Rainfall-Runoff and Sediment yield Modeling of Watershed Using FEM and Geospatial Techniques

By

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Organization of Presentation

- Introduction
- Review of Literature
- Methodology and Model Development
- Model Applications and Evaluation
- Comparison of Models and Results
- Discussion
- Summary and Conclusions
Introduction

➢ Motivation of the Study
➢ Types of **Soil Erosion**
➢ Process of Soil Erosion by Water
➢ Objectives of the Study
Types of soil erosion
Importance of the Study
Erosion due to Raindrop Impact
Soil Erosion Process (Meyer and Wischmeier 1969)

Detachment by Rain

Detachment by Runoff

Transport capacity of Rain

Transport capacity of Runoff

Detachment on increment

Total detached soil

compare

Total transport capacity

IF DET. < TRANS.

IF TRANS. < DET.

Soil carried downslope
Objectives of the Study

➢ To develop physically-based distributed watershed models for soil erosion and sediment yield by considering the important hydrologic processes and using FEM.

➢ To investigate the utility of remotely sensed data and geographical information systems in soil erosion and sediment yield assessment.

➢ To apply, validate and compare the developed models on four small and medium watersheds.

➢ To carry out sensitivity analysis to identify important parameters affecting soil erosion and sediment yield.
Frame work for Model Development

Selection of watershed

Input data to model

Field data, remotely sensed data and analysis with GIS

Rainfall Intensity

Governing Equations (Kinematic & Diffusion Wave Approximation)

FEM formulation

Interception, Infiltration & Rainfall-Runoff model

Soil erosion and Sediment yield model

Sediment yield

Selection of watershed

Soil maps

Soil parameter

DEM

LU/LC

Slope

Roughness

Crop management factor
Model Formulation

- **Interception** Model
- **Infiltration Model**
  - **GAML** Model
  - **Philip** Model
- **Overland Flow** Model
- **Stream Flow** Model
- **Overland Sediment Flow Model**
- **Stream Sediment Flow Model**
Model Formulation for Overland Sediment Flow

Upland phase sediment load: \( q_s = \rho_s \cdot c \cdot q; \quad q = v \cdot h; \quad A_s = \left( \frac{q_s}{v} \right) \)

Continuity equation for sediment flow:
\[
D_L = D_R + D_F
\]
\[
\frac{\partial q_s}{\partial x} + \frac{\partial A_s}{\partial t} = D_L
\]

Method-I:

Soil detachment by raindrop impact:
\[
D_R = \omega \cdot C_F \cdot K_F \cdot r^2
\]

Soil detachment by flow:
\[
D_F = \eta \cdot C_F \cdot K_F \cdot S_0 \cdot q
\]

Method-II:

Soil detachment by raindrop impact:
\[
D_R = \omega \cdot F_w \cdot C_F \cdot K_F \cdot r^2 \cdot (2.96 S_0^{0.79} + 0.56)
\]

Soil detachment by flow:
\[
D_F = \eta \cdot C_F \cdot K_F \cdot \tau^{1.5}
\]

Transport capacity of flow:
\[
T_F = \xi_1 \cdot K_F \cdot S_0 \cdot q^{1/2} \quad \text{for} \quad q < 0.046 \left( \frac{m^2}{\text{min}} \right)
\]
\[
T_F = \xi_2 \cdot K_F \cdot S_0 \cdot q^2 \quad \text{for} \quad q > 0.046 \left( \frac{m^2}{\text{min}} \right)
\]
Model Formulation for Stream Sediment Flow

Lowland stream phase:

Sediment load in stream flow:
\[ Q_{SC} = \rho_s \cdot c_c \cdot Q \]

Sediment continuity equation in stream flow:
\[ \frac{\partial Q_{SC}}{\partial x} + \frac{\partial A_{SC}}{\partial t} = D_T \]

Transport capacity of flow in stream:
\[ T_{FC} = \Psi \cdot K_F \cdot S_0 \cdot Q^2 \]
FEM Formulation

**Overland Sediment Flow:**

\[ \int_{0}^{L} N^T \left[ \frac{\partial q_s}{\partial x} + \frac{\partial A_s}{\partial t} - D_L \right] dx = 0 \]

\[
[C] \{ A_s \}_{t+\Delta t} = [C] \{ A_s \}_t - \Delta t [B] \left\{ (1-\theta) \{ q_s \}_t + \theta \{ q_s \}_{t+\Delta t} \right\} + \Delta t \{ f \} \left\{ (1-\theta) \{ D_L \}_t + \theta \{ D_L \}_{t+\Delta t} \right\}
\]

**Stream Sediment Flow:**

\[ \int_{0}^{L} N^T \left[ \frac{\partial Q_{SC}}{\partial x} + \frac{\partial A_{SC}}{\partial t} - D_T \right] dx = 0 \]

\[
[C] \{ A_{CS} \}_{t+\Delta t} = [C] \{ A_{CS} \}_t - \Delta t [B] \left\{ (1-\theta) \{ Q_s \}_t + \theta \{ Q_s \}_{t+\Delta t} \right\} + \Delta t \{ f \} \left\{ (1-\theta) \{ D_T \}_t + \theta \{ D_T \}_{t+\Delta t} \right\}
\]

[B], [C], \{ f \} are the global matrices. \( \theta \) is taken as 0.5.
Input data of rainfall, time step, elements details and watershed parameters etc., Calculation of Interception and Infiltration losses

Generation of global matrix by assembling element matrices and applying boundary conditions for flow

Solve the system for overland sediment flow

Solve the system for stream sediment flow

if \[ h^{t+\Delta t}_{k} - h^{t+\Delta t}_{k} < \varepsilon \]
\[ A^{t+\Delta t}_{s} - A^{t+\Delta t}_{s} < \varepsilon_{s} \]
Yes

if \[ A^{t+\Delta t}_{k} - A^{t+\Delta t}_{k} < \varepsilon \]
\[ A^{t+\Delta t}_{sc} - A^{t+\Delta t}_{sc} < \varepsilon_{s} \]
Yes

if: \( t + \Delta t \leq t_{\text{max}} \)

Stop

No

No

No

No

Combined flow chart for overland and stream sediment flow model
Remote Sensing and GIS Application to Watershed Modelling

Input parameter (Precipitation)

GIS analysis

Preparation of Thematic Maps
- DEM
- LU/LC
- Drainage map
- Soil map

Runoff, Soil erosion and sediment yield model

Sediment yield

Remotely sensed data

Topographic map

Other related soil parameters

Socio-economic Management, etc.
**Study Area and Database Preparation for Harsul watershed**

**Watershed**: Harsul watershed located in Nashik district, Maharastra state, India.

**Latitude**: 20° 04’ N to 20° 08’ N

**Longitude**: 73° 25’ E to 73° 29’ E

**Study Area**: 10.92 Sq. km

**Soil Type**: Sandy silt loam

**Land use**: Groundnut, Paddy, Maize etc.,

**Map Information**: IRS 1D LISS – III, January 13, 1998 data has been used to prepare LU/LC map using ERDAS IMAGINE software

**Manning’s Roughness (overland flow) and Crop Management factors of Harsul watershed**

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Landuse/Landcover</th>
<th>Manning’s Roughness (n)</th>
<th>Crop management Factor (C_F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Agricultural Land</td>
<td>0.035</td>
<td>0.315</td>
</tr>
<tr>
<td>2</td>
<td>Forest Land</td>
<td>0.1</td>
<td>0.01</td>
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<tr>
<td>3</td>
<td>Waste Land</td>
<td>0.015</td>
<td>0.1</td>
</tr>
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</table>
Finite element grid and drainage map of Harsul watershed;  Digital Elevation Model of Harsul watershed
Standard False Colour Composite of Harsul watershed; Land use/Land cover map of Harsul watershed
Observed and simulated hydrographs and sedigraphs for calibration rainfall events of Harsul watershed (DGM-II model)
Observed and simulated hydrographs and sedigraphs for validation rainfall events of Harsul watershed (DGM-II model)
## DGM-II Model results for calibration and validation rainfall events of Harsul watershed

<table>
<thead>
<tr>
<th>Rainfall Events</th>
<th>Total sediment yield</th>
<th>Peak sediment rate</th>
<th>Time to peak sediment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Obs. (N)</td>
<td>Sim. (N)</td>
<td>Diff. (%)</td>
</tr>
<tr>
<td><strong>calibration events</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>July 27, 1997</td>
<td>191651</td>
<td>53878</td>
<td>-71.88</td>
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<tr>
<td>July 28, 1997</td>
<td>590009</td>
<td>103804</td>
<td>-82.40</td>
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<td>Aug. 4, 1997</td>
<td>83001</td>
<td>56328</td>
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<td>Aug. 22, 1997</td>
<td>452858</td>
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<tr>
<td><strong>validation events</strong></td>
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<td></td>
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<tr>
<td>July 26, 1997</td>
<td>671912</td>
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<td>July 30, 1997</td>
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<td>Aug. 21, 1997</td>
<td>37997</td>
<td>11999</td>
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<tr>
<td>Aug. 23, 1997</td>
<td>1638300</td>
<td>1516466</td>
<td>-7.43</td>
</tr>
</tbody>
</table>
Scatter plots of observed vs. simulated values for all rainfall events of Harsul watershed (DGM-II model)

(a) Total sediment yield

(b) Peak sediment rate

(c) Time to peak sediment
Study Area and Database Preparation for Khadakohol watershed

Watershed: Khadakohol watershed located in Nashik district, Maharashtra state, India.
Latitude: 20° 07’ N to 20° 09’ N
Longitude: 73° 17’ E to 73° 20’ E
Study Area: 5.89 Sq. km
Soil Type: Sandy silt loam
Land use: Groundnut, Paddy, Maize etc.,
Map Information: IRS 1D LISS – III, January 13, 1998; resolution 23.5m data has been used to prepare LU/LC map using ERDAS software

Manning’s Roughness (overland flow) and Crop Management factors of Khadakohol watershed

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Landuse/Landcover</th>
<th>Manning’s Roughness (n)</th>
<th>Crop management Factor (C_F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Agricultural Land</td>
<td>0.035</td>
<td>0.20</td>
</tr>
<tr>
<td>2</td>
<td>Forest Land</td>
<td>0.1</td>
<td>0.01</td>
</tr>
<tr>
<td>3</td>
<td>Fallow Land</td>
<td>0.030</td>
<td>1.0</td>
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</table>
FEM grid and drainage map of Khadakohol watershed (260 m)  

FEM grid and drainage map of Khadakohol watershed (300 m)
Digital Elevation Model of Khadakohol watershed

Slope map of Khadakohol watershed
Standard False Colour Composite of Khadakohol watershed  Land Use/ Land Cover map of Khadakohol watershed
Observed and simulated hydrographs and sedigraphs for calibration rainfall events of Khadakohol watershed (KGM-II model).
Observed and simulated hydrographs and sedigraphs for validation rainfall events of Khadakohol watershed (KGM-II model).
KGM-II Model results for calibration and validation rainfall events of Khadakohol watershed

<table>
<thead>
<tr>
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<th>Total sediment yield</th>
<th>Peak sediment rate</th>
<th>Time to peak sediment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Obs. (N)</td>
<td>Sim. (N)</td>
<td>Diff. (%)</td>
</tr>
<tr>
<td>Calibration events:</td>
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<td></td>
<td></td>
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<tr>
<td>July 25, 1997</td>
<td>10852</td>
<td>2254</td>
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<tr>
<td>Aug. 9, 1997</td>
<td>409</td>
<td>262</td>
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<tr>
<td>Aug. 23, 1997</td>
<td>198499</td>
<td>212989</td>
<td>7.29</td>
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<tr>
<td>Aug. 25, 1997</td>
<td>7944</td>
<td>9088</td>
<td>14.40</td>
</tr>
<tr>
<td>Sept. 24, 1997</td>
<td>496459</td>
<td>208871</td>
<td>-57.92</td>
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<tr>
<td>Validation events:</td>
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<td></td>
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<tr>
<td>Aug. 22, 1997</td>
<td>39338</td>
<td>18872</td>
<td>-52.02</td>
</tr>
<tr>
<td>Sept. 26, 1997</td>
<td>2634</td>
<td>4741</td>
<td>79.98</td>
</tr>
</tbody>
</table>
Scatter plots of observed vs. simulated values for all rainfall events of Khadakohol watershed (KGM-II model).

(a) Total sediment yield
(b) Peak sediment rate
(c) Time to peak sediment
Study Area and Database Preparation for Banha Watershed

Watershed: Banha watershed located in Itkhori block of Chatra district in Jharkhand State, India.

Latitude: 24° 13′ 45″ N to 24° 17′ N
Longitude: 85° 12′ 15″ E to 85° 16′ 15″ E

Study Area: 16.72 Sq. km

Soil Type: Sandy loam

Map Information: IRS 1D LISS – III, January 5, 1998 with resolution 23.5m data has been used to prepare LU/LC map using ERDAS software.

Manning’s Roughness (overland flow) and Crop management factors of Banha watershed (Jain et al. 2005)

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Landuse/Landcover</th>
<th>Manning’s Roughness (n)</th>
<th>Crop management Factor (C_F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cultivated Land</td>
<td>0.035</td>
<td>0.30</td>
</tr>
<tr>
<td>2</td>
<td>Fallow Land</td>
<td>0.03</td>
<td>0.30</td>
</tr>
<tr>
<td>3</td>
<td>Forest Land</td>
<td>0.10</td>
<td>0.005</td>
</tr>
<tr>
<td>4</td>
<td>Scrub Land</td>
<td>0.07</td>
<td>0.202</td>
</tr>
</tbody>
</table>
Finite element grid and drainage map of Banha watershed; Digital Elevation Model of Banha watershed
Standard False Colour Composite of Banha watershed

Land use/Land cover map of Banha watershed
Observed and simulated hydrographs and sedigraphs for calibration rainfall events of Banha watershed (KPM-II model).
Observed and simulated hydrographs and sedigraphs for validation rainfall events of Banha watershed (KPM-II model).
# Jain et al., 2005;
Scatter plots of observed vs. simulated values for all rainfall events of Banha watershed (KPM-II model).

(a) Total sediment yield

(b) Peak sediment rate

(c) Time to peak sediment
**Study Area and Database Preparation for Catsop watershed**

**Watershed**: Catsop Experimental Watershed Monitored by Utrecht University, South Limburg, The Netherlands

**Study Area**: 41.56 hectares

**Soil Type**: Silty Loam

**Map Information**: DEM, Slope, LU/LC and Soil maps available in ASCII format with 10m grid resolution

**Land Use**: Winter wheat, sugar beet and potatoes

**Manning’s Roughness (overland flow) and Crop management factor of Catsop watershed (Jetten 2005, personal communication)**

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Landuse/Landcover</th>
<th>Manning’s Roughness (n)</th>
<th>Crop management Factor (C_f)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Grass land</td>
<td>0.259</td>
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<td>2</td>
<td>Winter wheat</td>
<td>0.14</td>
<td>0.019</td>
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<tr>
<td>3</td>
<td>Sugar beet</td>
<td>0.124</td>
<td>0.30</td>
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<tr>
<td>4</td>
<td>Potatos</td>
<td>0.144</td>
<td>0.290</td>
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<tr>
<td>5</td>
<td>Maize</td>
<td>0.08</td>
<td>0.260</td>
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<tr>
<td>6</td>
<td>Fallow (stuble)</td>
<td>0.12</td>
<td>0.640</td>
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<tr>
<td>7</td>
<td>Field beans</td>
<td>0.124</td>
<td>0.380</td>
</tr>
</tbody>
</table>
Finite element grid and drainage map of Catsop watershed with element Length of 50m
Catsop grid map with element length of 75 m. Digital Elevation Model of Catsop watershed
Landuse map of Catsop Watershed (June 26, 1987); Soil map of Catsop watershed
Observed and simulated hydrographs and sedigraphs for calibration rainfall events of Catsop watershed (KGM-II Model).
Observed and simulated hydrographs and sedigraphs for validation rainfall events of Catsop watershed (KGM-II Model).
KGM-II Model results for calibration and validation rainfall events of Catsop watershed

<table>
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<th>Peak sediment rate</th>
<th>Time to peak sediment</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Obs. (N)</td>
<td>Sim. (N)</td>
<td>Diff. (%)</td>
</tr>
<tr>
<td><strong>calibration events:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>24623(^#)</td>
<td>9.13</td>
</tr>
<tr>
<td>Aug. 18, 1987</td>
<td>8240</td>
<td>9780(^*)</td>
<td>91(^*)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15696(^#)</td>
<td>64.29</td>
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<tr>
<td><strong>validation events:</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>May 13, 1987</td>
<td>9810</td>
<td>859(^*)</td>
<td>9810</td>
</tr>
<tr>
<td></td>
<td></td>
<td>16480.8(^#)</td>
<td>68.0</td>
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<tr>
<td>Jan. 22, 1993</td>
<td>30411</td>
<td>4750(^*)</td>
<td>217782</td>
</tr>
<tr>
<td></td>
<td></td>
<td>28939.5(^#)</td>
<td>616.0</td>
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<tr>
<td>May 30, 1993</td>
<td>300186</td>
<td>91580(^*)</td>
<td>73575 (^#)</td>
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<td></td>
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<td>43458.3(^#)</td>
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<td>Oct. 14, 1993</td>
<td>101043</td>
<td>66787(^*)</td>
<td>250155 (^#)</td>
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<td></td>
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<td>134397(^#)</td>
<td>148.0</td>
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</table>

* Folly et al., 1999; # Jain et al., 2005
Scatter plots of observed vs. simulated values for all rainfall events of Catsop watershed (KGM-II model).

(a) Total sediment yield

(b) Peak sediment rate

(c) Time to peak sediment
Comparison of Models and Discussions
Comparison of eight model results for some rainfall events of Harsul watershed
Comparison of eight model results for some rainfall events of Khadakohol watershed
Comparison of eight model results for some rainfall events of Banha watershed
Comparison of four model results for rainfall events of Catsop watershed.
Sensitivity Analysis

- **Calibrated parameters**
  \( \omega, \eta, \xi_1, \xi_2, \psi, C_F, K_F \) and \( n_0 \) (Calibration coefficients and watershed parameters)

- **For grid size**
  - Element lengths of 50 m and 75 m (Catsop watershed)
  - Element length of 260 m and 300 m (Khadakohol watershed)

- **Time step**
  - Time steps of 15, 30 and 60 seconds
Effect of change in calibration parameters on simulated values for Harsul watershed (DGM-II model)
Effect of change in calibration parameters on simulated values for Khadakohol watershed (KGM-II model)
Effect of change in calibration parameters on simulated values for Banha watershed (KPM-I model)
Effect of change in calibration parameters on simulated values for Catsop watershed (KGM-II model)
Sensitivity Analysis of grid size for Khadakohol and Catsop watersheds

**Khadakohol watershed (KPM-I model)**

<table>
<thead>
<tr>
<th>Rainfall event</th>
<th>Total sediment yield (N)</th>
<th>Peak sediment rate (N s⁻¹)</th>
<th>Time to peak sediment (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed</td>
<td>Grid size (300m)</td>
<td>Grid size (260m)</td>
</tr>
<tr>
<td>Aug. 25, 1997</td>
<td>7944</td>
<td>3475</td>
<td>5954</td>
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<tr>
<td>Sept. 26, 1997</td>
<td>2634</td>
<td>1471</td>
<td>2706</td>
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**Catsop watershed (KGM-II model)**

<table>
<thead>
<tr>
<th>Rainfall event</th>
<th>Total sediment yield (N)</th>
<th>Peak sediment rate (N s⁻¹)</th>
<th>Time to peak sediment (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed</td>
<td>Grid size (75m)</td>
<td>Grid size (50m)</td>
</tr>
<tr>
<td>May 13, 1987</td>
<td>9810</td>
<td>558</td>
<td>859</td>
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<tr>
<td>Aug. 18, 1987</td>
<td>8240</td>
<td>6929</td>
<td>9780</td>
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</table>
Sensitivity analysis of time step of Banha watershed (KPM-I model)
Total sediment yield varied in the range of -15% to 43% for 60s and -12% to -42% for 15s
Peak sediment yield varied in the range of -6% to 10 % and -4 % to 13%
Time to peak sediment yield varied in the range of -1% to 15% for 60s and 15s

<table>
<thead>
<tr>
<th>Rainfall event</th>
<th>Total sediment yield (N)</th>
<th>Peak sediment rate (N s⁻¹)</th>
<th>Time to peak sediment (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Obs. 60 (s) 30 (s) 15 (s)</td>
<td>60 (s) 30 (s) 15 (s)</td>
<td>60(s) 30(s) 15 (s)</td>
</tr>
<tr>
<td>July 24, 1996</td>
<td>3832767 3274941 3081539</td>
<td>3354540 253.51 315.51</td>
<td>476 492 474</td>
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<tr>
<td>Aug.23, 1996</td>
<td>6079257 3452913 3008732</td>
<td>3544555 236.96 419.24</td>
<td>304 327.5 305.25</td>
</tr>
<tr>
<td>Aug.30, 1996</td>
<td>2711484 2175011 2333614</td>
<td>2177533 187.34 291.14</td>
<td>277 354 276</td>
</tr>
</tbody>
</table>

Sensitivity analysis of time step of Catsop watershed (KGM-II model)
Total sediment yield varied in the range of 32 to 53% for 60s and 11 to 33% for 15s
Peak sediment yield varied in the range of -5 to 29% and -16 to 7%
Time to peak sediment yield varied in the range of -19% to 3% for 60s and 15s

<table>
<thead>
<tr>
<th>Rainfall event</th>
<th>Total sediment yield (N)</th>
<th>Peak sediment rate (N s⁻¹)</th>
<th>Time to peak sediment (min)</th>
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<tr>
<td></td>
<td>Obs. 60 (s) 30 (s) 15 (s)</td>
<td>60 (s) 30 (s) 15 (s)</td>
<td>60(s) 30(s) 15 (s)</td>
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<td>5.07 4.55 4.23</td>
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Conclusions
Conclusions

♦ All combinations of the developed models have reasonably simulated the hydrographs and sedigraphs at the outlet of the watersheds.

♦ From the simulation results of Harsul watershed with eight model combinations, it is seen that Method-II models performed better than Method-I models in simulating total sediment yield, peak sediment rate and time to peak sediment.

♦ From the simulation results of Harsul watershed with eight model combinations, it is seen that KGM-II and DGM-II models performed better than other models.

♦ From the simulation results of Khadakohol watershed with eight model combinations, it is seen that Method-I and Method-II models performed equally well in simulating total sediment yield, peak sediment rate and time to peak sediment.
From the simulation results of Khadakohol watershed with eight model combinations, it is seen that KGM-II and DGM-II models performed better than other models.

From the simulation results of Banha watershed with eight model combinations, it is seen that Method-I models performed better than Method-II models in simulating total sediment yield, peak sediment rate and time to peak sediment for calibration events and Method-II models performed better than Method-I models for validation events.

From the simulation results of Banha watershed with eight model combinations, it is seen that KPM-II and DPM-II models performed better than other models.

From the simulation results of Catsop watershed with four model combinations, it is seen that KGM-II model performed better than other models.
The sensitivity analysis of various model parameters and watershed parameters show that, the simulated total sediment yield, peak sediment rate and time to peak sediment are more sensitive to Manning’s roughness for overland flow and coefficient of transport capacity of stream.

A sensitivity study on the grid size and time step variation shows that the models are moderately sensitive to grid size and time step.

The FEM based distributed models for soil erosion and sediment yield using GIS have been found to be adequate to represent the process of overland and stream erosion.

Results of model applications on watersheds indicate that the physically based distributed watershed models developed in the present study are useful in generating the hydrographs and sedigraphs for overland sediment flow and channel sediment flow in the ungauged watersheds.
Very few studies have been attempted by integrating FEM, GIS and remote sensing for soil erosion and sediment yield modeling. Hence, the major contribution of the study is in development of FEM based integrated soil erosion and sediment yield models using GIS and remote sensing incorporating various hydrologic processes such as interception, infiltration, runoff (overland/stream flow).

Computer code was developed for the kinematic and diffusion wave based models for the overland and stream sediment flow.

Eight distributed watershed models with various combinations were developed for the event based estimation of spatial and temporal variation of the soil erosion and sediment yield for overland flow and stream flow.

The developed models were applied to watersheds of two different physiographic regions i.e. India and The Netherlands.

Research Contributions from the Study
The models are capable to predict the distributed runoff, soil erosion and sediment yield for the given rainfall events in a watershed.

Results of model applications on watersheds indicate that the physically based distributed watershed models developed in the present study are useful in generating the hydrographs and sedigraphs for overland sediment flow and channel sediment flow in the ungauged watersheds.

Total sediment yield and peak sediment rate are found to be more sensitive to $n\_\text{a}$ and $\Psi$, for the considered watersheds. Sensitivity of the model with respect to grid size and time step showed that the model is moderately sensitive to grid size and time step.
Thank You
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Interception Model

- To calculate the effective rainfall after the interception loss
- LISEM model (Jetten, 2002)

Cumulative interception during a rainfall event is given by

\[ I_c = c_p \cdot S_{c_{\text{max}}} \left[ 1 - e^{-c_{vd} \cdot \frac{P_{\text{cum}}}{S_{c_{\text{max}}}}} \right] \]

\[ c_{vd} = 0.046 \times LAI \]

\[ S_{c_{\text{max}}} = 0.935 + 0.498 \times LAI - 0.00575 \times LAI^2 \]
Philip Infiltration Model

The rate of infiltration is given by:

\[ f = \frac{1}{2} s_i \ t^{-1/2} + K \]

Infiltration sorptivity:

\[ s_i = 2(1 - s_{ini}) \left[ \frac{5\eta_e K_s \Psi_s \Phi(d, s_{ini})}{3\lambda \pi} \right]^{1/2} \]
Green-Ampt Mein Larson Infiltration model

- The Green-Ampt equation for infiltration rate

\[ f_p = K_s \left[ 1 + \frac{MS_c}{F} \right] \]

- Mein and Larson (1973) modification

\[ f_i = f_p = K_s (1 + \frac{s_{av} M}{F_p}) \]

  Upto time of ponding infiltration rate

  Cumulative infiltration at ponding time

\[ f_i = r_i \]

\[ F_o = r_i t_p \]

- Equation given by Chu (1978)

\[ \frac{F_p}{s_{av}} - \ln \left[ 1 + \frac{F_p}{s_{av} M} \right] = \frac{K(t-t_p+t_s)}{s_{av} M} \]
Morel-Seytoux Infiltration model

- Morel-Seytoux’s (1978) model is a modification version of Green-Ampt infiltration model.
- The cumulative infiltration \( F(t) \) is calculated as:

\[
F(t) = F_p - \left[ S_f + F_p \left( 1 - \frac{1}{\beta} \right) \right] \ln \left( \frac{S_f + F(t)}{S_f + F_p} \right) = \frac{K_s (t - t_p)}{\beta}
\]

- storage and suction factor \( S_f \) that can be expressed as a function of the soil hydraulic properties (Morel-Seytoux, 1978) as:

\[
S_f = (\theta_s - \theta_i) H_c \left[ 1 - \frac{1}{3} \left( \frac{\theta_i - \theta_r}{\theta_s - \theta_r} \right)^6 \right]
\]

- \( H_c \) is the capillary height (cm),
- \( \theta_s \) the volumetric soil water content at saturation (m\(^3\) m\(^{-3}\)),
- \( \theta_r \) is the volumetric residual soil water content (m\(^3\) m\(^{-3}\)),
- \( \theta_i \) initial condition
• Governing equations for overland flow

1. Continuity equation
\[ \frac{\partial q}{\partial x} + \frac{\partial h}{\partial t} = r_c \]

2. Momentum equation
- Kinematic wave form -
  \[ S_o = S_f \]
- Diffusion wave form -
  \[ \frac{\partial h}{\partial x} = S_o - S_f \]

• Finite element formulation
  - Galerkin’s criterion is used

\[ [C]\{h\}^{t+\Delta t} = [C]\{h\}^t - \Delta t [B]\{(1-\omega)q^t + \omega q^{t+\Delta t}\} + \Delta t \{f\}\{(1-\omega)(r_c)^t + \omega (r_c)^{t+\Delta t}\} \]
• Governing equations for stream flow
  The equation of continuity
  \[
  \frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} - q = 0
  \]

  Momentum equation
    Kinematic wave form
      \[ S = S_{fe} \]
    Diffusion form
      \[ \frac{\partial h}{\partial x} = S - S_{fe} \]
  Manning’s equation
      \[
      Q = \frac{1}{n} R^{(2/3)} S_{fe}^{(1/2)} A
      \]

• Finite element formulation

  \[
  [C]\{A\}^{t+\Delta t} = [C]\{A\}^t - \Delta t [B]\{ (1-\theta)Q' + \theta Q^{t+\Delta t} \} + \Delta t \{ f \} \{ (1-\theta)q' + \theta q^{t+\Delta t} \}
  \]
Governing Equations

Saint Venant equations for flow and sediment (Bennett 1974)

Upland phase:

Continuity equation:
\[
\frac{\partial h}{\partial t} + u \frac{\partial h}{\partial x} + h \frac{\partial u}{\partial x} = q
\]

Momentum Equation:
\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + g \frac{\partial h}{\partial x} = g \left( S_0 - S_f \right) - \frac{qu}{h}
\]

Continuity equation for sediment:
\[
\frac{\partial (hc)}{\partial t} + \left( 1 - \lambda \right) \frac{\partial y}{\partial t} + \frac{\partial (h u_p c)}{\partial x} = \frac{\partial}{\partial x} h \in_p \frac{\partial c}{\partial x}
\]

Lowland stream phase:

\[
\frac{\partial A}{\partial t} + u \frac{\partial A}{\partial x} + A \frac{\partial u}{\partial x} = q_A
\]

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + g \frac{\partial h}{\partial x} = g \left( S_0 - S_f \right) - \frac{q_A u}{A}
\]

And
\[
\frac{\partial (Ac)}{\partial t} + B \left( 1 - \lambda \right) \frac{\partial y}{\partial t} + \frac{\partial (A u_p c)}{\partial x} = \frac{\partial}{\partial x} A e_p \frac{\partial c}{\partial x}
\]
Kinematic/Diffusion Wave Modeling for Soil Erosion and Sediment yield

**Continuity equation for flow:**

\[
\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = r_c
\]

**Simplified momentum Equation (kwa/dwa):**

\[
S_o = S_f ; \quad \frac{\partial h}{\partial x} = S - S_f ;
\]

**Kinematic depth-discharge relation:**

\[
Q = \alpha h^\beta ;
\]

\[
u = \alpha h^{\beta - 1} ; \quad \alpha = \frac{S_o^{1/2}}{n}
\]

**Continuity equation for Sediment Flow:**

\[
\frac{\partial q_s}{\partial x} + \rho_s \frac{\partial (ch)}{\partial t} = D_R + D_F
\]

\[
\frac{\partial q_s}{\partial x}
\]

is the build up or loss of the sediment load with distance

\[
\rho_s \frac{\partial (ch)}{\partial t}
\]

is the storage rate of sediment within the flow depth

\[
D_R, D_F
\]

are the contribution of sediment from lateral inflow

FEM Formulation for Overland Sediment Flow

\[
\int_0^L N^T \left[ \frac{\partial q_s}{\partial x} + \frac{\partial A_s}{\partial t} - D_L \right] dx = 0
\]

\[
\int_0^L N^T \frac{\partial N}{\partial x} \{q_s\} dx + \int_0^L N^T N \left\{ \frac{\partial A_s}{\partial t} \right\} dx - \int_0^L N^T \{D_L\} dx = 0
\]

\[
[B]^{(e)} \{q_s\} + [C]^{(e)} \left\{ \frac{\partial A_s}{\partial t} \right\} - \{f\}^{(e)} \{D_L\} = 0
\]

\[
[B]^{(e)} = \frac{1}{2} \begin{bmatrix} -1 & 1 \\ -1 & 1 \end{bmatrix}; \quad [C]^{(e)} = \frac{L}{6} \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix}; \quad \{f\}^{(e)} = \frac{L}{2} \begin{bmatrix} 1 \\ 1 \end{bmatrix};
\]

\[
[C] \{A_s\}_{t+\Delta t} = [C] \{A_s\}_t - \Delta t [B] \left\{ (1-\theta) \{q_s\}_t + \theta \{q_s\}_{t+\Delta t} \right\} + \Delta t \{f\} \left\{ (1-\theta) \{D_L\}_t + \theta \{D_L\}_{t+\Delta t} \right\}
\]

[B], [C], \{f\} are the global matrices. Weighting factor \theta is used to determine the types of finite difference scheme.
FEM Formulation for Channel Sediment Flow

\[
\int_{0}^{L} N^T \left[ \frac{\partial Q_{sc}}{\partial x} + \frac{\partial A_{sc}}{\partial t} - D_T \right] dx = 0
\]

\[
\int_{0}^{L} N^T \frac{\partial N}{\partial x} \{Q_{sc}\} dx + \int_{0}^{L} N^T N \left\{ \frac{\partial A_{sc}}{\partial t} \right\} dx - \int_{0}^{L} N^T \{D_T\} dx = 0
\]

\[
[B]^{(c)} \{Q_{sc}\} + [C]^{(c)} \left\{ \frac{\partial A_{sc}}{\partial t} \right\} - \{f\}^{(c)} \{D_T\} = 0
\]

\[
[C] \{A_{sc}\}_{t+\Delta t} = [C] \{A_{sc}\}_t - \Delta t [B] \left\{ (1-\theta) \{Q_{sc}\}_t + \theta \{Q_{sc}\}_{t+\Delta t} \right\} + \Delta t \{f\} \left\{ (1-\theta) \{D_T\}_t + \theta \{D_T\}_{t+\Delta t} \right\}
\]

[B], [C], \{f\} are the global matrices