in each case. The results indicate that the null hypothesis, that the two samples belong to the same distribution, is rejected in the test on the 4th row. The same hypothesis, however, is accepted in the other test. The significance level in both tests is 0.05.

It can be seen from Figures 6.19 and 6.20 that the distribution of rill flow using uniform rill pattern has larger variation. It is not possible, however, to draw more specific conclusions about the overall effect of randomness in rill patterns on the model results. On one hand, limitations imposed by manual computations dictated the use of a small mesh, which produces a small sample of rill segments, leading to higher probability of sampling error. On the other hand, the results of the statistical testing are marginal. Therefore, it is believed that this point warrants further investigation. The above analysis, however, presents a possible starting point.

It is important to notice that the randomness in the generated surface creates randomness in the overland flow.
Auxiliary mechanisms of ponding and low humps account for this randomness, and thus, reduce the degree of idealization of a uniform rill pattern. Consider, for example, the mesh shown in Figure 6.21(a). Before superposing any random component on the elevations of surface points, a cross section such as A.A would result in a uniform profile, as shown in Figure 6.21(b). This profile is composed of identical and equidistant rill segments. Such surface is probably an unrealistic representation of the actual surface.

When the random component of elevation is imposed on each of the points 1-9 on Figure 6.21(a), two kinds of profiles can be obtained. In the first, the random components alter the heights of different points on the profile, yet the original rill pattern is basically the same, with minor differences only in the size of the rills. This case is presented in Figure 6.21(c). This can take place mostly in cases where the random component is generally small. On the other hand, if some points such as 3 and 7 have a relatively large negative random component, low humps are created at points 3 and 7. This results in a significantly different rill pattern, as shown in Figure 6.21(d). The mechanism explained in Section 5.2.4 shifts the flow from the rill passing by point 4 to the adjacent rill passing by point 2. Therefore, the rill passing by point 4 no longer contributes to rill erosion computation. Another possibility is
that a hump such as that at point 7 is so low that it eliminated the two adjacent rills and formed a ponding zone in place of the hump.

The above examples indicate that the uniform hexagonal grid actually serves as a "reference" frame for computations, rather than a fixed rill pattern. This allows for geometrical irregularities such as low humps and ponded zones to be simulated.
Figure 6.1 ER vs T curve for a 20 x 50 mesh

Figure 6.2 ER vs T curve for a 50 x 20 mesh
Figure 6.3 Relationship between Erosion rate and time interval; short range

Figure 6.4 Relationship between Erosion rate and time interval; long range
Figure 6.5 Effect of Manning's Coeff. on erosion rate

Figure 6.6 Effect of Manning's Coeff. on R/T Erosion ratio
Figure 6.7 R/T vs T curve for $n = 0.04$ for an 8-hr test
Figure 6.8 Effect of the constant ASR on Erosion rate

Figure 6.9 Effect of the constant ASR on R/I erosion ratio
Figure 6.10 Effect of the constant ASH on Erosion rate

Figure 6.11 Effect of the constant ASH on R/I Erosion ratio
Figure 6.12 Effect of the exponent p on Erosion rate

Figure 6.13 Effect of the exponent p on R/I erosion ratio
Figure 6.14 Effect of the factor SLIMIT on Erosion Rate

Figure 6.15 Effect of the factor SLIMIT on R/I erosion ratio
Figure 6.16 Erosion on uniform surface.
Figure 6.17 Test Samples from Uniform Rill Pattern

Figure 6.18 Test Samples from Random Rill Pattern
Figure 6.19 Effect of Rill Pattern Randomness on Flow; Test no. 1

Figure 6.20 Effect of Rill Pattern Randomness on Flow; Test no. 2
Figure 6.21 Irregularity in Generated Surfaces
CHAPTER VII

NUMERICAL EXPERIMENTS

Having examined the sensitivity of the model to important parameters and mechanisms, it is now possible to conduct some numerical experiments. Successful simulation models are extremely useful in understanding simulated processes, and in predicting their behavior. The numerical experiments discussed in this chapter serve as an indication of the potential benefit of this model in that regard.

First, the predictions of the model are compared with some field experiments. However, it is important to emphasize that we are only interested in comparing the orders of magnitude of erosion. A close agreement between predicted and measured values is not expected at this stage. This is because proper verification of the model requires that the experiments be made on bare slopes with no large-scale variations in surface geometry, and data on micro-relief of the original surface be available. We also need to obtain the model parameters, particularly the soil representative diameter, D, and the Manning's coefficient, n. Most of this information is not available in published erosion data at the present time. In addition, the results of the experimental studies on rill-interrill erosion characteristics are mostly preliminary.
In fact, the available results are obtained from plots with artificial straight rills (24, 25). Such conditions are not suitable for comparison with the predictions of this model.

Next, model predictions are used to establish the influence of important physical conditions which are slope gradients, slope length, and rainfall intensity, and compared with trends known from experience and existing empirical relations.

7.1 Comparison with Field Measurements

Some measurements from newly formed highway embankments are used to compare the model's results with field data. To study the effect of erosion control methods on highway backslopes, Barnett et al. (1) conducted field experiments at four different locations using rainfall simulators. In each location, seven plots with different mulch treatments were prepared, one of which was left as bare surface. Each site was graded to 2½:1 slope, seeded, rototilled, and then firmed with a cultipacker.

In two of the four locations, the soil was classified as clay. The soil in the other two locations was classified as sandy clay loam.

The test storm was applied at an intensity of 2½ i.p.h. in two increments of 30 minutes each. The first increment, 1¼ inches in 30 minutes, corresponds to a one-year frequency storm; the entire test represents a 10-year frequency storm within the geographical region of the test, which is Georgia.
Obviously, many parameters and measurements are needed as input data to the model. Nevertheless, some of those parameters are assumed common for slope erosion problems. Among those are the constants, ASR, ASH and p, and the constants describing the properties of water. On the other hand, some data such as the representative size of soil particles, the Manning's coefficient, and the surface roughness measurements are unique characteristics of each site.

It is not surprising that no information about the surface roughness was reported in the paper by Barnett et al. With due reservations, the roughness data obtained from Wooster, Ohio, which has been analyzed in Chapter III, is used here to represent a well-cultivated surface.

Since the field study was not concerned with comparing flow and erosion results with any theoretical model, no estimate of Manning's coefficient, n, was presented. Use is made of the results of the investigation by Ree et al. (30) on the value of n in overland flow. Values as high as 0.3 were reported in their study, for poor-cover conditions. Even higher values (0.6) were reported for fair and good cover conditions. For the bare surface in question, computations are made for a range of n from 0.025 to 0.2.

According to Foster and Meyer (8), clay particles are detached by rainfall as aggregates. These aggregates move along the bottom of the rills as cohesionless particles.
The previous consideration is the basis for the choice of the values of the soil particle representative diameter, D, in the two types of soils. For the plot classified as clay, the reported gradation was 39% sand, 27% silt, and 34% clay. The clay particles in the USDA classification have a diameter of less than 0.002 mm. Therefore, to represent the clay aggregates, and in the same time, allow for the non-aggregate representation of sand and silt, the value of D = 0.01 mm is selected. In the second plot, with the gradation of 57% sand, 17% silt and 26% clay, we used the value of 0.05 for D.

Using a time interval of 2 minutes, the model computed the total soil loss at the middle, and at the end of a 60-minute storm period. The soil losses computed, for different values of n, for the two sites are shown in Figures 7.1 and 7.2, respectively. The value of n required to produce the measured soil loss is also shown.

Examination of the model results on Figures 7.1 and 7.2 indicates that in order to achieve a value of soil loss comparable to that obtained from field measurements, the value of Manning's n has to be around 0.085 for clay and over 0.2 for sandy clay. Given the surface condition, as a bare slope, and comparing with the estimates produced by Ree et al. (30), those n values, especially for the sandy clay, may be too high. However, the values of n for overland flow in general, and for bare slopes in particular, are not yet well established.
It is possible, however, that the model tends to underestimate the soil loss, because of the approximation used in the side slope failure mechanism, as explained in Section 5.2.3. It is difficult, though, to determine the specific source of discrepancy between the field measurements and the model results, because of the factors discussed in the introduction to this chapter. Therefore, it seems inevitable that a proper verification of the present model requires specific surface preparation and measurements.

7.2 Effect of Slope Gradient

The slope gradient of a soil surface is one of the most important factors which control the process of slope erosion. Investigators, since the earliest erosion studies, have always attempted to determine the relation between the slope steepness and the amount of soil eroded. Experimental as well as theoretical studies agree that soil erosion increases with slope gradient. A unique relation, however, is not yet well established (See Li et al. (19)).

In testing the effect of slope gradient in the present model, the erosion rate is computed for four plots with slopes of 5, 10, 15 and 20 degrees, respectively. Figure 7.3 shows the change of erosion rate with time for the four cases.

The results on Figure 7.3 indicate that steeper slopes result in larger erosion rates. The relation between slope gradient and erosion rate is time-dependent, as shown in Figure 7.4. This
behavior may provide a possible explanation for the differences in the results of experimental studies on the effect of slope gradient on the erosion rate.

7.3 **Effect of Slope Length**

Since this overland flow tends to increase downslope, longer slopes result in longer and deeper rills. Therefore, the slope length can be expected to have a significant influence on the rill-interrill erosion features.

The relation between the erosion rate and time is computed for three plots of lengths 0.73, 2.29 and 3.85 meters, respectively. These values correspond to values of NY of 10, 30 and 50, respectively, as shown in Figure 7.5. To achieve a value of NY = 50, NX is reduced to 39 throughout this test.

The model's results, as shown in Figure 7.5, indicate that the erosion rate decreases with the increase of slope length. This behavior contradicts empirical models in general (see Reference 19). Determination of the mechanism responsible for such behavior requires additional investigation.

The effect of the slope length on the rill-interrill erosion features is very important, since transport and detachment capacities of rills increase with distance downslope. Figure 7.6 shows the relation between rill-interrill erosion ratio with time for the same plots. It is clear that the contribution of
rills increases with slope length. This means that rill erosion increases with distance down slope. Such behavior has been confirmed in many studies (24, 25, 26).

7.4 Effect of Rainfall Intensity

Rainfall characteristics, such as intensity, angle of incidence, spatial, and temporal distribution, have variable impact on the erosion process. The present model is concerned only with the effect of rainfall intensity.

The test area is subjected to three storms of 50, 25 and 12.5 mm/hr rainfall intensity, respectively. The erosion rate is computed for the test periods of 3, 6 and 12 hours, respectively. This means that at the end of each test, all plots would have received the same amount of rainfall, which is 150 mm (≈ 6 inches). Each of the three storms is applied to three plots of slopes of 5, 10 and 20 degrees, respectively. Results of the three storms are shown in Figures 7.7, 7.8 and 7.9.

As expected, storms of larger intensity result in higher values of erosion rate at all times. The relation between rainfall intensity and erosion rate seems to be dependent on the average slope gradient of the plot, as shown from Figure 7.10.

7.5 Evaluation of Eroding Surfaces

The purpose of this section is to illustrate the temporal and spatial changes in the surface geometry under erosion, as simulated by this model.
The shape of the original random surface generated by the model (i.e., prior to erosion) is shown in Figure 7.11. Subsequent changes in the surface geometry are shown in Figures 7.12 and 7.13 at times 200, and 400 minutes, respectively. For the constant rainfall intensity of 50 mm/hr, the total amount of rain at the end of the test is 333 mm (= 13.1 inches).

Observation of the figures illustrates the growth of rill size with time. Moreover, we can see the effect of the random surface elevations on development of nonuniform rill pattern. The results are in qualitative agreement with observed rilling on slopes.

It is important to emphasize that the rill pattern developed in the above test is only one of many probable realizations whose occurrence depends on the generated random surface. All those realizations, however, are supposed to have the same statistical properties.
Figure 7.1 Soil Loss from the Clay Site

Figure 7.2 Soil Loss from the Sandy Clay Site
Figure 7.3 Effect of slope gradient on erosion rate

Figure 7.4 Effect of time on the slope gradient - Erosion rate relation
Figure 7.5 Effect of slope length on erosion rate

Figure 7.6 Effect of slope length on R/I erosion ratio
Figure 7.7 Effect of Rainfall intensity on erosion rate; 
RNL = 50 mm/hr

Figure 7.8 Effect of Rainfall intensity on erosion rate; 
RNL = 25 mm/hr
Figure 7.9 Effect of Rainfall intensity on erosion rate; 
RNL = 12.5 mm/hr

Figure 7.10 Relationship between Rainfall Intensity, Slope Gradient and Erosion Rate
Figure 7.11 Original Surface, $t = 0$
Figure 7.12 Eroded Surface; $t = 200$ minutes
Figure 7.13 Eroded Surface, $t = 400$ minutes
8.1 Summary and Conclusions

The review of literature on soil erosion reveals the need to consider the effect of the random rill patterns which develop as a result of the surface irregularities. An attempt has been made in this study to simulate the erosion process on the basis of the rill-interrill characteristics as they change with space and time.

The measured roughness of a surface is analyzed and used in generating random surfaces for the simulation process. The rill pattern developing on the random surface is approximated by a hexagonal mesh which covers the test area. Erosion computations are then carried out over a number of time intervals, according to the specified rainfall and infiltration characteristics. During each time interval, computations are made assuming a steady state condition. Changes in the surface geometry, due to erosion, during any time interval are considered in the subsequent interval. The model uses simplified mechanisms to simulate ponding, deposition, and failure of side slopes of rills.

A sensitivity analysis of the model was made to examine the effect of important parameters and mechanisms. The length
of time intervals is important because of the cumulative effect of the elevation-updating procedure. Therefore, shorter time intervals give better estimates of erosion rate.

Part of the sensitivity analysis was directed to the study of the influence of the parameters in the erosion equation on the model results. The erosion rate increases with the increase of the value of Manning's coefficient, n. The difference in transport capacity of flow in rills and over interrill areas is mainly expressed in the value of the constants ASR and ASH. The value of ASR does not have significant effect on the total erosion rate. However, an increase in its value produces higher rill-interrill erosion ratio. The model is more sensitive to the value of ASH. An increase in its value increases the erosion rate and, at the same time, decreases rill-interrill erosion ratio. The model is sensitive to the exponent p in Kalinske's bed load equation, Equation (4.10). A lower value of p results in a higher erosion rate, and higher R/I ratio as well.

The randomness incorporated in the generation of the simulated surface has a significant effect on reducing the erosion rate. This means that surfaces with more random variations experience smaller erosion rates.

As part of the sensitivity analysis, a preliminary study was made to investigate the potential difference in the model behavior when using a random mesh to simulate the rill pattern.
The distribution of rill flow in the uniform pattern results has more variations than that of the random pattern. However, the study was not conclusive because of the small sample size used in the analysis.

The results of the model were compared with some data from field experiments. The results are of the right order of magnitude, but it is not possible to determine the extent of agreement between the two results since many parameters and data, including the original surface roughness, were not available.

The effect of the slope gradient on the model results was studied. Steeper slopes result in faster erosion rates. Moreover, the relationship between slope gradient and erosion rate is found to be time-dependent.

The length of the slope has a significant effect on rill characteristics. According to the model results, longer slopes result in larger contribution of rills to the erosion process. However, the total erosion rate seems to decrease for longer slopes. This behavior is not in agreement with the results of existing empirical models.

The influence of rainfall intensity on the erosion rate was also studied. For the same accumulative amount of rainfall, the model showed that the higher the rainfall intensity, the faster the erosion rate. However, the effect of increasing the rainfall intensity is found to be more significant for steeper slopes.
8.2 Recommendations for Further Research

Because this is a first step in stochastic simulation of the erosion process, numerous problems both in formulation and in documentation have been encountered. Consequently, many simplifications were made. The structure of the simulation model, however, allows for sufficient flexibility in refining different submodels and mechanisms when feasible.

Proper verification of the model requires field experiments which meet the model requirements in terms of surface preparation and measurements. Also, more study is needed to determine appropriate values for the parameters of the erosion model, such as Manning's n, the constant $a_s$, and the exponent $p$, as they are related to the overland flow problem.

The erosion model can be further improved by considering the detachment and the transport capacity of the rill flow separately. Moreover, the computation of rill flow can be modified so that the continuity of energy at nodal points is satisfied. Such consideration is expected to improve the mechanisms of ponding and deposition.

The use of only one wave component out of the spectrum of the surface roughness to determine the shape of the rill pattern may be too simplistic. The possibility of constructing a rill pattern using a combination of wave components which have comparable contributions to the surface variations warrants further effort.
The study on the use of random rill patterns was not concluded. The use of the method of zero crossing analysis seems to provide a good starting point in that regard.

It is important to notice that the stochastic aspect of the model is based only on the random characteristics of the surface roughness. Other factors such as rainfall distribution, soil properties, and infiltration, are also random in nature, and contribute to the overall behavior. Recently, Freeze (10) presented a simulation model to account for some of those factors in computing overland flow. A similar technique can be used so that the model uses random values for those parameters as they change with time and/or with space.
REFERENCES


15. International Mathematical and Statistical Library

16. Kamil Eren (1979) Personal communication


39. Van Doren (1978) Personal communication


47. Zingg, A.W. (1940) "Degree and length of land slope as it affects soil loss in runoff", Agricultural Engineering 21: (2) 59-64, February
Meyer et al. (25) presented some results of some simulated rainfall field investigations on erosion in rills. A number of artificial rills were prepared in a Russell silt loam field. The rills were 4.6 m long and had bed slope of 6% and side slopes of 25%.

The present comparison is made for the case of 64 mm/hr rainfall intensity. The test was conducted for several values of base flow, as shown in Table A.1.

To use Equation (4.18), which is derived for rill erosion, several constants and parameters in the equation must be estimated. The silt loam is assumed to aggregate and form larger particles of diameter 0.2 mm. Since the test is on rill erosion, the value of the constant $a_s$ is taken as 300. The exponent $p$ is kept equal to 2.0. For a Manning coefficient of 0.025 and a runoff factor of 0.5, the computed erosion for different base flows is given in Table A.1. The comparison is specifically made between the measured and the computed values of the erosion rate in kg/hr/m length of the rill.
**TABLE A.1** COMPARISON BETWEEN MEASURED AND COMPUTED VALUES OF RILL EROSION

<table>
<thead>
<tr>
<th>Base Flow $Q_1$, kg/hr</th>
<th>End Flow $Q_2$, kg/hr</th>
<th>Soil Loss* kg</th>
<th>Erosion Rate kg/hr/m</th>
<th>$3ER$ m$^3$/sec/m</th>
<th>Erosion Rate kg/hr/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>114</td>
<td>1.51</td>
<td>0.32</td>
<td>$0.031 \times 10^{-6}$</td>
<td>0.15</td>
</tr>
<tr>
<td>700</td>
<td>732</td>
<td>4.98</td>
<td>1.08</td>
<td>$0.53 \times 10^{-6}$</td>
<td>2.5</td>
</tr>
<tr>
<td>700</td>
<td>712</td>
<td>4.89</td>
<td>1.07</td>
<td>$0.53 \times 10^{-6}$</td>
<td>2.5</td>
</tr>
<tr>
<td>1400</td>
<td>1436</td>
<td>18.45</td>
<td>4.01</td>
<td>$0.53 \times 10^{-6}$</td>
<td>4.5</td>
</tr>
<tr>
<td>1400</td>
<td>1200</td>
<td>9.35</td>
<td>2.03</td>
<td>$0.53 \times 10^{-6}$</td>
<td>4.5</td>
</tr>
<tr>
<td>2000</td>
<td>2053</td>
<td>35.72</td>
<td>7.76</td>
<td>$1.31 \times 10^{-6}$</td>
<td>6.1</td>
</tr>
<tr>
<td>2000</td>
<td>2007</td>
<td>13.20</td>
<td>2.87</td>
<td>$1.31 \times 10^{-6}$</td>
<td>6.1</td>
</tr>
<tr>
<td>2800</td>
<td>2963</td>
<td>37.40</td>
<td>8.13</td>
<td>$1.75 \times 10^{-6}$</td>
<td>8.15</td>
</tr>
<tr>
<td>2800</td>
<td>2885</td>
<td>41.85</td>
<td>9.10</td>
<td>$1.75 \times 10^{-6}$</td>
<td>8.15</td>
</tr>
</tbody>
</table>

* Values indicated are the net soil loss from rill erosion only. It is computed by deducting the interrill erosion, as estimated by Meyer et al. (25), from the total measured soil loss.
APPENDIX B

LISTING AND SAMPLE OUTPUT
OF THE COMPUTER PROGRAM
***************
- A STOCHASTIC MODEL -
- FOR -
- SOIL EROSION -
- BY -
- MOSTAFA MOSSAAD -
- APRIL 1981 -
***************

Definition of Principal Variables:

- DMLM*: REPRESENTATIVE SOIL PARTICLE DIAMETER, MILLIMETER
- UWT*: UNIT WEIGHT OF SOIL, N/CUBIC METER
- RO*: DENSITY OF WATER, KG/C. METER
- C*: GRAVITY ACCEL., M/SQ. SEC
- SC*: SPECIFIC GRAVITY OF SOIL
- R*: MANNING'S COEFFICIENT
- P*: EXPONENT IN KALINSKE'S EQUATION
- ASR*: CONSTANT IN RILL EROSION EQUATION
- ASH*: CONSTANT IN INTER-RILL EROSION EQUATION
- NX*: # OF MESH POINTS IN X-DIRECTION
- NY*: # OF MESH POINTS IN Y-DIRECTION
- SLOPE*: AVERAGE SLOPE OF SURFACE, DEGREES
- RNL*: RAIFALL INTENSITY, MLTR/HR
- RN*: RUNOFF COEFFICIENT
- ARR*: ANNUAL RATE OF RAIN
- TI*: DURATION OF TIME INTERVAL, MINUTES
- RT*: # OF TIME INTERVALS
- RS*: # OF RANDOM SURFACES (I.E. SAMPLE SIZE)
- AMP*: AMPLITUDE OF BASIC WAVE
- WL*: WAVELENGTH OF
- SL*: LENGTH OF SHORT SIDE OF BASIC RECTANGULAR MESH ELEMENT, METER
- SH*: HORIZONTAL PROJECTION OF SL
- SDT(1)*: TOTAL VOLUME OF SEDIMENT WHICH PASSED BY POINT 1 DURING A TIME INTERVAL, CUBIC METERS
- TRE(1)*: VOLUME OF RILL EROSION PART OF SEDIMENT WHICH PASSED BY POINT 1 DURING A TIME INTERVAL, C. METERS
- SDT(1)*: TOTAL VOLUME OF SEDIMENT WHICH PASSED BY POINT 1 DURING A TIME INTERVAL, CUBIC METERS
- TRE(1)*: VOLUME OF RILL EROSION PART OF SEDIMENT WHICH PASSED BY POINT 1 DURING A TIME INTERVAL, C. METERS
- TTBTH*: WEIGHT OF TOTAL SEDIMENT ACCUMULATED AT THE BOTTOM DURING A TIME INTERVAL, NEWTONS
- TBBTH*: WT. OF INTER-RILL EROSION
- TRBTH*: WT. OF RILL-EROSSION
- RATIO*: RILL/INTER-RILL EROSION DURING A TIME INTERVAL
- FTSDT(NS)*: TOTAL SEDMT. FROM RANDOM SURFACE NO. NS, NEWTNS
- FRSDT(NS)*: RILL EROSION
- FBSDT(NS)*: INTER RILL EROSION
- FRATE(NS)*: TOTAL EROSION RATE
- ***************

Data cards are put in the following order:

1) NP,NPF,CUT,TLEN,DX (SEE FORMAT STATEMENT # 1)
2) ROUGHNESS DATA CARDS (SEE FORMAT STATEMENT # 2)
3) DMLM,UWT,RO,SC (SEE FORMAT STATEMENT # 3)
4) RN,P,ASR,ASH (SEE FORMAT STATEMENT # 4)
5) NX,NY,SLOPE,RNL,RNF,ARRATE (SEE FORMAT STATEMENT # 5)
6) TNF, NRS (See format statement *6)
7) SLIMT, SSTART (See format statement *7)
8) NRUN (10). See note * 2
9) NRUN values of parameter being studied, see note * 2
***************************************************************

NOTE * 1
***************************************************************
THIS PROGRAM USES TWO SUBROUTINES CALLED FFTR AND FFTP FROM
THE * IMSL LIBRARY:
FFTR: COMPUTES FOURIER TRANSFORM, AND
FFTP: COMPUTES INVERSE FOURIER TRANSFORM.
MAKE SURE THEY STILL EXIST IN THE COMPUTER LIBRARY UNDER
THE SAME NAME
***************************************************************

DIMENSION VARPLT(10)
DIMENSION XP(200), YP(200), RSD(200)
DIMENSION YYP(1000)
DIMENSION TBTH(100), BTH(100), BTH(100)
DIMENSION FTSDT(100), FRSDT(100), FRSDT(100), FRATIO(100), FRATE(100)
COMMON/NODES/XI, XM, MM, SL, SH, WL, QQ
COMMON/MESSAGE/XX, YY, TT, SL, SH, WL, QQ
COMMON/ACCESS/Morra, Morra, Morra, Morra
COMMON/V/P L, P C, SC, RC, RN

***************************************************************

READ (5, 1) N P, NPF, C U T, TLEN, DX
NTOTAL=N P*NPF
READ (5, 2)(YYP(1), I=1, N T O T A L )

***************************************************************

READ PHYSICAL PARAMETERS
***************************************************************

READ (5, 3) DM L M, U V T, RO, C, GC
READ (5, 4) R M, P, ASR, ASB

***************************************************************

READ STORM AND SLOPE DATA
***************************************************************

READ (5, 5) NX, NY, SLOPE, RNL, RNF, ANRATE
READ (5, 6) TNF, NRS
READ (5, 7) SLIMT, SSTART
D=DM L M/1000.
T T M E = T N F / 60.

THE FOLLOWING FOUR CARDS ARE TO BE USED ONLY WHEN
COMPUTING RESULTS FOR (NRUN) VALUES OF ANY PARAMETER. FOR
EXAMPLE, RN, IN THE CASE BELOW

READ (5, 2000) KRUN
C READ (5, 3000) (VARPLT(1), I=1, KRUN)
C DO 1000 NRUN=1, KRUN
C RM=VARPLT(NRUN)
C WRITE (25) NRUN, VARPLT(NRUN)
C 2000 FORMAT (18)
C 3000 FORMAT (18F8.3)
C
S L P R = T A N ( S L O P E = 2 2 . / 7 . . . / 1 8 0 . . ) * 1 0 0
R A Y = N Y R * R N L * T T M E / A N R A T E / 1 0 .
WRITE (6, 50)
WRITE (6, 209)
WRITE (6, 203)
WRITE (6, 230)
WRITE (6, 263)
WRITE(6,209)
WRITE(6,310)
WRITE(6,315)
WRITE(6,320) MPF,NP,DX
WRITE(6,330)
WRITE(6,315)
WRITE(6,340) DNLN,UVT,SG
WRITE(6,350) P,ASR,ASR,NR
WRITE(6,360)
WRITE(6,315)
WRITE(6,370) NX,NY,SLOPE,SLOP,RLN,RNF
WRITE(6,375) ARATE,RAINF,RS
WRITE(6,380) TL,TTIME,MR
WRITE(6,390) SLINIT,SSTART
WRITE(6,60)
XP(I)=0.0
DO 14 I=2,NP
XP(I)=XP(I-1)+DX
14 CONTINUE
IF(NRUN.GT.1) GO TO 4000
WRITE(6,50)
WRITE(6,209)
WRITE(6,205)
WRITE(6,400)
WRITE(6,203)
WRITE(6,209)
WRITE(6,300)

C****************************************************************************************************
C... THE CHARACTERISTICS OF THE BASIC WAVE
C****************************************************************************************************
C
CALL CWAWE(XP,YP,YYP,NP,MPF,CUT,TLEN,AMP,VL,NSD,
# RMEAN,STDEV)
WRITE(6,300) AMP,VL
C
WRITE(6,305) RMEAN,STDEV
C... CONVERT TO METERS
C
AMP=AMP/1000.
VL=VL/100.
STDEV=STDEV/1000.
RMEAN=RMEAN/1000.
C****************************************************************************************************
C... CONSTRUCT THE HEXAGONAL MESH
C****************************************************************************************************
C
SL=VL/(2.*(3.*10.5))
SLO=SLOPE*22.7/100.
S=P=SL/COS(SLO)

4000 CONTINUE
DO 3007 I=1,NMAX
X(I)=0.
Y(I)=0.
CODE(I)=0
MAJ(I)=0
KPN(K(I))=0
3007 CONTINUE
CALL HEMESH
TAREA=Y(NY)*X(NMAX)
FSHAPE=X(NMAX)/Y(NY)
PL=Y(NY)
PW=X(NMAX)
WRITE(6,40) PL,PW
WRITE(6,30) TAREA,FSHAPE
WRITE(6,60)
CAMA=ROGc/9.81
C****************************************************************************************************
C... COMPUTE PARAMETERS OF EROSION EQUATIONS
C****************************************************************************************************
C
CALL PARAM(DP,ASR,ASH,RCH,HCH,EX)
C
C... START DO LOOP 200 FOR DIFFERENT RANDOM SURFACES
C
C

DO 200 NS=1,NRS
DO 201 I=1,NMAX
ELV(I)=0.0
DH(I)=0.0

201 HUMP(I)=0.0
DO 202 I=1,NRS
FTSDT(I)=0.0
FRSDT(I)=0.0
FRAT10(I)=0.0
FRATE(I)=0.0

202 FRATE(I)=0.0

C ... ASSIGN ORIGINAL ELEVATIONS TO ALL MESH POINTS
C
C CALL ELEVTN(SLOPE,AMP,RMAX,STDEV,NS)

C ... ASSIGN CALL NUMBERS, COORDINATES, AND ELEVATIONS TO ALL HUMPS
C
C CALL HUMP(RMAX,STDEV,SLOPE,AMP,NEUMP)

C ... START DO LOOP 100 FOR THE SEQUENCE OF TIME INTERVALS FOR THE
C RANDOM SURFACE UNDER CONSIDERATION
C
DO 100 NT=1,NT1
DO 101 I=1,NMAX
SDT(I)=0.0
TRE(I)=0.0
TIRE(I)=0.0
QLC(I)=0.0
QR(I)=0.0
QT(I)=0.0
IF(Y(I).EQ.0.0) GO TO 73

101 CONTINUE

CALL SFAILR(SLIMT,START)
CALL POND
CALL ACJNT

888 FORMAT(3(15,F15.5,15))

C ... STORE INITIAL ELEVATIONS OF ALL POINTS ON FILE # 35
C
IF(NT.GT.1) GO TO 635
REWRIND 35
CALL STORE(NNOD,NEUMP)

635 CONTINUE

C *****************************************************
C ... COMPUTE STEADY STATE FLOW AT MESH POINTS DURING A TIME INTERVAL
C *****************************************************

CALL FLOW(RSL,RSF)

C *****************************************************
C ... COMPUTE EROSION FOR RILL SEGMENTS WITH UPSTREAM POINT HAVING
C CODE = 1
C *****************************************************
C
80 CALL ERSN1(I,QT(I-1),RCH,RCH,EX,TI)
GO TO 70
C
**COMPUTE EROSION FOR ALL SEGMENTS WITH UPSTREAM POINT HAVING CODE-2.**

---

```fortran
85 CALL ERSW2(I,QL(I),QR(I),HCH,RCH,EX,TI)
75 IF(CODE(I).EQ.0.0) NVOID=NVOID+1
70 CONTINUE
777 FORMAT(3(I5.2F15.5))
999 FORMAT(15.7F13.B)
105 HMP(I)=(HMP(I-1)+HMP2(I)+HMP3(I)+HMP4(I)+HMP5(I)+HMP6(I))/6.
TBTHM=0.0
TBTHM=0.0
TBTHM=0.0
DO 110 K=1,NX
J=1+(K-1)*NY
TBTHM(K)=SDT(J)*UWT
TTBTHM=TTBTHM+TBTHM(K)
RBTM(K)=TRE(J)*UWT
TTBTHM=TTBTHM+RBTM(K)
HBTM(K)=TIRE(J)*UWT
TTBTHM=TTBTHM+HBTM(K)
110 CONTINUE
RAT0=TTBTHM/THBTHM
RAT=TTBTHM*60.0/TAREA/TI
260 FORMAT(130(’*’),/130(’*’))
100 CONTINUE

---

**STORE EROSION RATE RESULTS ON FILE #25**

```fortran
C XP1,TI,NT
YPLT,RATE
ZPLT=RATE
WRITE(25) XP1,YPLT,ZPLT
WRITE(25) FTSDT(NS)+TBTHM
WRITE(25) FRSDT(NS)+TRBTHM
FRATIO(NS)=FRSDT(NS)/FRSDT(NS)
WRITE(25) NT,TTBTHM,RATIO,RATE,FTSDT(NS),FRATIO(NS),FRATE(NS)
260 CONTINUE
```

---

**STORE FINAL ELEVATIONS OF ALL POINTS ON FILE #35**

```fortran
C CALL STORE(NNOD,NHUMP)
END FILE 35
```

---

**CHECK DATA STORED ON FILE #35**

```fortran
C625 READ(35,END=600) NY,NNOD,NHUMP
C630 FORMAT(3I10)
C612 FORMAT(2F20.5)
C605 READ(35,END=600) XXX,YYY,ZZZ
C600 CONTINUE
C610 FORMAT(3F20.5)
C200 CONTINUE
```

---

**CHECK DATA STORED ON FILE #25**

```fortran
C REVIND 25
C READ(25) NNUR,VARPLT(NNUR)
```

---

**END FILE 25**

```fortran
C```

---

**END FILE 35**

```fortran
C```
SUBROUTINE STORE(NMOD, NHUMP)
COMMON/MESH/NX,NY,NMAX,SL,SH,WL,GQ
COMMON/NHEX-1,KHEX(500),XYM(500),YHMP(500)
WRITE(35)NX,NMOD,NHUMP
WRITE(35)X(NMAX),Y(NY),SL
DO 505 I=1,NMAX
  IF(CODE(I).EQ.0) GO TO 505
  WRITE(35)X(I),Y(I),ELV(I)
505 CONTINUE
DO 620 I=1,NHUMP
  WRITE(35)XHMP(I),YHMP(I),NHMP(I)
620 CONTINUE
XEND=88888.
WRITE(35)XEND,YEND,ZEND
RETURN
END

SUBROUTINE Cwave(XP,YP,NYP,NPF,CUT,TLEN,AMP,WL,RS)
COMMON/Fmean,STDEV)
* M E A N , S T D E V )
*************************************************************************
THE FUNCTION OF THIS SUBPROGRAM IS:
1) PROCESS SURFACE ROUGHNESS DATA FOR SPECTRAL ANALYSIS, AND
2) IDENTIFY THE BASIC WAVE
*************************************************************************
COMPUTATIONS ARE BASED ON THE METHOD OF AVERAGE COEFFICIENTS.
*************************************************************************
REAL*8 Fmean
REAL*3 XP(1),YP(1),YP(1)
REAL*1 AN(1000),BN(1000),DPW(1000),RR(1000),CC(1000),VLAM(1000)
REAL*5 AN(1000),BN(1000),RR(1000),CC(1000),DDPW(1000)
DIMENSION NDEC(1000)
NB=NP/2+1
DO 401 I=1,NB1
  AAN(I)=0.
  BBN(I)=0.
  DDPW(I)=0.
  RR(I)=0.
  CCC(I)=0.
401 CONTINUE
DO 405 K=1,NPF
  DO 404 J=1,NP
    NP(K)=NP(K)+YP(J)
 404 CONTINUE
CALL FILTER(XP,YP,NPF,NDEC,AN,BN,DPW,RR,CC,VLAM,Fmean)
C ... COMPUTE AVERAGE VALUES OF AN,BN,...,ETC FOR ALL PROFILES:
C*************************************************************************
DO 410 J=1,NB1
  AAN(J)=AAN(J)+AN(J)/(1.*NP)
  BBN(J)=BBN(J)+BN(J)/(1.*NP)
  DDPW(J)=DDPW(J)+DPW(J)/(1.*NP)
  RR(J)=RR(J)+RR(J)/(1.*NP)
  CCC(J)=CCC(J)+CC(J)/(1.*NP)
410 CONTINUE
C*************************************************************************
C ... DETERMINE THE BASIC WAVE: PICK-UP THE WAVE WITH MAX. POWER IN
THE "MICRO ROUGHNESS" RANGE. THE MICR. ROUGH. RANGE INCLUDES
ALL WAVES LENGTH LESS THAN OR EQUAL TO 39.0 CENTIMETERS.
C*************************************************************************
P=1.0
DO 430 J=1,NB1
  IF(VLAM[J].LT.39.) GO TO 430
  IF(VLAM[J].GT.39.) GO TO 439
430 P=P+1
439 CONTINUE
C*************************************************************************
*************************************************************************
P=1.0
DO 440 J=1,NB1
  IF(VLAM[J].LE.39.) GO TO 440
  IF(VLAM[J].LE.39.) GO TO 443
440 P=P+1
443 CONTINUE
C*************************************************************************
*************************************************************************

G00010
G00020
G00030
G00040
G00050
G00060
G00070
G00080
G00090
G00100
G00110
G00120
G00130
G00140
G00150
G00160
G00170
G00180
G00190
G00200
G00210
G00220
G00230
G00240
G00250
G00260
G00270
G00280
G00290
G00300
G00310
G00320
G00330
G00340
G00350
G00360
G00370
G00380
G00390
G00400
G00410
G00420
G00430
G00440
G00450
G00460
G00470
G00480
G00490
G00500
G00510
G00520
G00530
CONTINUE
AMF=2*(AM(1)+AM(2)+BBN(1)+BBN(2))

DO 450 K=1,NP
XPS1(1)=XPS1(1)+AMF
FAZ1(1)=FAZ1(1)+AMF

450 CONTINUE
CALL RESDL(RSD,NP,ANUE,SIGMA)
RMEEAN(RMEAN-NRUE/(1.*RPP))
STDEV(STDEV-SIGMA/(1.*RPP))
WRITE(6,455) (RSD(1),I=1,NP)

CONTINUE
CALL RESDL(RSD,NP,ANUE,SIGMA)
RMEEAN(RMEAN-NRUE/(1.*RPP))
STDEV(STDEV-SIGMA/(1.*RPP))
WRITE(6,455) (RSD(1),I=1,NP)

FORMAT(//,56X,'AVERAGE VALUES FOR ALL PROFILES',/)
CALL RESDL(RSD,NP,ANUE,SIGMA)
RMEEAN(RMEAN-NRUE/(1.*RPP))
STDEV(STDEV-SIGMA/(1.*RPP))
WRITE(6,455) (RSD(1),I=1,NP)

FORMAT(//,56X,'DEGREE',56X,'AN',56X,'BN',56X,'TS1',56X,'TS2',56X,'POWER',56X,'CONTR.',/)
= T48,'TOTAL',T56,'L (CM)',/

FORMAT(2(110,2F8.2,F11.3,2F8.4,F8.1,2X))
FORMAT(1(1E2X,F8.2))
FORMAT(1E2X,F8.2))
RETURN
END

SUBROUTINE FILTER(X,Y,N,NDEG,AN,BN,DPOW,R,C,VLAM,FMEAN)
**================================================================**
C THIS SUBPROGRAM PROCESSES THE DATA BEFORE AND AFTER SPECTRAL ANAL.
C IF MEASUREMENTS ARE NOT EQUALLY SPACED, THE PROGRAM GENERATES
C AN INTERPOLATED PROFILE WITH INTERVAL=DX, USING THE FUNCTION TEP1.
C =========================================================================
C IMPLICIT REAL*8(A-H,O-Z)
REAL*4 TLEN,CUT
REAL*4 X(1),Y(1)
REAL*4 YMS(1000),YORC(1000)
REAL*4 XX(1000),YTEMP(1000)
REAL*8 AN(1),BN(1),R(1),C(1)
DIMENSION NDEG(1)
DIMENSION F(1000),DPOW(1000),VLAM(1000)
DIMENSION IL(1000),ILL(1000),ILLL(1000)
COMPLEX*16 FM(1000)
EQUIVALENCE (IL(1),ILL(1),ILLL(1))
COMMON /SAME/TLEN,CUT
C ... INTERPOLATE TO HAVE EQUALLY SPACED DATA
C WRITE(6,720)
C WRITE(6,705)(X(1),Y(1),I=1,N)
C WRITE(6,700)
DO 9 I=1,N
YORC(I)=Y(I)
9 CONTINUE
FINT=0.5
XX(I)=X(I)
F(I)=Y(I)
DELTA=TLEN/(N-1)
ABS=X(I)
DO 11 I=2,N
ABS=ABS+DELTA
11 F(I)=FINT(ABS,I,N,FINT)
C WRITE(9,705)(XX(I),F(I),I=1,N)
C ... REMOVE THE MEAN
SUM=0.
DO 10 I=1,N
10 SUM=SUM+F(I)
FMEAN=SUM/N
C WRITE(6,710)FMEAN
DO 15 I=1,N
15 F(I)=F(I)-FMEAN
C WRITE(6,721)
C WRITE(6,705)(XX(I), F(I), I=1,N)
C WRITE(6,700)
C ... COMPUTE COMPLEX FOURIER COEFFICIENTS
CALL POWER(F, FN, NDEC, AN, BN, DPW, R, C, WLAN, N)
C ... COMPUTE DATA VECTOR IN TIME DOMAIN
NB=N/2
NB1=NB+1
NB2=NB+2
C ... FILTER OUT HIGH FREQUENCIES
C ... SPLIT -F(N1)- AND -F(NH1)- INTO HALF TO USE FOLLOWING LOGIC
FN(1):=FN(1)/2.  
FN(NH1):=FN(NH1)/2.
DO 16 I=2,NH1
 IF(DABS(WLAN(1)).LT.CUT) GO TO 100
 16 CONTINUE
100 CONTINUE
NHIGH=1
 IF(I.EQ.NH) NHIGH=I+1
 DO 20 I=NHIGH,N
 20 FN(I)=0., 0.
C ... COMPUTE INVERSE FOURIER TRANSFORM
CALL FFTR(FN, FN, NH, NH, ILLL)
DO 25 I=1,N
 25 FN(I)=FN(I)+DCONJG(FN(I))
DO 26 I=1,N
 26 F(I)=F(I)+FMEAN
DO 30 I=1,N
 30 YTEMP(I)=F(I)
DO 35 I=1,N
ABSIS=K(I)
 35 Y(I)=TERP((ABSIS, XX, YTEMP, N, FINT)
C WRITE(6,706)
C WRITE(6,722)
C WRITE(6,705)(XX(I), Y(I), I=1,N)
C ... COMPUTE FILTERED-OUT DATA 'YNS'
DO 36 I=1,N
 YNS(I)=Y(RNG(I)-F(I))
36 CONTINUE
C WRITE(6,706)
C WRITE(6,722)
C WRITE(6,705)(XX(I), YNS(I), I=1,N)
C WRITE(6,726)

700 FORMAT(///)
705 FORMAT(5(2F10.2, 5X))
715 FORMAT(///, 'MEAN VALUE = ',F10.3, ' MLNTR',///)
720 FORMAT(///, '55X, 'ORIGINAL DATA',///)
721 FORMAT(55X, 'REMOVED-MEAN DATA',///)
722 FORMAT(55X, 'FILTERED DATA',///)
723 FORMAT(55X, 'FILTERED-OUT DATA',///)
726 FORMAT(///)

RETURN
END

SUBROUTINE POWER(F, FN, NDEC, AN, BN, DPW, R, C, WLAN, N)

C **************************************************************************************************
C C THIS SUBPROGRAM PERFORMS SPECTRAL ANALYSIS ON SURFACE ROUGHNESS
C C MEASUREMENTS
C C **************************************************************************************************
C
C GRD = REAL($) - E, B - 0.0 - Z)
REAL*4 CUT, TLEN
DIMENSION F(1), DPW(1), WLAM(1)
DIMENSION AN(1000), BN(1000), NDEC(1000), S(1000), C(1000), R(1000)
DIMENSION M(1000)
COMPLEX*16 CANN, FR(1)
COMMON /SAME/TLEN,cut
C ... NB=N/2
NB1=NB+1
NB2=NB+2
C ... COMPUTE THE VARIANCE OF THE SIGNAL
VAR=0.
DO 10 I=1, N
 10 VAR=VAR+F(I)**2
VAR=VAR/N
C ... COMPUTE COMPLEX FOURIER COEFFICIENTS OF -F- BY FFT
CALL FFTR(F, CANN, N, M)
C ... TAKE CONJUGATE OF OUTPUT AND DIVIDE BY N TO GET INV. FFT
FN(1)=DCMPLX(F(1), -F(2))/N
DO 15 I=2, NB
C ...
FUNCTION TERP(X,XI,YI,N,F)

**FUNCTION TERP**

**TERP** computes an equally spaced profile (if measurements were not so).

This subprogram produces an equally spaced profile (if measurements were not so).

15 AN = DCNPLX(F(1),-F(1))/N
16 AN + = DCNPLC(FN(1))
17 AN(NH1) + = DCNPLC(GAPM)/N
18 C ... COMPUTE -AN- AND -BN- COEFFICIENTS

19 AN(I) = FN(1)
20 WLAM(I) = 9
21 DO 16 I = 2, NH
22 AN(I) = 2. * FN(I)
23 BN(I) = 2. * DIMAG(FN(I))
24 WLAM(I) = TLEN/I-1/
25 CONTINUE
26 AN(NH1) = FN(NH1)
27 WLAM(NH1) = TLEN/NH
28 C ... COMPUTE DEGREE POWER, CONTRIBUTION ETC....

29 VAR2 = 0.
30 BN(I) = 0.
31 BN(NH1) = 0.
32 DO 17 I = 1, NH
33 NDEC(I) = 1 - 1
34 DPOW(I) = (AN(I)**2 + BN(I)**2)*2. * DPOW(I)
35 IF (I.EQ. 1 . OR. I.EQ. NH1) DPOW(I) = 2. * DPOW(I)
36 VAR2 = 2. * DPOW(I)
37 SL(I) = VAR2
38 CONTINUE
39 SUM = VAR2
40 R(I) = 0.
41 C(I) = 0.
42 DO 20 I = 2, NH
43 R(I) = DPOW(I) / VAR2
44 C(I) = SL(I) / VAR2
45 CONTINUE
46 C WRITE (6, 700)
47 C WRITE (6, 701) VAR1, VAR2
48 C ... FIND THE POWER FROM COMPLEX FOURIER COEFF. TO CHECK THE RESULT

49 DO 25 I = 2, NH
50 DPOW(I) = 2. * (FN(I) * DCNPLC(FN(I))
51 DPOW(NH1) = FN(NH1) * DCNPLC(FNH(I))
52 CONTINUE
53 C WRITE (6, 700)
54 C WRITE (6, 701) NDEC(I), AN(I), BN(I), DPOW(I), R(I), C(I), WLAM(I), I = 1, NH
55 ***********
58 J = TD, 'TOTAL', T135, 'TOTAL POWER IN TIME DOMAIN = ', F17.5, ' MLTR*2*', ',/', 30X,
59 * 'TOTAL POWER IN FREQ. DOMAIN = ', F17.5, ' MLTR*2*', ', '/
60 RETURN
61 END
62 FUNCTION TERP1(X,XI,YI,N,F)
63 ***********
64 THIS SUBPROGRAM PRODUCES AN EQUALLY SPACED PROFILE (IF MEASUREMENTS WERE NOT SO)
65 ***********
66 IMPLICIT REAL*8 (A-H,O-Z)
67 REAL*4 XI(1), YI(1)
68 C X IS THE INDEPENDENT VARIABLE
69 C XI IS AN ARRAY OF VALUES OF THE INDEPENDENT VARIABLE
70 C YI IS AN ARRAY OF CORRESPONDING VALUES OF DEPENDENT VARIABLE
71 C N IS THE SIZE OF THE ARRAYS
72 C F IS A FACTOR FOR THE END SEGMENTS; BALANCE OF FIRST AND SECOND
73 C ORDER INTERPOLATION
74 C ALL VALUES OUTSIDE THE LIMITS OF THE ARRAY ARE COMPUTED BY
75 C FIRST ORDER EXTRAPOLATION
76 C FUNCTION RETURNS INTERPOLATED VALUE OF DEPENDENT VARIABLE
77 DIMENSION F(2), E(2), I8(4,2)
78 LOGICAL OUT
79 DATA IS/-1.0,.2-.1.0,1.0/-
80 OUT = .FALSE.
81 J = 1
82
IF (N-2) .LE. 1, 12, 3
1 TEP1=Y1(J)
RETURN
3 KPL=1
KPU=2
DO 4 J=1,N
7 IF (XI(J) - X) .LE. 4, 1, 6
4 CONTINUE
J = N
GO TO 2
6 IF (J-2) .LE. 12, 8, 9
8 KPL = 2
GO TO 10
9 IF (J - N) .LE. 10, 11, 2
12 J=2
2 OUT=.TRUE.
11 KPU=1
10 AL = (X-XI(J-1)) / (XI(J)-XI(J-1))
TERP1=AL*Y1(J)+(1.0-AL)*Y1(J-1)
IF (OUT) RETURN
DO 16 KP=KPL,KPU
P(KP)=0.0
DO 15 K=1,3
J0=J+KP + K - 4
X0=XI(J0)
Y0=Y1(J0)
J1=J+IS(K,KP)
J2=J+IS(K+1,KP)
15 P(KP)=P(KP)+Y0*(X-XI(J1))/(XI(J1)-XI(J2))
16 IF (KP .NE. KPU) GO TO 16
J1=J-KPL
P(J1)*TERP1=F*(P(KP)-TERP1)
C ... BE CAREFUL FOR FOLLOWING CARDS IF ..ABS.. OR ..DABS...
16 E(KP)=DABS(P(KP)-TERP1)
IF (E(1) + E(2) .EQ. 0.0) RETURN
TERP1=((E(1)*AL)*P(2)+E(2)*(1.0-AL))*P(1) /
*(E(1)*AL) + (E(2)*(1.0-AL))
RETURN
END
SUBROUTINE RESDL(RSD, NP, RMEAN, STDEV)
C ******************************************
C THIS SUBPROGRAM COMPUTES THE MEAN AND THE STANDARD DEVIATION OF
C THE NORMALLY DISTRIBUTED RESIDUAL DATA.
C ******************************************
C DIMENSION RSD(200)
C ... COMPUTE MEAN
C SUM=0.0
DO 101 I=1,NP
SUM=SUM+RSD(I)
101 CONTINUE
RMEAN=SUM/NP
C ... COMPUTE THE VARIANCE
C SUMV=0.0
DO 102 I=1,NP
SUMV=SUMV+(RSD(I)-RMEAN)*(RSD(I)-RMEAN)
102 CONTINUE
VARV=SUMV/NP
SD=VARV**0.5
STDEV=ABS(SD)
RETURN
END
SUBROUTINE PARAM(D,P,ASR,ASH,RCH,BCH,EX)

**THIS SUBPROGRAM USES THE PROBLEM PARAMETERS TO COMPUTE THE MAIN COEFFICIENTS IN EROSION EQUATIONS.**

- CMA = UNIT WEIGHT OF SOIL
- SG = SPECIFIC WEIGHT OF SOIL
- RO = WATER DENSITY
- C = GRAVITY ACCELERATION
- RR = MANNING’S COEFFICIENT OF FRICTION

**COMMON /PROP/CMA,RO,C,SG,RR**

\[
z = \left((\text{SG} - 1.) \times C \times (D \times (P - 1))\right)
\]

\[
\text{BBETA} = \text{ASR} / Z
\]

\[
\text{BBETA} = \text{ASH} / Z
\]

\[
X = (1. + 2. \times P) / 2.
\]

\[
\text{RCH} = \text{BBETA} \times (1. + 2. \times P) / 2. / \text{RO} \times X
\]

\[
\text{ECH} = \text{BBETA} \times (1. + 2. \times P) / 2. / \text{RO} \times X
\]

\[
E = \left(2. \times P - 1. \right) / 2.
\]

RETURN

END

SUBROUTINE RANUD(IX, IY, R)

**THIS SUBPROGRAM GENERATES A RANDOM NUMBER WITH VALUE 0.0 TO 1.0 FROM A UNIFORM DISTRIBUTION**

**COMMON /RAN/IX, IY, R**

\[
IY = IX \times 65536
\]

IF (IY) 5, 6, 6

5

\[
IY = IX \times 2147483647 + 1
\]

6

\[
R = 1Y
\]

R = R \times 465613E-9

RETURN

END

SUBROUTINE RANORM(NMAX, RMEAN, STDEV, RY, NS)

**IT GENERATES NORMALLY DISTRIBUTED RANDOM NUMBERS FOR THE GIVEN MEAN AND STANDARD DEVIATION**


IF(NS.CT.1) GO TO 800

1X = 123456789

500

DO 810 K=1, NMAX

SUM = 0.0

DO 820 K=1, 12

CALL RANUD(IX, IY, R)

IX = IY

SUM = SUM + R

810 CONTINUE

820 CONTINUE

X = (SUM - 5.0) * STDEV + RMEAN

RY(I) = X

810 CONTINUE

C WRITE(6, 12) (1, RY(I), I=1, NMAX)

12 FORMAT (15, 5X, F10.6)

RETURN

END

SUBROUTINE XHME

**THIS SUBPROGRAM CALCULATES THE COORDINATES AND ASSIGN CODES FOR Nodal Points of the Hexagonal Mesh**

**COMMON /MESH/NX, NY, RNAX, SL, SH, WL, QQ**


C COMPUTE X AND Y COORDINATES OF NODAL POINTS

\[
\text{WMAX} = \text{NX} \times \text{NY}
\]

J = 1

X(J) = 0
NS = 1
NE = NY
11 DO 10 I = NS, NE, 2
   K = I + 1
   IF (I.EQ.1) GO TO 15
   IF (I.EQ.NS) GO TO 17
   Y (I) = Y (I - 1) + SL
   X (K) = XX (J)
   X (1) = XX (J)
   GO TO 10
15 Y (1) = 0
   Y (2) = Y (1) + 2* SL
   X (1) = XX (J)
   X (2) = XX (J)
   GO TO 10
16 Y (NS) = 0
   Y (NS) = Y (NS) + 2* SL
   X (NS) = XX (J)
   X (NS) = XX (J)
   GO TO 10
17 Y (1) = Y (1 - 1) + SL
   X (1) = X (1 - 1)
10 CONTINUE
   J = J + 1
   IF (J.CT.NX) GO TO 1000
   XX (J) = XX (J - 1) + WL/2.
   NE = NE + NY
   NS = NS + NY
   IF (NE.CT.NMAX) GO TO 1000
   GO TO 11
1000 H = NY
C ... ASSIGN CODES TO MODAL POINTS
   MAX = 2*NY
   K = 1
   DO 30 J = K, M, 4
      DO 30 I = J, NMAX, MAX
      CODE (I) = 1
30 CONTINUE
   H = NY
   K = 1
   DO 40 J = K, M, 4
      DO 40 I = J, NMAX, MAX
      CODE (I) = 1
40 CONTINUE
   H = NY
   K = 2
   DO 50 J = K, M, 4
      DO 50 I = J, NMAX, MAX
      CODE (I) = 1
50 CONTINUE
   H = NY
   K = 3
   DO 60 J = K, M, 4
      DO 60 I = J, NMAX, MAX
      CODE (I) = 1
60 CONTINUE
RETURN
END

SUBROUTINE ELEVAT(SLOPE, AMP, RMEAN, STDEV, RS)
******************************************************************************
C THIS SUBPROGRAM CALCULATES THE ORIGINAL (PRE-EROSSION) ELEVATIONS
C OF MODAL POINTS
C ELEVATION OF EACH MODAL POINT IS COMPUTED AS THE SUM OF THE
C FOLLOWING COMPONENTS
C 1) FROM THE AVERAGE SLOPE
C 2) FROM THE BASIC WAVE, NY
C 3) RESIDUAL COMPONENT GENERATED RANDOMLY , RY
******************************************************************************
DIMENSION RY(2000)
COMMON/MESS/NX, NY, NMAX, SL, SH, WL, QQ
P1 = 22.0/7.0
THETA = SLOPE * P1/180
C
DO 710 M=NY,NMAX,1
DO 720 I=1,M,4
ELV(I)=YC(I)*SINC THETA)-VY+RYC(I)
 IF(YC(I).EQ.0) GO TO 730
ELV(I+1)=Y(I+1)*SINC THETA)-VY+RYC(I+1)
 IF(Y(I+1).EQ.0) GO TO 730
ELV(I+2)=Y(I+2)*SINC THETA)+VY+RYC(I+2)
 IF(Y(I+3).EQ.0) ELV(I+3)=Y(I+3)*SINC THETA)+VY+RYC(I+3)
730 CONTINUE

L=L+NY
710 CONTINUE
 C WRITE(6,790) (I,X(I),Y(I),RY(I),ELV(I),I=1,NMAX)
790 FORMAT(10X,15,4F10.6)
RETURN
END

SUBROUTINE BUMP(RMEAN,STDEV,AMF,NHUMP)

DIMENSION RHYC500)
COMMON/1 MESH^NX, NY, NMAX, S L , SH, VL, OQ
COMMON/'NODES/'XC 2000) .Y C 2000) .CODEC 2000) , ELVC2 0 0 0 )
COMMON/'HHMPP/'HHMPC 5 0 0 ) , X H M PC 3 0 0 ) .YHMPC 3 0 0 )
COMMON/6LOPES/HHPI1500), HHP2C 5 0 0 ) . HHP3C 5 0 0 ) , HHP4C5 0 0 ) . HHP5C5 0 0 )
+ HMP6C500)

DETERMINE THE TOTAL NUMBER OF HUMPS .NHUMP
NZ*NY+1
M1-NZ/4
RHI=1.*NZ/4
DM1=RM1-N1
 IF(DM1.CT.0.AND.DM1.LE.0.5) GO TO 1210
1210 NHUMP=M1*NX
 GO TO 1225
1220 N1=NX/2
RM1=1.*NX/2
 DM1=RM1-N1
 IF(DM1.EQ.0) GO TO 1230
 IF(DM1.0) GO TO 1231
NHUMP=2*M1+N1+N+1
 GO TO 1225
1231 NHUMP=N1*(2*M1+1)
 GO TO 1225
1230 IF(DM1.EQ.0) GO TO 1235
NHUMP=2*M1-N1+M1-1
 GO TO 1225
1235 NHUMP=N1*(2*M1-1)
 GO TO 1225
1225 CONTINUE
C
C ... DETERMINE THE TOTAL NUMBER OF HUMPS ,NHUMP
NZ=NY+1
M1=NZ/4
RM1=1.*NZ/4
 DM1=RM1-N1
 IF(DM1.CT.0.AND.DM1.LE.0.5) GO TO 1210
1210 NHUMP=M1*NX
 GO TO 1225
1220 N1=NX/2
RM1=1.*NX/2
 DM1=RM1-N1
 IF(DM1.EQ.0) GO TO 1230
 IF(DM1.0) GO TO 1231
NHUMP=2*M1+N1+N+1
 GO TO 1225
1231 NHUMP=N1*(2*M1+1)
 GO TO 1225
1230 IF(DM1.EQ.0) GO TO 1235
NHUMP=2*M1-N1+M1-1
 GO TO 1225
1235 NHUMP=N1*(2*M1-1)
 GO TO 1225
1225 CONTINUE
C
C ... COMPUTE X AND Y COORDINATES
K=1
 DO 1250 I=1,NMAX
 IF(CODE(I) .LE. 0) 1260,1270
1270 GO TO 1250
1260 IF(CODE(I) .NE. 0) GO TO 1250
XEMP(I)=X(I)
 YEMP(K)=(Y(I)+Y(I-1))/2.
 K=K+1
1250 CONTINUE
C
C ... COMPUTE ELEVATIONS
CALL RANORM(NHUMP, RMEAN, STDEV, RY)
C CALL RANORM(NHUMP, RMEAN, STDEV, RY)
A*AMP*COS(SLOPE*22./7./180.)
DO 1280 I=1,NHUMP
HMP1(I)=YHMP(I)+2.*SL*SIN(SLOPE*22./7./180.)+A+RHY(I)
1280 CONTINUE
C WRITE(6,1290)(I,YHMP(I),YHMP(I),HMP(I),I=1,NHUMP)
1290 FORMAT(15,3F20.6)
C

C ... COMPUTE "FICTIOUS" ELEVATIONS OF THE HUMP CENTER FOR EACH OF
C THE SIX SIDES OF THE "PYRAMID"
C
DO 1295 I=1,NHUMP
HMP1(I)=YHMP(I)
HMP2(I)=YHMP(I)
HMP3(I)=YHMP(I)
HMP4(I)=YHMP(I)
HMP5(I)=YHMP(I)
HMP6(I)=YHMP(I)
1295 CONTINUE
RETURN
END

SUBROUTINE IDHMP(NY,1,IDL,1DR,1DC)

C **********************************************************************
C THIS SUBPROGRAM IDENTIFIES THE HUMPS ASSOCIATED WITH DIFFERENT
C RILL SEGMENTS
C
IDL*CALL* OF HUMP LEFT OF I
1DR*CALL* OF HUMP RIGHT OF I
1DC*CALL* OF HUMP BELOW I (IF CODE(I)*#2)
C NC*# COMPLETE MESH COLUMNS BEFORE I
C NHB*# OF HUMPS BELOW I
C **********************************************************************
C
COMMON NT
NZ=NY+1
M=NZ/4
RM=1.*NZ/4.
DM=RM-N
KD=DM*4+1
NC=I/NY
RNC=(1.*I)/(1.*NY)
IF(RNC.GT.NC) GO TO 1501
NC=NC-1
1501 HHB=((1+NC+1)-(NC*NZ))/4
IF(1.LT.NY) GO TO 1505
INC=NC/2
RRC=1.*INC/2.
IF(RRC.EQ.1NC) GO TO 1505
GO TO 1505
1505 IDL* (NC-1)*M+(NC-1)/2*M+1+NHB
GO TO 1530
1510 IDL* (NC-1)*M+NHB
GO TO 1535
1520 IDL* (NC-1)/2*M+(NC-1)/2*M+1+NHB
GO TO 1540
1530 IDL* (NC+1)/2*M+(NC+1)/2*M+1+NHB
GO TO 1550
1535 IDL* (NC+1)*M+NHB
GO TO 1555
1540 IDL* (NC+1)/2*M+(NC+1)/2*M+NHB
GO TO 1560
1550 IDL* (NC+2)*M+(NC+2)*M+NHB
GO TO 1595
1555 IDL* (NC+2)*M+NHB
GO TO 1595
1560 IDL* (NC+2)*M+NC/2*M+1+NHB
GO TO 1595
1580 GO TO (1570,1575,1580,KD)
1570 IDL* (NC-1)/2*M+(NC-1)/2*M+NHB+1
GO TO 1573
1575 IDL* (NC-1)*M+NHB+1
GO TO 1578
1580 IDL* (NC-1)/2*M+(NC-1)/2*M+1+NHB+1
GO TO 1585
1585 IDL* (NC+1)/2*M+(NC+1)/2*M+NHB+1
GO TO 1593
1590 IDL* (NC+1)/2*M+(NC+1)/2*M+NHB+1
GO TO 1593
1595 IDL* (NC+2)*M+NHB+1
GO TO 1595

GO TO 1574

1578 IDR=<(NC+1)*M*NHB+1
GO TO 1579

1581 IDR=<(NC+1)/2+1)*M<(NC+1)/2(M+1)+NHB+1
GO TO 1590

1574 IDC=<(NC/2)*M<(NC/2)+M-NHB
GO TO 1595

1579 IDC=NC*M+NHB
GO TO 1595

1590 IDC=<(NC/2)*M<(NC/2)+M-NHB
CONTINUE
RETURN

END

SUBROUTINE FLOW(RNL,RNF)

FLOW RATE IN A RILL SEGMENT IS THE SUM OF:
1) DIRECT RAINFALL ON SURFACES OF RILL AND INTERRILL AREAS, AND
2) FLOW ARRIVING FROM AREA UPSLOPE

AT A BIFURCATION POINT THE FLOW IS DIVIDED BETWEEN THE LEFT AND
THE RIGHT BRANCH ACCORDING TO THE RELATIVE MAGNITUDES OF BED
SLOPES RAISED TO THE POWER OF 0.5.

QT(1) IS THE AMOUNT OF WATER ACCUMULATED AT POINT 1
QR(1) IS THE AMOUNT OF WATER BRANCHING OUT FROM POINT 1
QL(1) IS THE AMOUNT OF WATER BRANCHING OUT FROM POINT 1
FLOW QUANTITY IS IN CUBIC METERS/SEC.

IF A "LOW" HUMP OCCURS, THE FLOW IS REDISTRIBUTED IN (RDISTB).

COMMON/MESH/NX, NY, NMAX, SL, WL, QQ
COMMON/NODES/X(200), Y(200), CODE(200), ELV(200)
COMMON/TOLDC/KPMD(200), NAJC(200), DH(200)
COMMON/HRMPC/HMP(500), XHMPC(500), YHMPC(500)
COMMON/QLFLOW/QT(200), QL(200), QR(200)
COMMON NT

COMPUTE RAINFALL FLOW RATE / UNIT TIME / UNIT AREA:

QQ=(RNF*RNL)/(3.6*10**6)

DQ IS THE AMOUNT OF WATER DRAINED TO A RILL SEGMENT FROM BOTH SIDES
PER UNIT TIME.

DQ=2.0*QQ*SL*SL*(3.**0.5)

COMPUTE TOTAL FLOW RATE AT EACH NODAL POINT:

DO 901 I=1,NY
K=NY+(I-L)
DO 901 I=1,NMAX, NY
IF(CODE(I)=1) 902,903,904

POINTS WITH CODE=0:

902 QQ(I)=0
QL(I)=0
QT(I)=0
GO TO 901

POINTS WITH CODE=1:

903 IF(Y(I).LT.Y(NY)) GO TO 905
GO TO 902

905 IF(X(I).EQ.0) GO TO 915
SL=-(ELV(I+1)-ELV(I))/2.0/SH
IF(X(I).EQ.K(NMAX)) GO TO 907

915 SLR=-(ELV(I+1)-ELV(I))/2.0/SH
IF(X(I).EQ.0) GO TO 906
IF(X(I).LT.K(NMAX)) GO TO 907
IF(SLL.LE.0.AND.SLR.LE.0) GO TO 908
IF(SLL.LE.0.AND.SLR.LE.0) GO TO 909
IF(SLL.GT.0.AND.SLR.GT.0) GO TO 910
QT(I)=QT(I)+QR(I+NY)+QL(I+NY+1)+2*DQ
CALL RDISTB(1,CODE(I))
GO TO 901

908 QT(I)=0
GO TO 901

909 QTC(I) = QTC(I) + QR(I-NY+1)+DQ
CALL RDISTB(I, CODE(I))
GO TO 901

910 QTC(I) = QTC(I) + QL(I+NY+1)+DQ
CALL RDISTB(I, CODE(I))
GO TO 901

906 IF(SLR.LE.0.0) GO TO 911
QTC(I) = QTC(I) + QL(I+NY+1)+DQ
CALL RDISTB(I, CODE(I))
GO TO 901

911 QTC(I) = 0.0
GO TO 901

907 IF(SLL.LE.0.0) GO TO 911
QTC(I) = QTC(I) + QR(I-NY+1)+DQ
CALL RDISTB(I, CODE(I))
GO TO 901

C POINTS OF CODE=2 (BIFURCATION POINTS):

904 IF(Y(I).EQ.Y(NY)) GO TO 902
SLM1 = (ELV(I+1) - ELV(I))/2.0/SH
IF(SLM1.LE.0.0) GO TO 916
QTC(I) = 0.0
GO TO 902

916 IF(X(I).EQ.X(NMAX)) GO TO 940
QTC(I) = QTC(I) + QT(I+1)+DQ
SLR* = ELV(I) - ELV(I-NY+1))/2.0/SH
SLR2 = ELV(I) - ELV(I+NY-1))/2.0/SH
IF(SLR2.LE.0.0) GO TO 920
IF(SLR.LE.0.0) GO TO 921
IF(SLR.GT.0.0) GO TO 922
SLL1 = (ELV(I-NY-1) - ELV(I-NY-2))/2.0/SH
SLL2 = (ELV(I-NY-1) - ELV(I-NY-2))/2.0/SH
SLAV = (SLL1+SLL2)/2.0
IF(SLAV.LE.0.0) SLAV = 0.0
ISR = SRAV = (SLL1+SLL2)/2.0
SQR = SLAV**0.5 + SRAV**0.5
QL(I) = QL(I) + QR(I)*((SLAV+0.5)/SQR)
QR(I) = QR(I) + QR(I)*((SRAV+0.5)/SQR)
CALL RDISTB(I, CODE(I))
GO TO 991

920 QLC(I) = 0.0
QR(I) = 0.0
GO TO 991

921 QLC(I) = 0.0
QR(I) = QR(I) + QT(I)
CALL RDISTB(I, CODE(I))
GO TO 991

922 QLC(I) = 0.0
QL(I) = QL(I) + QT(I)
CALL RDISTB(I, CODE(I))
GO TO 991

930 QTC(I) = QTC(I) + QT(I+1)+DQ
SLR* = ELV(I) - ELV(I-NY+1))/2.0/SH
SLR = 0.0
QL(I) = 0.0
IF(SLR.GT.0.0) GO TO 932
QR(I) = 0.0
GO TO 991

932 QRC(I) = QR(I) + QT(I)
CALL RDISTB(I, CODE(I))
GO TO 991

940 QTC(I) = QTC(I) + QT(I+1)+DQ
SLR = ELV(I) - ELV(I-NY-1))/2.0/SH
SLR = 0.0
QR(I) = 0.0
IF(SLR.GT.0.0) GO TO 942
QL(I) = 0.0
GO TO 991

942 QLC(I) = QLC(I) + QT(I)
CALL RDISTB(I, CODE(I))
CONTINUE
IF(NX.NE.1) RETURN

C WRITE(6,990) (X(I), Y(I), CODE(I), QR(I), QL(I), QT(I), I=1,NMAX)

990 FORMAT(2X,15,6F20.8)
RETURN
END
SUBROUTINE RDISTB( I, CKODE )

*****************************************************************************
THE THIS SUBPROGRAM CHECKS THE EXISTANCE OF NEGATIVE SIDE SLOPES
RESULT FROM HUMPS DEPRESSED BY FAILURE MECHANISM. THEN
RE Distributes THE QUANTITY OF WATER AMONG M ODAL POINTS. THIS
PROCESS IS REPEATED BEFORE EVERY TIME INTERVAL.
*****************************************************************************

COMMON/MESH/NX, NY, NMAX, SL, SH, VL, QQ
COMMON/HMPF/HMP(500), XHMP(500), YHMP(500)
COMMON/SLOPES/HMP1(500), HMP2(500), HMP3(500), HMP4(500), HMP5(500),
HMP6(500)
COMMON NT
IF (Y(1).EQ.0.0) GO TO 100
IF (CKODE-1.0) 100, 200, 300

AELV = (ELV(1)+ELV(-1))/2.
SO = (ELV(1)-ELV(-1))/2./SH
CALL IDHMP(NY, I, IDL, IDR, IDC)
IF (X(1).EQ.0.0) GO TO 210
IF (X(1).EQ.X(NMAX)) GO TO 220
SI = (HMP(1)-AELV)/SH/3.*0.5
SZ = (HMP(1)-AELV)/SH/3.*0.5
20 FORMAT( A , 8SLOPES : ,15.3F20.6)
A = ABS(S1)
B = ABS(S2)
IF (S1.GT.0.0 .AND. S2.GT.0.0) GO TO 100
IF (S1.LE.0.0 .AND. S2.GT.0.0) GO TO 215
IF (S1.GT.0.0 .AND. S2.LE.0.0) GO TO 225
CONTINUE

NK = 1-2*NY
NV = 1
F = 0.5
KK = 1
HHH = (ELV(NK)+ELV(NK-1))/2.
IF (HHH.GT.HMP1(IDL)) QT(NV) = 0.0
GO TO 200

211 NK = 1+2*NY
NV = 1
F = 0.5
KK = 2
GO TO 200

215 IF (SO.GE.AS1) GO TO 290
NK = 1-2*NY
NV = 1
F = 1.0
KK = 2
HHH = (ELV(NK)+ELV(NK-1))/2.
IF (HHH.GT.HMP1(IDL)) QT(NV) = 0.0
GO TO 200

225 IF (SO.GE.AS2) GO TO 290
NK = 1+2*NY
NV = 1
F = 1.0
KK = 2
GO TO 200

210 S2 = (HMP1(IDR)-AELV)/SH/3.*0.5
A2 = ABS(S2)
IF (S2.LE.0.0) GO TO 225
GO TO 100

220 S1 = (HMP4(IDL)-AELV)/SH/3.*0.5
A1 = ABS(S1)
IF (S1.LE.0.0) GO TO 215
GO TO 100

290 QT(NK) = QT(NK)+F*QT(NV)
IF (F.EQ.1) GO TO 211
QT(NV) = 0.0

300 CALL IDHMP(NY, I, IDL, IDR, IDC)
10 FORMAT( A , 8SLOPES : ,15.3F20.6)
IF (X(1).EQ.0.0) GO TO 400
AELV = (ELV(1)+ELV(-1))/2.

159
SUBROUTINE SFAIL(SLIM1,TSTART)

C***********************************************************************
C THIS SUBPROGRAM CHECKS THE STABILITY OF SIDESLOPES OF ALL RILL
C SEGMENTS BEFORE EVERY TIME INTERVAL
C SLIM1: THE UPPER LIMIT A SIDESLOPE CAN REACH BEFORE FAILURE
C TSTART: THE STARTING VALUE OF THE SIDESLOPE AFTER FAILURE
C DSBD: THE VOLUME OF THE SOIL CHUNK SEPARATED DUE TO FAILURE
C NOTE: AT THE PRESENT STAGE DSBD IS NOT ADDED TO THE AMOUNT OF
C SOIL ERODED.
C***********************************************************************

COMMON/WSEX/NX,NY,NMAX,SL,SH,VL,QQ
COMMON/HMNP,HMP(500),XHNP(500),YHNP(500)
COMMON/SLOPES/HMP(100),HMP2(500),HMP3(500),HMP4(500),HMP5(500)

COMMON WT

16 FORMAT(15,2,F20.6,
10 FORMAT(15,3F10.5)
15 FORMAT(15,F10.5)
100 FORMAT(31,10.3F10.8)
BETA=ATAN(SSTART)
PHI=ATAN(SLIMIT)-BETA
DY=SH*(SLIMIT-TSTART)+3.*1.*3.*0.5*COS(BETA)
DSBD=SH+SH*(SLIMIT-SSTART)
DSBD=0.0
DO 100 J=1,NY
K=NY*(J-1)
DO 100 I=1,NMAX,NY
IF(Y(I).EQ.0.0) GO TO 100
IF(CODE(I)-1) 100,200,300
AEV=(ELV(I)+ELV(I-1))/2.
CALL IDMP(NY,1,IDL,IDR,IDC)
IF(X(I).EQ.0.0) GO TO 210
IF(X(I).EQ.X(NMAX)) GO TO 220
S1=HMP4(IDL)-AEV)/SH/3.*0.5
S2=HMP4(IDR)-AEV)/SH/3.*0.5
IF(S1.LT.SLIMIT) GO TO 205
HMP4(IDL)=HMP4(IDL)-(S1-TSTART)+SH*3.*0.5
SDT(1)=SDT(1)+DSBD
TIRE(1)=TIRE(1)+DSBD
100 CONTINUE
205 IF(S2.LT.SLIMIT) GO TO 200
HMP4(IDR)=HMP4(IDR)-(S2-TSTART)+SH*3.*0.5
SDT(1)=SDT(1)+DSBD
TIRE(1)=TIRE(1)+DSBD
GO TO 100
210 S2=HMP4(IDR)-AEV)/SH/3.*0.5
S1=S2
GO TO 230
220 S1=HMP4(IDL)-AEV)/SH/3.*0.5
S2=S1
GO TO 230
CALL IDMP(NY,1,IDR,IDC)

FORMAT(*162,2F12.5,/)  
IF(X(I)).EQ.0.0) GO TO 330  
AELV=(ELV(I)+ELV(1-I-NY))/2.  
S2=(EMP2(IDC)-AELV)/SH/3.*.5  
HP5=EMP5(IDC)  
IF(Y(I)).EQ.Y(NY)) HP5=EMP2(IDC)  
S1=(HP5-AELV)/SH/3.*.5  
IF(S1.LT.SLIMIT) GO TO 310  
IF(Y(I)).EQ.Y(NY)) GO TO 305  
EMP5(IDC)=EMP5(IDC)-(S1-SSTART)*SH/3.*.5  
305 CONTINUE  
SDT(I-NY-1)=SDT(I-NY-1)+DSDT  
TIRE(I-NY-1)=TIRE(I-NY-1)+DSDT  
310 IF(Y(I)).EQ.Y(NY)) GO TO 330  
EMP2(IDC)=EMP2(IDC)-(S2-SSTART)*SH/3.*.5  
SDT(I-NY-1)=SDT(I-NY-1)+DSDT  
TIRE(I-NY-1)=TIRE(I-NY-1)+DSDT  
333 IF(X(I)).EQ.X(NMAX)) GO TO 100  
HP6=EMP6(IDC)  
IF(Y(I)).EQ.Y(NY)) HP6=EMP3(IDC)  
AELV=(ELV(I)+ELV(1-I-NY))/2.  
S1=(EMP3(IDC)-AELV)/SH/3.*.5  
S2=(HP6-AELV)/SH/3.*.5  
IF(S1.LT.SLIMIT) GO TO 340  
EMP3(IDC)=EMP3(IDC)-(S1-SSTART)*SH/3.*.5  
SDT(I-NY-1)=SDT(I-NY-1)+DSDT  
TIRE(I-NY-1)=TIRE(I-NY-1)+DSDT  
340 IF(S2.LT.SLIMIT) GO TO 100  
HP3=EMP3(IDC)  
IF(Y(I)).EQ.Y(NY)) GO TO 350  
EMP6(IDC)=EMP6(IDC)-(S2-SSTART)*SH/3.*.5  
350 CONTINUE  
SDT(I-NY-1)=SDT(I-NY-1)+DSDT  
TIRE(I-NY-1)=TIRE(I-NY-1)+DSDT  
100 CONTINUE  
RETURN  

SUBROUTINE POND  
*****************************************************************************  
** THIS SUBPROGRAM IDENTIFIES NODAL POINTS WHICH ARE THE UPSTREAM **  
** POINTS OF RILL SEGMENTS OF NEGATIVE SLOPE, (UPWARD), AND AT WHICH **  
** PONDING OCCURS **  
*****************************************************************************  
COMMON/MASS/NX,NY,NMAX,SL,SH,VL,QQ  
COMMON NT  
DO 10 1=1,NMAX  
KPND(I)=0  
IF(Y(I)).EQ.0.0) GO TO 10  
IF(CODE(1)-1.0)10,20,30  
10  
FOR NODAL POINTS WITH CODE=1  
KPND(I)=0 IMPLIES NO PONDING  
KPND(I)=11 IMPLIES PONDING  
20 DZ=ELV(1)-ELV(I-1)  
IF(DZ.GT.0.0) GO TO 10  
KPND(I)=11  
GO TO 10  
FOR NODAL POINTS WITH CODE=2  
KPND(I)=0 IMPLIES NO PONDING  
KPND(I)=11 IMPLIES TOTAL PONDING  
KPND(I)=1 IMPLIES PARTIAL PONDING , (LEFT BRANCH ONLY).  
KPND(I)=2 IMPLIES PARTIAL PONDING , (RIGHT BRANCH ONLY).  
30 IF(X(I)).EQ.0.0) GO TO 35  
DZELV(1-1)-ELV(1-I-NY)  
IF(X(I)).EQ.X(NMAX)) GO TO 40  
DZELV(1-1)-ELV(1-I-NY)  
IF(DZL.LE.0.0) AND.DZR.LE.0.0) GO TO 45  
IF(DZL.LT.0.0) AND.DZR.GT.0.0) GO TO 10  
IF(DZL.GT.0.0) AND.DZR.LE.0.0) GO TO 50  
KPND(I)=1  
GO TO 10  
}
SUBROUTINE ACGNT

C THIS SUBPROGRAM COMPUTES THE NUMBER OF RILL SEGMENTS AT EACH
C NODE POINT

C
C COMMON/MESH/X,N,Y,NMAX,SL,SH,QQ
C COMMON NT
DO 10 I=1,NMAX
IF(CODE(I)=1)10,20,30
IF(Y(I).EQ.Y(NY))GO TO 15
NAJ(I)=3
GO TO 10
15 NAJ(I)=1
GO TO 10
25 NAJ(I)=2
GO TO 10
30 IF(Y(I).EQ.0.0)GO TO 15
IF(Y(I).EQ.Y(NY))GO TO 35
IF(X(I).EQ.X(NMAX).OR.X(I).EQ.0.0)GO TO 25
NAJ(I)=3
GO TO 10
35 IF(X(I).NE.0.0.AND.X(I).NE.X(NMAX))GO TO 25
GO TO 15
10 CONTINUE
WRITE(6,5)(1.X(I),Y(I),CODE(I),KPND(I),MAJ(I),I=1,NMAX)
5 FORMAT(15,3F20.5,215)
RETURN
END

SUBROUTINE CSEC(SL,Q,S1,S2,SO,RR,CC)

C THIS SUBPROGRAM COMPUTES DEPTH AND BREADTH OF THE FLOW AT ANY
C NODE POINT. COMPUTATIONS ARE BASED ON M A N N I M G 'S FORMULA.
C FLOW MEAN VELOCITY AND VELOCITY HEAD ARE ALSO COMPUTED HERE.

C

COMMON/PROP/GAMA,RO,G,RC,RR
COMMON NT
THETA1=ATAN(S1)
THETA2=ATAN(S2)
C1=1/S1+1/S2
C2=ISIN(THETA1)+1/ISIN(THETA2)
C3=C1/C2
CC=2.*ISIN(THETA1)+ISIN(THETA2)
B=(CC/SS+0.5)*SQRT(0.375*QQ+0.375)

C

CHECK FOR OVERFLOW
EM1=SL*X(3,0.5)
EM2=SS*SL*X(3,0.5)
IF(EM1.LT.EM2)GO TO 1710
EMAX=EM2
GO TO 1720
1710 EMAX=EM1
1720 IF(B.GT.EMAX)B=EMAX
B=B*C1
RR=RR*C3
V=1./RR*(RR**(2./3.))**SS**0.5
ECO=VV/2./C
WRITE(6,10)ECO
10 FORMAT(/,10X,' VELOCITY=',F12.8,10X,' ENERGY=',F12.8,/)
SUBROUTINE HERSN(S0, SL,SH,RCH,C1,H1,B2,EX,B1,B2,T1,TE,DE) U0010
C U0020
C THIS SUBPROGRAM COMPUTES THE AMOUNT OF MATERIAL ERODED FROM U0030
C A RILL SEGMENT (RILL EROSION). U0040
C COMPUTATIONS ARE BASED ON THE ASSUMPTION OF UNIFORM RILL FLOW. U0050
C K A L I N S K E 'S BED LOAD FORMULA IS USED AS THE SEDIMENT U0060
C PICK-UP CRITERION. U0070
C DE = THE REDUCTION IN BED ELEVATION DUE TO EROSION. U0080
C U0090
C REAL*4 TE,DE U00100
C COMMON /PROP/GAMA,RO,G,SG,RN U00110
C COMMON NT U00120
C TAU=GAMA*C1*SG*H1*B1/2. U00130
C TAU2=GAMA*C1*SG*H2*B2/2. U00140
C XL=2.*SL U00150
C E=RCH*(TAU2-TAU1)/XL*([TAU2+TAU1]/2.)**60 U00160
C C ... E = EROSION RATE IN CUBIC METERS/METER LENGTH/Min U00170
C TE=EX*XL/T1 U00180
C U00190
C C ... TE IS DEDUCTED UNIFORMLY ALONG THE RILL LENGTH U00200
C KF=2 U00210
C WD=2.*SL*3.*0.5 U00220
C 30 BB=(B1+B2)/2.*KF U00230
C IF(BB.GT.0.) GO TO 40 U00240
C DE=0.0 U00250
C RETURN U00260
C 40 IF(BB.GT.WD) GO TO 35 U00270
C DE=2.*TE/SH/BB U00280
C RETURN U00290
C 35 KF=KT-1 U00300
C IF(KF.LE.1) KF=1 U00310
C GO TO 30 U00320
C 50 RETURN U00330
C END U00340
C SUBROUTINE HERSN(GO,SL,EM,EH,RCH,B1,B2,H1,H2,EX,T1,TEH) V0010
C U0020
C THIS SUBPROGRAM COMPUTES THE AMOUNT OF MATERIAL ERODED FROM SIDE V0030
C HUMPS OF ANY RILL SEGMENT (INTERRILL AREAS). V0040
C COMPUTATIONS ARE BASED ON THE ASSUMPTION OF UNIFORM SHEET FLOW V0050
C OVER AN EQUIVALENT RECTANGULAR AREA. V0060
C K A L I N S K E 'S BED LOAD FORMULA IS USED AS THE SEDIMENT V0070
C PICK-UP CRITERION. V0080
C U0090
C REAL*4 EM,EH,TEH V00110
C COMMON /PROP/GAMA,RO,G,SG,RN V00120
C COMMON NT V00130
C ZR0=1.*(10.*20.) V00140
C IF(B1.GE.1000..AND.B2.GE.1000.) GO TO 30 V00150
C XB=SL/(3.*0.5) V00160
C HH=EH-EM V00170
C SO=(EH-EM)/XH V00180
C THETA=ATAN(SO) V00190
C ZL=HH*SIN(THETA) V00200
C HAV=(B1+B2)/2. V00210
C RL=ZL-HAV*SIN(THETA) V00220
C C IF WATER OVERFLOWS ON THIS SIDE, THEN N EROSION WILL TAKE V00230
C PLACE ON IT. V00240
C IF(RL.LE.0.0) GO TO 100 V00250
C YL=2.*RL*SL/ZL V00260
C XL=RL/2. V00270
C 50 GO=QL V00280
C Y=RL*Q+50*0.5)**0.6 V00290
C TAU=GAMA*Y*SO V00300
C E=RCH*(TAU2-TAU1)/XL*([TAU2+TAU1]/2.)***60 V00310
C TE=EX*XL*YL*T1 V00320
C FORMAT(15.8) V00330
C RETURN V00340
C 100 TEH=0.0 V00350
C RETURN V00360
C 30 SO=ABS(SI) V00370
C IF(SO.LE.ZRO) RETURN V00380
C XL=0.5*SL V00390
C YL=2.*SL V00400
C GO TO 50 V00410
C END V00420
SUBROUTINE ERSN1(1, QTT, BCH, BCH, EX, TI)

******************************************************************************

THIS SUBPROGRAM PERFORMS EROSION COMPUTATIONS ON RILL SEGMENTS
WITH UP-STREAM POINT HAVING CODE = 1.

Q1 = FLOW RATE AT UPSTREAM END OF THE RILL SEGMENT
Q2 = FLOW RATE AT DOWNSTREAM END OF THE RILL SEGMENT
SDT(I), TRE(I), TIRE(I) ARE DEFINED IN MAIN PGM
CHANGES IN ELEVATION OF I AT THE END OF A TIME INTERVAL

******************************************************************************

COMMON/MESH/XX, NY, MMAX, SL, SH, WL, GG
COMMON/HEMPFH(500), XHEMP(500), YHEMP(500)
COMMON/SLOPES/HMP1(500), HMP2(500), HMP3(500), HMP4(500), HMP5(500),
COMMON/PROP/GAMA, RO, G, SC, RUN
COMMON/RHUM/NT, ZRO, ID, I0, SC, RH
COMMON/RHUM/PCON, NPM(5), XHPM(5), XHPM(5), YHPM(5), XHPM(5)

IDENTIFY HUMPS ON LEFT AND ON RIGHT
CALL IDEMP(NY, 1, IDL, IDR, NDUMY)
IF(X(I)): EQ. 0 GO TO 1920
IF(X(I)): EQ. X(MMAX) GO TO 1930

IDENTIFY HUMPS ON LEFT AND ON RIGHT
CALL IDEMP(NY, 1, IDL, IDR, NDUMY)

COMPUTATIONS FOR RILL SEGMENTS NOT ON THE BOUNDARIES
******************************************************************************

S1(HEMP4(IDL) - AELV)/SH/3**0.5
S2(HEMP4(IDR) - AELV)/SH/3**0.5
S0(E1 - E2)/2/SH
IF(S0.LE.ZRO) GO TO 1065

CONTINUE
DQ2*QQ*SL*SL*(3**0.5)
Q2*QTT
Q1*Q2*DQ
IF(Q1.LT.0.0) Q1=0.0
IF(Q2.LT.0.0) Q2=0.0

CHECK FOR NEGATIVE SIDE SLOPES
IF(S1.LE.ZRO.OR.S2.LE.ZRO) GO TO 1025

CONTINUE

COMPUTE DEPTH AND WIDTH OF THE FLOW AT THE TWO END POINTS
CALL CSEC(SL, Q1, S1, S2, 50, E1, B1, C1)
CALL CSEC(SL, Q2, S1, S2, 50, B2, C1)

COMPUTE EROSION FROM NEIGHBORING HUMPS
CALL HERSN(QQ, SL, AELV, HMP4(IDL), BCH, B1, B2, E1, EX, TI, TEHL)
CALL HERSN(QQ, SL, AELV, HMP4(IDR), BCH, B1, B2, E1, EX, TI, TEHR)

CHECK FOR PONDING. IF IT OCCURS, DEPOSIT SEDIMENT LOAD AT
DESIGNATED POINTS(SEE NEXT COMMENT STATEMENT).
IF(KPND(I-1).NE.11) GO TO 1017
TDP=SDT(I)+TEHL+TEHR

SEDIMENT LOAD AT I IS DEPOSITED ON RILL SEGMENTS OF SIX MESH
"BACK STEPS" (BETWEEN I-1 AND I+3) .
SINK BACK STEPS.

CONTINUE
KF=2
WD=WL

CONTINUE
IF(BB.LT.0.0) GO TO 35
BB=(B1+B2)/2.*KF
DD1=2.5/29.*2.*TDP/SH/BB
GO TO 48

KF=KF-1
IF(KF.LT.1) KF=1
CO TO 39

40

DB2 = 0.8 * DD1
DB3 = 0.6 * DD1
DB4 = 0.4 * DD1
DB5 = 0.2 * DD1

IF(Y(1) + DD1 > LTY(1)) GO TO 200

IF((I = 1). AND DD1 .GT. MM) GO TO 20

IF((I = 1). AND LE 0) GO TO 21

IF((I = 1). AND DD1 .GT. MM) GO TO 22

IF((I = 1). AND LE 0) GO TO 23

IF((I = 1). AND DD1 .GT. MM) GO TO 24

200 CONTINUE

C ... COMPUTE RILL EROSION
CALL HERSN(SO, SL, SE, B1, B2, EX, BI, B2, TI, TE, DE)

C ... COMPUTE CHANGE IN ELEVATION OF TWO END POINTS

DH(I) = DB(I + DE) - NAJ(I) - 1.

DH(I) = DB(I - 1) - DE(NAJ(I - 1) - 1.)

C ... COMPUTE SEDIMENT DISCHARGE AT NODE POINTS
SDT(I) = SDT(I) - SDT(I) + TEH + TEH

TRE(I) = TRE(I) - TRE(I) + TEH

TIRE(I) = TIRE(I) + TIRE(I) + TEH + TEH

C ... COMPUTATIONS FOR RILL SEGMENTS WITH NEGATIVE SIDE SLOPE(S).
C NO RILL EROSION IN THIS CASE.

C ... LARGE VALUES OF B1 AND B2 (.1000) IS FOR IDENTIFICATION ONLY
CALL HERSN(SQ, SL, AELV, HMP(1), B1, B2, S1, EX, BI, B2, TI, TE1)
C... RILL SECTIONS ON THE BOUNDARY ARE ASSUMED TO HAVE SYMMETRICAL

C SIDE SLOPES
C THE SAME SEQUENCE OF COMPUTATION IS FOLLOWED

1020 S = HMP(1) - AELV - SE/3. ** 0.5
EH = HMP(1) - DR
CO TO 1049

1030 S = HMP(1) - AELV - SE/3. ** 0.5
S1 = S
S2 = S
EH = HMP(1) - DR

1049 GO = (ELV(I) + ELV(I - 1)) / 2. / SE
IF(SO.LE.ZRO) GO TO 1063

12 CONTINUE
AELV = (ELV(I) + ELV(I - 1)) / 2.
DQ = 2. * QQ + SL + S1 ** (3. ** 0.5)
Q2 = Q2 + DQ
IF(Q1.LT.0.) Q1 = 0.0
IF(Q2.LT.0.) Q2 = 0.0
IF(SO.LE.ZRO) GO TO 1065
13 CONTINUE
CALL CSEC (SL, Q1, S, SO, B1, B1, C1)
CALL CSEC (SL, Q2, S, SO, B2, B2, C1)
CALL DERSR (QQ, SL, AELV, ELV, B1, B2, B2, EX, TI, TE)
IF (KPNF (1-1) .NE. 11) GO TO 1016
TDF = SDLT (1) + TEH
GO TO 29
1016 CONTINUE
CALL DERSR (SO, SL, SH, B1, B2, EX, B1, B2, TI, TE)
DB (1) = DB (1) + DE / (NAJ (1) * 1.1)
DB (1-1) = DB (1-1) + DE / (NAJ (1-1) * 1.1)
SDLT (1) = SDLT (1-1) + SDLT (1) * TE + TEH
TRE (1) = TRE (1-1) + TRE (1-1) + TRE (1) + TE
TIRE (1) = TIRE (1-1) + TIRE (1-1) + TIRE (1) + TEH
RETURN
1035 B1 = 1000
B2 = 1000
CALL DERSR (QQ, SL, AELV, ELV, B1, B2, S, EX, TI, TE)
CALL SNECTV (1.5, S, TE, TE, KODE, T, R, B, NBRANCH)
RETURN
1065 CONTINUE
WRITE (6, 1070) 1, 80
1070 FORMAT (2, 10X, 'FONDING OCCURRED AT PT. ', 15, 5X, 'S0=', F12.8)
RETURN
END
SUBROUTINE DERSR (QQ, SL, AELV, ELV, B1, B2, S, EX, TI)
THIS SUBPROGRAM PERFORMS EROSION COMPUTATIONS ON RILL SEGMENTS
WITH UP-STREAM POINT HAVING CODE+2.
C******************************************************************************
C THIS SUBPROGRAM PERFORMS EROSION COMPUTATIONS ON RILL SEGMENTS
WITH UP-STREAM POINT HAVING CODE+2.
C******************************************************************************
C S1 = SLOPE OF THE LEFT SIDE OF THE RILL SIDE WALLS
C S2 = SLOPE OF THE RIGHT SIDE OF THE RILL SIDE WALLS
C Q1 = FLOW RATE AT UPSTREAM END OF THE RILL SEGMENT
C Q2 = FLOW RATE AT DOWNSTREAM END OF THE RILL SEGMENT
C SDLT (1) = CHANGE IN ELEVATION OF 1 AT THE END OF A TIME INTERVAL
C******************************************************************************
C******************************************************************************
COMMON /NESH/ NX, NY, NMAX, SL, SH, WL, QQ
COMMON /HDSPP/HMP (500), XEMP (500), YEMP (500)
COMMON /SLOPES/HMP1 (500), HMP2 (500), HMP3 (500), HMP4 (500), HMP5 (500),
HMP6 (500), HMP7 (500)
COMMON /PROP/CAMA, RO, C, SC, RN
COMMON NT
ZRO = 1.0 / (10.0 ** 20.)
KODE = 2
DE = 0.0
TE = 0.0
DQ = 2.0 * QQ / SL + SL (3.0 ** 0.5)
C IDENTIFY THE THREE NEIGHBORING HUMPS
CALL IDHMP (NY, 1, IDL, IDR, IDC)
SOL = (ELV (1) - (ELV (1-1)) / 2. / SH
SQR = (ELV (1) - (ELV (1-1)) / 2. / SH
IF (X (1) .EQ. 0) GO TO 1110
IF (X (1) .EQ. (X (MAX))) GO TO 1120
IF (SOL.LT.ZRO.AND.SQR.LE.ZRO) GO TO 1170
IF (SOL.LT.ZRO.AND.SQR.GT.ZRO) GO TO 1110
IF (SOL.GT.ZRO.AND.SQR.LT.ZRO) GO TO 1120
201 CONTINUE
C SEDIMENT LOAD IS DIVIDED BETWEEN THE TWO BRANCHES ACCORDING TO
C THE RELATIVE MAGNITUDES OF BED SLOPES RAISED TO THE POWER OF 1.25
C SOL2 = (ELV (1-1) - ELV (1-2)) / 2. / SH
C SOL2 = (ELV (1-1) - ELV (1-2)) / 2. / SH
C SOL2 = (SOL + SOL2) / 2.
C IF (SAVE.LT.0.0) SAVE = 0.0
C SAVE = (SAVE + SAVE2) / 2.
C IF (SAVE.LT.0.0) SAVE = 0.0
C SS = SAVE = 1.25 + SAVE * 1.25
C IF (SS.LT.0.0) GO TO 210
C STL = SDLT (1) / SAVE = 1.25 / SS
C REMN + TRE (1) = SAVE = 1.25 / SS
C REMN + TIRE (1) = SAVE = 1.25 / SS
C GO TO 220
**Computations for Rill Segment on the Left**

**Rill Segments on the Boundary Are Assumed to Have Symmetrical Side Slopes**

**Check for Negative Side Slopes**

**Compute Depth and Width of the Flow at the Two End Points**

**Compute Erosion from Neighboring Humps**

**Check for Ponding. If It Occurs, Deposit Sediment Load at Designated Points (See Next Comment Statement).**

**Sediment Load at 1 Is Deposited on Rill Segments of Six Mesh Back Steps**

**Back Steps**

**Depth and Width of Material Deposited at Different Back Steps**

**End**
13 IF(Y(I+NY+3).LT.Y(I)) GO TO 100
   IF((1+NY+3).GT.MAX) GO TO 14
   DH(1+NY+3)=DH(1+NY+3)-1.*DD5
   IF((1+NY+3).LE.0) GO TO 15
   DH(1+NY+3)=DH(1+NY+3)-1.*DD5
15 IF((I-3*NY+3).LE.0) GO TO 100
   DH(1-3*NY+3)=DH(1-3*NY+3)-1.*DD5
100 CONTINUE
1021 RETURN
1115 CONTINUE

C ... COMPUTE RILL EROSION
   CALL HERSN(SL,SH,RCH,C1,B1,E2,EX,B1,B2,TE,DE)

C ... COMPUTE CHANGE IN ELEVATION OF TWO END POINTS
   DBH(1)=DBH(1)+DE/(1.*NAI(I))
   DBH(1-1)=DBH(1-1)+DE/(1.*NAI(1-NY))

C ... COMPUTE SEDIMENT DISCHARGE AT NODE POINTS
   SDT(I-1)=SDT(I-1)+STL+TE+TEHL+TEHLC
   TRE(I-1)=TRE(I-1)+TRE(I-1)+RENL+TE
   TIRE(I-1)=TIRE(I-1)+TIRE(I-1)+RENL+TEHLC

C ... CHECK FOR -VE. SIDE SLOPES
1145 IF((S1.GT.0.0).AND.(S2.GT.0.0)) GO TO 1150
   NBRLCH=1
   B1=1000.
   B2=1000.

C NOTE: THE LARGE VALUES OF B1, AND B2 (1000) ARE USED ONLY AS FLAGS
1150 IF(K.EQ.1) GO TO 1160
   RETURN

C ... COMPUTATIONS FOR RILL SEGMENTS WITH NEGATIVE SIDE SLOPE(S).
   NO RILL EROSION IN THIS CASE.
   CALL HERSN(QQ,SL,DNY1,DNY2,RCH,B1,B2,S2,EX,T1,TE2)
   CALL HERSN(QQ,SL,DNY1,DNY2,RCH,B1,B2,S2,EX,T1,TE1)
   KDE=2

C ... REDISTRIBUTE THE SEDIMENT LOAD WHEN EITHER SIDE SLOPES IS -VE.
   CALL SNECTV(I,S1,S2,TE1,TE2,KODE,STL,RENL,BRENL,NBRLCH)

C ... COMPUTATIONS FOR RILL SEGMENT ON THE RIGHT
   *******************************************************

C ... THE SAME SEQUENCE OF COMPUTATIONS IS FOLLOWED
1170 IF((S0R.LE.0)) GO TO 1170
   STL=0
   RENL=0.
   BRENL=0.

1160 STR=SDT(I)-STL
   RENR=TRE(I)-RENL
   BRENR=TIRE(I)-BRENL
   SD0=S0R
   AELV=(ELV(I)+ELV(I+NY-1))/2.
   S1*(HMP3(1DC)-AELV)/SB/3.**0.5
   HP6*HMP6(IDR)
   IF(Y(I),EQ,Y(NY)), HP6=HMP3(IDC)
   S2*(HMP6-AELV)/SB/3.**0.5
   Q1=QRR
   IF(Q1.LT.0.) Q1=0.
   Q2=Q1+QD
   IF(S1.LE.ZRO.OR.S2.LE.ZRO) GO TO 1155

203 CONTINUE

   CALL CSECF(SL,Q1,S1,S2,SO,B1,B1,C1)
   CALL CSECF(SL,Q2,S1,S2,SO,B2,B2,C1)
   CALL HERSN(QQ,SL,AELV,HP6,1DC,RCH,B1,B2,E2,EX,T1,TEHRC)
   IF(KPND(I+NY-1).NE.11) GO TO 1116
   TDP=STL+TEH+TEHRC
   KF=2
   WD=WL

60 BB=(B1+B2)/2.*KF
   IF(BB.GT.WD) GO TO 65
   DD1=2.5*35.*2.*TDP/NS/BB
   GO TO 70

65 IF(KF.LT.1) KF=1
SUBROUTINE SNECTV(I, SL, SE, TE1, TE2, KODE, T, R, B, NBRANCH)

C THIS SUBPROGRAM MODIFIES THE EROSION COMPUTATIONS WHEN EITHER
C SLOPES OF A RILL SEGMENT IS NEGATIVE.

C
C MV = LOCATION OF SEDIMENT LOAD BEFORE MODIFICATION
C NK = LOCATION OF SEDIMENT LOAD AFTER MODIFICATION
C TE1 = VOLUME OF SOIL ERODED FROM LEFT SLOPE
C TE2 = VOLUME OF SOIL ERODED FROM RIGHT SLOPE
C
C******************************************************************************

COMMON/WX, NY, NMAX, XL, SH, WL, QQ
COMMON/HREH/P, HREH(500), XREH(500), YREH(500)
COMMON/SLOPES, HNP(500), HNP(500), HNP(500), HMP4(500), HMP5(500),
* HMP6(500)
COMMON NT

1 FORMAT(1, 10X, 'POINT ', I3, 5F20.8, /)
   E1 = TE1
   E2 = TE2
   CALL IDEMP(NY, 1, IDL, 1DR, IDC)

RETURN

END

Ckehk1 1.

Ckehk2 1.

Ckehk3 1.
GO TO (100, 200), KODE
100 S0 = (ELV(I) - ELV(I+1)) / 2. /EH
   IF (X(I) .EQ. 0.0) GO TO 120
   IF (X(I) .EQ. X(NMAX)) GO TO 110
   IF (S1.LE.0.0 .AND. S2.GT.0.0) GO TO 110
   IF (S1.GT.0.0 .AND. S2.LE.0.0) GO TO 120
   IF (K = 1-2*NY-1) NV=1
   IF (X(NV) .LE. X(NY+1)) NK = NMAX+5
   F = 0.5
   KK = 1
   E2 = 0.0
   HHH = (ELV(NK)+ELV(NK+1)) / 2.
   IF (HHH.GE.EMP1(IDL)) GO TO 105
   GO TO 100
105 F = 0.0
   E1 = 0.0
   E2 = 0.0
   GO TO 100
110 NK = 1+2*NY-1
   NV = 1
   IF (X(NV) .LE. X(NMAX-NY)) NK = NMAX+5
   F = 0.5
   KK = 2
   AS1 = ABS(S1)
   IF (S0.GE.AS1) GO TO 117
   HHH = (ELV(NK)+ELV(NK+1)) / 2.
   IF (HHH.GE.EMP1(IDL)) GO TO 115
   GO TO 100
115 F = 0.0
   E1 = 0.0
   E2 = 0.0
   GO TO 100
117 F = 0.0
   E2 = E2
   KK = 3
   GO TO 100
120 NK = 1+2*NY-1
   NV = 1
   IF (X(NV) .LE. X(NMAX-NY)) NK = NMAX+5
   F = 1.0
   KK = 2
   HHH = (ELV(NK)+ELV(NK+1)) / 2.
   IF (HHH.GE.EMP1(IDL)) GO TO 115
   AS2 = ABS(S2)
   IF (S0.GE.AS2) GO TO 127
   GO TO 100
127 F = 0.0
   E = E1
   E1 = 0.0
   KK = 3
   GO TO 1000
1000 SDT(NK) = SDT(NK)+F*SDT(NV)+E1+E2
   TRE(NK) = TRE(NK)+F*TRE(NV)
   TIRE(NK) = TIRE(NK)+F*TIRE(NV)+E1+E2
   IF (KK.EQ.1) GO TO 111
   IF (KK.EQ.3) GO TO 1200
   GO TO 1700
1200 CONTINUE
RETURN
200 CALL IDHMP(NY, IDL, IDR, IDC)
   IF (MBRANCH.EQ.2) GO TO 300
   IF (X(I) .EQ. 0.0) GO TO 300
SOL=(ELV(I)-ELV(I-1))/2./SH
AS1=ABS(S1)
AS2=ABS(S2)
IF(S1.LE.0.0.AND.S2.LE.0.0) GO TO 210
IF(S1.GT.0.0.AND.S2.LE.0.0) GO TO 220
NK=1-2*NY+1
IF(Y(I).GE.Y(NY-1)) NK=MAX+5
IF(X(I).EQ.X(NY-1)) NK=MAX+5
F=0.5
KK=1
E2=0.0
HBB=(ELV(NK)+ELV(NK+NY+1))/2.
IF(HBB.GT.0.0) GO TO 205
GO TO 2000
205 F=0.0
E1=0.0
E2=0.0
GO TO 2000
211 NK=1-3
IF(Y(I).EQ.Y(3)) NK=1+NY-2
F=0.3
KK=2
E2=TE2
E1=0.0
HBB=(ELV(NK)+ELV(NK+NY+1))/2.
IF(HBB.GT.0.0) GO TO 205
GO TO 2000
210 NK=1-2*NY+1
IF(Y(I).GT.Y(NY-1)) NK=MAX+5
IF(X(I).EQ.X(NY-1)) NK=MAX+5
F=1.0
KK=2
IF(SOL.GT.AS1) GO TO 217
HBB=(ELV(NK)+ELV(NK+NY+1))/2.
IF(HBB.GT.0.0) GO TO 205
GO TO 2000
217 F=0.0
E=E2
E2=0.0
KK=3
GO TO 2000
220 NK=1-3
IF(Y(I).EQ.Y(3)) NK=1+NY-2
F=1.0
KK=2
IF(SOL.GT.AS2) GO TO 227
IF(X(I).GT.X(MAX)) GO TO 2000
HBB=(ELV(NK)+ELV(NK+NY+1))/2.
IF(HBB.GT.0.0) GO TO 205
GO TO 2000
227 F=0.0
E=E1
E1=0.0
KK=3
GO TO 2000
2000 SDT(NK)=SDT(NK)+F*T+E1+E2
TRE(NK)=TRE(NK)+F*R
TIRE(NK)+TIRE(NK)+F*R+E1+E2
IF(KK.EQ.1) GO TO 211
IF(KK.EQ.3) GO TO 2500
GO TO 2700
2500 SDT(I-NY-1)=SDT(I-NY-1)+T*E
TRE(I-NY-1)=TRE(I-NY-1)+R
TIRE(I-NY-1)+TIRE(I-NY-1)+R+H
GO TO 2700
2700 CONTINUE
4 FORMAT(6F20.10,/) RETURN
300 IF(X(I).EQ.X(MAX)) RETURN
SOR=(ELV(I)-ELV(I+NY-1))/2./SH
AS2=ABS(S2)
AS1=ABS(S1)
IF(S1.CT.0.0.AND.S2.LE.0.0) GO TO 310
IF(S1.LE.0.0.AND.S2.CT.0.0) GO TO 320
NK=+2*NY+1
IF(Y(1).GE.Y(NY-1)) NK=NMAX+5
IF(X(1).EQ.X(NMAX-NY)) NK=NMAX+5
F=0.5
XE=1
E1=0.0
HHH=(ELV(NK)+ELV(NK-NY+1))/2.
IF(HHH.GT.HMP3(IDR)) GO TO 305
GO TO 3000

305 F=0.0
E1=0.0
E2=0.0
GO TO 3000

310 NK=+2*NY+1
IF(Y(1).GE.Y(NY-1)) NK=NMAX+5
IF(X(1).EQ.X(NMAX-NY)) NK=NMAX+5
F=1.0
XE=2
E1=+1
E2=0.0
HHH=(ELV(NK)+ELV(NK-NY+1))/2.
IF(HHH.GT.HMP6(IDC)) GO TO 305
GO TO 3000

317 F=0.0
E=E1
E1=0.0
XE=3
GO TO 3000

320 NK=+1
IF(Y(1).EQ.Y(3)) NK=1-NY-2
F=1.0
XE=2
IF(SOR.CT.AS1) GO TO 317
IF(X(1).EQ.0.0) GO TO 3000
HHH=(ELV(NK)+ELV(NK-NY+1))/2.
IF(HHH.GT.HMP6(IDC)) GO TO 305
GO TO 3000

327 F=0.0
E=E1
E1=0.0
XE=3
GO TO 3000

3000 SDT(NK)=SDT(NK)+F*E1+E2
TRE(NK)=TRE(NK)+F*R
TIRE(NK)=TIRE(NK)+F*E1+E2
IF(KK.EQ.1) GO TO 311
IF(KK.EQ.3) GO TO 3500
GO TO 3700

3500 SDT(I+NY-1)=SDT(I+NY-1)+T+E
TRE(I+NY-1)=TRE(I+NY-1)+R
TIRE(I+NY-1)=TIRE(I+NY-1)+E
CONTINUE
RETURN
END
GROUP # 1: SURFACE ROUGHNESS DATA

NO. OF ELEVATION TRACES = 7
NO. OF POINTS PER TRACE = 100
SPACING = 2.00 CM

GROUP # 2: PROBLEM PARAMETERS

SOIL PARTICLE DIAMETER = 0.010 MLMT
SOIL UNIT WEIGHT = 16660. N/C. METER
SOIL SPECIFIC WEIGHT = 2.65

EXPONENT OF KALINSKE EQN. = 1.50
EQN. CONSTANT FOR RILLS = 400.0
EQN. CONSTANT FOR HUMPS = 20.0
MANNING CONSTANT = 0.040

GROUP # 3: STORM AND SLOPE DATA

NO. OF MESH POINTS IN CROSS-DIRECTION = 65
NO. OF MESH POINTS IN LONGT-DIRECTION = 30

AVERAGE SLOPE = 20.0 DEGREES
RAINFALL INTENSITY = 50.0 MLMT/HR
RUNOFF COEFFICIENT = 0.50

ANNUAL RAINFALL RATE = 100.0 CM/MT
EQUIVALENT YEARS OF RAIN = 0.25 YEARS

TIME INTERVAL = 10.0 MINUTES
TOTAL RAIN PERIOD = 5.00 HOURS
NO. OF RANDOM SURFACES = 1

FAILURE LIMIT FOR SIDE SLOPE = 1.40
STARTING LIMIT FOR SIDE SLOPE = 1.10
### Spectral Analysis Results

#### Average Values for All Profiles

<table>
<thead>
<tr>
<th>Degree</th>
<th>AN</th>
<th>BN</th>
<th>Power</th>
<th>Contr.</th>
<th>Total</th>
<th>L (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.00</td>
<td>0.0</td>
<td>0.000</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>1</td>
<td>-3.73</td>
<td>5.68</td>
<td>26.373</td>
<td>0.1021</td>
<td>0.1021</td>
<td>198.00</td>
</tr>
<tr>
<td>2</td>
<td>5.14</td>
<td>3.61</td>
<td>28.660</td>
<td>0.1213</td>
<td>0.2234</td>
<td>99.00</td>
</tr>
<tr>
<td>3</td>
<td>-7.44</td>
<td>0.63</td>
<td>31.573</td>
<td>0.2830</td>
<td>0.4263</td>
<td>66.00</td>
</tr>
<tr>
<td>4</td>
<td>-1.39</td>
<td>2.23</td>
<td>6.368</td>
<td>0.0237</td>
<td>0.0520</td>
<td>49.30</td>
</tr>
<tr>
<td>5</td>
<td>0.08</td>
<td>1.61</td>
<td>4.693</td>
<td>0.0287</td>
<td>0.0772</td>
<td>39.00</td>
</tr>
<tr>
<td>6</td>
<td>0.23</td>
<td>0.23</td>
<td>5.473</td>
<td>0.0236</td>
<td>0.0493</td>
<td>33.00</td>
</tr>
<tr>
<td>7</td>
<td>-0.36</td>
<td>-0.94</td>
<td>3.866</td>
<td>0.0160</td>
<td>0.0523</td>
<td>28.29</td>
</tr>
<tr>
<td>8</td>
<td>0.36</td>
<td>1.16</td>
<td>3.866</td>
<td>0.0166</td>
<td>0.0539</td>
<td>24.75</td>
</tr>
<tr>
<td>9</td>
<td>-4.40</td>
<td>0.36</td>
<td>4.253</td>
<td>0.0187</td>
<td>0.0577</td>
<td>22.00</td>
</tr>
<tr>
<td>10</td>
<td>2.30</td>
<td>0.35</td>
<td>4.087</td>
<td>0.0156</td>
<td>0.0563</td>
<td>19.80</td>
</tr>
<tr>
<td>11</td>
<td>3.00</td>
<td>-2.23</td>
<td>10.397</td>
<td>0.0429</td>
<td>0.0661</td>
<td>18.00</td>
</tr>
<tr>
<td>12</td>
<td>-1.62</td>
<td>1.22</td>
<td>4.259</td>
<td>0.0171</td>
<td>0.0622</td>
<td>16.50</td>
</tr>
<tr>
<td>13</td>
<td>0.30</td>
<td>0.51</td>
<td>4.778</td>
<td>0.0268</td>
<td>0.0736</td>
<td>15.23</td>
</tr>
<tr>
<td>14</td>
<td>1.00</td>
<td>0.25</td>
<td>3.735</td>
<td>0.0163</td>
<td>0.0593</td>
<td>14.14</td>
</tr>
<tr>
<td>15</td>
<td>0.55</td>
<td>1.08</td>
<td>3.243</td>
<td>0.0143</td>
<td>0.0477</td>
<td>13.28</td>
</tr>
<tr>
<td>16</td>
<td>0.72</td>
<td>-0.42</td>
<td>5.569</td>
<td>0.0217</td>
<td>0.0935</td>
<td>12.38</td>
</tr>
<tr>
<td>17</td>
<td>0.21</td>
<td>-0.62</td>
<td>4.183</td>
<td>0.0173</td>
<td>0.0712</td>
<td>11.65</td>
</tr>
<tr>
<td>18</td>
<td>0.22</td>
<td>-1.19</td>
<td>3.568</td>
<td>0.0147</td>
<td>0.0504</td>
<td>11.00</td>
</tr>
<tr>
<td>19</td>
<td>-0.55</td>
<td>-0.57</td>
<td>1.665</td>
<td>0.0066</td>
<td>0.0339</td>
<td>10.42</td>
</tr>
<tr>
<td>20</td>
<td>2.32</td>
<td>-0.62</td>
<td>3.620</td>
<td>0.0161</td>
<td>0.0751</td>
<td>9.90</td>
</tr>
<tr>
<td>21</td>
<td>1.22</td>
<td>-1.47</td>
<td>2.547</td>
<td>0.0192</td>
<td>0.0742</td>
<td>9.43</td>
</tr>
<tr>
<td>22</td>
<td>-0.46</td>
<td>-0.50</td>
<td>2.871</td>
<td>0.0099</td>
<td>0.0288</td>
<td>9.00</td>
</tr>
<tr>
<td>23</td>
<td>1.96</td>
<td>-2.24</td>
<td>4.619</td>
<td>0.0179</td>
<td>0.0881</td>
<td>8.61</td>
</tr>
<tr>
<td>24</td>
<td>-1.05</td>
<td>-0.67</td>
<td>2.347</td>
<td>0.0094</td>
<td>0.0227</td>
<td>8.25</td>
</tr>
<tr>
<td>25</td>
<td>-0.73</td>
<td>0.63</td>
<td>5.763</td>
<td>0.0242</td>
<td>0.0821</td>
<td>7.92</td>
</tr>
<tr>
<td>26</td>
<td>-0.18</td>
<td>0.37</td>
<td>1.868</td>
<td>0.0067</td>
<td>0.0283</td>
<td>7.62</td>
</tr>
<tr>
<td>27</td>
<td>0.07</td>
<td>-0.11</td>
<td>2.686</td>
<td>0.0105</td>
<td>0.0381</td>
<td>7.33</td>
</tr>
<tr>
<td>28</td>
<td>0.98</td>
<td>-1.87</td>
<td>3.876</td>
<td>0.0160</td>
<td>0.0547</td>
<td>7.07</td>
</tr>
<tr>
<td>29</td>
<td>1.45</td>
<td>-0.56</td>
<td>4.667</td>
<td>0.0167</td>
<td>0.0715</td>
<td>6.83</td>
</tr>
<tr>
<td>30</td>
<td>1.12</td>
<td>-0.42</td>
<td>1.495</td>
<td>0.0061</td>
<td>0.0276</td>
<td>6.60</td>
</tr>
<tr>
<td>31</td>
<td>0.36</td>
<td>0.62</td>
<td>0.577</td>
<td>0.0025</td>
<td>0.0080</td>
<td>6.39</td>
</tr>
<tr>
<td>32</td>
<td>1.12</td>
<td>-0.86</td>
<td>2.618</td>
<td>0.0185</td>
<td>0.0456</td>
<td>6.19</td>
</tr>
<tr>
<td>33</td>
<td>-0.22</td>
<td>0.12</td>
<td>1.397</td>
<td>0.0058</td>
<td>0.0086</td>
<td>6.00</td>
</tr>
<tr>
<td>34</td>
<td>0.50</td>
<td>-0.34</td>
<td>1.149</td>
<td>0.0044</td>
<td>0.0068</td>
<td>5.82</td>
</tr>
<tr>
<td>35</td>
<td>1.08</td>
<td>0.85</td>
<td>1.981</td>
<td>0.0074</td>
<td>0.0062</td>
<td>5.66</td>
</tr>
<tr>
<td>36</td>
<td>0.25</td>
<td>-0.47</td>
<td>1.384</td>
<td>0.0056</td>
<td>0.0037</td>
<td>5.50</td>
</tr>
<tr>
<td>37</td>
<td>0.59</td>
<td>-0.29</td>
<td>1.815</td>
<td>0.0061</td>
<td>0.0118</td>
<td>5.35</td>
</tr>
<tr>
<td>38</td>
<td>0.99</td>
<td>-0.94</td>
<td>2.421</td>
<td>0.0096</td>
<td>0.0294</td>
<td>5.21</td>
</tr>
<tr>
<td>39</td>
<td>1.17</td>
<td>0.19</td>
<td>2.047</td>
<td>0.0088</td>
<td>0.0192</td>
<td>5.08</td>
</tr>
<tr>
<td>40</td>
<td>0.52</td>
<td>0.51</td>
<td>3.057</td>
<td>0.0121</td>
<td>0.0384</td>
<td>4.95</td>
</tr>
<tr>
<td>41</td>
<td>0.23</td>
<td>0.33</td>
<td>1.819</td>
<td>0.0072</td>
<td>0.0084</td>
<td>4.83</td>
</tr>
<tr>
<td>42</td>
<td>0.75</td>
<td>0.78</td>
<td>1.481</td>
<td>0.0062</td>
<td>0.0092</td>
<td>4.71</td>
</tr>
<tr>
<td>43</td>
<td>0.00</td>
<td>0.25</td>
<td>1.049</td>
<td>0.0042</td>
<td>0.0046</td>
<td>4.60</td>
</tr>
<tr>
<td>44</td>
<td>0.48</td>
<td>-0.15</td>
<td>1.288</td>
<td>0.0047</td>
<td>0.0072</td>
<td>4.50</td>
</tr>
<tr>
<td>45</td>
<td>0.61</td>
<td>0.31</td>
<td>0.861</td>
<td>0.0037</td>
<td>0.0033</td>
<td>4.45</td>
</tr>
<tr>
<td>46</td>
<td>-0.16</td>
<td>-0.76</td>
<td>1.393</td>
<td>0.0057</td>
<td>0.0083</td>
<td>4.30</td>
</tr>
<tr>
<td>47</td>
<td>0.57</td>
<td>-0.07</td>
<td>1.139</td>
<td>0.0047</td>
<td>0.0067</td>
<td>4.21</td>
</tr>
<tr>
<td>48</td>
<td>0.91</td>
<td>-0.56</td>
<td>1.196</td>
<td>0.0048</td>
<td>0.0091</td>
<td>4.13</td>
</tr>
<tr>
<td>49</td>
<td>-0.22</td>
<td>-0.22</td>
<td>1.079</td>
<td>0.0043</td>
<td>0.0045</td>
<td>4.04</td>
</tr>
<tr>
<td>50</td>
<td>-0.17</td>
<td>-0.0</td>
<td>0.993</td>
<td>0.0042</td>
<td>0.0042</td>
<td>3.96</td>
</tr>
</tbody>
</table>
AMPLITUDE OF REPRESENTATIVE WAVE: 3.740 MLNR
LENGTH OF REPRESENTATIVE WAVE = 18.000 CM
MEAN OF NORMAL DIST. = 4.719 MLNR
STAND. DEVIATION OF NORMAL DIST. = 18.906 MLNR

PLOT LENGTH: 2.286 METERS
PLOT WIDTH: 5.760 METERS

TEST AREA = 13.169 SQ. METERS
SHAPE FACTOR = 2.519
### RESULTS OF EACH INTERVAL

<table>
<thead>
<tr>
<th>INTERVAL</th>
<th>TTL SDMT (N)</th>
<th>R/I RATIO</th>
<th>ERSN RATE (N/SN/HR)</th>
<th>CUMULATIVE RESULTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13.27</td>
<td>0.22</td>
<td>6.04</td>
<td>13.27</td>
</tr>
<tr>
<td>2</td>
<td>24.78</td>
<td>0.23</td>
<td>11.29</td>
<td>38.04</td>
</tr>
<tr>
<td>3</td>
<td>30.12</td>
<td>0.24</td>
<td>13.73</td>
<td>68.17</td>
</tr>
<tr>
<td>4</td>
<td>37.34</td>
<td>0.24</td>
<td>17.01</td>
<td>105.51</td>
</tr>
<tr>
<td>5</td>
<td>36.49</td>
<td>0.24</td>
<td>16.63</td>
<td>142.00</td>
</tr>
<tr>
<td>6</td>
<td>37.52</td>
<td>0.23</td>
<td>17.09</td>
<td>179.52</td>
</tr>
<tr>
<td>7</td>
<td>42.37</td>
<td>0.23</td>
<td>19.31</td>
<td>221.89</td>
</tr>
<tr>
<td>8</td>
<td>39.04</td>
<td>0.21</td>
<td>17.79</td>
<td>260.94</td>
</tr>
<tr>
<td>9</td>
<td>40.28</td>
<td>0.21</td>
<td>18.35</td>
<td>301.22</td>
</tr>
<tr>
<td>10</td>
<td>43.46</td>
<td>0.20</td>
<td>19.00</td>
<td>344.68</td>
</tr>
<tr>
<td>11</td>
<td>43.06</td>
<td>0.20</td>
<td>19.62</td>
<td>387.75</td>
</tr>
<tr>
<td>12</td>
<td>44.32</td>
<td>0.20</td>
<td>20.19</td>
<td>432.87</td>
</tr>
<tr>
<td>13</td>
<td>42.74</td>
<td>0.18</td>
<td>19.47</td>
<td>474.81</td>
</tr>
<tr>
<td>14</td>
<td>54.38</td>
<td>0.19</td>
<td>24.78</td>
<td>529.19</td>
</tr>
<tr>
<td>15</td>
<td>49.46</td>
<td>0.18</td>
<td>22.54</td>
<td>578.65</td>
</tr>
<tr>
<td>16</td>
<td>45.40</td>
<td>0.16</td>
<td>20.69</td>
<td>624.96</td>
</tr>
<tr>
<td>17</td>
<td>45.21</td>
<td>0.17</td>
<td>20.60</td>
<td>669.26</td>
</tr>
<tr>
<td>18</td>
<td>52.54</td>
<td>0.17</td>
<td>23.94</td>
<td>721.80</td>
</tr>
<tr>
<td>19</td>
<td>47.14</td>
<td>0.16</td>
<td>21.48</td>
<td>768.94</td>
</tr>
<tr>
<td>20</td>
<td>51.98</td>
<td>0.16</td>
<td>23.68</td>
<td>820.92</td>
</tr>
<tr>
<td>21</td>
<td>56.11</td>
<td>0.17</td>
<td>25.96</td>
<td>877.83</td>
</tr>
<tr>
<td>22</td>
<td>57.40</td>
<td>0.16</td>
<td>26.15</td>
<td>934.43</td>
</tr>
<tr>
<td>23</td>
<td>58.24</td>
<td>0.16</td>
<td>26.54</td>
<td>992.68</td>
</tr>
<tr>
<td>24</td>
<td>55.59</td>
<td>0.16</td>
<td>25.33</td>
<td>1048.27</td>
</tr>
<tr>
<td>25</td>
<td>62.91</td>
<td>0.16</td>
<td>28.66</td>
<td>1111.17</td>
</tr>
<tr>
<td>26</td>
<td>56.27</td>
<td>0.15</td>
<td>25.64</td>
<td>1167.45</td>
</tr>
<tr>
<td>27</td>
<td>60.49</td>
<td>0.15</td>
<td>27.56</td>
<td>1227.94</td>
</tr>
<tr>
<td>28</td>
<td>54.82</td>
<td>0.15</td>
<td>24.98</td>
<td>1282.76</td>
</tr>
<tr>
<td>29</td>
<td>64.35</td>
<td>0.15</td>
<td>29.32</td>
<td>1347.11</td>
</tr>
<tr>
<td>30</td>
<td>56.14</td>
<td>0.15</td>
<td>25.58</td>
<td>1403.25</td>
</tr>
</tbody>
</table>

*Random Surface No. 1*