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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International Conference
Sediment Transport Modeling in
Hydrological Watersheds and Rivers
Conférence Internationale
Modélisation du transport de sédiments
dans les bassins versants et dans les rivières
Istanbul Turkey/Turquie
14.-16.11.2012

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

I Motivation for coupled runoff-sediment modelling

1. Understand, quantify and predict hydrological fluxes in different geo-ecosystems

I 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

Peculiarities of drylands …

Episodic runoff processes trigger rather sudden sediment mobilisation and deposition

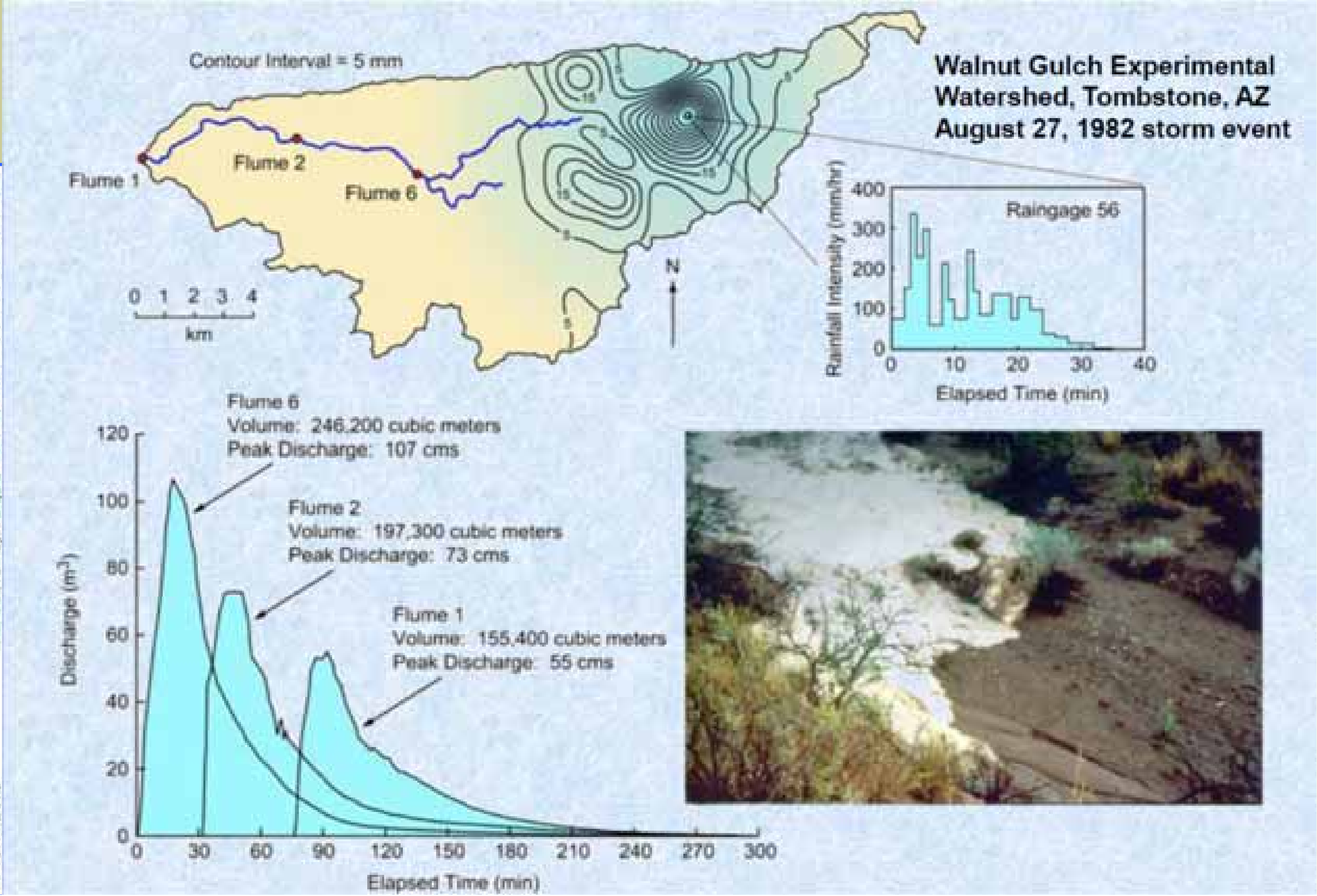
Peculiarities of drylands …

Soil losses and sediment deposition is the major threat for sustainable landscape and water resources functions

Sedimentation in the Barasona reservoir, Isábena/Èsera River [Bronstert, 2005]

Peculiarities of drylands …

water & sediment events: highly variable in time and space



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I Motivation for coupled runoff-sediment modelling

4. **Understand, quantify and predict chemical transport and transformation processes**

II An integrated hydro-sedimentological model: WASA-SED

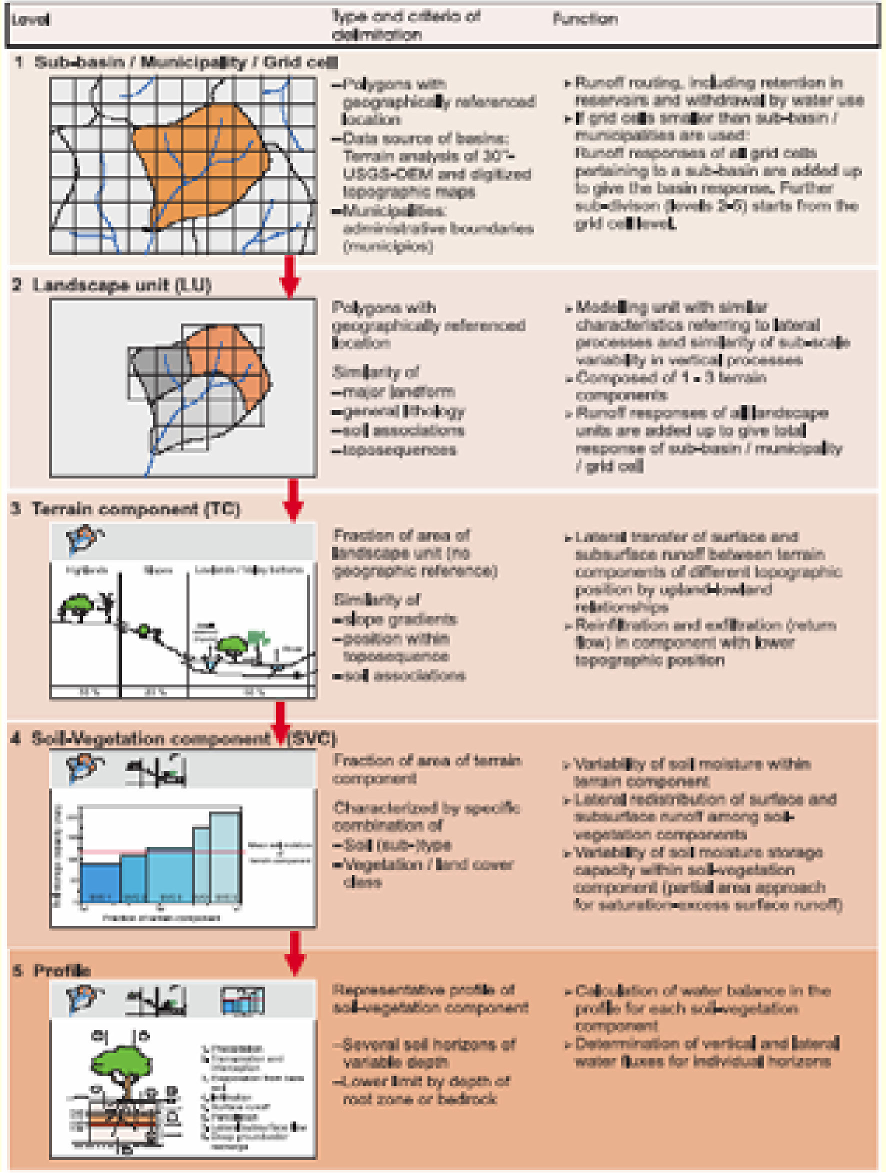
WASA-SED:
A meso-scale hydro-sedimentological model:

- **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

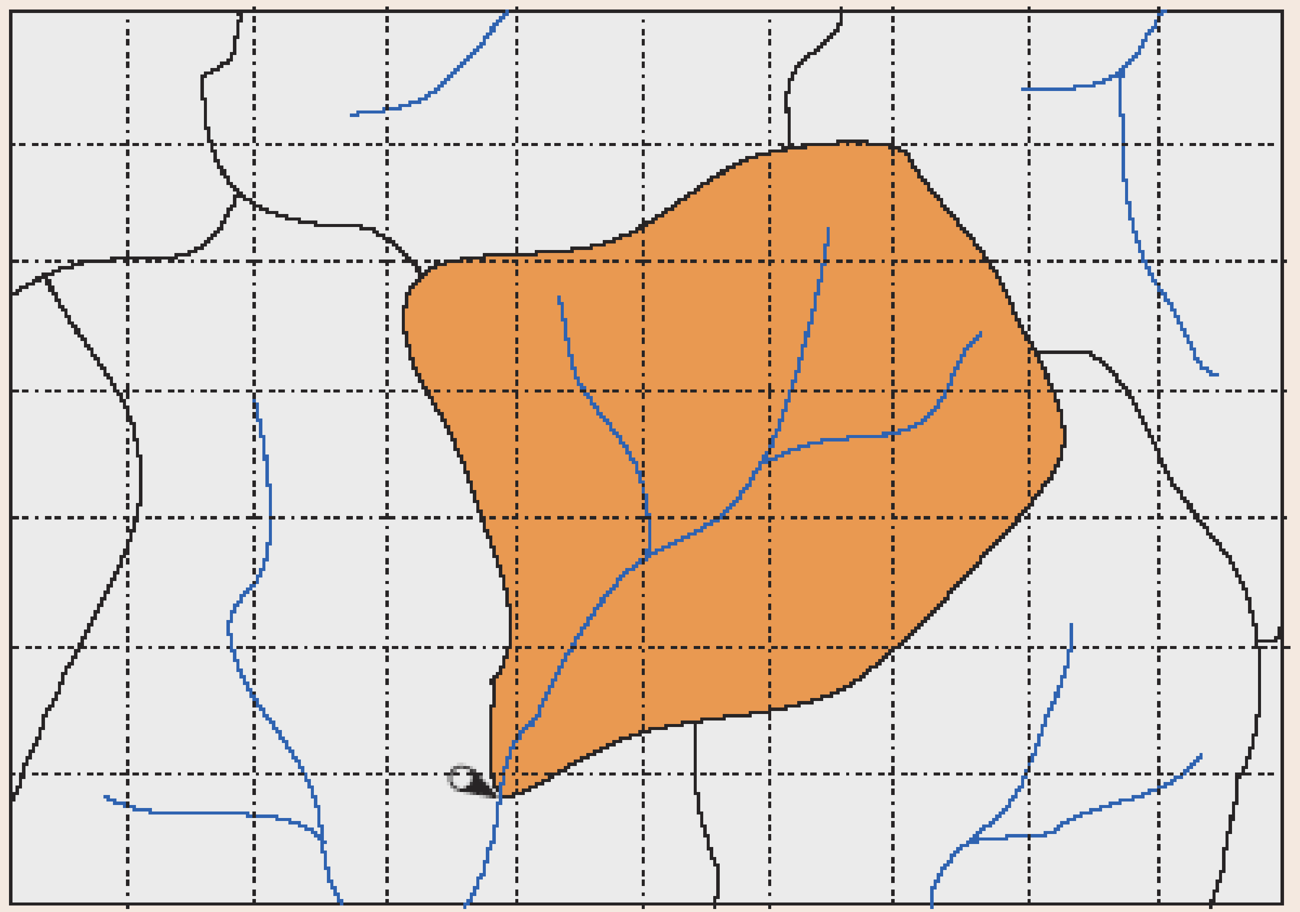
Güntner, A., Bronstert, A., 2004, Journal of Hydrology

Structure of spatial modelling units

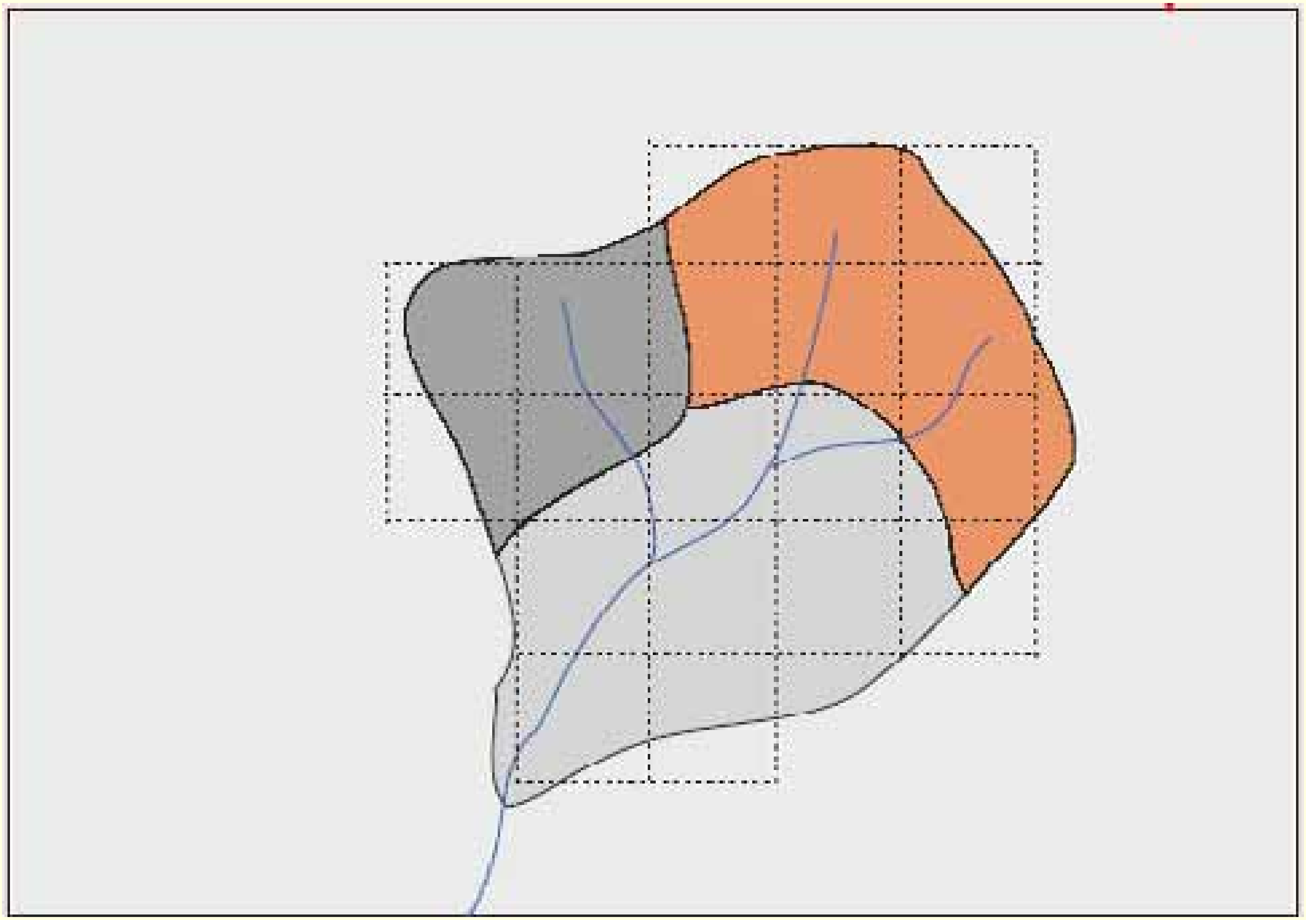


Level	Type and criteria of delimitation	Function
1 Sub-basin / Municipality / Grid cell	–Polygons with geographically referenced location –Data source of basins: Terrain analysis of 30''-USGS-DEM and digitized topographic maps –Municipalities: administrative boundaries (municipios)	▸ Runoff routing, including retention in reservoirs and withdrawal by water use ▸ If grid cells smaller than sub-basin / municipalities are used: Runoff responses of all grid cells pertaining to a sub-basin are added up to give the basin response. Further sub-divison (levels 2-6) starts from the grid cell level.
2 Landscape unit (LU)	Polygons with geographically referenced location Similarity of –major landform –general lithology –soil associations –toposequences	▸ Modelling unit with similar characteristics referring to lateral processes and similarity of sub-scale variability in vertical processes ▸ Composed of 1 - 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	▸ Lateral transfer of surface and subsurface runoff between terrain components of different topographic position by upland-lowland relationships ▸ Reinfiltration and exfiltration (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 class	▸ 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	Representative profile of soil-vegetation component –Several soil horizons of variable depth –Lower limit by depth of root zone or bedrock	▸ 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)



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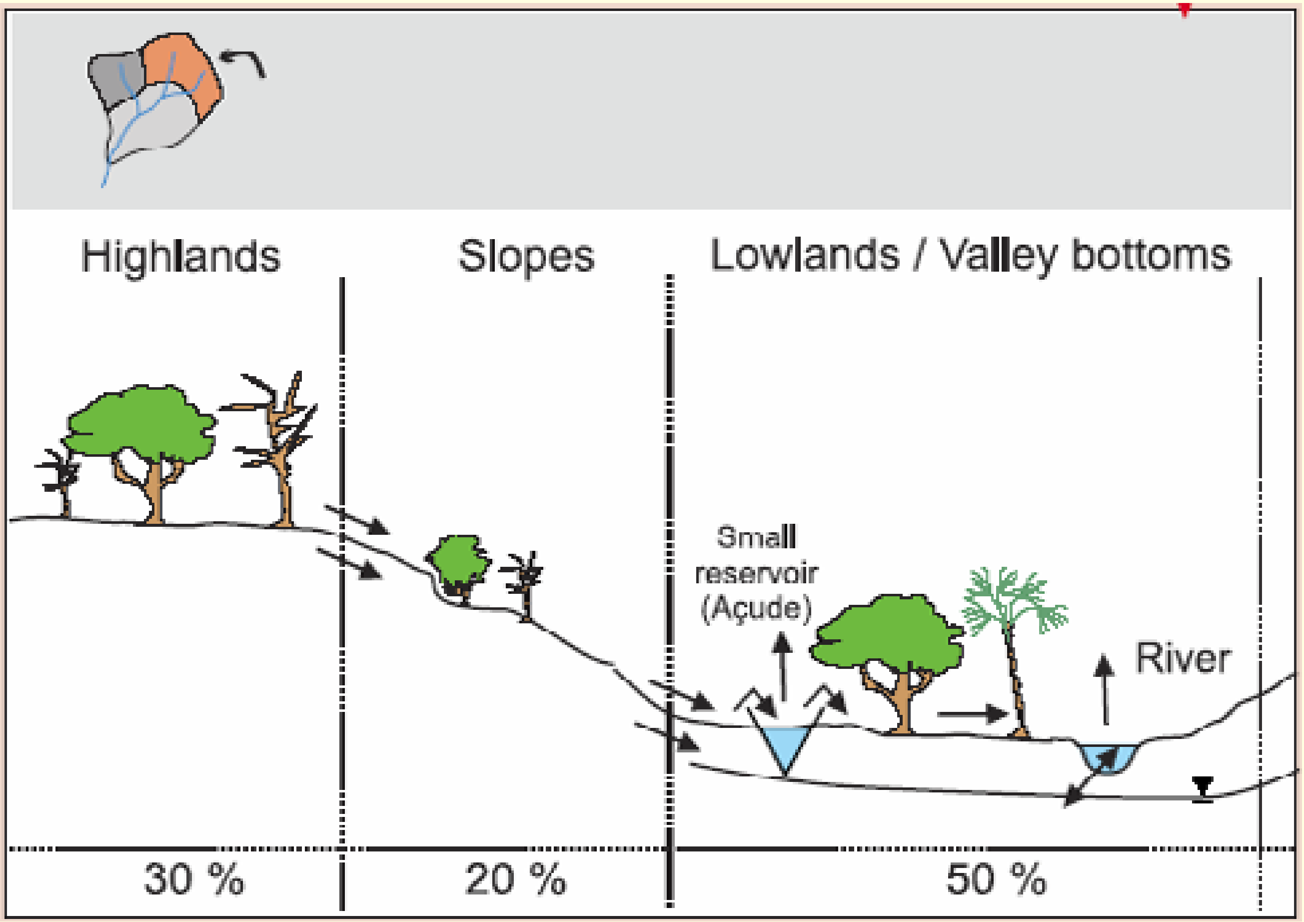
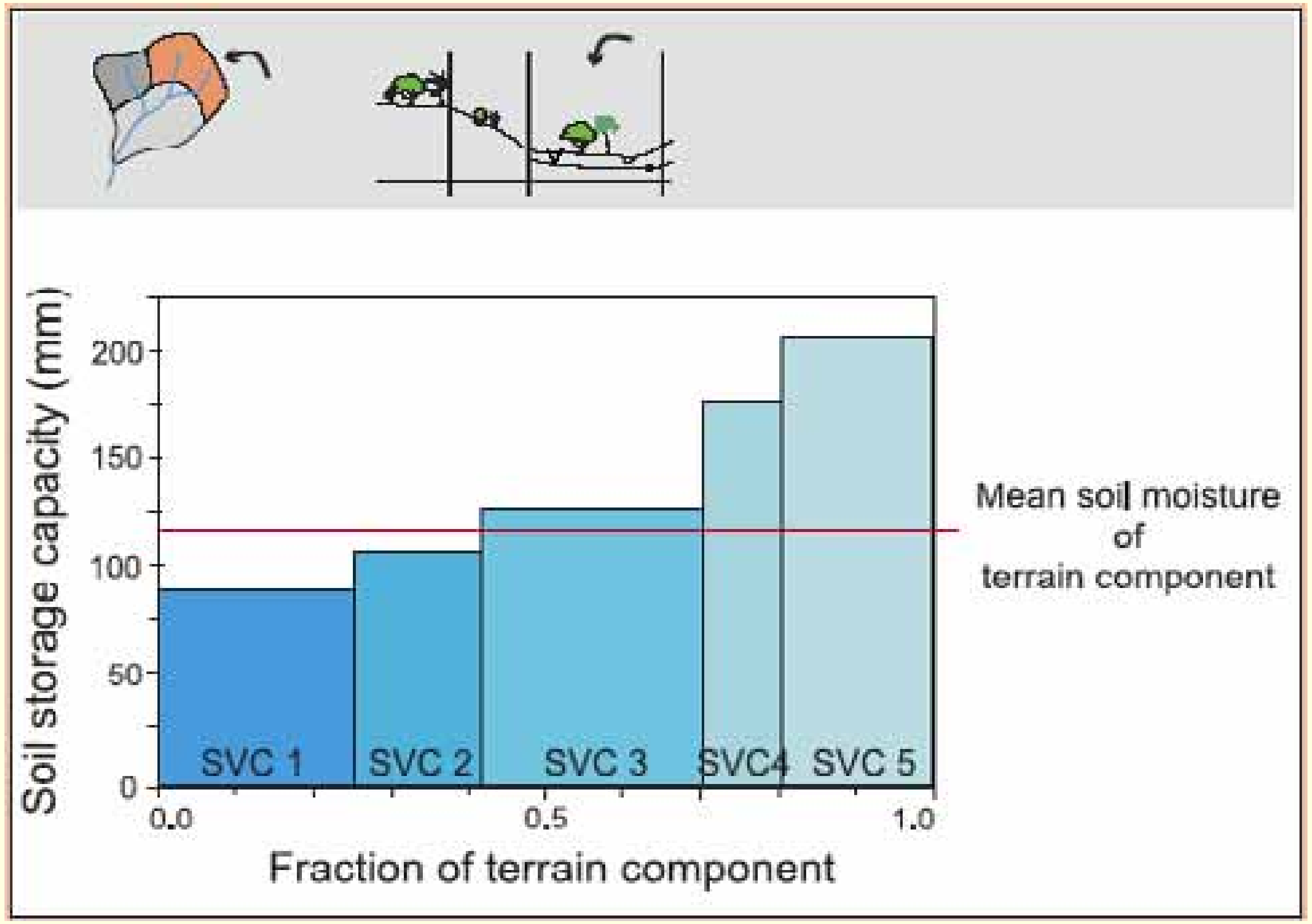
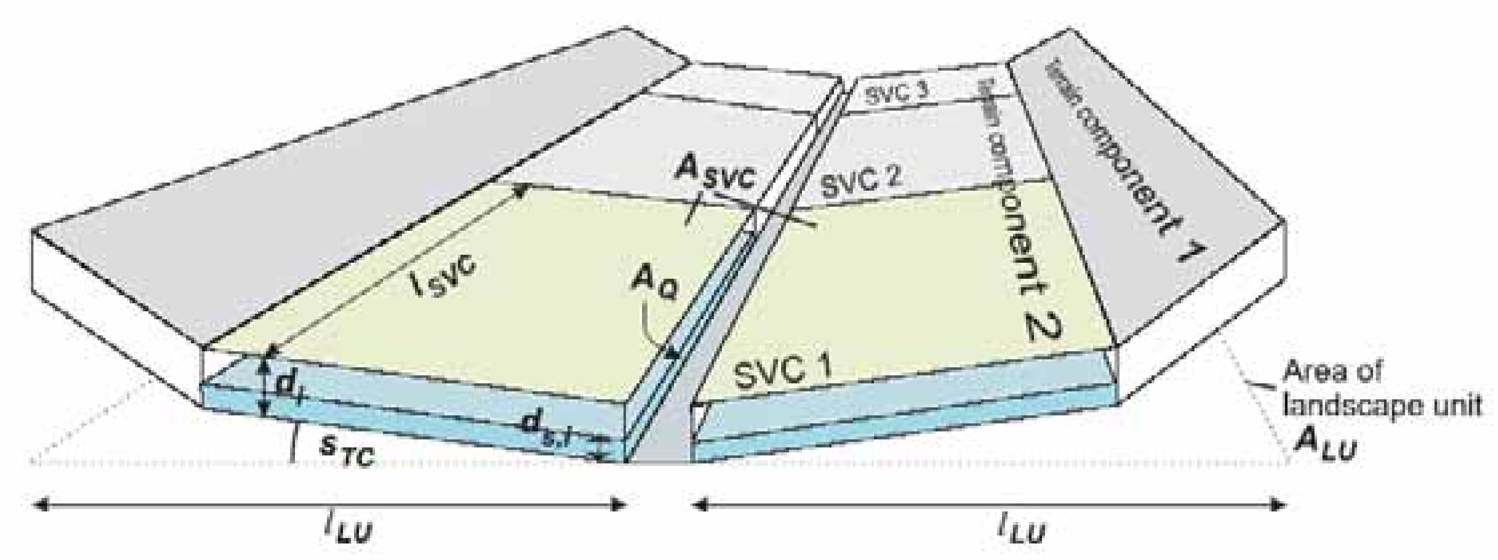
Terrain components (TC)



Soil-vegetation components (SVC)



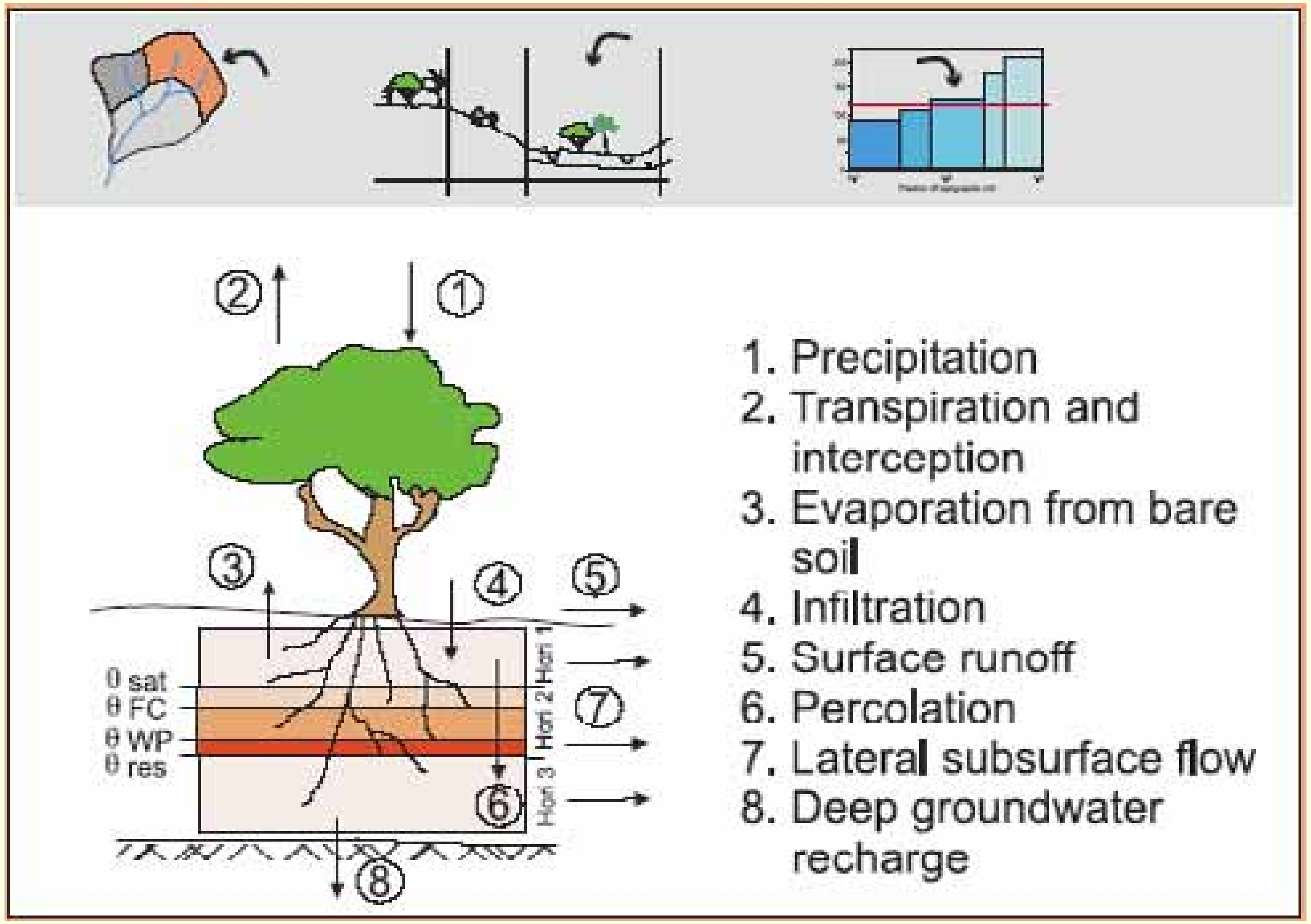
Scheme of the structure TC and SVCs



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

d_i = total depth of horizon i (m)
$d_{s,i}$ = 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:

$$I_t = I_{t-1} + P_I - E_I$$, with: $$P_I = \min(P\,,\,(I_c - I_{t-1}))$$ $$E_I = \min(E_{pot}\,,\,I_t)$$

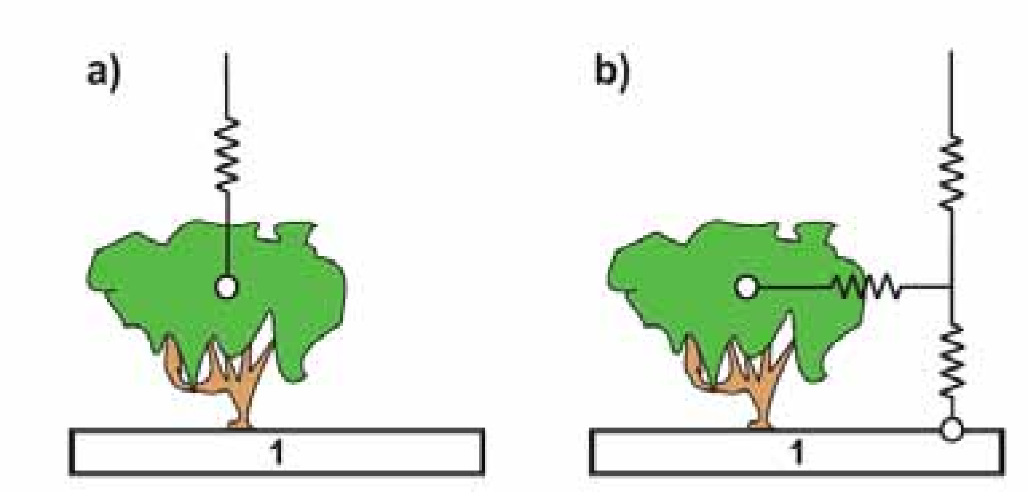
I_t = water in interception storage at timestep t (mm)
I_c = capacity of canopy interception storage (mm)
P = precipitation (mm)
P_I = intercepted precipitation (mm)
E_I = evaporation from interception storage (mm)
E_{pot} = potential evaporation (mm)

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 Δt^{-1})
P = precipitation (mm Δt^{-1})
P_I = intercepted precipitation (mm Δt^{-1})
$R_{s,TC}$ = lateral surface inflow from a TC of a higher topographic position (mm Δt^{-1})
$R_{s,SVC}$ = lateral surface inflow from SVCs within the same TC (mm Δt^{-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)
Qi = 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**

Erosion

MUSLE (Modified Universal Soil Loss Equation):

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

Y is the gross sediment yield [t]

Q_{surf} is the surface runoff volume [mm water/ha]

q_{peak} is the peak runoff rate [m^3/s]

A_{TC} is the area of the *TC* [ha]

K_{USLE}, C_{USLE}, P_{USLE} , LS_{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

$$q_{out,2} = C_1 \cdot q_{in,2} + C_2 \cdot q_{in,1} + C_3 \cdot qout,1$$

Muskingum Routing

$$C_1 = \frac{(\Delta t - 2KX)}{2K(1-X)+\Delta t}$$

$$C_2 = \frac{(\Delta t + 2KX)}{2K(1-X)+\Delta t}$$

$$C_3 = \frac{(2K(1-X)-\Delta t)}{2K(1-X)+\Delta t}$$

Sediment transport in the river

Suspended sediment:

Transport capacity concept

$$Sed\_conc_{s,\max} = a \cdot v_{s,peak}{}^{b}$$

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

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

$v_{peak}(t)$: peak channel velocity (m/s),

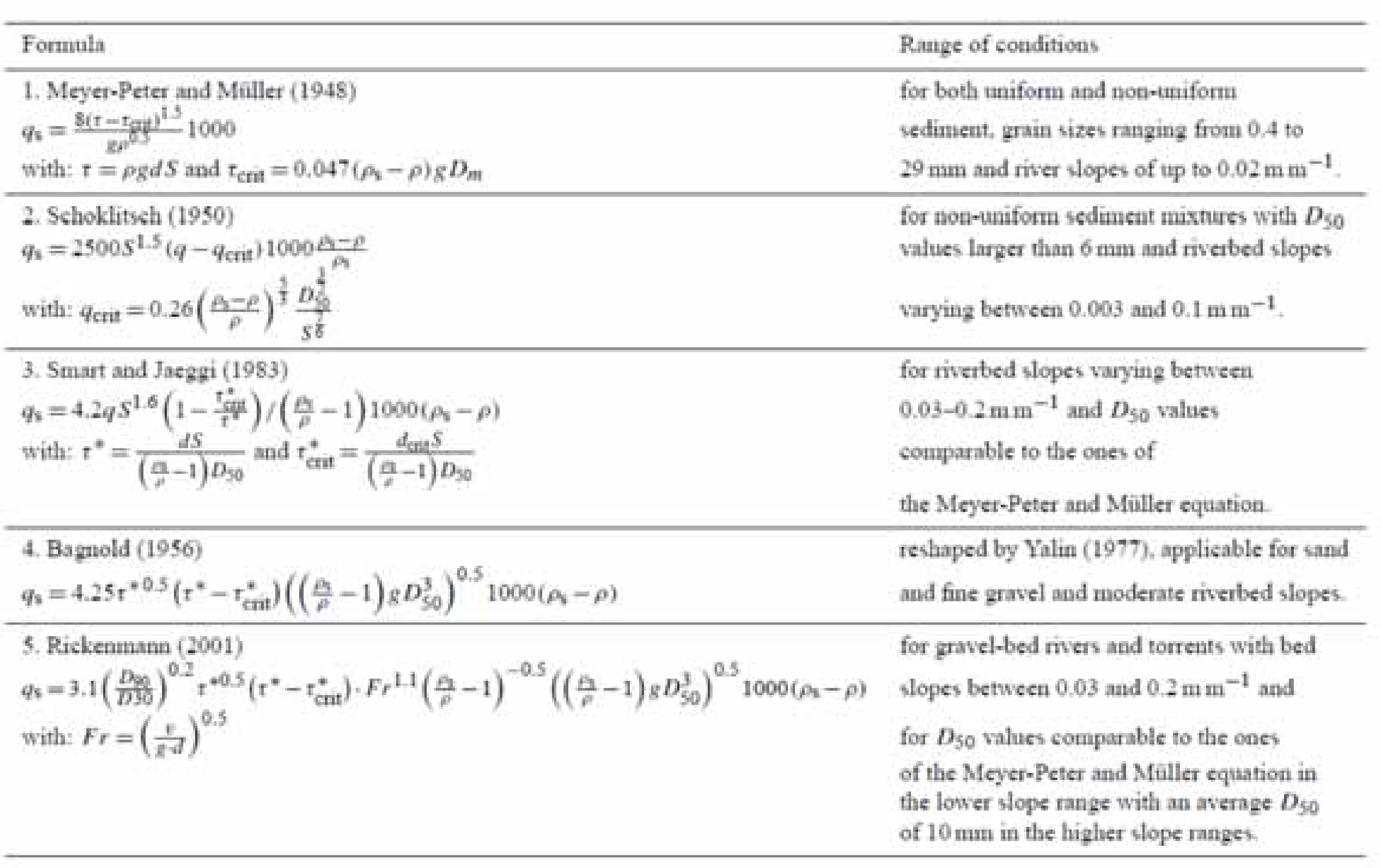
V: Volume of water in the reach (m³)

K: channel erodibility factor (cm / (h * Pa))

C: channel cover factor (–)

Sediment transport in the river

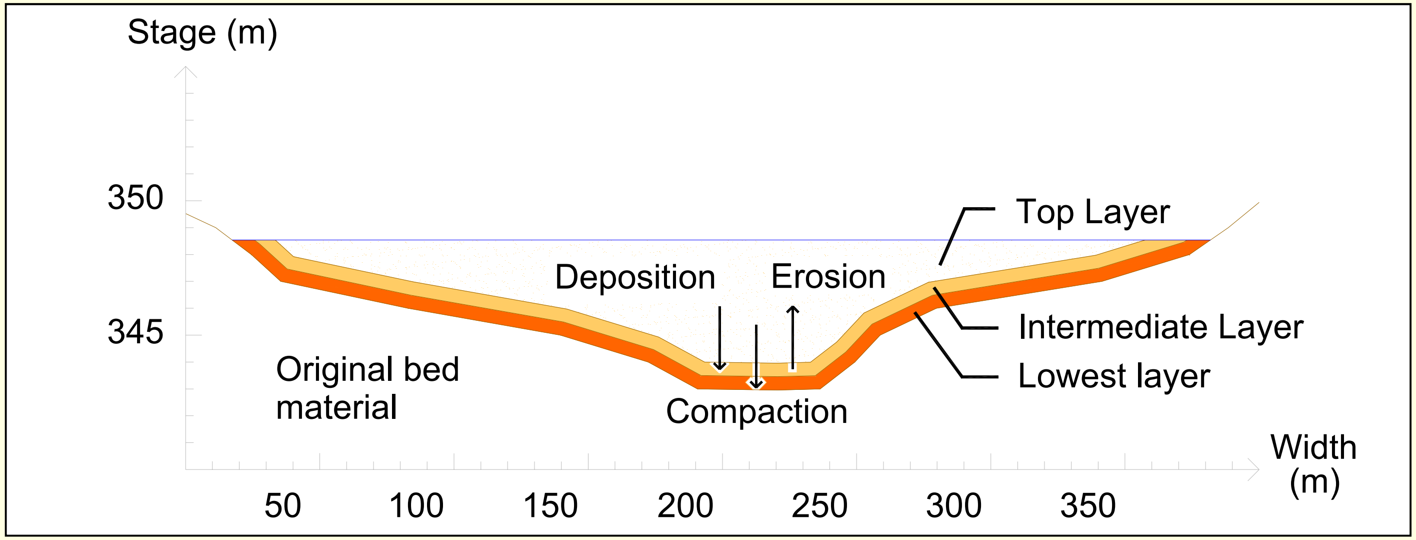
Bedload:

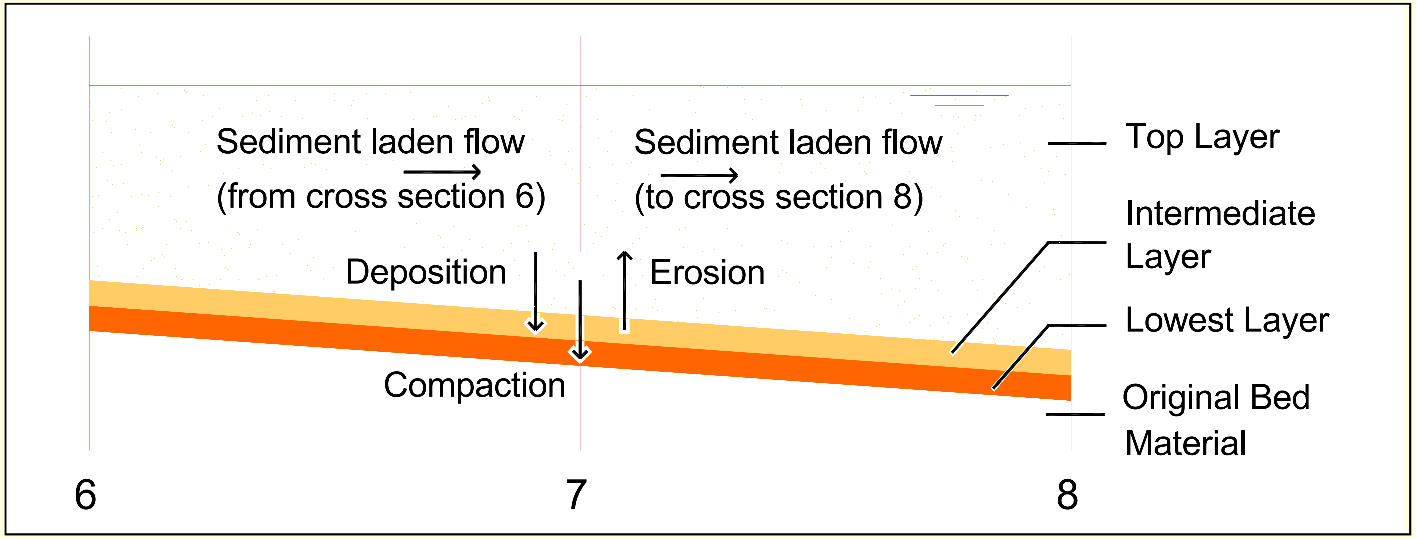


Formula	Range of conditions
1. Meyer-Peter and Müller (1948) $q_s = \frac{8(\tau-\tau_{crit})^{1.5}}{g\rho^{0.5}} 1000$ with: $\tau = \rho g d S$ and $\tau_{crit} = 0.047(\rho_s-\rho) g D_m$	for both uniform and non-uniform sediment, grain sizes ranging from 0.4 to 29 mm and river slopes of up to $0.02\,\mathrm{m\,m^{-1}}$.
2. Schoklitsch (1950) $q_s = 2500 S^{1.5}(q-q_{crit}) 1000 \frac{\rho_s-\rho}{\rho_s}$ with: $q_{crit} = 0.26\left(\frac{\rho_s-\rho}{\rho}\right)^{\frac{5}{3}} \frac{D_{50}^{\frac{3}{2}}}{S^{\frac{7}{6}}}$	for non-uniform sediment mixtures with D_{50} values larger than 6 mm and riverbed slopes varying between 0.003 and $0.1\,\mathrm{m\,m^{-1}}$.
3. Smart and Jaeggi (1983) $q_s = 4.2 q S^{1.6}\left(1-\frac{\tau^*_{crit}}{\tau^*}\right) / \left(\frac{\rho_s}{\rho}-1\right) 1000(\rho_s-\rho)$ with: $\tau^* = \frac{dS}{\left(\frac{\rho_s}{\rho}-1\right)D_{50}}$ and $\tau^*_{crit} = \frac{d_{crit}S}{\left(\frac{\rho_s}{\rho}-1\right)D_{50}}$	for riverbed slopes varying between $0.03\text{–}0.2\,\mathrm{m\,m^{-1}}$ and D_{50} values comparable to the ones of the Meyer-Peter and Müller equation.
4. Bagnold (1956) $q_s = 4.25\tau^{*0.5}(\tau^*-\tau^*_{crit})\left(\left(\frac{\rho_s}{\rho}-1\right) g D_{50}^3\right)^{0.5} 1000(\rho_s-\rho)$	reshaped by Yalin (1977), applicable for sand and fine gravel and moderate riverbed slopes.
5. Rickenmann (2001) $q_s = 3.1\left(\frac{D_{90}}{D30}\right)^{0.2} \tau^{*0.5}(\tau^*-\tau^*_{crit}) \cdot Fr^{1.1}\left(\frac{\rho_s}{\rho}-1\right)^{-0.5}\left(\left(\frac{\rho_s}{\rho}-1\right) g D_{50}^3\right)^{0.5} 1000(\rho_s-\rho)$ with: $Fr = \left(\frac{v}{g \cdot d}\right)^{0.5}$	for gravel-bed rivers and torrents with bed slopes between 0.03 and $0.2\,\mathrm{m\,m^{-1}}$ and for 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.

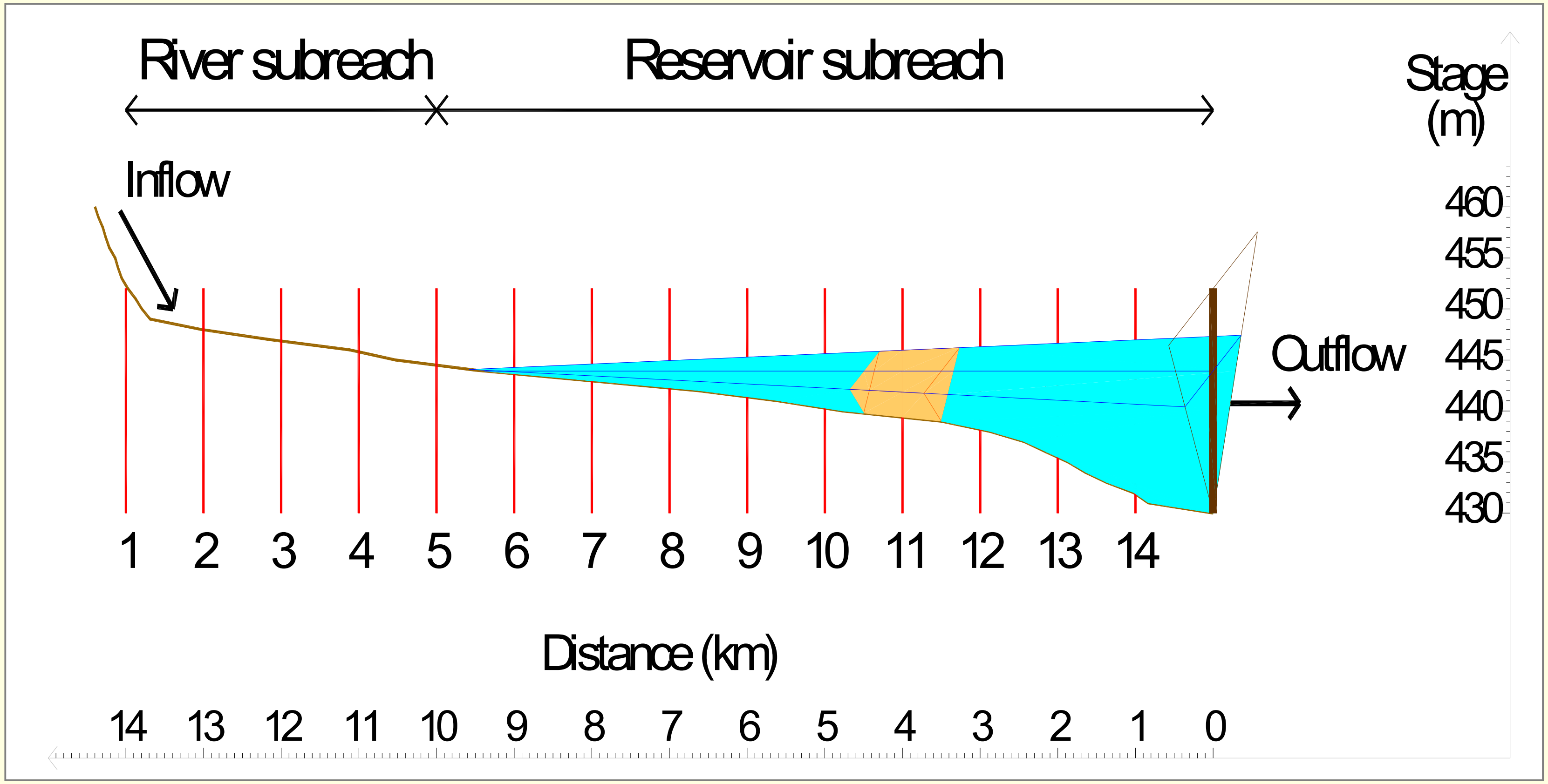
Bedload transport formulae in the river module (Mueller *et al.*, 2010)

Reservoir Module: Conceptual layers





Reservoir Module: Spatial representation of the reservoir



Sediment transport in the reservoir

Water discharge in the reservoir's cross sections:

Simple mass conservation concept

$$Q_j = Q_{in} - (Q_{in} - Q_{out}).\sum_{k=m}^{j} v_k$$

Qj: *w*ater discharge at the cross-section *j*;
vk: fraction of reservoir volume represented by that cross-section

Sediment transport in the reservoir

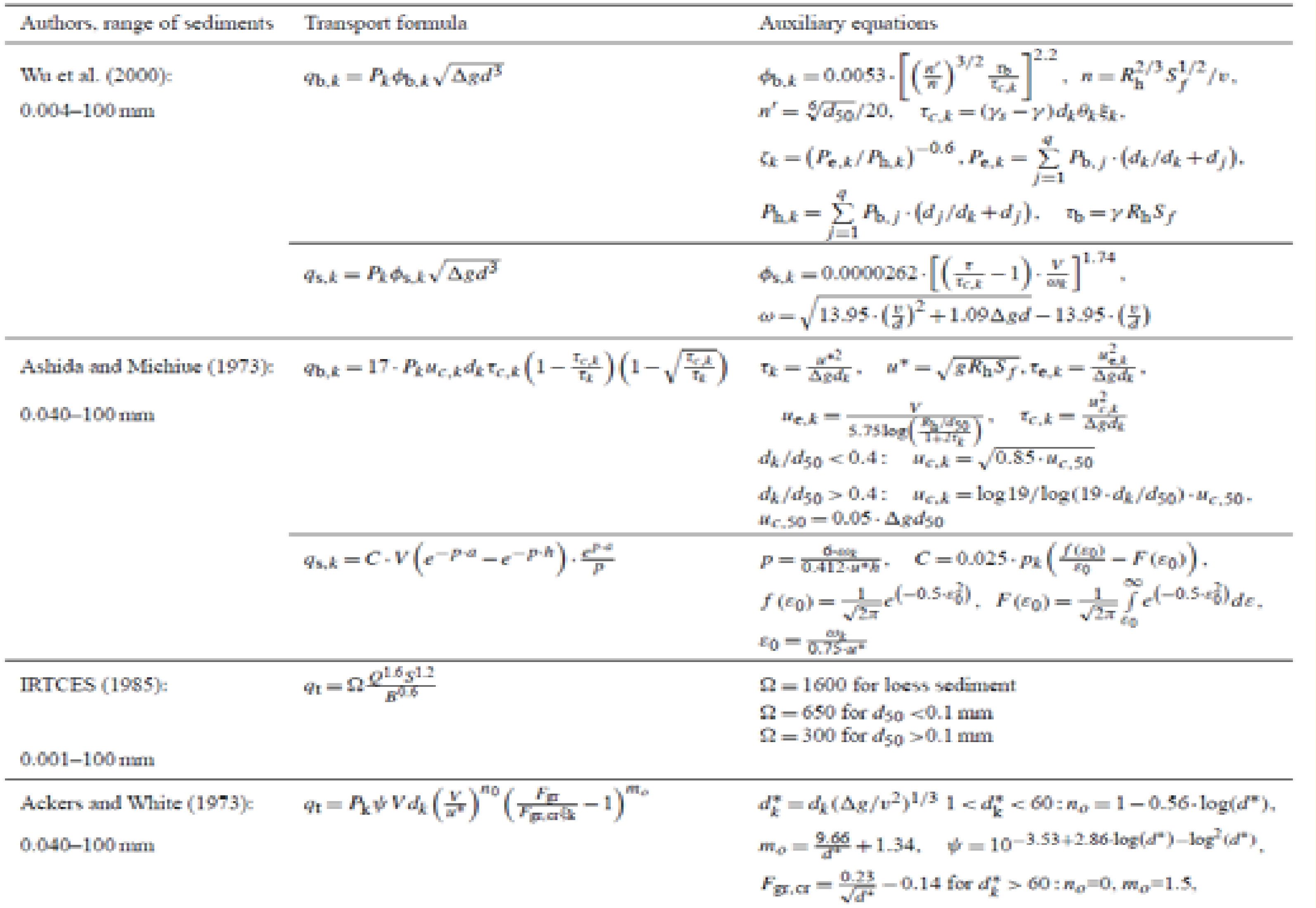
non-equilibrium sediment transport in the reservoir’s cross sections:

Approach by Han and He (1990):

$$\frac{dS}{dx} = \frac{\alpha\omega}{q}(S^{*} - S) \qquad S_{j} = S_{j}^{*} + (S_{j-1} - S_{j}^{*}).e^{-\left(\frac{\alpha.\omega.L}{q}\right)}$$

S: *sediment concentration;*
S:* *sediment carrying capacity;*
Q: *discharge per unit width;*
ω: *settling velocity;*
α: *coefficient of saturation recovery*

Sediment transport in the reservoir

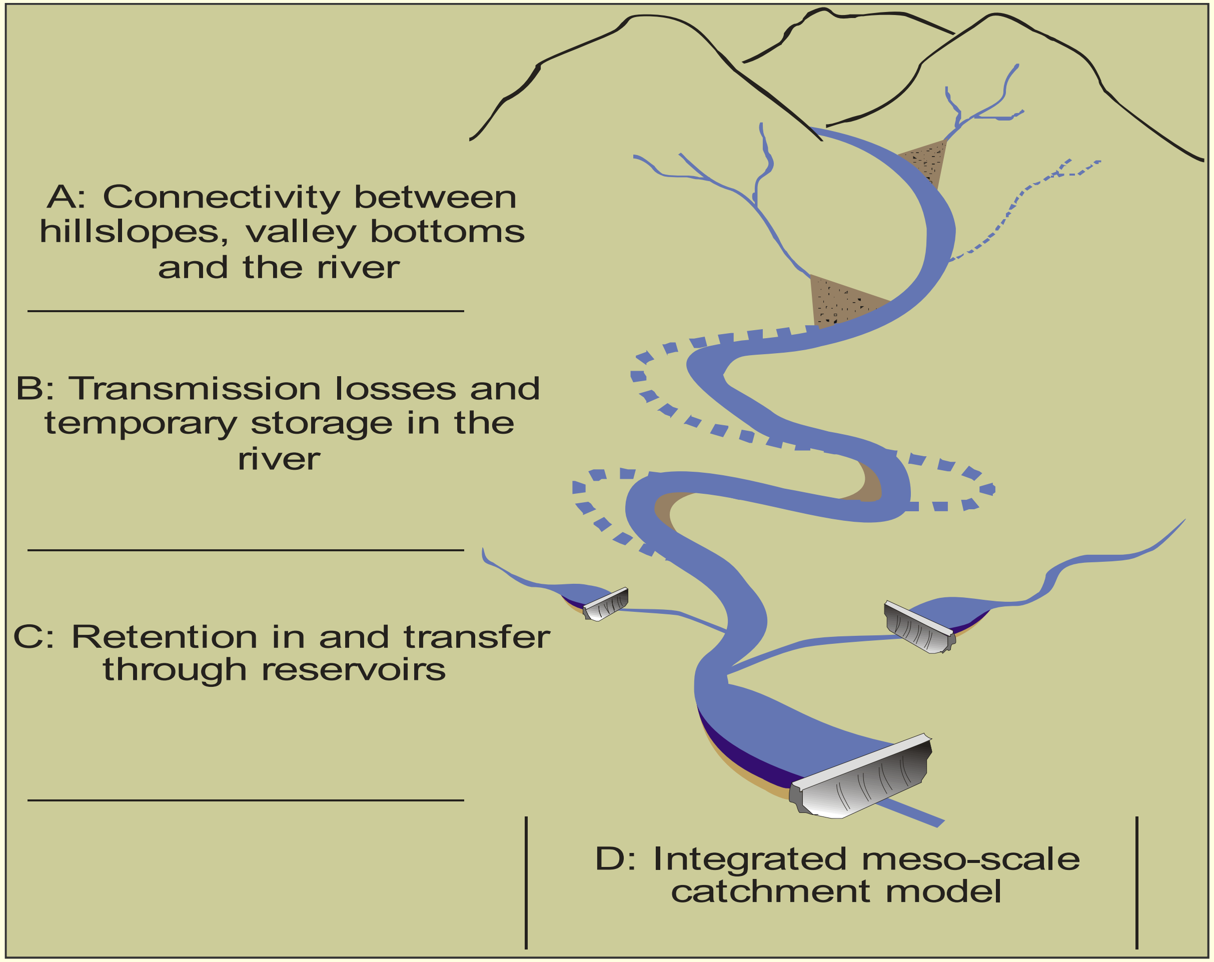


Authors, range of sediments	Transport formula	Auxiliary equations
Wu et al. (2000): 0.004–100 mm	$q_{b,k} = P_k \phi_{b,k} \sqrt{\Delta g d^3}$	$\phi_{b,k} = 0.0053 \cdot \left[\left(\frac{n'}{n} \right)^{3/2} \frac{\tau_b}{\tau_{c,k}} \right]^{2.2}, \quad n = R_h^{2/3} S_f^{1/2} / v,$ $n' = \sqrt[6]{d_{50}}/20, \quad \tau_{c,k} = (\gamma_s - \gamma) d_k \theta_k \xi_k,$ $\zeta_k = (P_{e,k}/P_{h,k})^{-0.6}, P_{e,k} = \sum_{j=1}^{q} P_{b,j} \cdot (d_k/d_k + d_j),$ $P_{h,k} = \sum_{j=1}^{q} P_{b,j} \cdot (d_j/d_k + d_j), \quad \tau_b = \gamma R_h S_f$
	$q_{s,k} = P_k \phi_{s,k} \sqrt{\Delta g d^3}$	$\phi_{s,k} = 0.0000262 \cdot \left[\left(\frac{\tau}{\tau_{c,k}} - 1 \right) \cdot \frac{V}{\omega_k} \right]^{1.74},$ $\omega = \sqrt{13.95 \cdot \left(\frac{v}{d}\right)^2 + 1.09 \Delta g d} - 13.95 \cdot \left(\frac{v}{d}\right)$
Ashida and Michiue (1973): 0.040–100 mm	$q_{b,k} = 17 \cdot P_k u_{c,k} d_k \tau_{c,k} \left(1 - \frac{\tau_{c,k}}{\tau_k}\right)\left(1 - \sqrt{\frac{\tau_{c,k}}{\tau_k}}\right)$	$\tau_k = \frac{u^{*2}}{\Delta g d_k}, \quad u^* = \sqrt{g R_h S_f}, \tau_{e,k} = \frac{u_{e,k}^2}{\Delta g d_k},$ $u_{e,k} = \frac{V}{5.75 \log\left(\frac{R_h/d_{50}}{1+2\tau_k}\right)}, \quad \tau_{c,k} = \frac{u_{c,k}^2}{\Delta g d_k}$ $d_k/d_{50} < 0.4: \quad u_{c,k} = \sqrt{0.85 \cdot u_{c,50}}$ $d_k/d_{50} > 0.4: \quad u_{c,k} = \log 19 / \log(19 \cdot d_k/d_{50}) \cdot u_{c,50},$ $u_{c,50} = 0.05 \cdot \Delta g d_{50}$
	$q_{s,k} = C \cdot V \left(e^{-p \cdot a} - e^{-p \cdot h}\right) \cdot \frac{e^{p \cdot a}}{p}$	$p = \frac{6 \cdot \omega_k}{0.412 \cdot u^* h}, \quad C = 0.025 \cdot p_k \left(\frac{f(\varepsilon_0)}{\varepsilon_0} - F(\varepsilon_0) \right),$ $f(\varepsilon_0) = \frac{1}{\sqrt{2\pi}} e^{(-0.5 \cdot \varepsilon_0^2)}, \quad F(\varepsilon_0) = \frac{1}{\sqrt{2\pi}} \int_{\varepsilon_0}^{\infty} e^{(-0.5 \cdot \varepsilon_0^2)} d\varepsilon,$ $\varepsilon_0 = \frac{\omega_k}{0.75 \cdot u^*}$
IRTCES (1985): 0.001–100 mm	$q_t = \Omega \frac{Q^{1.6} S^{1.2}}{B^{0.6}}$	$\Omega = 1600$ for loess sediment $\Omega = 650$ for $d_{50} < 0.1$ mm $\Omega = 300$ for $d_{50} > 0.1$ mm
Ackers and White (1973): 0.040–100 mm	$q_t = P_k \psi V d_k \left(\frac{V}{u^*}\right)^{n_0} \left(\frac{F_{gr}}{F_{gr,cr_k}} - 1\right)^{m_o}$	$d_k^* = d_k (\Delta g / v^2)^{1/3} \; 1 < d_k^* < 60: n_o = 1 - 0.56 \cdot \log(d^*),$ $m_o = \frac{9.66}{d^*} + 1.34, \quad \psi = 10^{-3.53 + 2.86 \cdot \log(d^*) - \log^2(d^*)},$ $F_{gr,cr} = \frac{0.23}{\sqrt{d^*}} - 0.14$ for $d_k^* > 60: n_o = 0, m_o = 1.5,$

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

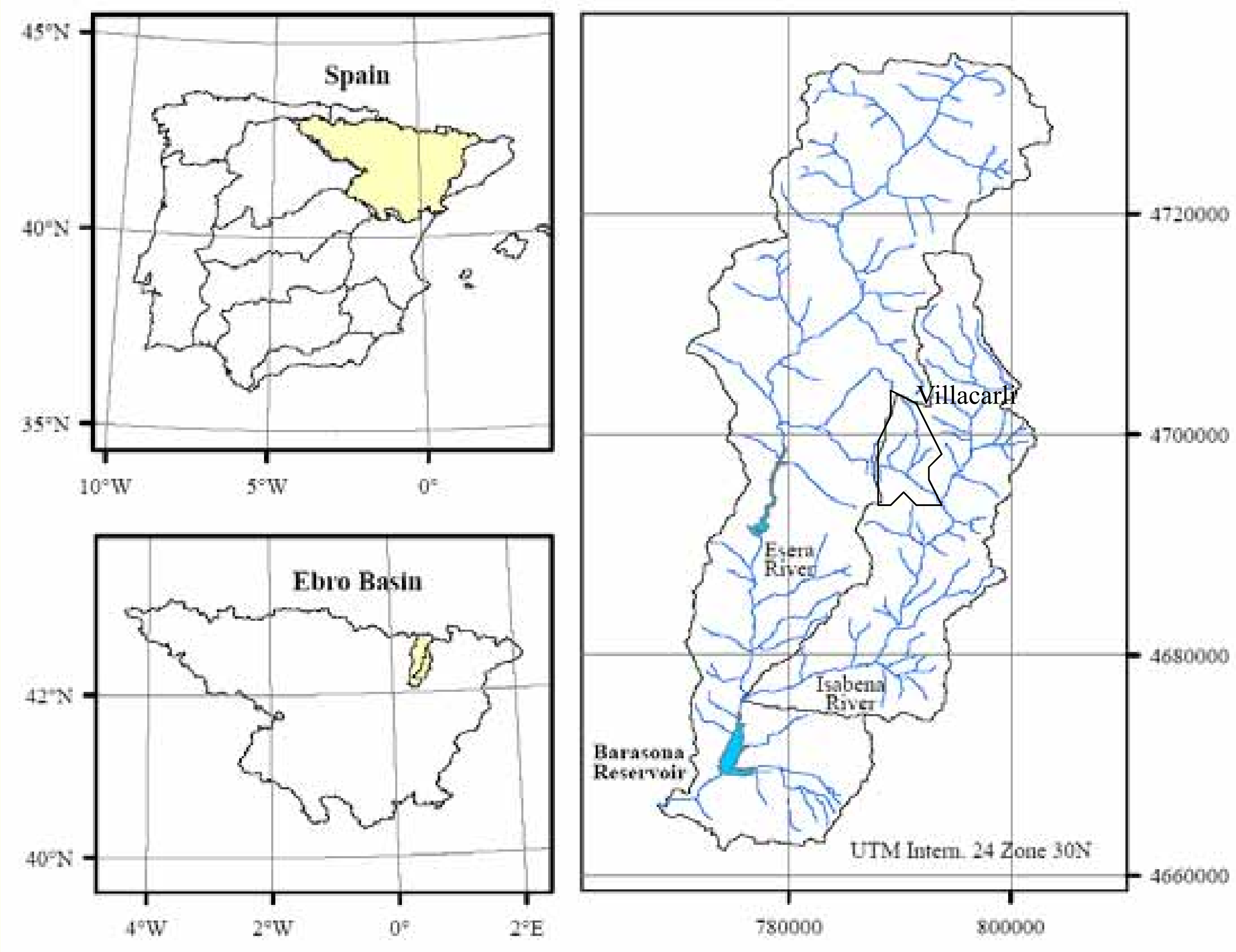
These research regions include of a set of individual (but nested) catchments of different spatial scales

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)

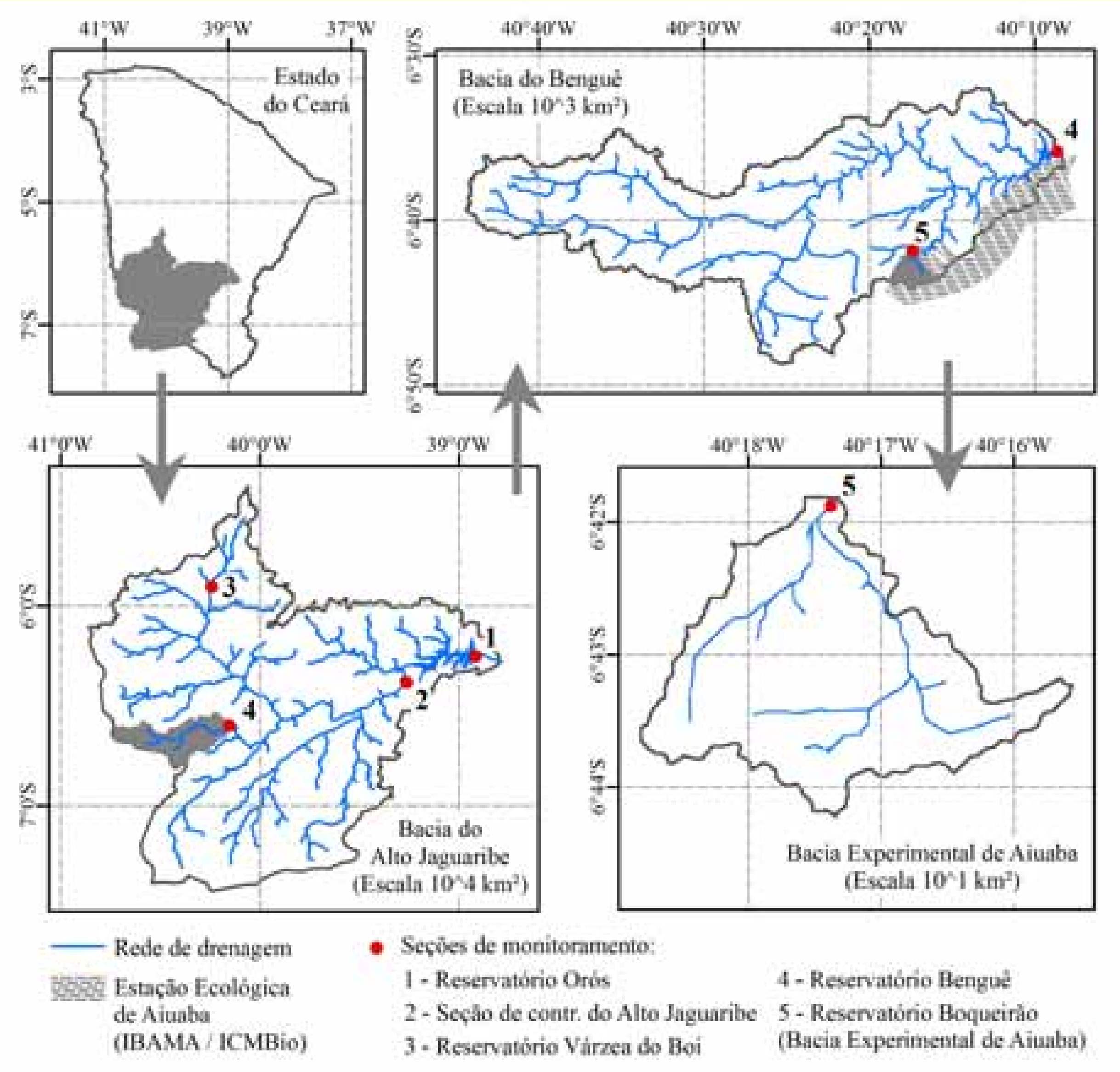
No.	Name of the catchment	Area (km²)	annual rainfall (mm)	Main Water measurements	Main Sediment measurements
S1	*badland*	~ 0.03	~750	Discharge flume	Tubiditymeter; Isco sampling
S2	*Ball*	10	~750	Water level sensor	Tubiditymeter; Isco sampling
S3	*Villacarli*	41	730	Water level sensor	Tubiditymeter;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

Uppe Yaguaribe (NE Brazil)

➔ Várzea do Boi ➔ Bengue ➔ Aiuaba ➔ exp. hillslopes

Uppe Yaguaribe (NE Brazil)

➔ Várzea do Boi ➔ Bengue ➔ Aiuaba ➔ exp. hillslopes

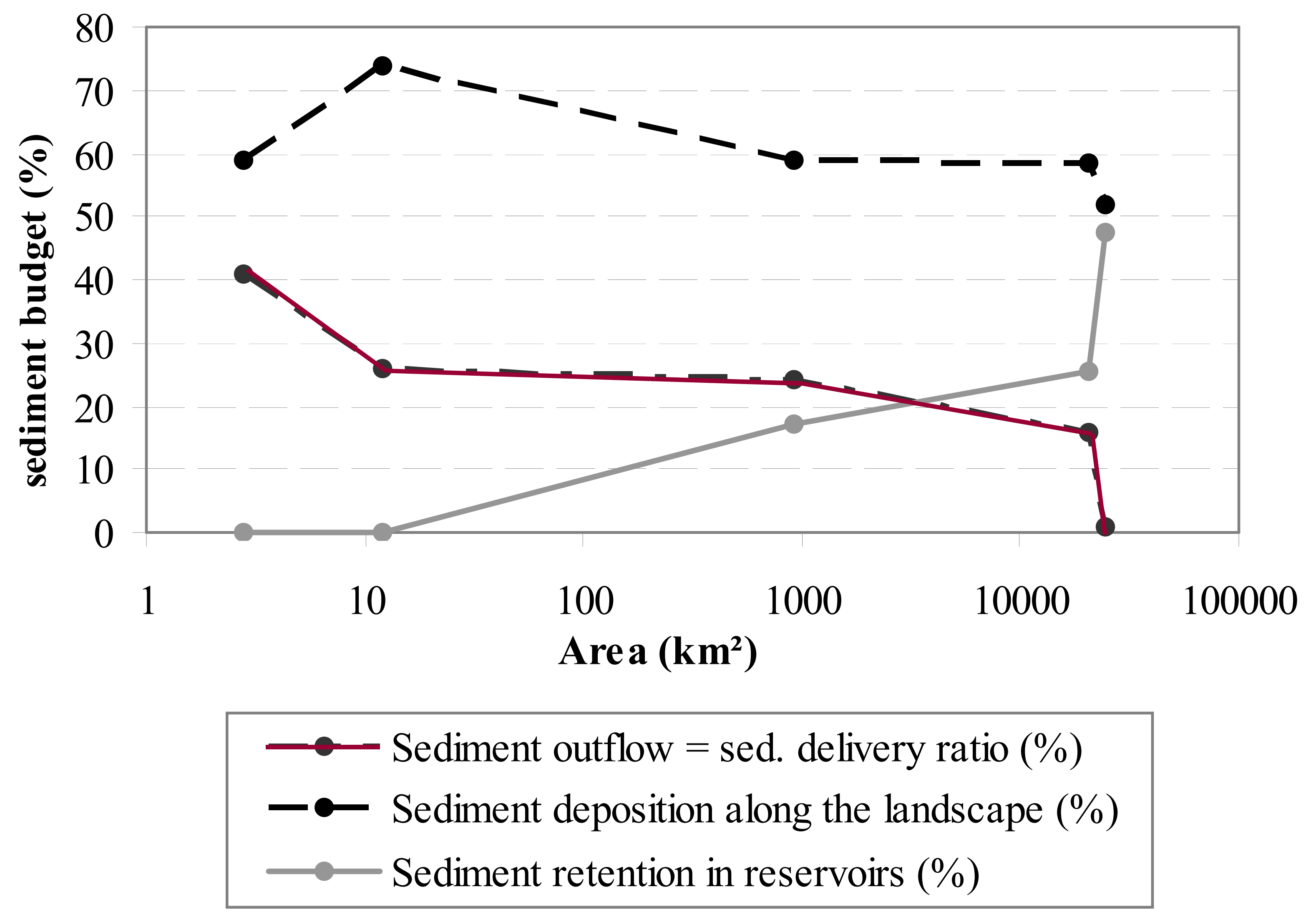


Monitoring sections and the hydrologic and sediment measurements in the Upper Jaguaribe Basin

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

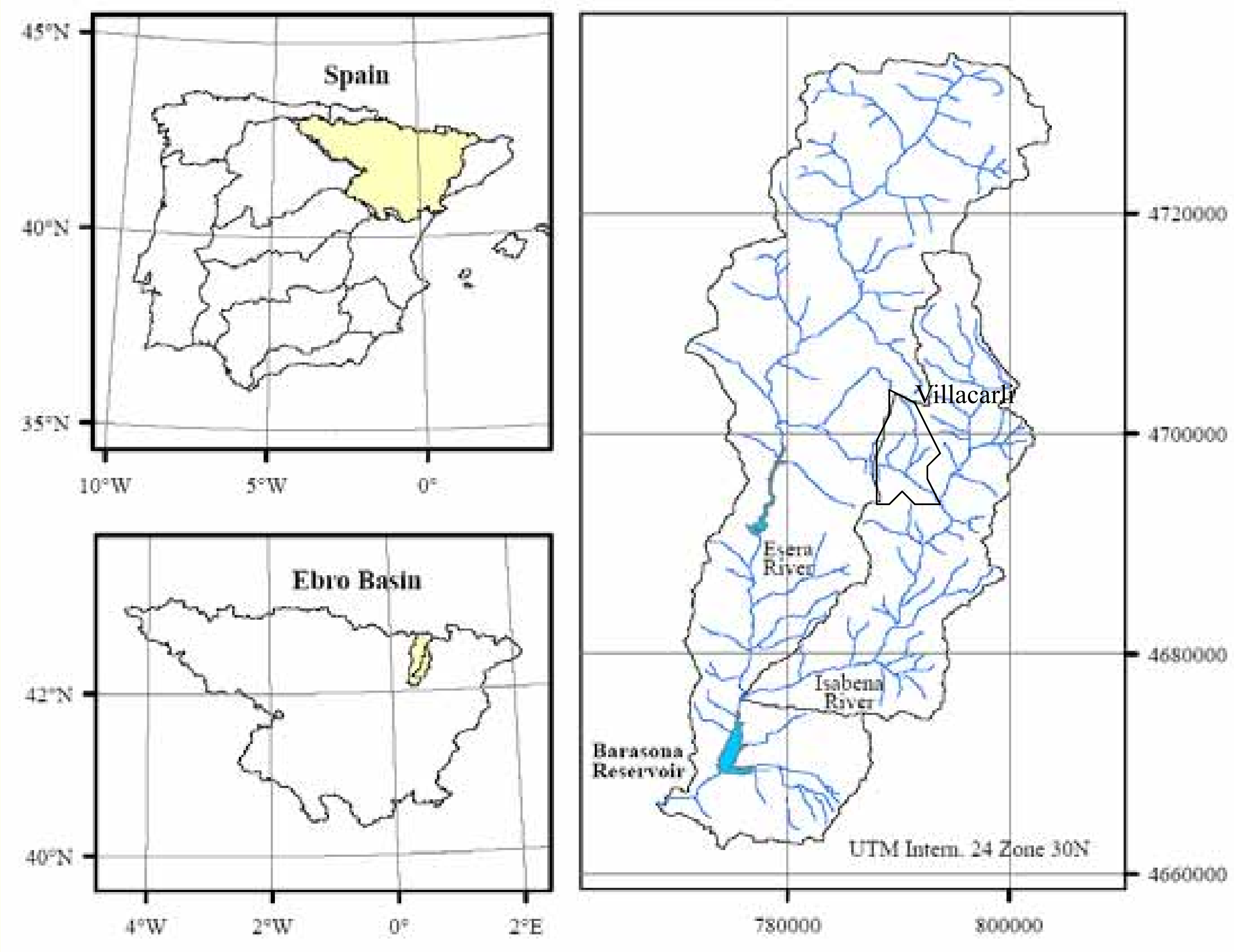
a - Balanço hídrico no reservatório
b - Nível de água + curva-chave
c - Sedimento em suspensão - curva-chave de sedimentos
d - Arraste de leito - ajuste, com dados de campo, da equação modificada de Meyer-Peter e Müller
e - Sedimento em suspensão e arraste de eleito - medida do assoreamento do açude

Sediment budgets at the nested catchments in the Upper Jaguaribe Basin, Brazil

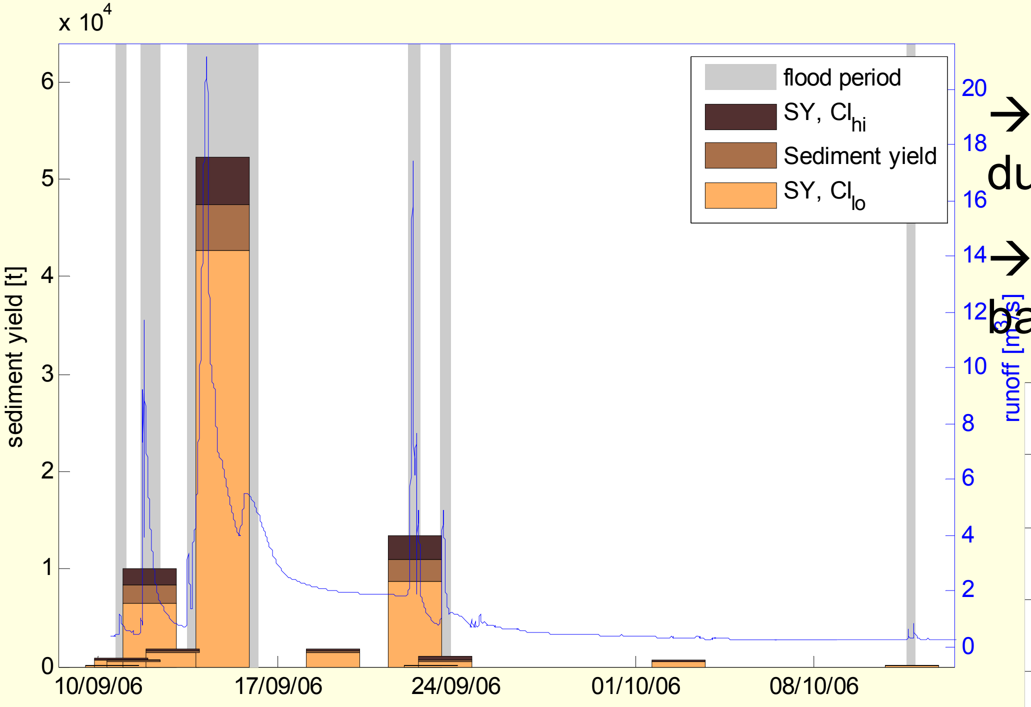


Ésera (NE Spain, Ebro region)

➔ Isábena ➔ Villacarli ➔ Ball ➔ exp. badlands



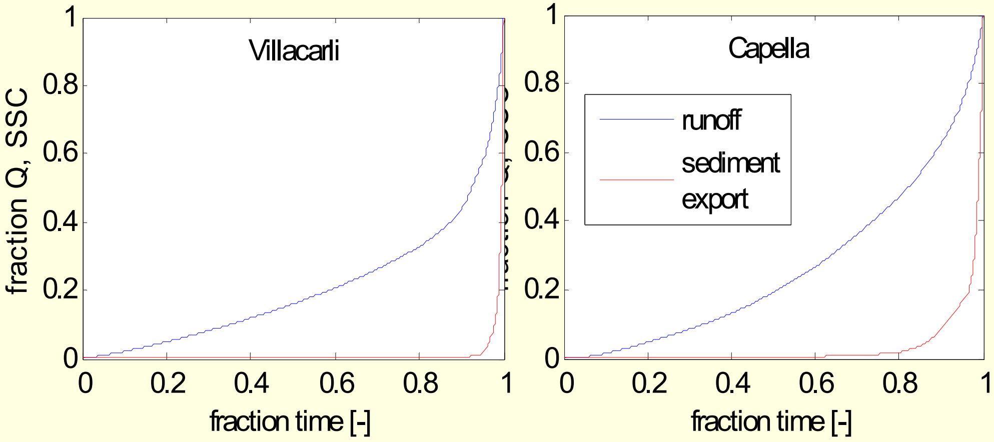
NE Spain: Assessment of water flows and sediment yields



→ sediment export occurs mainly during -late summer floods

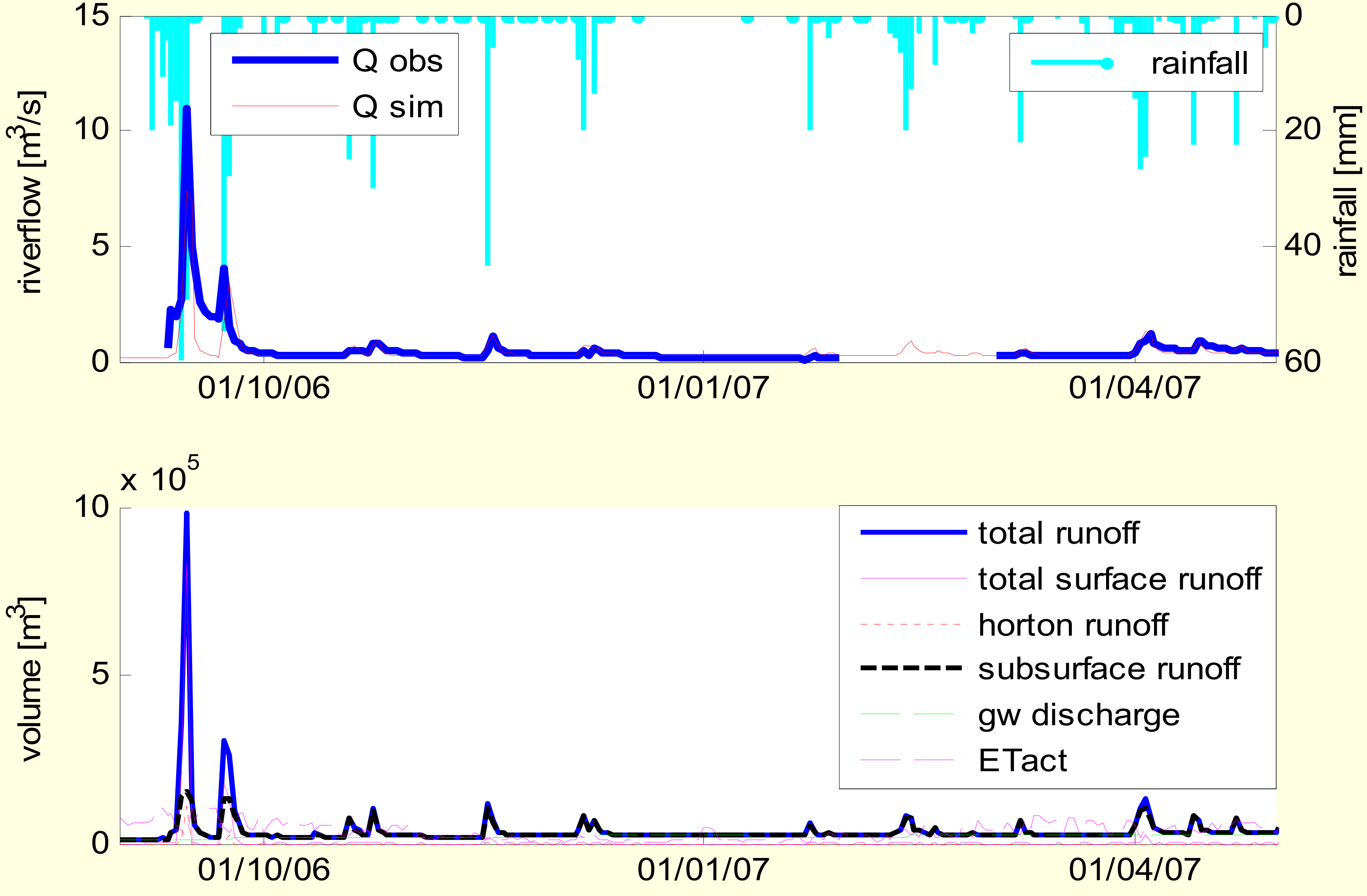
→ very high specific sediment for badland areas (Villacarli)

gauge	SSY [t/km^2]
Torrelaribera	6277
Villacarli	1971
Cabecera	139
Capella	409



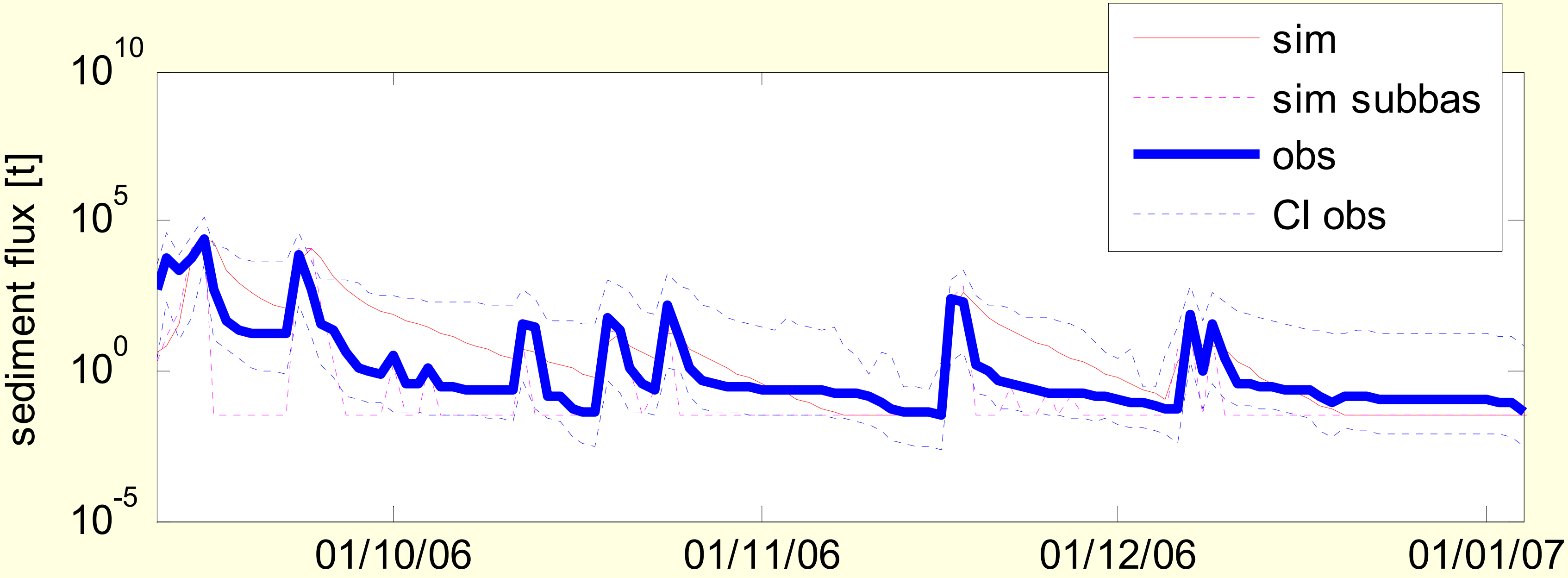
→ highly episodic sediment fluxes from headwaters are strongly attenuated towards outlet

NE-Spain: Modeled Water hydrological fluxes at the Villacarli, Catchment



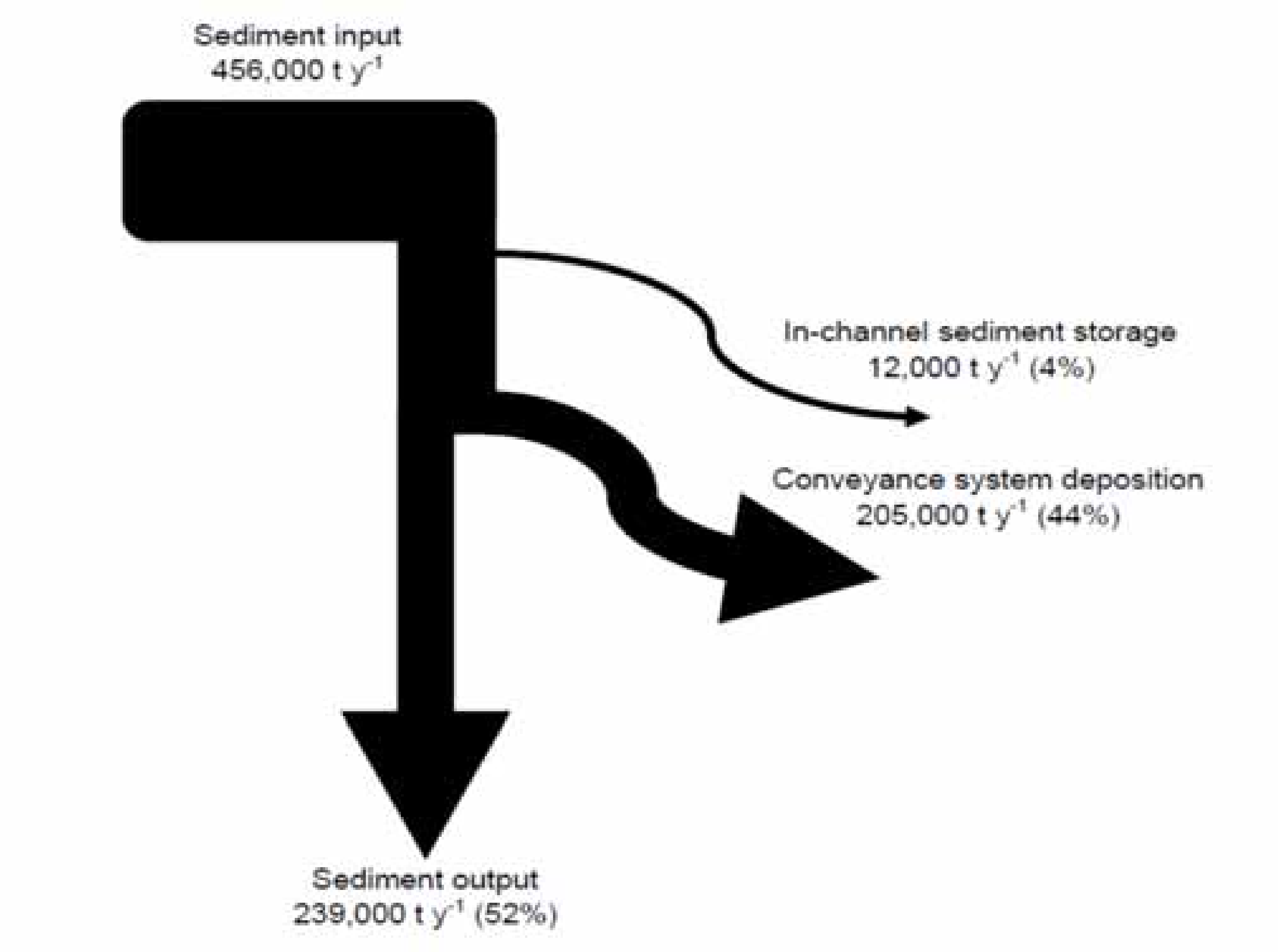
WASA-SED results for Villacarli catchment (Francke, 2009)

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,



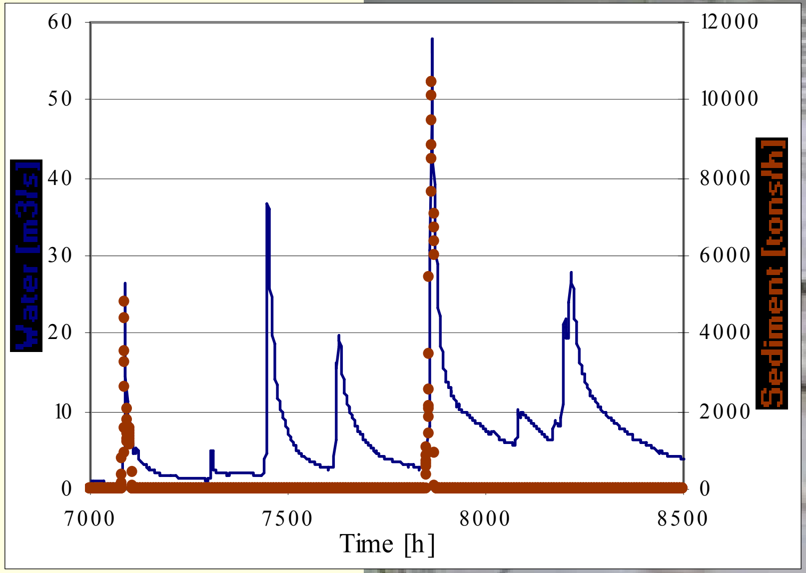
Estimates of sediment transfer and deposition rates in the Isábena catchment for the period 2007 – 2009 (López-Tarazón et al. (2012)

RIVER Modelling Temporary river storage of sediments

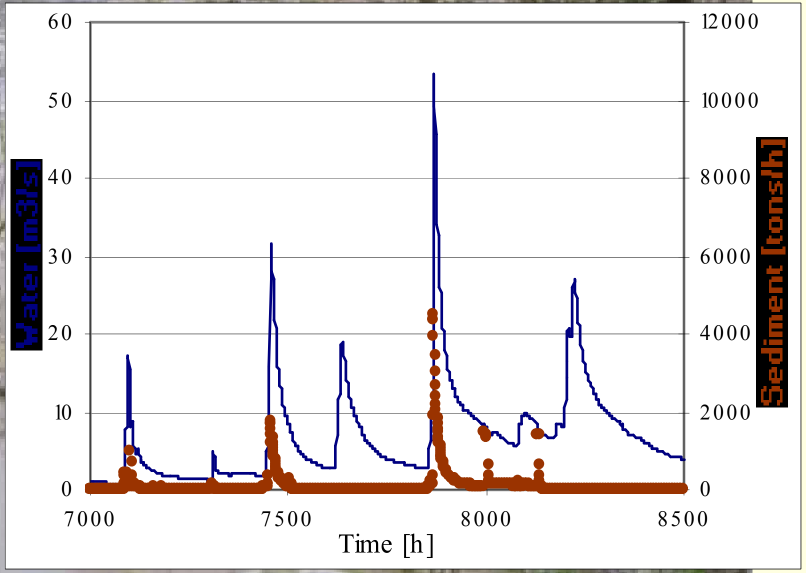
RIVER Modelling

Sediment Transport in the River System

Upstream River Stretch in the Mountains

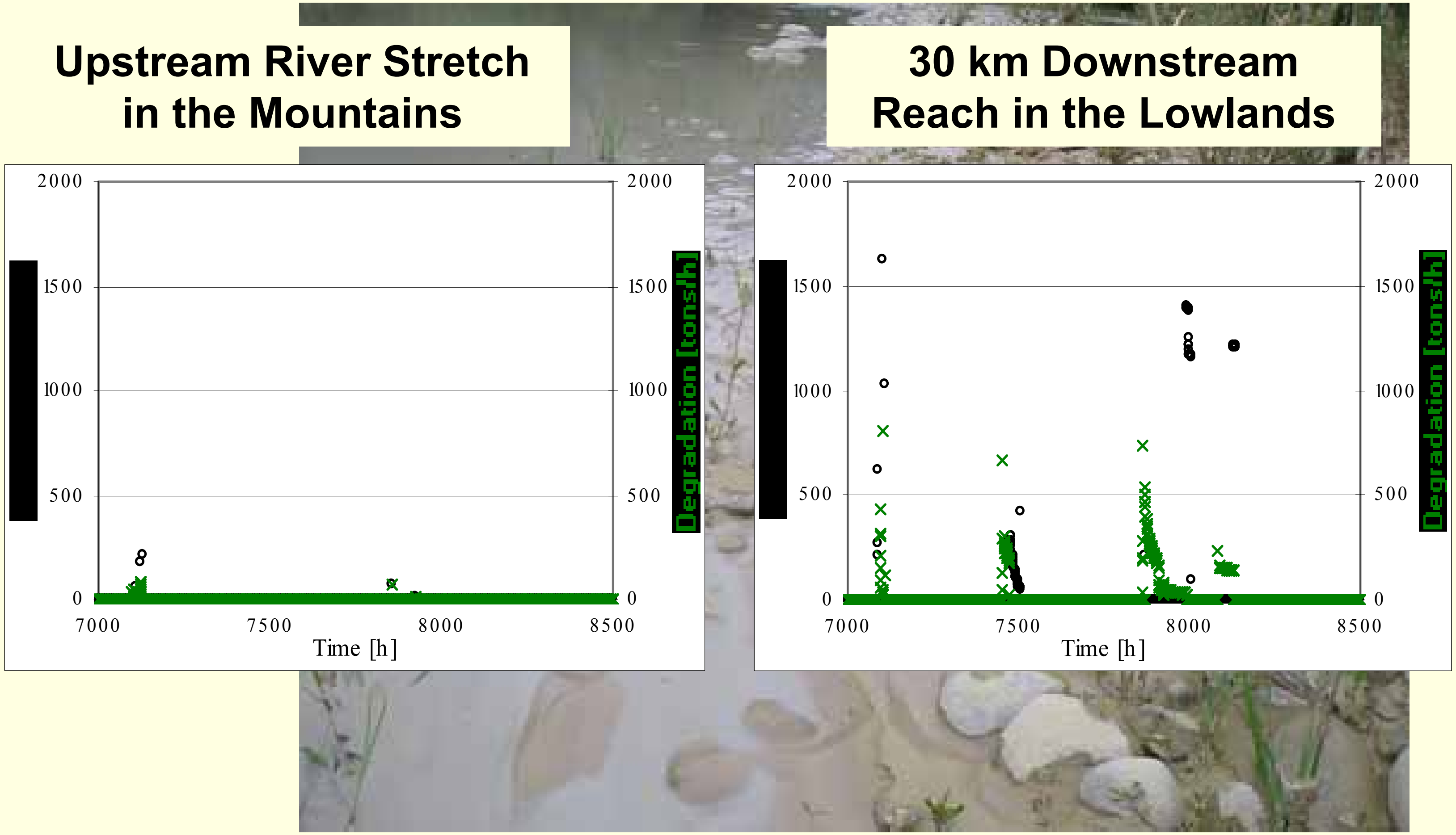


30 km Downstream Reach in the Lowlands



RIVER Modelling

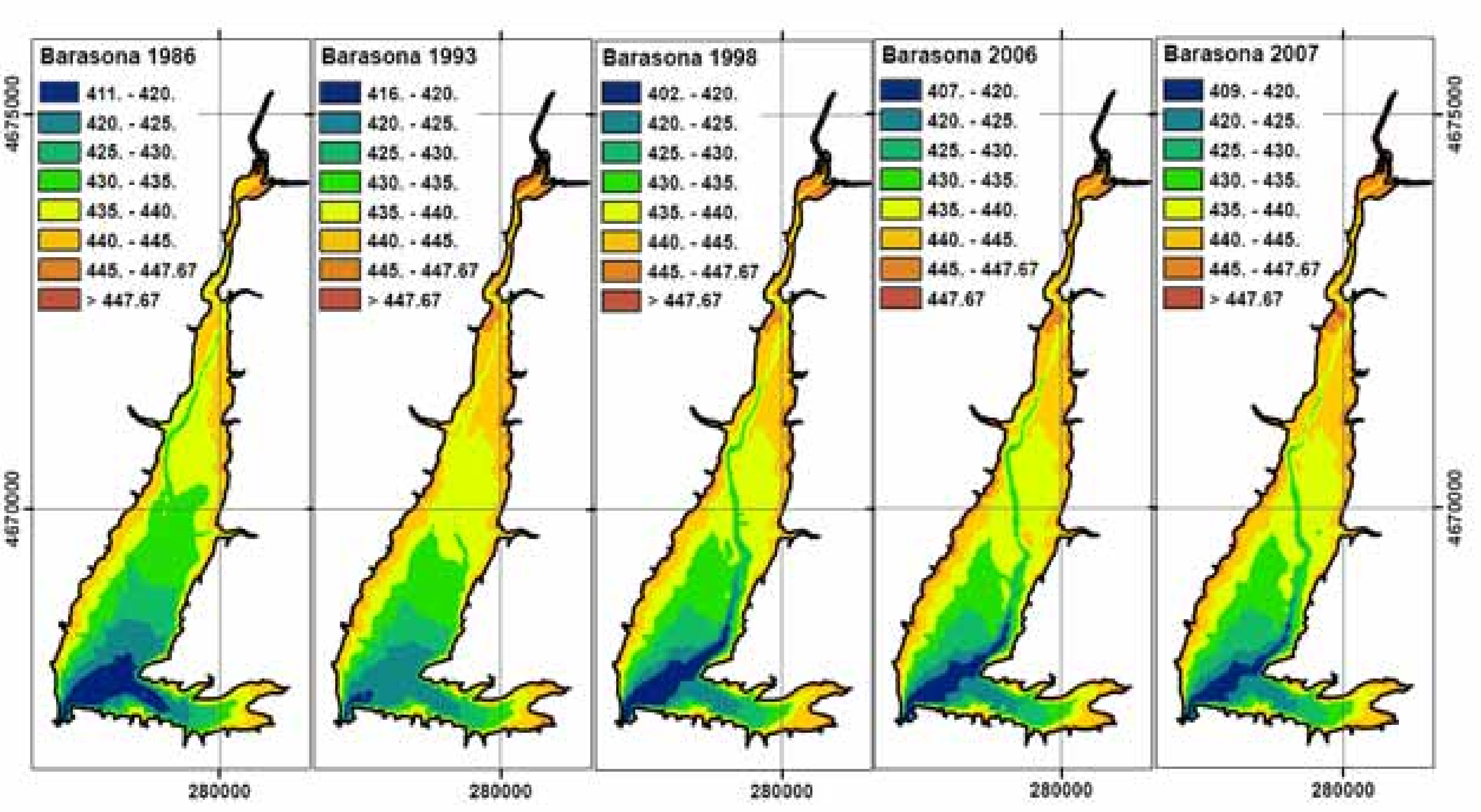
Temporary river storage of sediments


Upstream River Stretch in the Mountains

30 km Downstream Reach in the Lowlands

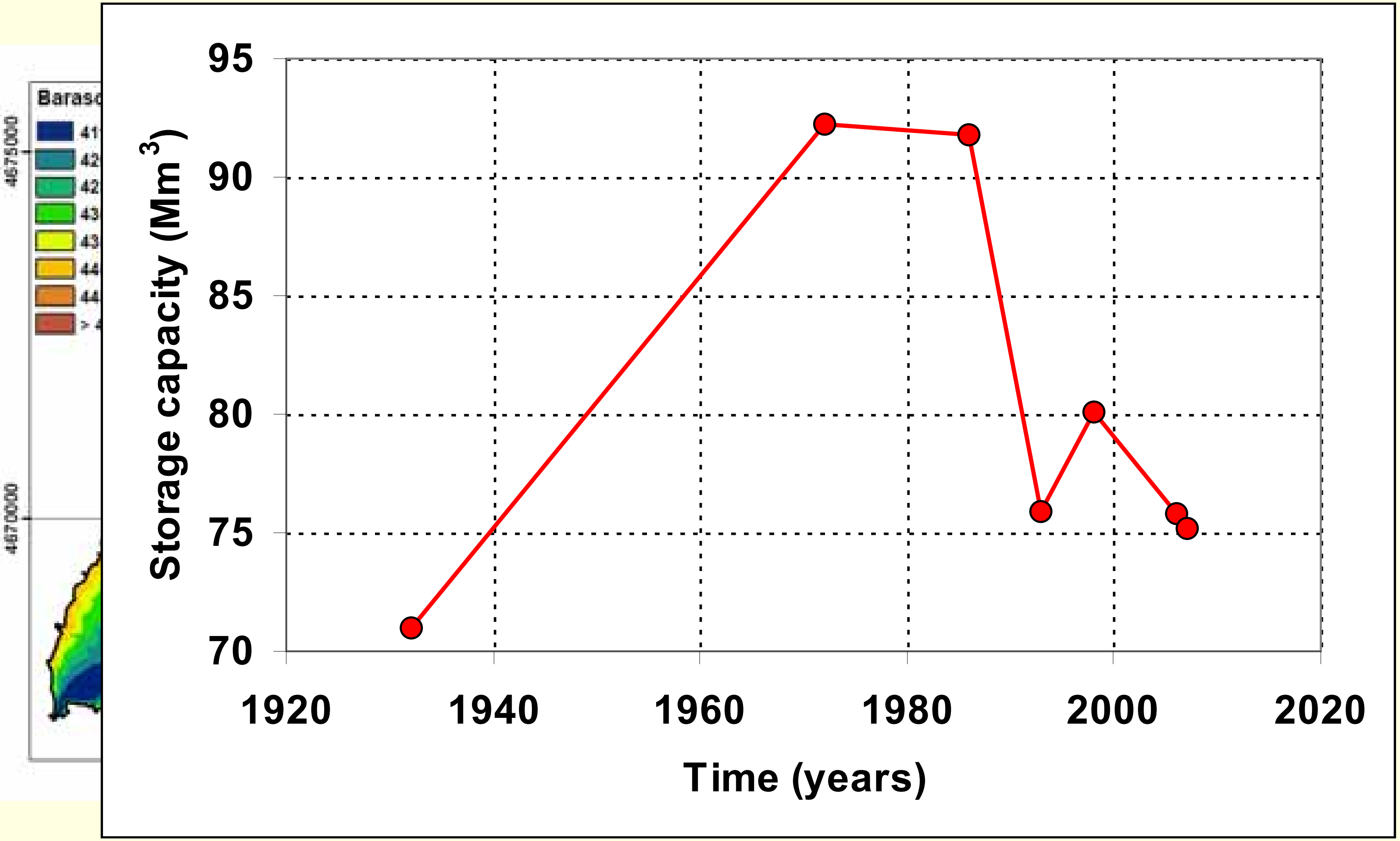
Barasona Reservoir (Spain) (ca. 1340 km^2)

Reservoir Sedimentation



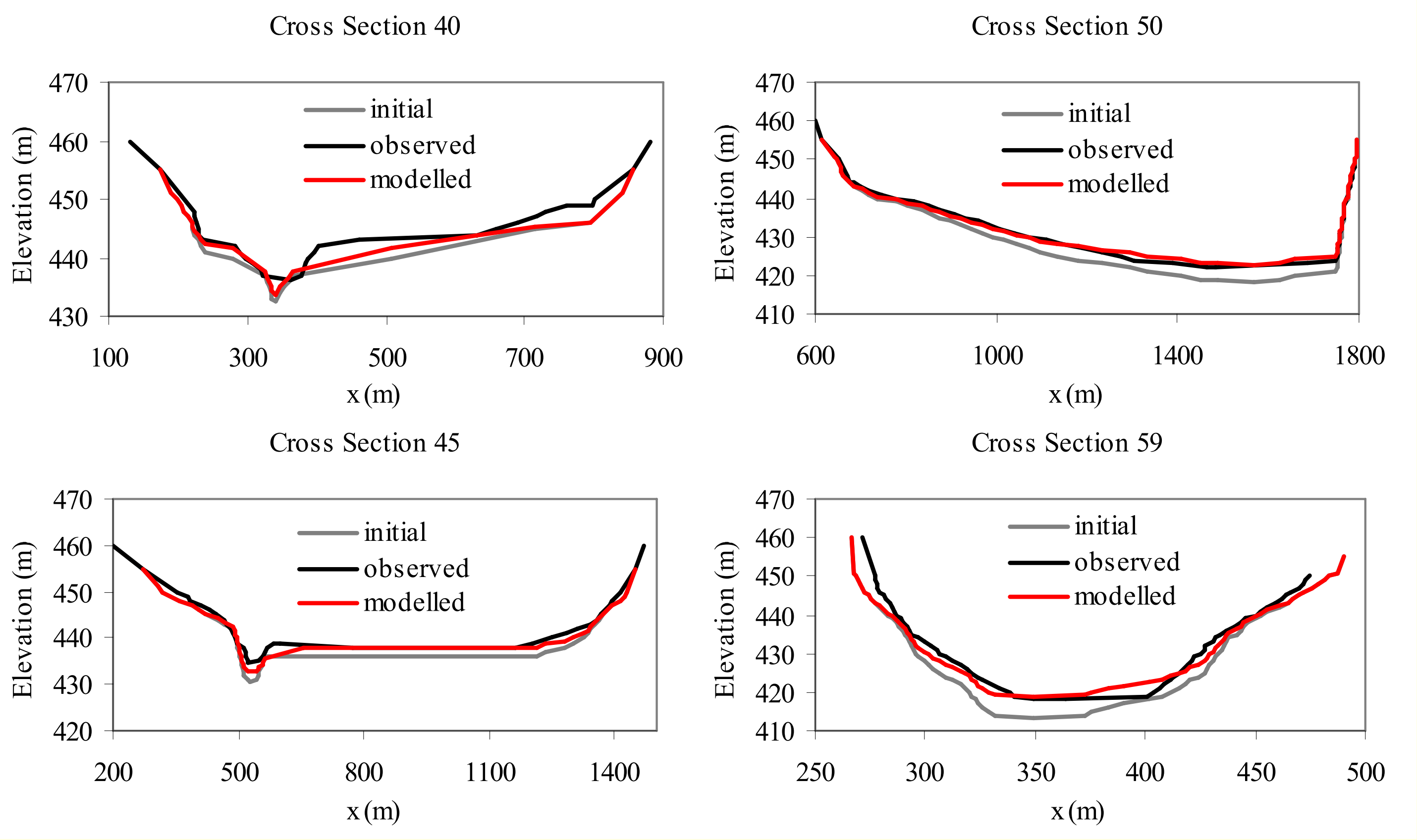
comparison of bathymetric surveys of the Barasona Reservoir, Spain

Reservoir Sedimentation



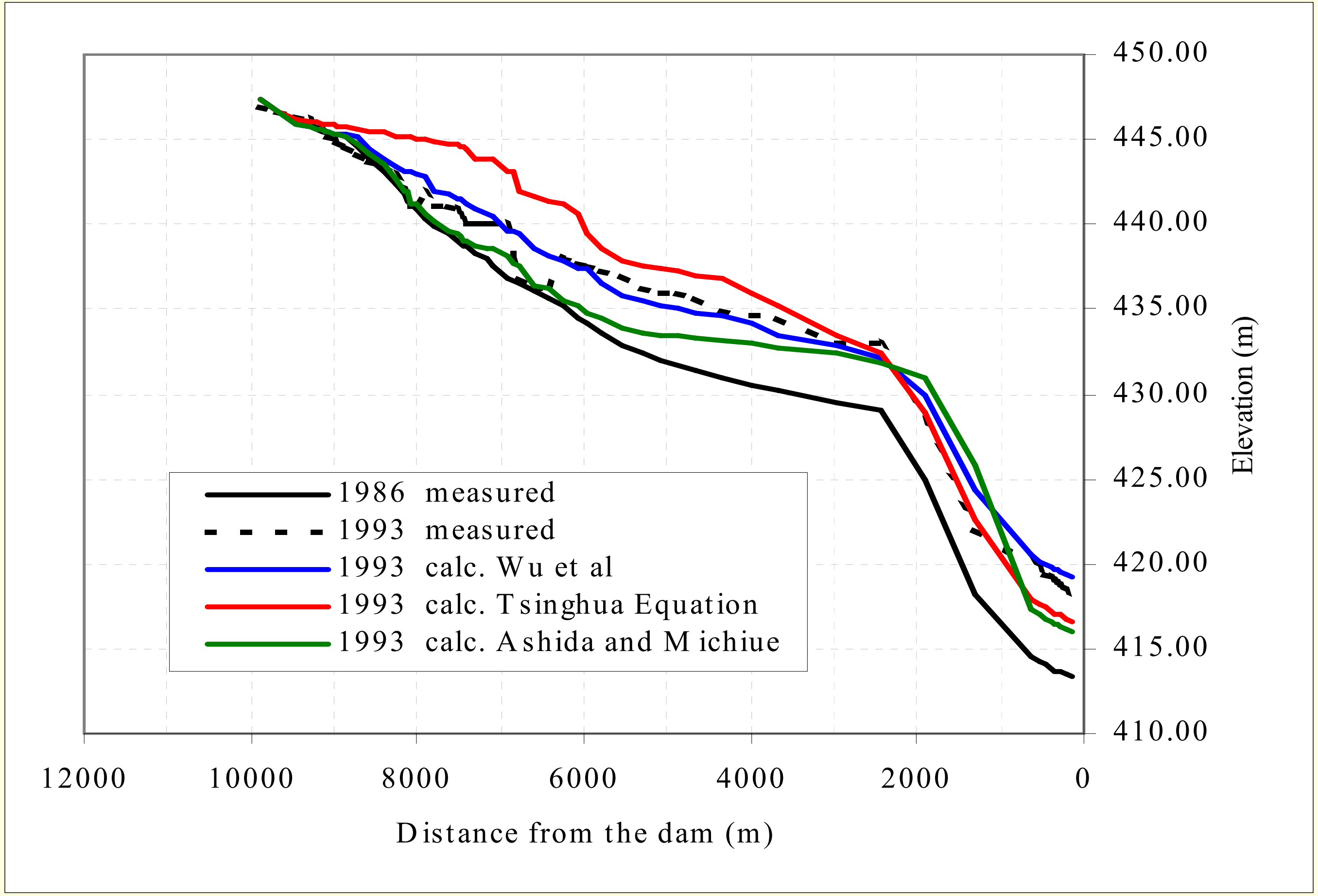
comparison of bathymetric surveys of the Barasona Reservoir, Spain

RESERVOIR Monitoring & Modelling



Bed elevation changes at four different cross sections of the Barasona reservoir, 1986-1993

RESERVOIR Monitoring & Modelling



Deposition patterns of the Barasona Reservoir (1986-1993)

V Conclusions and Outlook

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

V Conclusions and Outlook

- **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

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