Process-based Modeling of Erosion and Sediment Transport in meso-scale Mediterranean Catchments: from the Hillslopes via the River System to Reservoirs

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Outline

I. Motivation for coupled runoff-sediment modelling
II. An integrated hydro-sedimentological model
III. Connectivity: the special challenge of dryland regions
IV. Applications examples
V. Conclusions and outlook
1 Motivation for coupled runoff-sediment modelling

1. Understand, quantify and predict hydrological fluxes in different geo-ecosystems
1. Motivation for coupled runoff-sediment modelling

2. Understand, quantify and predict water related erosion processes
I Motivation for coupled runoff-sediment modelling

3. Understand, quantify and predict fluvial sediment transport and deposition processes
Episodic runoff processes trigger rather sudden sediment mobilisation and deposition
Soil losses and sediment deposition is the major threat for sustainable landscape and water resources functions.
Peculiarities of drylands ...

water & sediment events: highly variable in time and space —
1. Motivation for coupled runoff-sediment modelling

4. Understand, quantify and predict chemical transport and transformation processes
II \ An integrated hydro-sedimentological model: WASA-SED

WASA-SED:
A meso-scale hydro-sedimentological model:
- spatially distributed,
- process-oriented,
- catena-based,

- **Spatial resolution**: hillslope to meso-scale
- **Temporal resolution**: hourly or daily time steps
- Code in Fortran90, currently ca. 50 sub-routines

Structure of spatial modelling units

1. Sub-basin / Municipality / Grid cell
   - Polygons with geographically referenced location
   - Data source of basins: Terrain analysis of 3D USGS SRTM and digitized topographic maps
   - Municipalities, administrative boundaries (municipios)
   - Function: Runoff routing, including retention in reservoirs and withdrawal by water use
   - Grid cells smaller than sub-basins / municipalities are used
   - Runoff responses of all grid cells pertaining to a sub-basin are added up to give the basin response. Further subdivision (levels ≤ 0) starts from the grid cell level.

2. Landscape unit (LU)
   - Polygons with geographically referenced location
   - Similarity of major landform
   - General lithology
   - Soil associations
   - Toposequences
   - Function: Modelling unit with similar characteristics referring to lateral processes and similarity of sub-scale variability in vertical processes
   - Composed of 1 x 3 terrain components
   - Runoff responses of all landscape units are added up to give total response of sub-basin / municipality / grid cell

3. Terrain component (TC)
   - Fraction of area of landscape unit (no geographic reference)
   - Similarity of slope gradients
   - Position within toposequence
   - Soil associations
   - Function: Lateral transfer of surface and subsurface runoff between terrain components of different topographic position by upslope / downhill relationships
   - Runoff and infiltration (return flow) in component with lower topographic position

4. Soil-vegetation component (SVC)
   - Fraction of area of terrain component
   - Characterized by specific combination of soil sub-type
   - Vegetation / land cover classes
   - Function: Variability of soil moisture within terrain component
   - Lateral redistribution of surface and subsurface runoff among soil-vegetation components
   - Variability of soil moisture storage capacity within soil-vegetation component (partial area approach for saturation-excess surface runoff)

5. Profile
   - Several soil horizons of variable depth
   - Lower limit by depth of root zone or bedrock
   - Function: Calculation of water balance in the profile for each soil-vegetation component
   - Determination of vertical and lateral water fluxes for individual horizons
Sub-basins
Landscape Units (LU)
Terrain components (TC)
Soil-vegetation components (SVC)
Scheme of the structure TC and SVCs

\[ d_{s,i} = d_i \cdot \frac{\theta_i - \theta_{FC,i}}{\theta_{sat,i} - \theta_{FC,i}} \]

\( d_i = \text{total depth of horizon } i \) (m)

\( d_{s,i} = \text{saturated depth of horizon } i \) (m)
Profile

1. Precipitation
2. Transpiration and interception
3. Evaporation from bare soil
4. Infiltration
5. Surface runoff
6. Percolation
7. Lateral subsurface flow
8. Deep groundwater recharge
Process Representation at the Hillslope Scale

1) Interception model
2) Evapotranspiration model
3) Infiltration model
4) Soil water model
5) Lateral redistribution among spatial units
6) Deep groundwater
7) Erosion
1) Interception model

Simple bucket approach is used in WASA:

\[ I_t = I_{t-1} + P - E_I \]

, with:

\[ P_I = \min(P, (I_c - I_{t-1})) \]

\[ E_I = \min(E_{pot}, I_t) \]

\[ I_t \] = water in interception storage at timestep \( t \) (mm)
\[ I_c \] = capacity of canopy interception storage (mm)
\[ P \] = precipitation (mm)
\[ P_I \] = intercepted precipitation (mm)
\[ E_I \] = evaporation from interception storage (mm)
\[ E_{pot} \] = potential evaporation (mm)
2) Evapotranspiration model

a) The classical Penman-Monteith approach (1965):
   - is used for evaporation calculation from the interception storage and from open water bodies

b) The Shuttleworth & Wallace approach (1985)
3) Infiltration model

Green-AMPT approach in an adaptation of Peschke (1977, 1987) and Schulla (1997)

\[ R_F = P - P_I + R_{s, TC} + R_{s, SVC} \]

- \( R_F \): Infiltration routine (mm \( \Delta t^{-1} \))
- \( P \): Precipitation (mm \( \Delta t^{-1} \))
- \( P_I \): Intercepted precipitation (mm \( \Delta t^{-1} \))
- \( R_{s, TC} \): Lateral surface inflow from a TC of a higher topographic position (mm \( \Delta t^{-1} \))
- \( R_{s, SVC} \): Lateral surface inflow from SVCs within the same TC (mm \( \Delta t^{-1} \))
4) Soil water model

Soil water balance for each horizon $i$:

$$\theta_{i,t} = \theta_{i,t-1} + R_i - Q_i$$

$\theta_{i,t} =$ soil moisture of the horizon $i$ at the timestep $t$ (mm)
$R_i =$ incoming fluxes into the horizon $i$ (mm)
$Q_i =$ outgoing fluxes from the horizon $i$ (mm)

em que:

$$Q_i = Q_{v,i} + Q_{l,i}$$

$Q_{v,i} =$ percolation from one horizon $i$ next horizon below (mm)
$Q_{l,i} =$ lateral flow leaving the horizon $i$ (mm)
5) Lateral redistribution among spatial units

- Lateral surface flow
- Lateral subsurface flow
MUSLE (Modified Universal Soil Loss Equation):

\[ Y = 11.8 \cdot (Q_{surf} \cdot q_{peak} \cdot A_{TC})^{0.56} \cdot K_{USLE} \cdot C_{USLE} \cdot P_{USLE} \cdot L_{USLE} \cdot CFRG \]

- \( Y \) is the gross sediment yield [t]
- \( Q_{surf} \) is the surface runoff volume [mm water/ha]
- \( q_{peak} \) is the peak runoff rate [m³/s]
- \( A_{TC} \) is the area of the TC [ha]
- \( K_{USLE}, C_{USLE}, P_{USLE}, L_{USLE} \) are the USLE-factors
- \( CFRG \) is coarse fragment factor

+ transport capacity concept
River Flow

River flow:

Manning’s equation

\[ v(t) = \frac{R_s^{2/3} \cdot S^{1/2}}{n} \]

Continuity equation

\[ q_{out,2} = C_1 \cdot q_{in,2} + C_2 \cdot q_{in,1} + C_3 \cdot q_{out,1} \]

Muskingum Routing

\[ C_1 = \frac{(\Delta t - 2KX)}{2K(1-X) + \Delta t} \]
\[ C_2 = \frac{(\Delta t + 2KX)}{2K(1-X) + \Delta t} \]
\[ C_3 = \frac{(2K(1-X) - \Delta t)}{2K(1-X) + \Delta t} \]
Suspended sediment:

Transport capacity concept

\[
Sed\_conc_{s,\text{max}} = a \cdot v_{s,\text{peak}}^b
\]

\[
sed_{\text{deposition}} = (Sed\_conc_{s,\text{max}} - Sed\_conc_{\text{current}}) \cdot V
\]

\[
sed_{\text{erosion}} = (Sed\_conc_{s,\text{max}} - Sed\_conc_{\text{current}}) \cdot V \cdot K \cdot C
\]

\(v_{\text{peak}}(t)\): peak channel velocity (m/s),
\(V\): Volume of water in the reach (m³)
\(K\): channel erodibility factor (cm / (h * Pa))
\(C\): channel cover factor (−)
## Sediment transport in the river

### Bedload:

<table>
<thead>
<tr>
<th>Formula</th>
<th>Range of conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Meyer-Peter and Müller (1948)</td>
<td>for both uniform and non-uniform sediment, grain sizes ranging from 0.4 to 70 mm and river slopes of up to 0.02 m m⁻¹.</td>
</tr>
<tr>
<td>( q_s = \frac{8(\tau - \tau_{cr})^{1.5}}{gD^3} \times 1000 )</td>
<td>with: ( \tau = \rho gdS ) and ( \tau_{cr} = 0.047(\rho_s - \rho)gD_m )</td>
</tr>
<tr>
<td>2. Schoklitsch (1950)</td>
<td>for non-uniform sediment mixtures with ( D_{50} ) values larger than 6 mm and riverbed slopes varying between 0.003 and 0.1 m m⁻¹.</td>
</tr>
<tr>
<td>( q_s = 2500^{1.5} (q - q_{crit}) 1000(\Delta - \rho) \rho_D )</td>
<td>with: ( q_{crit} = 0.26 \left( \frac{\Delta - \rho}{\rho} \right)^{\frac{3}{4}} \frac{D_{50}^4}{g^{\frac{1}{8}}} )</td>
</tr>
<tr>
<td>3. Smart and Jaeggi (1983)</td>
<td>for riverbed slopes varying between 0.03–0.2 m m⁻¹ and ( D_{50} ) values comparable to the ones of the Meyer-Peter and Müller equation.</td>
</tr>
<tr>
<td>( q_s = 4.2qS^{1.6} \left( \frac{1 - \frac{\rho_s}{\rho}}{\frac{\rho_s}{\rho} - 1} \right) 1000(\rho_s - \rho) )</td>
<td>with: ( \tau^* = \frac{dS}{(\frac{\rho_s}{\rho} - 1)D_{50}} ) and ( \tau_{crit}^* = \frac{d_{crit}S}{(\frac{\rho_s}{\rho} - 1)D_{50}} )</td>
</tr>
<tr>
<td>( q_s = 4.25\tau^<em>^{0.5} \left( \tau^</em> - \tau_{crit}^* \right) \left( \frac{\rho_s}{\rho} - 1 \right) D_{50}^3 )</td>
<td>for gravel-bed rivers and torrents with bed slopes between 0.03 and 0.2 m m⁻¹ and ( D_{50} ) values comparable to the ones of the Meyer-Peter and Müller equation in the lower slope range with an average ( D_{50} ) of 10 mm in the higher slope ranges.</td>
</tr>
<tr>
<td>5. Rickenmann (2001)</td>
<td></td>
</tr>
<tr>
<td>( q_s = 3.1\left( \frac{D_{50}}{D_{500}} \right)^{0.2} \tau^<em>^{0.5} \left( \tau^</em> - \tau_{crit}^* \right) Fr^{0.5} \left( \frac{\rho_s}{\rho} - 1 \right) \left( \frac{\Delta - \rho}{\rho} \right)^{0.5} \left( \rho_s - \rho \right)^{0.5} \right) 1000(\rho_s - \rho) )</td>
<td>with: ( Fr = \left( \frac{\tau}{\tau_{crit}} \right)^{0.5} )</td>
</tr>
</tbody>
</table>
Reservoir Module: Conceptual layers

![Diagram of reservoir module showing layers and processes](image)

- **Original Bed Material**
- **Top Layer**
- **Intermediate Layer**
- **Lowest Layer**

Processes:
- **Compaction**
- **Deposition**
- **Erosion**

**Sediment laden flow**
- (from cross section 6)
- (to cross section 8)
Reservoir Module: Spatial representation of the reservoir

River subreach ↔ Reservoir subreach

Inflow

Stage (m)

460
455
450
445
440
435
430

Outflow

Distance (km)
Sediment transport in the reservoir

Water discharge in the reservoir’s cross sections:

Simple mass conservation concept

\[ Q_j = Q_{in} - (Q_{in} - Q_{out}) \cdot \sum_{k=m}^{j} v_k \]

- \( Q_j \): water discharge at the cross-section \( j \);
- \( v_k \): fraction of reservoir volume represented by that cross-section
Sediment transport in the reservoir

non-equilibrium sediment transport in the reservoir’s cross sections:

Approach by Han and He (1990):

\[
\frac{dS}{dx} = \frac{\alpha \omega}{q} (S^* - S) - \left( \frac{\alpha \omega L}{q} \right) 
\]

\[ S_j = S_j^* + (S_{j-1} - S_j^*) \cdot t \]

- \( S \): sediment concentration;
- \( S^* \): sediment carrying capacity;
- \( Q \): discharge per unit width;
- \( \omega \): settling velocity;
- \( \alpha \): coefficient of saturation recovery
Sediment transport in the reservoir

<table>
<thead>
<tr>
<th>Authors, range of sediments</th>
<th>Transport formula</th>
<th>Auxiliary equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wu et al. (2000): 0.004–100 mm</td>
<td>( q_{b,k} = P_k \phi_{b,k} \sqrt{\Delta gd^3} )</td>
<td>( \phi_{b,k} = 0.0053 \left( \left( \frac{d^*}{n'} \right)^{3/2} \frac{P_k}{c_{A,k}} \right)^{2.2}, n' = \frac{2R_t^2}{S_f V}, \tau_c,k = (\gamma - \gamma_0) d_k \phi_{b,k} )</td>
</tr>
<tr>
<td>Ashida and Michiue (1973): 0.040–100 mm</td>
<td>( q_{b,k} = 17 \cdot P_k u_{c,k} d_k \tau_c,k \left( 1 - \frac{d_k}{d_{50}} \right) \left( 1 - \sqrt{\frac{d_k}{d_{50}}} \right) )</td>
<td>( \tau_c,k = \frac{u_{c,k}^2}{\Delta gd_{50}}, \quad u_{c,k} = \sqrt{R_b S_f}, \quad \tau_c,k = \frac{u_{c,k}^2}{\Delta gd_{50}} )</td>
</tr>
<tr>
<td>IRTCES (1985): 0.001–100 mm</td>
<td>( q_t = \Omega \Omega_1 \frac{d_{50}^{1.2}}{B^{0.8}} )</td>
<td>( \Omega = 1600 ) for loess sediment, ( \Omega = 650 ) for ( d_{50} &lt; 0.1 ) mm, ( \Omega = 300 ) for ( d_{50} &gt; 0.1 ) mm</td>
</tr>
</tbody>
</table>
| Ackers and White (1973): 0.040–100 mm | \( q_t = P_k \psi V d_k \left( \frac{V}{n'} \right)^{0.4} \left( \frac{f_{m_o}}{V_{m_o}} - 1 \right) \) | \( d_k^2 = d_k (\Delta g/v^2)^{1/3}, 1 < d_k^2 < 60: n_o = 1 - 0.56 \log (d_k^2), m_o = 2.66 \frac{d_k^2}{\Delta g}, \psi = 10^{-3.53 + 2.86 \log (d_k^2) - \log (d_k^2)} \)}

Sediment carrying capacity formulae in the reservoir module (Mamede, 2008)
III. Connectivity: control of water and sediment delivery

Connectivity: transfer, storage and re-entrainment processes of water and sediments among different landscape components

A: Connectivity between hillslopes, valley bottoms and the river

B: Transmission losses and temporary storage in the river

C: Retention in and transfer through reservoirs

D: Integrated meso-scale catchment model
IV. Application Examples

- Northeast Spain (Catalonia and Aragón): sub-humid or semi-arid climate
- Northeast Brazil (Ceará): semi-arid climate with a pronounced seasonality

These research regions include a set of individual (but nested) catchments of different spatial scales.
Uppe Yaguaribe (NE Brazil)

Várzea do Boi ➔ Bengue ➔ Aiuaba ➔ exp. hillslopes
Ésera (NE Spain, Ebro region)

- Isábena
- Villacarli
- Ball
- exp. badlands
overview of the nested research catchments in Spain (S1 … S5) and Brazil (B1 … B6)

<table>
<thead>
<tr>
<th>No.</th>
<th>Name of the catchment</th>
<th>Area (km²)</th>
<th>Annual rainfall (mm)</th>
<th>Main Water measurements</th>
<th>Main Sediment measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td><em>badland</em></td>
<td>~ 0.03</td>
<td>~750</td>
<td>Discharge flume</td>
<td>Tubiditymeter, Isco sampling</td>
</tr>
<tr>
<td>S2</td>
<td><em>Ball</em></td>
<td>10</td>
<td>~750</td>
<td>Water level sensor</td>
<td>Tubiditymeter, Isco sampling</td>
</tr>
<tr>
<td>S3</td>
<td><em>Villacarli</em></td>
<td>41</td>
<td>730</td>
<td>Water level sensor</td>
<td>Tubiditymeter, Isco sampling</td>
</tr>
<tr>
<td>S4</td>
<td><em>Isábena (gauge Capella)</em></td>
<td>445</td>
<td>450-1600</td>
<td>Water level sensor</td>
<td>Tubiditymeter, Isco sampling</td>
</tr>
<tr>
<td>S5</td>
<td><em>Ésera (upstream Barasona res.), incl. Isábena</em></td>
<td>1224</td>
<td>500-2000 in the high mountains</td>
<td>Water level sensor</td>
<td>Reservoir bathymetry</td>
</tr>
<tr>
<td>B1</td>
<td>experim. hillslope within Bengué</td>
<td>2.8</td>
<td>~600</td>
<td>---</td>
<td>long-term sediment deposition by Cs137</td>
</tr>
<tr>
<td>B2</td>
<td><em>Aiuaba micro basin</em></td>
<td>12</td>
<td>650</td>
<td>Discharge flume &amp; reservoir level</td>
<td>Individual manual sampling</td>
</tr>
<tr>
<td>B3</td>
<td><em>Bengué</em></td>
<td>933</td>
<td>560</td>
<td>Water level sensor</td>
<td>Reservoir bathymetry</td>
</tr>
<tr>
<td>B4</td>
<td><em>Várzea do Boi</em></td>
<td>1,221</td>
<td>~500</td>
<td>Water level sensor</td>
<td>Reservoir bathymetry</td>
</tr>
<tr>
<td>B5</td>
<td><em>Jaguaribe upstr. Orós reservoir</em></td>
<td>20,700</td>
<td>400 in the SW to 800 in the NE</td>
<td>Water level sensor</td>
<td>Manual sampling</td>
</tr>
<tr>
<td>B6</td>
<td><em>Upper Jaguaribe</em></td>
<td>24,600</td>
<td></td>
<td>Water level sensor</td>
<td>----</td>
</tr>
</tbody>
</table>
Uppe Yaguaribe (NE Brazil)

- Várzea do Boi
- Bengue
- Aiuaba
- exp. hillslopes
Uppe Yaguaribe (NE Brazil) ➔ Várzea do Boi ➔ Bengue ➔ Aiuaba ➔ exp. hillslopes
Monitoring sections and the hydrologic and sediment measurements in the Upper Jaguaribe Basin

<table>
<thead>
<tr>
<th>Seção de monitoramento</th>
<th>Área (km²)</th>
<th>Medicação de vazão</th>
<th>Medicação de sedimento</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. Nome</td>
<td>Tipo</td>
<td>Intervalo</td>
<td>Tipo</td>
</tr>
<tr>
<td>1 Alto Jaguaribe</td>
<td>24.600</td>
<td>a Dia</td>
<td>---</td>
</tr>
<tr>
<td>2 Seção de controle - AJ</td>
<td>20.700</td>
<td>b Dia</td>
<td>c / d Dia</td>
</tr>
<tr>
<td>3 Várzea do Boi</td>
<td>1.221</td>
<td>a Dia</td>
<td>e Acumulado 47 anos</td>
</tr>
<tr>
<td>4 Benguê</td>
<td>933</td>
<td>a Dia</td>
<td>c / e Dia / Acumulado 4 anos</td>
</tr>
<tr>
<td>5 Aiuaba</td>
<td>12</td>
<td>a / b Dia / 15 min.</td>
<td>c Dia</td>
</tr>
</tbody>
</table>

a - Balanço hídrico no reservatório  
b - Nível de água + curva-chave  
c - Sedimento em suspensão - curva-chave de sedimentos  
d - Arraste de leito - ajuste, com dados de campo, da equação modificada de Meyer-Peter e Müller  
e - Sedimento em suspensão e arraste de eleito - medida do assoreamento do açude
Sediment budgets at the nested catchments in the Upper Jaguaribe Basin, Brazil

- Sediment outflow = sed. delivery ratio (%)
- Sediment deposition along the landscape (%)
- Sediment retention in reservoirs (%)
Ésera (NE Spain, Ebro region)

- Isábena
- Villacarli
- Ball
- exp. badlands
NE Spain: Assessment of water flows and sediment yields

- sediment export occurs mainly during late summer floods
- very high specific sediment for badland areas (Villacarli)

<table>
<thead>
<tr>
<th>gauge</th>
<th>SSY [t/km²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torrelaribera</td>
<td>6277</td>
</tr>
<tr>
<td>Villacarli</td>
<td>1971</td>
</tr>
<tr>
<td>Cabecera</td>
<td>139</td>
</tr>
<tr>
<td>Capella</td>
<td>409</td>
</tr>
</tbody>
</table>

- highly episodic sediment fluxes from headwaters are strongly attenuated towards outlet
NE-Spain: Modeled Water hydrological fluxes at the Villacarli, Catchment

WASA-SED results for Villacarli catchment (Francke, 2009)
NE Spain: Modeled of sediment yields

Observed and simulated sediment fluxes of the Villacarli sub-catchment Sept – Dec 2006 (Franke, 2009)
NE-Spain: Estimated Sediment transfer and deposition in the Isábena, Catchment,

Estimates of sediment transfer and deposition rates in the Isábena catchment for the period 2007 – 2009 (López-Tarazón et al. (2012))
RIVER Modelling  Temporary river storage of sediments
RIVER Modelling

Sediment Transport in the River System

Upstream River Stretch in the Mountains

30 km Downstream Reach in the Lowlands
Temporary river storage of sediments

Upstream River Stretch in the Mountains

30 km Downstream Reach in the Lowlands
Barasona Reservoir (Spain) (ca. 1340 km$^2$)
comparison of bathymetric surveys of the Barasona Reservoir, Spain
Reservoir Sedimentation

comparison of bathymetric surveys of the Barasona Reservoir, Spain
Bed elevation changes at four different cross sections of the Barasona reservoir, 1986-1993
Deposition patterns of the Barasona Reservoir (1986-1993)
Specific Conclusions (from the case studies)

- Water runoff tends to decrease with area: due to locally constrained rainfall patterns AND river transmission losses
- Sediment transfer from the hillslopes to the drainage network is the controlling factor of sediment connectivity at all scales.
- Deposition along the topography is responsible for retaining 50 to 60% of eroded sediment.
- At the Aiuaba experimental catchment, there is a higher percentage (74%) of sediment deposited in the landscape, probably due to protected natural vegetation and fractured hydro-geological conditions.
V Conclusions and Outlook

Generic Conclusions:

- High relevance of “hot-spots” for sediment production
- Connectivity between the landscape compartments plays a very relevant role for the mass transport (both water and sediment) and for transport times
- Varying relevance in different space-time scales!
- Integrated hydro-sedimentological modelling is essential for sustainable land use and reservoir use management in drylands
- Percentage of sediment retention in reservoirs is strongly dependent on the scale, increasing with increased area
- Stronger sensitivity of the reservoir sedimentation to land use and water management than to the climatic scenarios
Scientific challenges:

- Quantification at the large scale
  > how to consider connectivity issues at the relevant scales?
- In-stream retention and transport
- Parameterisation of variability of nature
- Scenario calculation and prognosis
- Management of sedimentation
- Integration of hydro-chemical fluxes
References for the WASA-SED Model

For hydrological modules:


For WASA-SED:


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