Development and testing of improved physically based streambank erosion and sediment routing routines in SWAT

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Outline

- Channel Erosion
- Sediment Routing
  - In SWAT2000 and SWAT2005
- Physically based approach
  - Erosion
  - Transportation
  - Deposition
- Field monitoring and model results

Channel Erosion

- Channel erosion
  - Can account for as much as 85% of total sediment yield of a watershed

Predicted loss in 3 km channel erosion = 1000 years of sheet and rill erosion at pre-conservation agriculture rates

Channel Erosion

- Three major processes
  - Subaerial processes
    - Climate
    - Alternate wet and dry cycles
    - Freeze/Thaw cycles
    - Cracking
  - Fluvial erosion (Hydraulic Erosion)
    - Removal of particles by streamflow
  - Bank Failure
    - Caused due to slope instability

SWAT2000 and 2005

- Simplified Bagnold stream power equation

$$conc_{sed,mx} = spcon \times v_{ch}^{sp_{\exp}}$$

$$sed_{\deg} = (conc_{sed,mx} - conc_{sed,ch}) V_{ch} K_{ch} C_{ch}$$

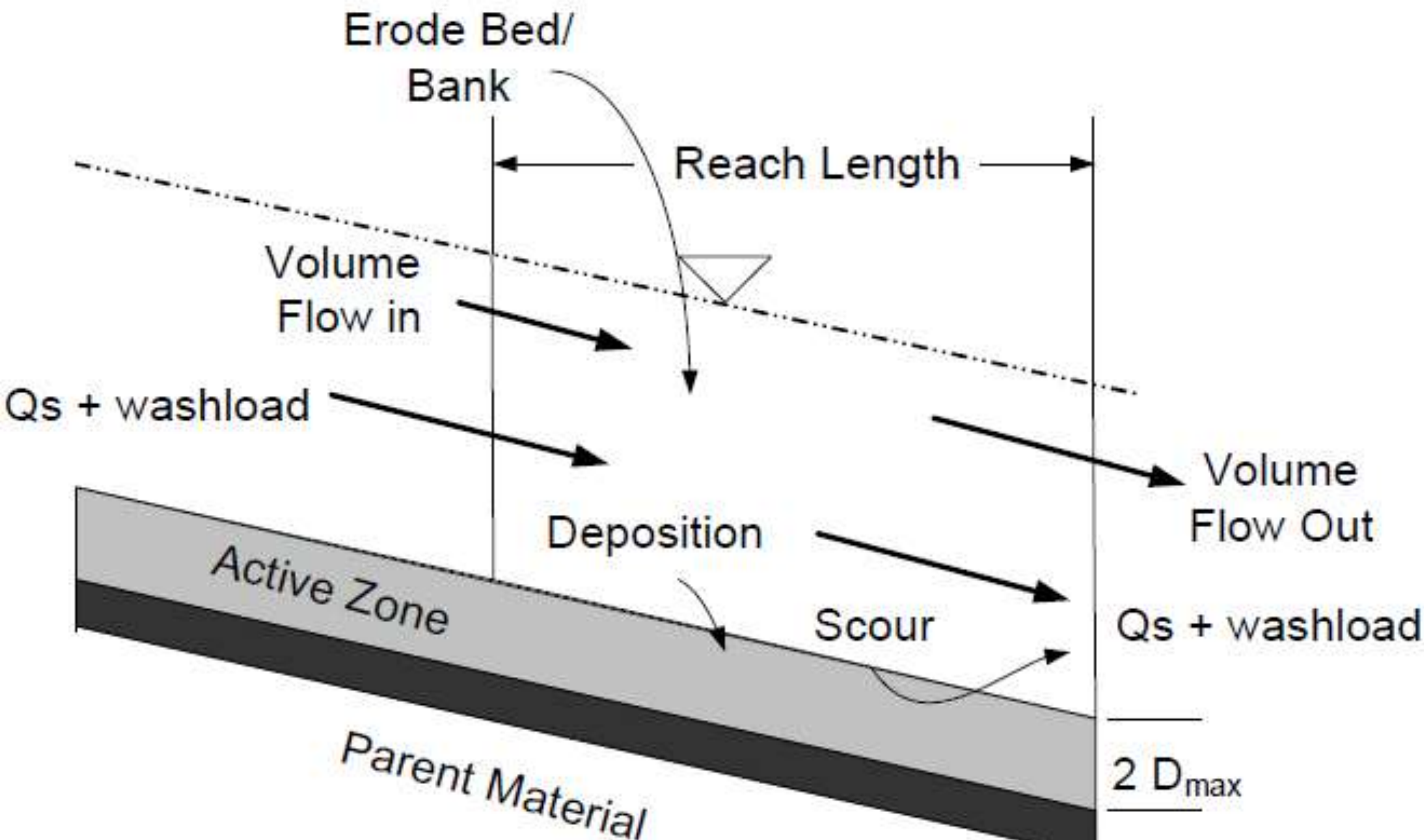
- Channel erosion
  - limited only by the stream power or transport capacity
  - but not by limits on sediment supply from the actual erosion process

SWAT2000 and 2005

- No particle size distribution of eroded sediment
  - No bedload
    - Hence, TSS calculated from sediment yield is often high and not directly comparable with observations

Organic nutrient load

- Are we missing to quantify a significant organic nutrient load from stream bank and attributing the nutrient loads only to overland?
  - Cedar Creek, Texas
    - 8% of orgN and
    - 15% of orgP from channel erosion
    - Channel erosion – 35% of total sediment yield
- Hence, accurate quantification of channel erosion is very important


Erode Bed/
Bank
Reach Length
Volume
Flow in
Qs + washload
Volume
Flow Out
Deposition
Qs + washload
Scour
Active Zone
Parent Material
2 Dmax

Complex Process: Simplify

Fluvial Erosion Process

- For the erosion to occur
  - There should be enough shear stress exerted by the flowing water on stream bank and stream bed to dislodge the sediments
  - The channel should have enough stream power to carry the eroded sediments (overland+channel)
  - Deposition will occur if the sediment transport capacity is low

Wash-load particle size distribution

- Sediment yield from overland (MUSLE) is partitioned using the approach used in CREAMS

$$PSA = (SAN)(1. - CLA)^{2.4}$$

$$PSI = 0.13SIL$$

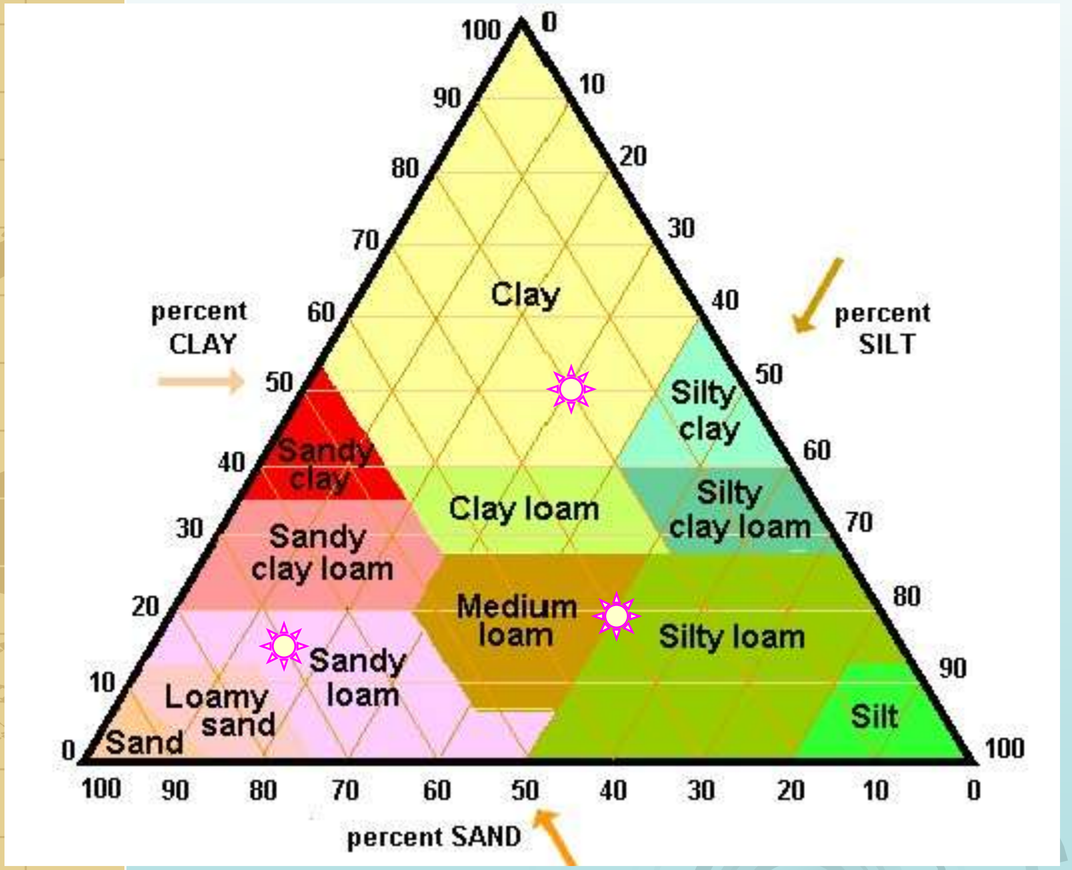
$$PCL = 0.20CLA$$

$$SAG = \begin{cases} 2.0CLA & \text{for CLA} < 0.25 \\ 0.28(CLA - 0.25) + 0.5 & \text{for CLA} \geq 0.25 \text{ CLA} \leq 0.5 \\ 0.57 & \text{for CLA} > 0.5 \end{cases}$$

$$LAG = 1.0 - PSA - PSI - PCL - SAG$$

Stream bank/bed erosion load particle distribution

- Channel bank and bed D50



Shear Stress

- Critical shear stress (τ_c)
  - Soil parameter that governs erosion
- Erosion based on excess shear stress:

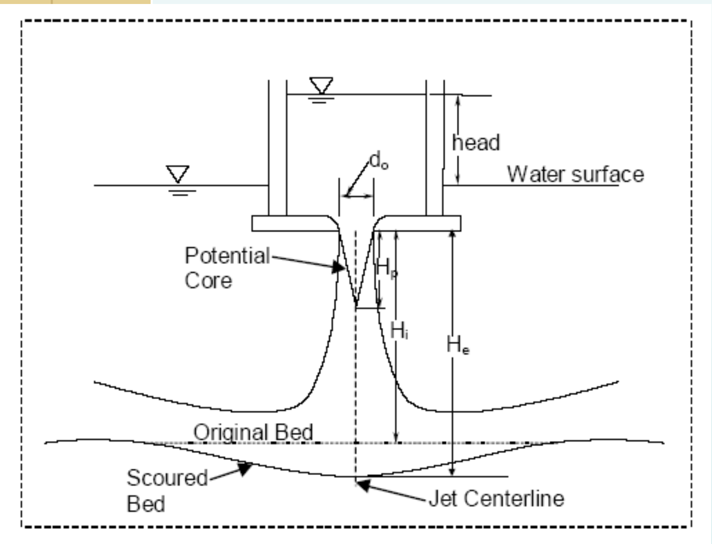
$$\xi_{bank} = k_{d,bank} \cdot (\tau_{e,bank} - \tau_{c,bank})^a \cdot 10^{-6}$$

$$\xi_{bed} = k_{d,bed} \cdot (\tau_{e,bed} - \tau_{c,bed})^a \cdot 10^{-6}$$

- where ξ – erosion rates of the bank and bed (m/s), k_d – erodibility coefficient of bank and bed (cm^3/N-s) and τ_c – Critical shear stress acting on bank and bed (N/m^2).

Critical Shear Stress and Erodibility Coefficient

- Submerged Jet Test (Hanson and Cook, 1997; Hanson and Simon, 2001)



Hanson and Simon, 2001

- Erodibility calculated as a function of jet index

$$k = 0.003e^{385J_i}$$

  - J_i – Jet index (depth of scour hole made by

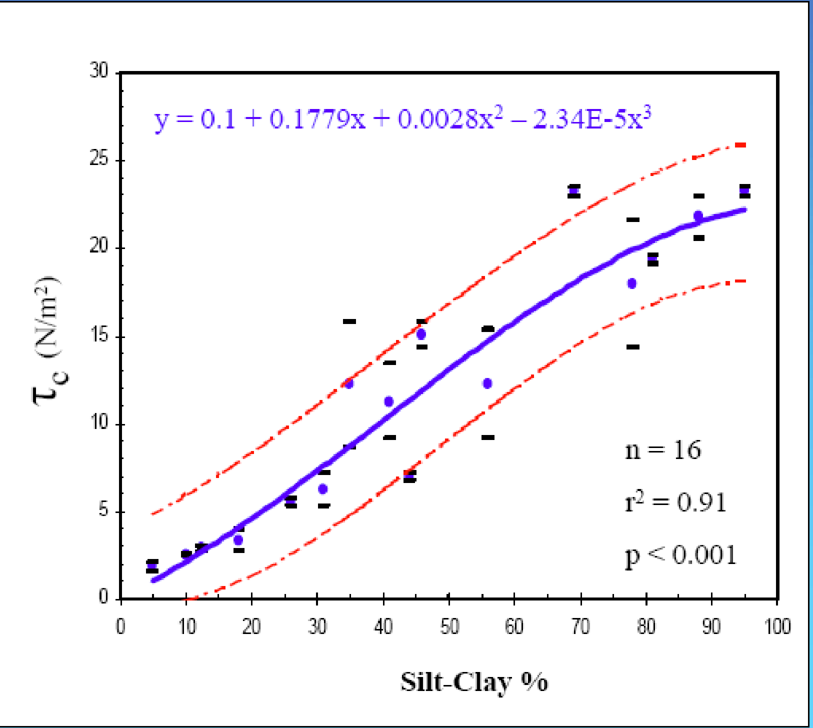
$$\tau_c = 0.16(I_w)^{0.84}$$

- I_w – Plasticity Index

Empirical Equation for τ_c

Critical Shear Estimates

Soil Composition



data from Dunn (1959)

Vegetation

Type / Density	τ_c coefficient
None	1
Ivy / Sparse	1.5
Ivy / Dense	2.5
Privet / Sparse	5.4
Privet / Dense	19.2

derived from Huang and Nanson (1998)

Range mostly between:
0 and 100 N/m^2
But could go as
High as 400 N/m^2

Julian and Torres, 2001

Shear Stress

- Effective shear stress based on channel hydraulics: (Eaton and Millar, 2004)

$$\frac{\tau_{e,bank}}{\gamma \cdot depth \cdot slp_{ch}} = \frac{SF_{bank}}{100}\left(\frac{(W + P_{bed}) \cdot \sin\theta}{4 \cdot depth}\right)$$

$$\frac{\tau_{e,bed}}{\gamma_w \cdot depth \cdot slp_{ch}} = \left(1 - \frac{SF_{bank}}{100}\right)\left(\frac{W}{2 \cdot P_{bed}} + 0.5\right)$$

$$\log SF_{bank} = -1.4026 \cdot \log\left(\frac{P_{bed}}{P_{bank}} + 1.5\right) + 2.247$$

Empirical Equation for K_d

- Erodibility Coefficient, K_d: (Temple and Hanson, 1994; Zhu et al. 2006)

$$K_d = 0.0034 \cdot \exp\left(\frac{0.0176}{M_e}\right)$$

$$M_e = \frac{\left((s-1)\cdot 9.8 \cdot D_{50}\right)^{0.5}}{(s-1)^3 \cdot C}$$

$$C = 4.14 \cdot (Clay\%)^{-0.91}$$

Where s is relative density of sediment

Range mostly between 0 and 0.01 cm^3/N-s but could go
As high as 3.75 cm^3/N-s for highly erodible material

Stream Power/Transport Capacity

- Four new transport equations
  - Simplified Bagnold Equation
    - Silt type bed material

$$conc_{sed,mx} = spcon \times v_{ch}^{sp_{\exp}}$$

  - Kodatie model
    - Silt to gravel size bed materials
  - Molinas and Wu model
    - Large sand bed rivers
  - Yangs sand and gravel model
    - Sand and gravel bed material

Kodatie Model

- Kodatie (2000)

$$conc_{sed,ch.mx} = \left(\frac{a \cdot v_{ch}{}^{b} \cdot y^{c} \cdot S^{d}}{Q_{in}} \right) \cdot \left(\frac{W + W_{btm}}{2} \right)$$

a, b, c and d coefficients depend on D_{50}

Table 7:2-2. Regression coefficients for Kodatie equation

	a	b	c	d
Silt-bed rivers (D_{50}* ≤ 0.05 mm)	281.4	2.622	0.182	0
Very fine to fine-bed river (0.05 mm < D_{50} ≤ 0.25 mm)	2,829.6	3.646	0.406	0.412
Medium to very coarse sand-bed rivers (0.25 mm < D_{50} ≤ 2 mm)	2,123.4	3.300	0.468	0.613
Gravel-bed rivers (D50 > 2mm)	431,884.8	1.000	1.000	2.000

*D_{50} – median bank/bed-sediment size

Molinas and Wu Model

- Molinas and Wu (2001):

$$C_w = \frac{1430 \cdot \left(0.86 + \sqrt{\psi}\right) \cdot \psi^{1.5}}{0.016 + \psi} \cdot 10^{-6}$$

$$\psi = \frac{v_{ch}{}^3}{(S_g - 1) \cdot g \cdot depth \cdot \omega_{50} \cdot \left[\log_{10}\left(\frac{depth}{D_{50}}\right)\right]^2}$$

$$\omega_{50} = \frac{411 \cdot D_{50}{}^2}{3600}$$

$$conc_{sed,ch.mx} = \frac{C_w}{C_w + (1 - C_w) \cdot S_g} \cdot S_g$$

Yangs Sand and Gravel Model

- Sand equation: (D_{50} less than 2mm):

$$\log C_w = 5.435 - 0.286 \log \frac{\omega_{50} D_{50}}{\upsilon} - 0.457 \log \frac{V_*}{\omega_{50}} + \left(1.799 - 0.409 \log \frac{\omega_{50} D_{50}}{\upsilon} - 0.314 \log \frac{V_*}{\omega_{50}}\right) \log\left(\frac{\nu_{ch} S}{\omega_{50}} - \frac{V_{cr} S}{\omega_{50}}\right)$$

- Gravel equation: (D_{50} between 2mm and 10mm)

$$\log C_w = 6.681 - 0.633 \log \frac{\omega_{50} D_{50}}{\upsilon} - 4.816 \log \frac{V_*}{\omega_{50}} + \left(2.784 - 0.305 \log \frac{\omega_{50} D_{50}}{\upsilon} - 0.282 \log \frac{V_*}{\omega_{50}}\right) \log\left(\frac{\nu_{ch} S}{\omega_{50}} - \frac{V_{cr} S}{\omega_{50}}\right)$$

Selecting the appropriate model

Model	Gravel	Sand	Very Fine sand and silt
Bagnold		X	X
Kodatie	X	X	X
Molinas and Wu		X	
Yangs	X	X	

Deposition

- If the sediment concentration in the channel is more than the transport capacity then deposition occurs:
- Einstein equation (1965):

$$Dep_{fract} = \left(1 - \frac{1}{e^x}\right)$$

$$x = \frac{1.055 \cdot L_{ch} \cdot \omega_{50}}{v_{ch} \cdot depth}$$

$$\omega_{50} = \frac{411 \cdot D_{50}{}^2}{3600}$$

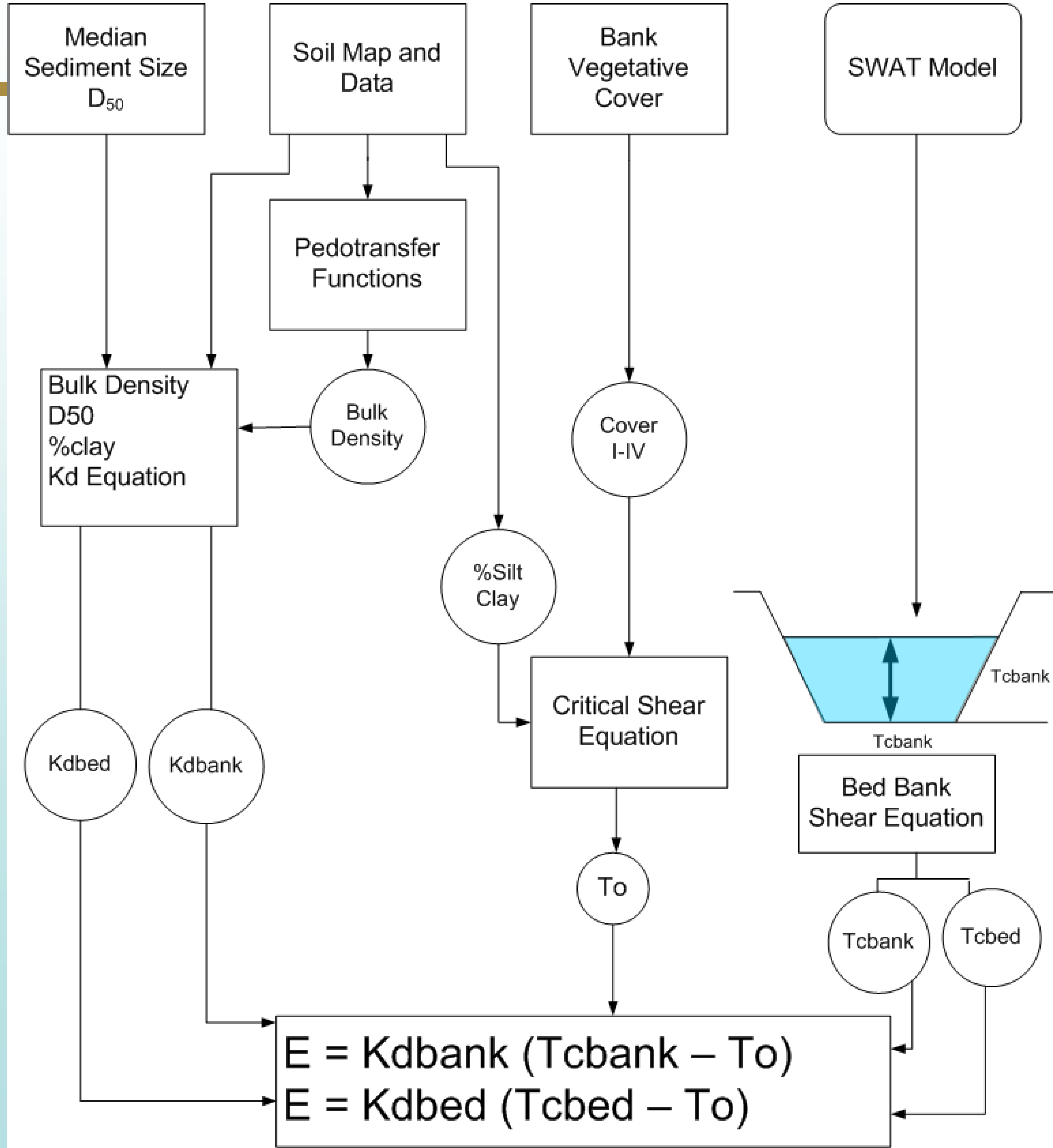
- Flood plain deposition
  - If the streamflow goes overbank

Excess transport capacity

$$SedEx = V_{ch} \cdot \left(conc_{sed,ch.mx} - conc_{sed,ch.i} \right)$$

- Excess sediment beyond transport capacity is also deposited
- But the channel is eroded only based on excess shear stress and not the available transport capacity
  - Bank scour always occurs when excess shear stress is available
  - Bed scour occurs only after all the deposited bed materials are scoured

Channel Erosion Procedure



Study Area

- Kings Creek Watershed

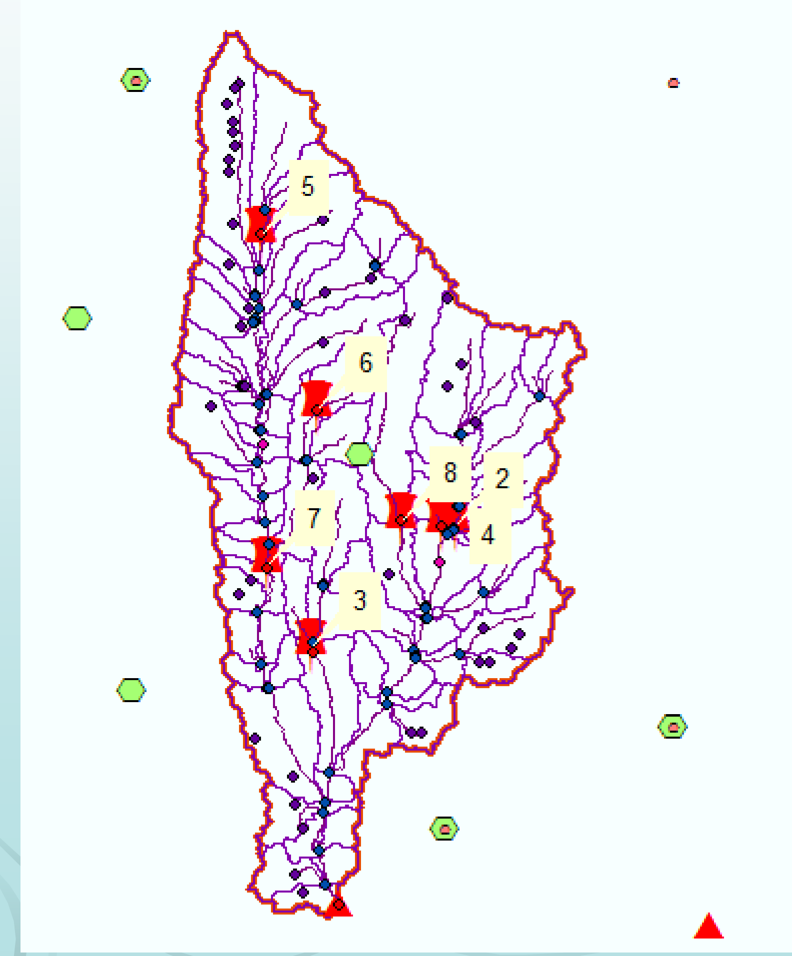
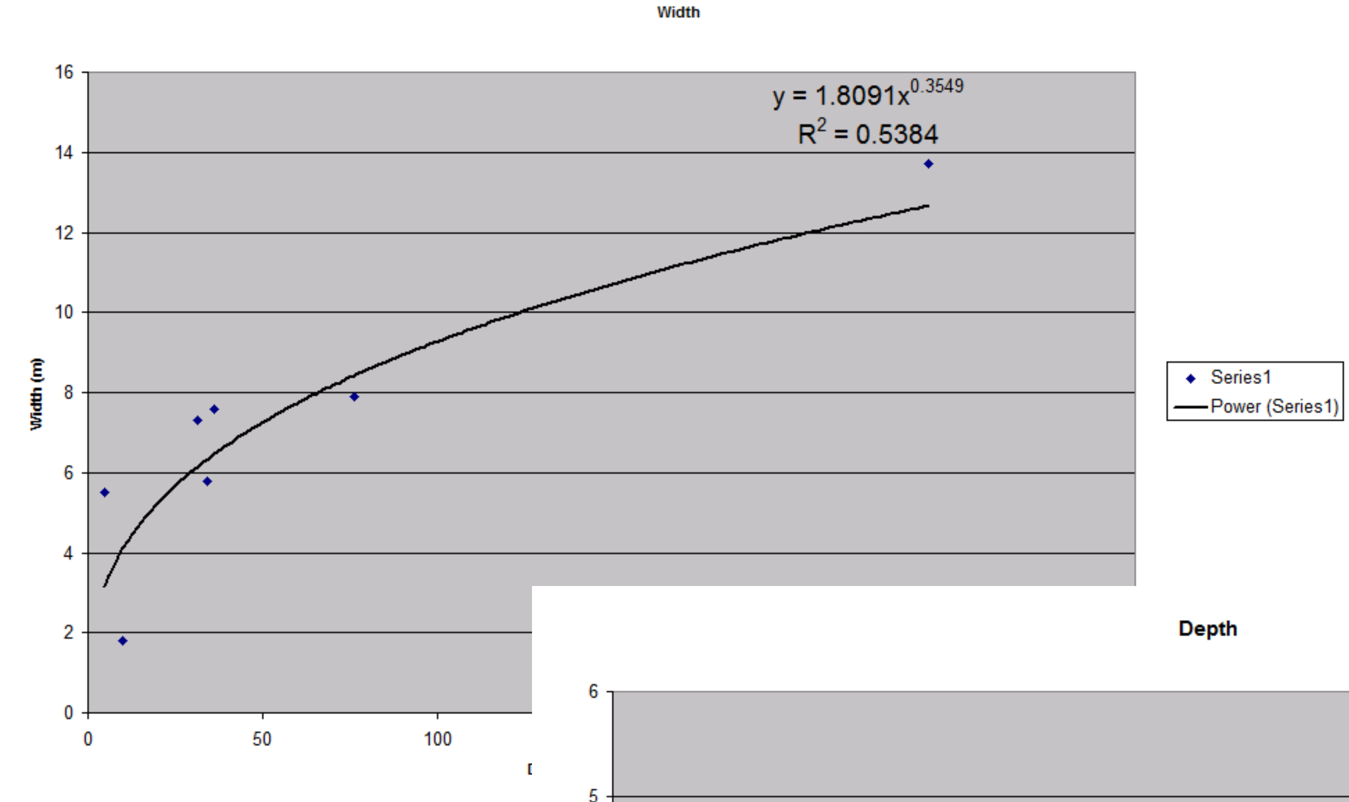


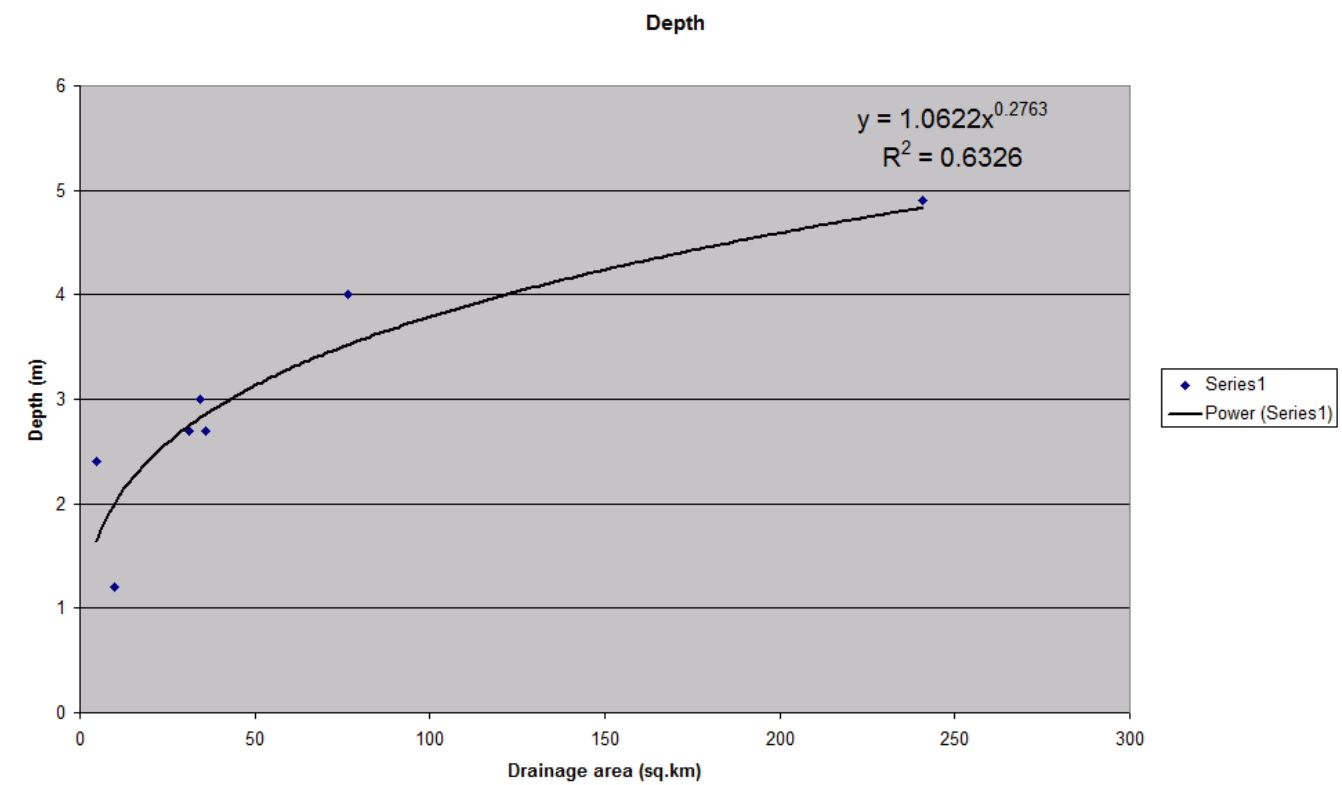
Figure 8. Photograph of the upper and lower bank erosion pin locations shown in yellow, spaced 1 m apart after Zaimes et al. 2005.

Field Data Collection

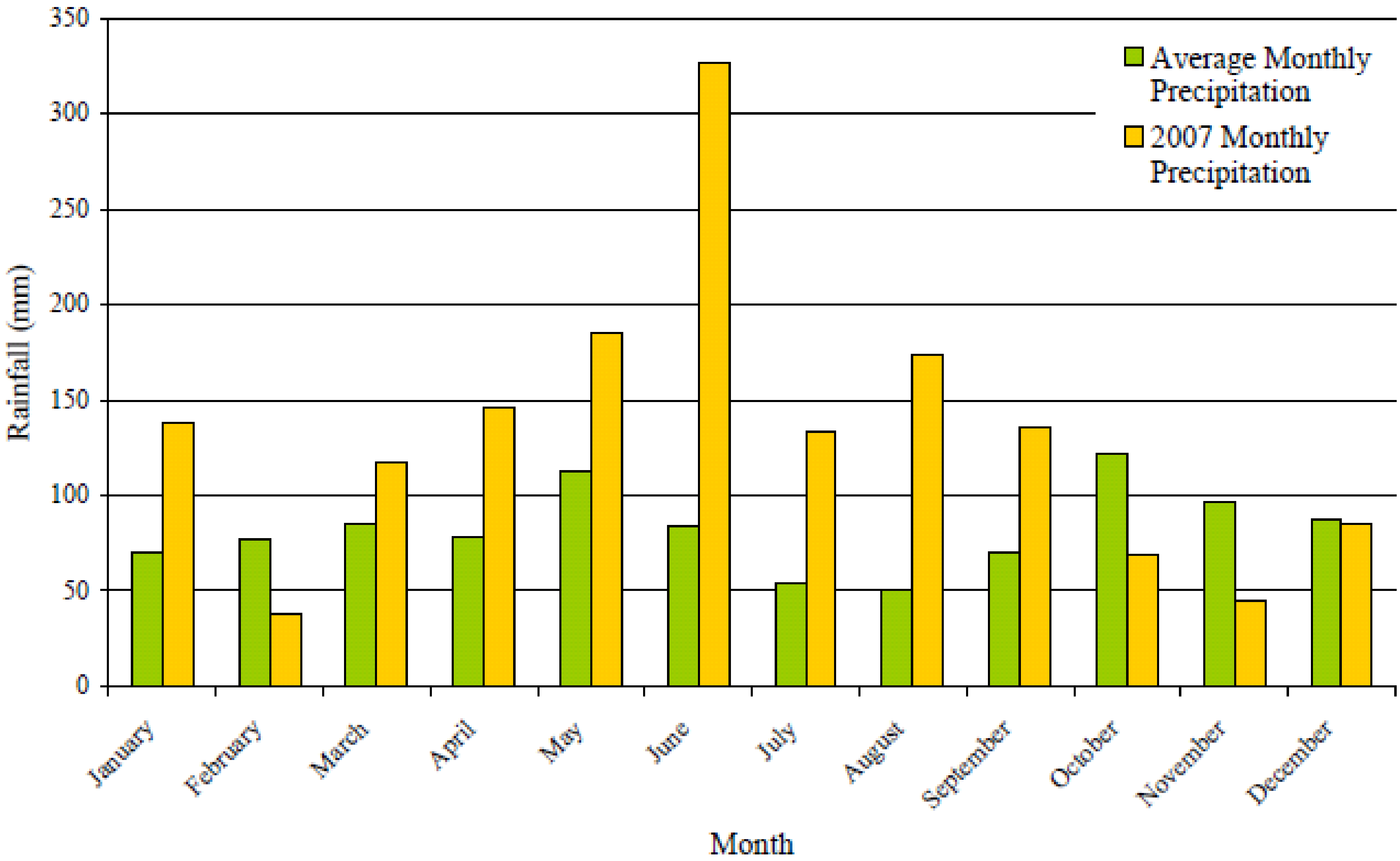
- Stage height
- Erosion rate (mm/event)
- Channel dimension
- Particle size distribution
- Submerged jet test
  - Erodibility
- Period: 2007



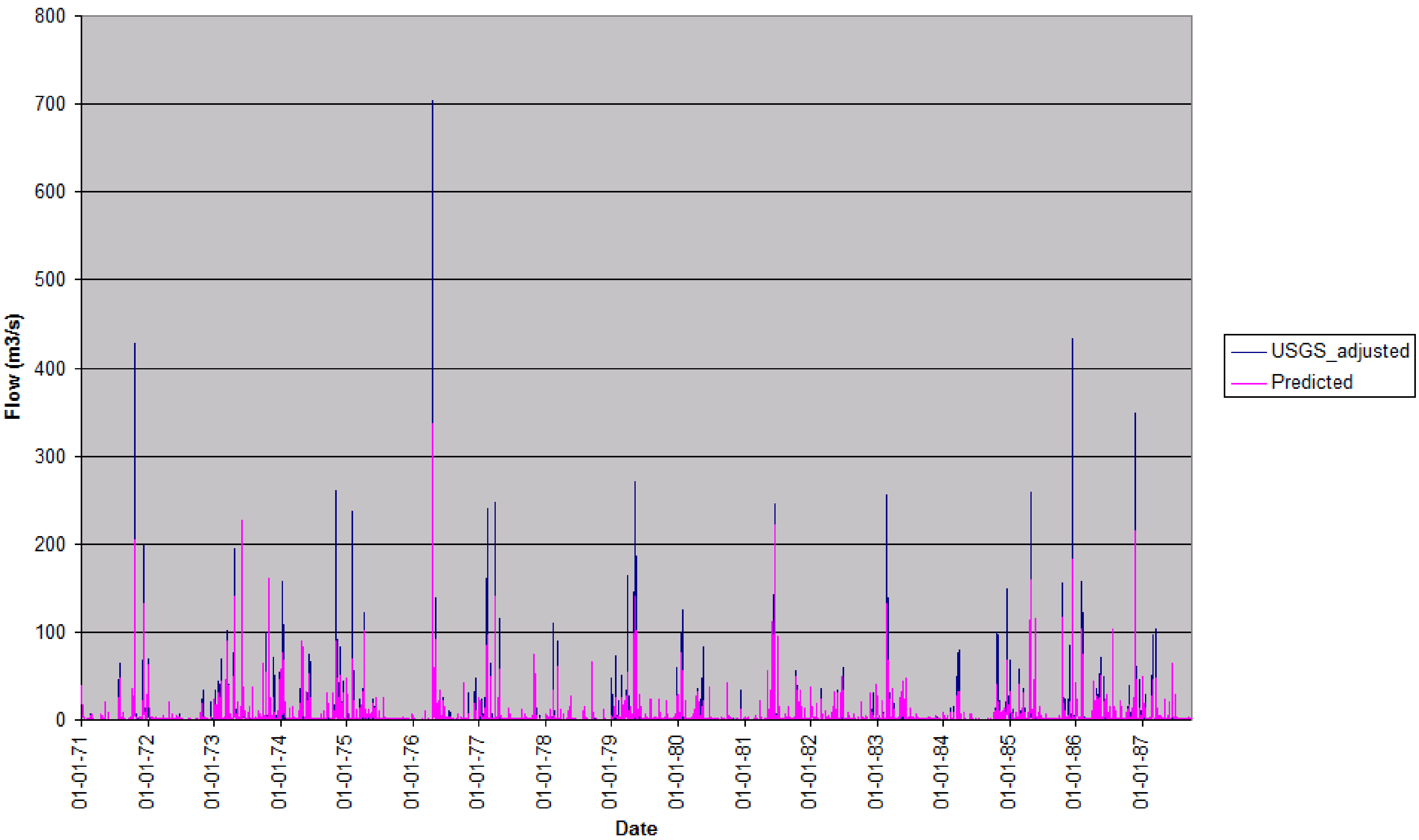
Width
y = 1.8091x^0.3549
R2 = 0.5384
Width (m)
Series1
Power (Series1)

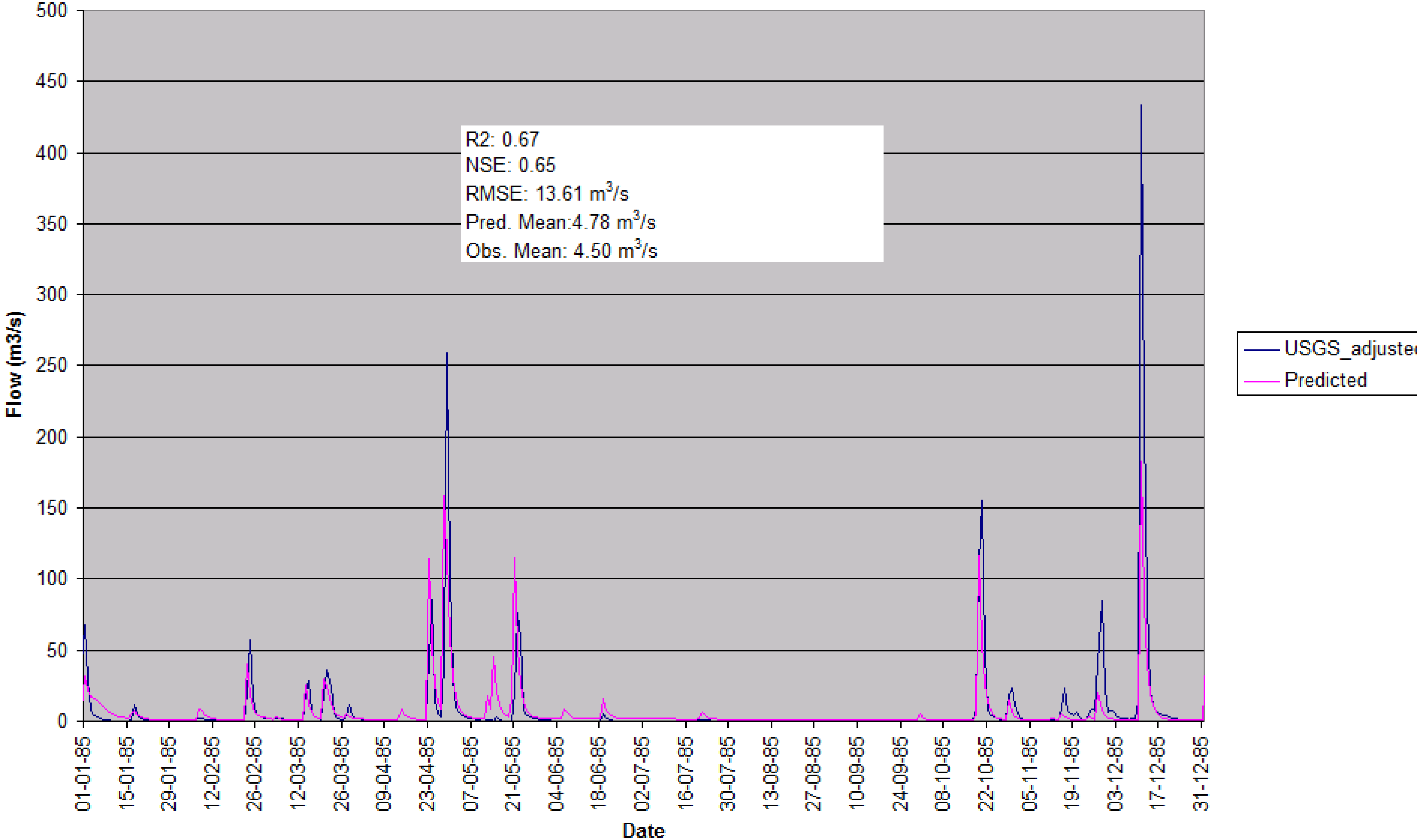


Depth
y = 1.0622x^0.2763
R2 = 0.6326
Depth (m)
Drainage area (sq.km)
Series1
Power (Series1)


Average Monthly Precipitation
2007 Monthly Precipitation
Rainfall (mm)
350
300
250
200
150
100
50
0
January
February
March
April
May
June
July
August
September
October
November
December
Month

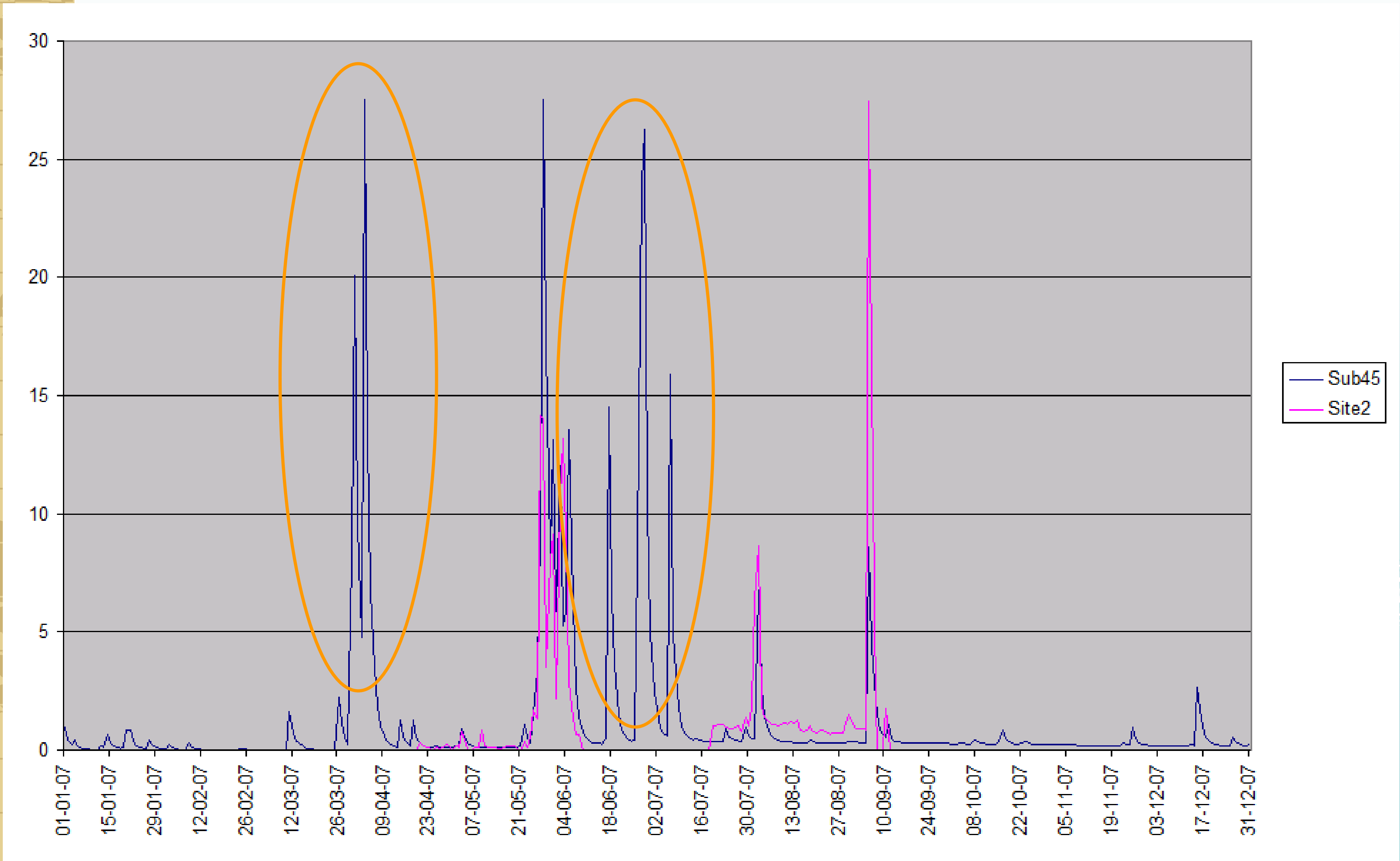
Flow Calibration (1971-1987)



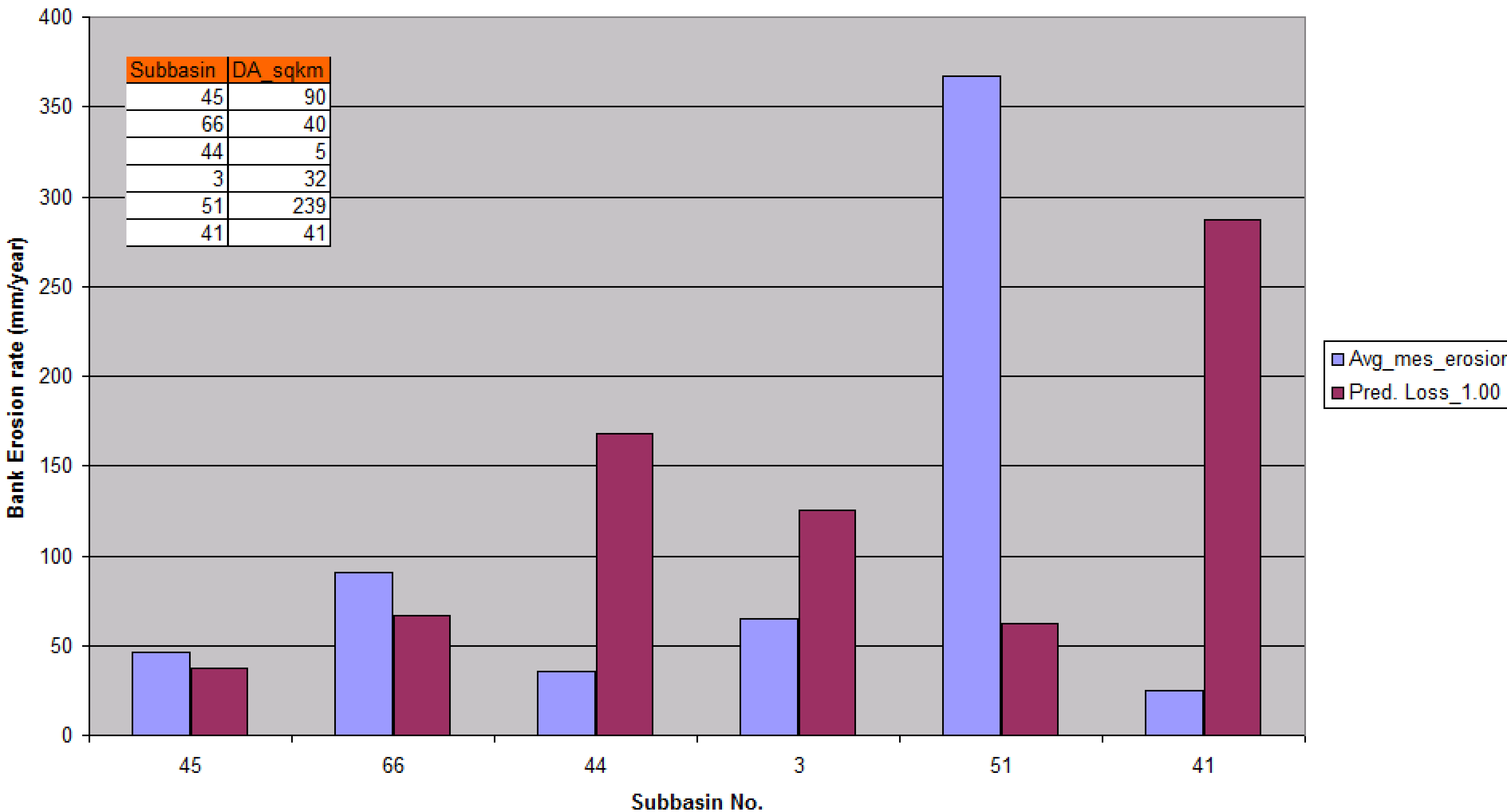


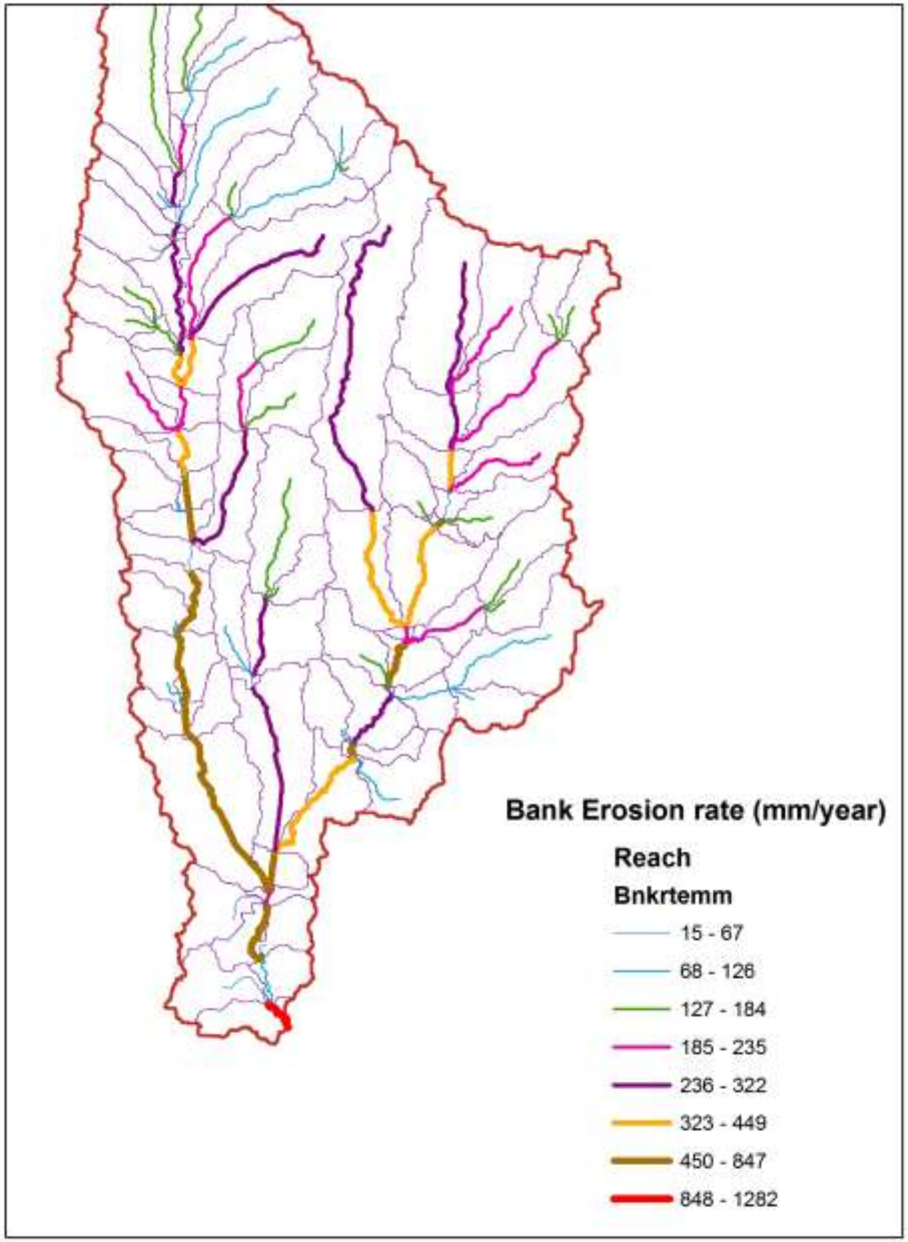
R2: 0.67
NSE: 0.65
RMSE: 13.61 m3/s
Pred. Mean:4.78 m3/s
Obs. Mean: 4.50 m3/s
Flow (m3/s)
Date
USGS_adjuste
Predicted
500
450
400
350
300
250
200
150
100
50
0
01-01-85
15-01-85
29-01-85
12-02-85
26-02-85
12-03-85
26-03-85
09-04-85
23-04-85
07-05-85
21-05-85
04-06-85
18-06-85
02-07-85
16-07-85
30-07-85
13-08-85
27-08-85
10-09-85
24-09-85
08-10-85
22-10-85
05-11-85
19-11-85
03-12-85
17-12-85
31-12-85

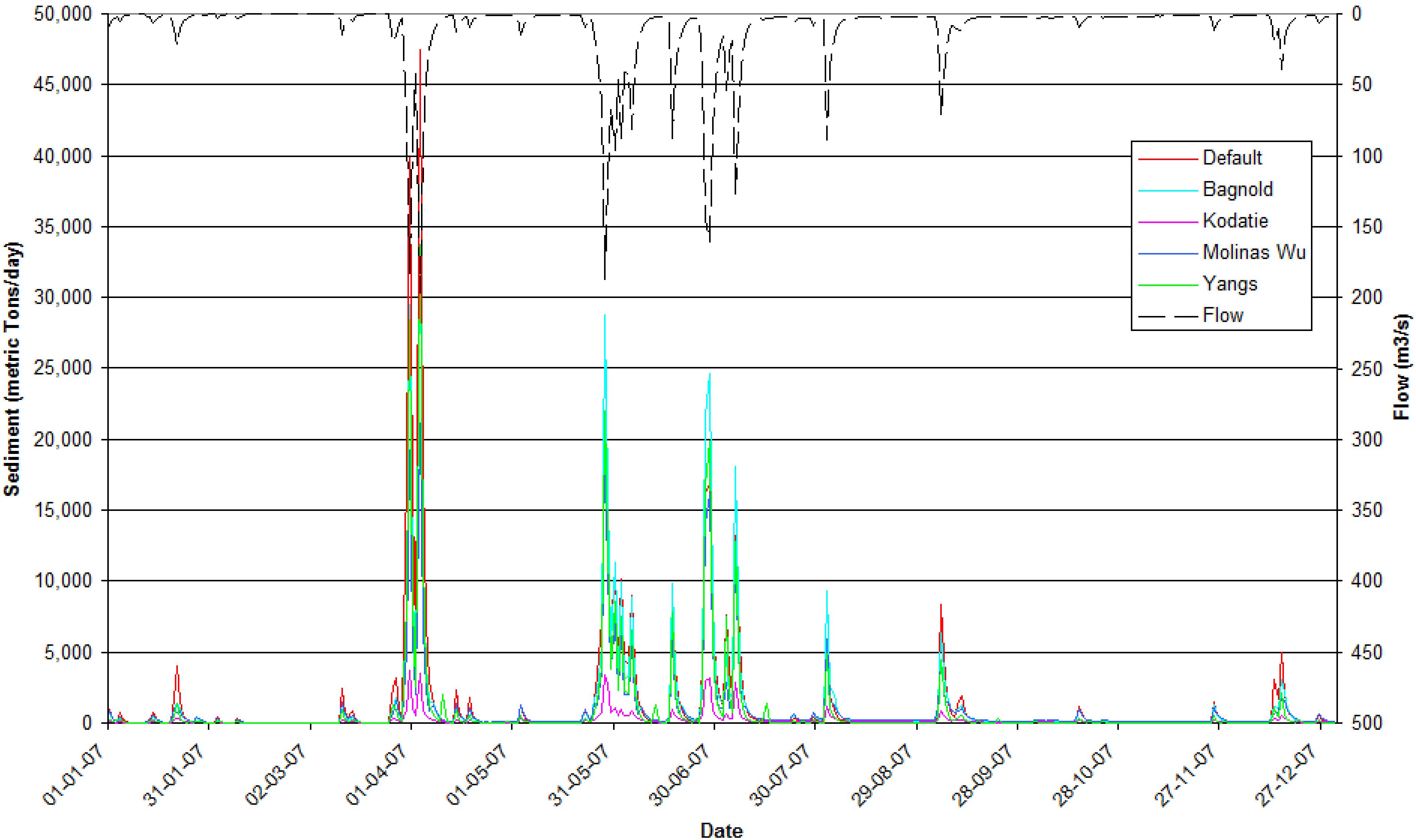
Flow Validation (2007)



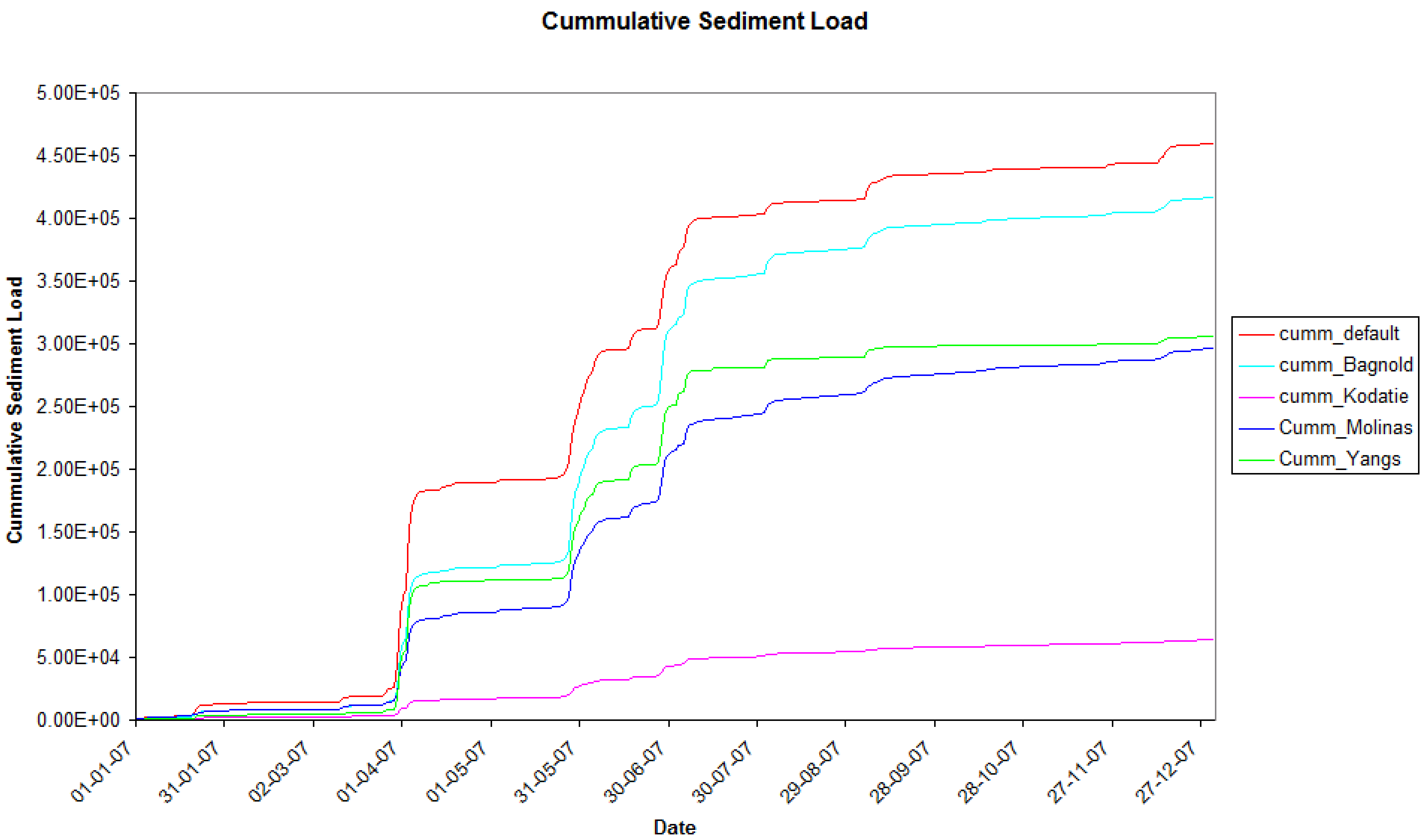
2007 Bank Erosion Rate



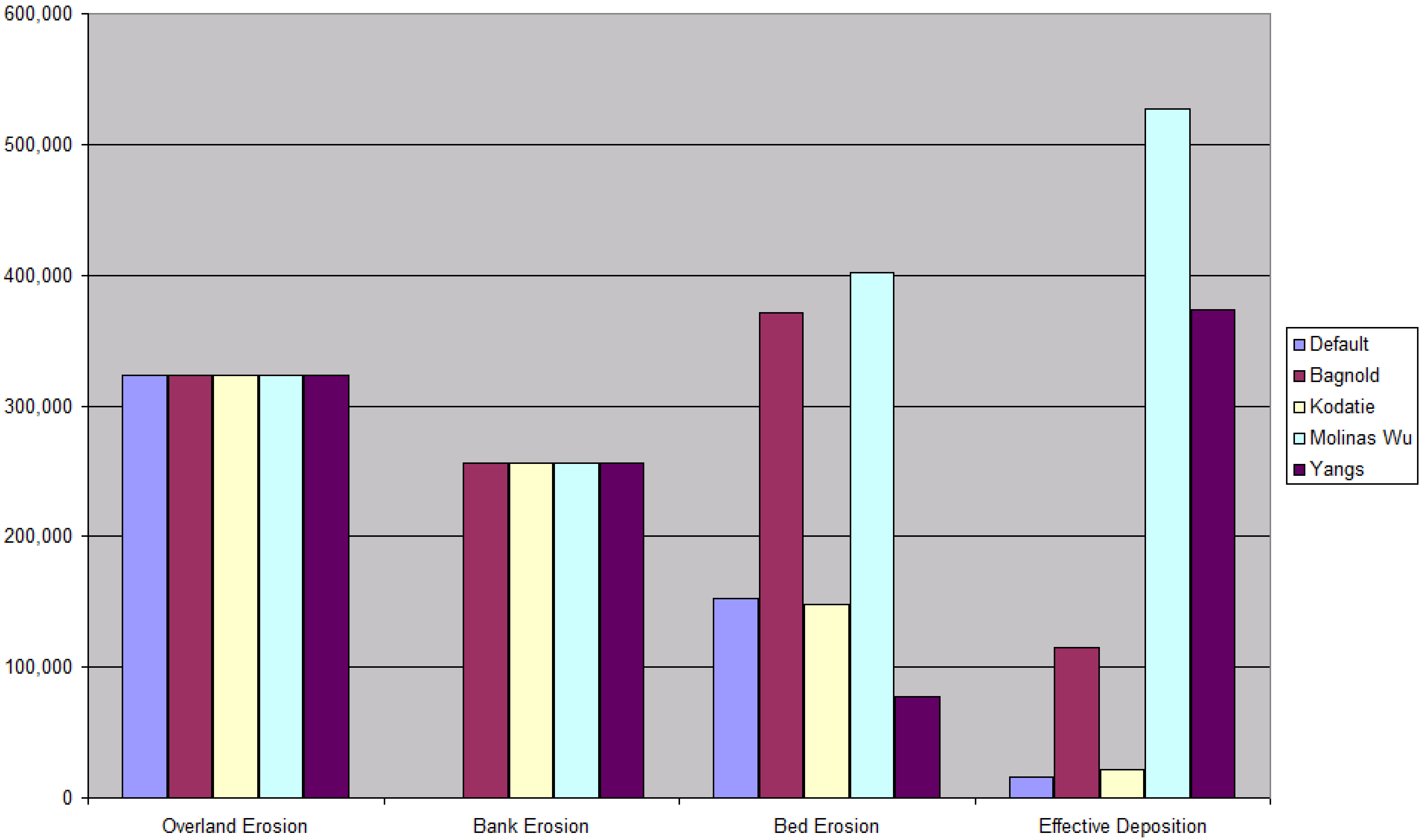

Bank Erosion rate (mm/year)
Reach
Bnkrtemm
15 - 67
68 - 126
127 - 184
185 - 235
236 - 322
323 - 449
450 - 847
848 - 1282



Sediment (metric Tons/day)
Flow (m3/s)
Date
50,000
45,000
40,000
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0
0
50
100
150
200
250
300
350
400
450
500
01-01-07
31-01-07
02-03-07
01-04-07
01-05-07
31-05-07
30-06-07
30-07-07
29-08-07
28-09-07
28-10-07
27-11-07
27-12-07
Default
Bagnold
Kodatie
Molinas Wu
Yangs
Flow



Cummulative Sediment Load
Cummulative Sediment Load
5.00E+05
4.50E+05
4.00E+05
3.50E+05
3.00E+05
2.50E+05
2.00E+05
1.50E+05
1.00E+05
5.00E+04
0.00E+00
01-01-07
31-01-07
02-03-07
01-04-07
01-05-07
31-05-07
30-06-07
30-07-07
29-08-07
28-09-07
28-10-07
27-11-07
27-12-07
Date
cumm_default
cumm_Bagnold
cumm_Kodatie
Cumm_Molinas
Cumm_Yangs


600,000
500,000
400,000
300,000
200,000
100,000
0
Overland Erosion
Bank Erosion
Bed Erosion
Effective Deposition
Default
Bagnold
Kodatie
Molinas Wu
Yangs

Model Inputs

- Default model
  - spcon, spexp, CH_cov, CH_Erod
- Physically based models
  - D50 – Median particle size of bank and bed material
  - Cover factor of bank and bed
  - Critical shear stress of bank and bed
    - If not given, calculated based on SC% and cover
  - Erodibility coefficient of bank and bed
    - If not given, calculated based on SC%
  - Bulk density of bank and bed
    - If not given, calculated based on SC%
  - Particle size distribution of bank and bed material
    - Assumed based on the D50 size

Model Output

- File name: output.sed
- Default
  - Total sediment
  - Bed erosion, deposition, TSS
- Physically based models
  - Total sediment
    - Sand, silt, clay, SAGG, LAGG, gravel
  - Bank erosion
  - Bed erosion
  - Channel deposition / Flood plain deposition
    - Total remaining in deposits at the end of the time step
  - TSS
    - Only based on silt and clay particles

Conclusion

- Already most of the code is available in the present release
- Few changes are being made to represent the mass balance in a better way
- Detailed calibration and validation study is underway to evaluate the new routines
- New Components
  - Active channel eroding length based on channel sinuosity
  - Effect of alternate wetting and drying on erodibility

Thank You