Watershed Processes and Modeling

Pierre Y. Julien

Department of Civil Engineering
Colorado State University
Fort Collins, Colorado

River Mechanics Course
Lima Peru – January 2016

Colorado State University
Knowledge to Go Places

Objectives

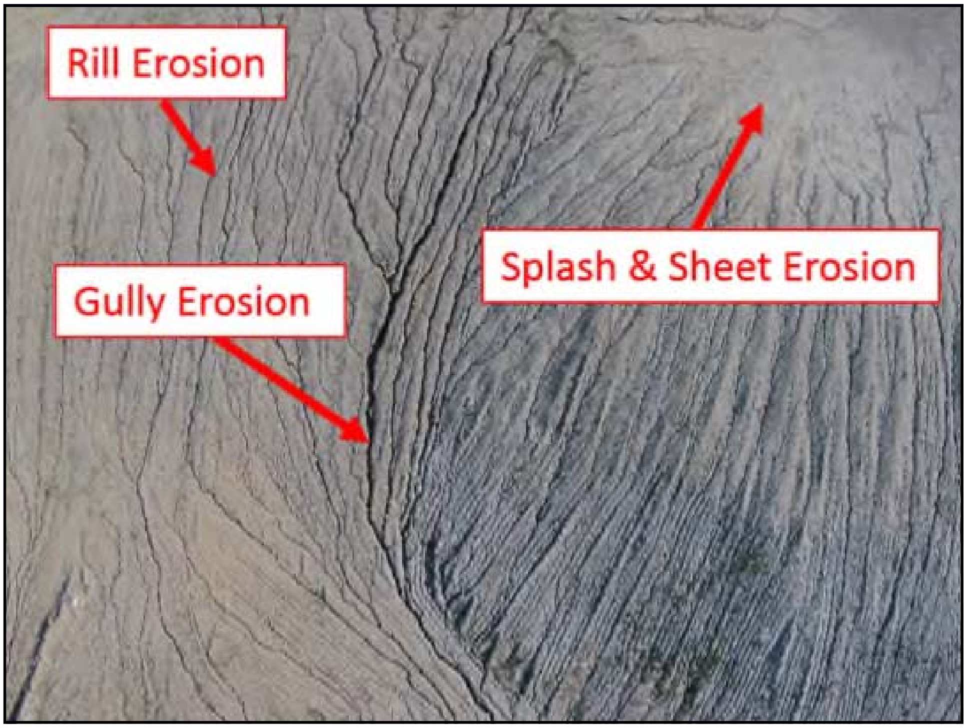
Brief overview of catchment modeling and trap efficiency of reservoirs:

1. Upland Erosion Modeling;
2. Dynamic Watershed Modeling;
3. Modeling of Naesung Stream, South Korea;
4. Sediment Yield;
5. Case Study in Haiti.

1. Upland Erosion Modeling

PROBLEM: Upland Erosion

Introduction



PROBLEM: ... and Deposition

Introduction

RUSLE

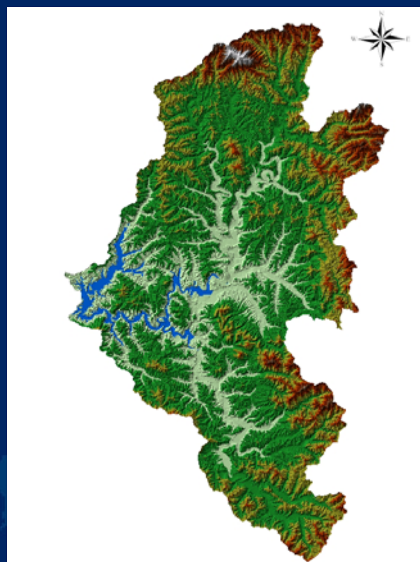
- **Revised Universal Soil Loss Equation**
- **Widely used method for estimating soil erosion**
- **The original USLE is an empirical equation**
  1. Derived from more than 10,000 plot years of data
  2. Natural runoff plots (72.6ft length, 9% slope)
- **Originally developed for agricultural purpose.**

Main parameters

$$A = R\ K\ L\ S\ C\ P$$

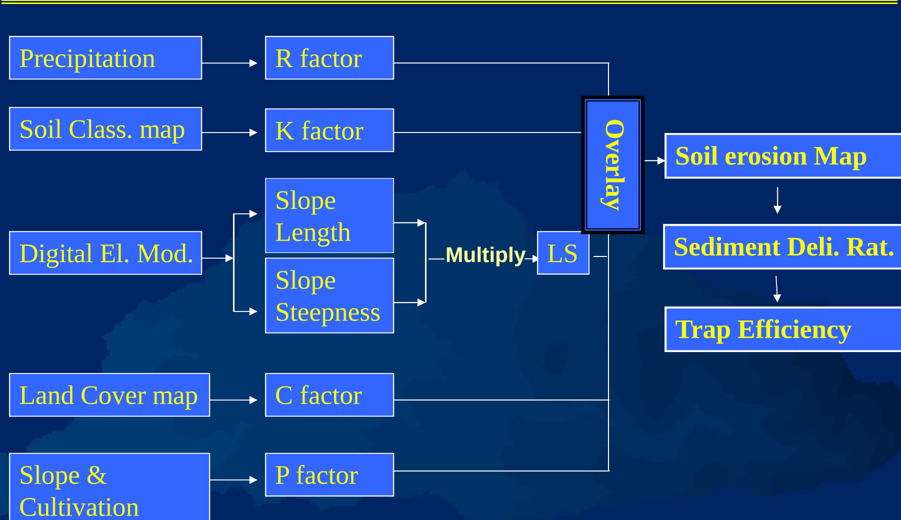
- A is the computed average soil loss (tons/acre/year)
- R is the rainfall-runoff erosivity factor
- K is the soil erodibility factor
- L is the slope length factor
- S is the slope steepness factor
- C is the cover management factor
- P is the support practice factor

Imha Watershed, South Korea



- Watershed area: 1,361km²
- Channel length : 96 km
- Average watershed slope: 40%
- Fast and high peak runoff characteristics

Methodology



Parameter estimation: Rainfall erosivity (R)

Basic equations (Wischmeier, 1959)

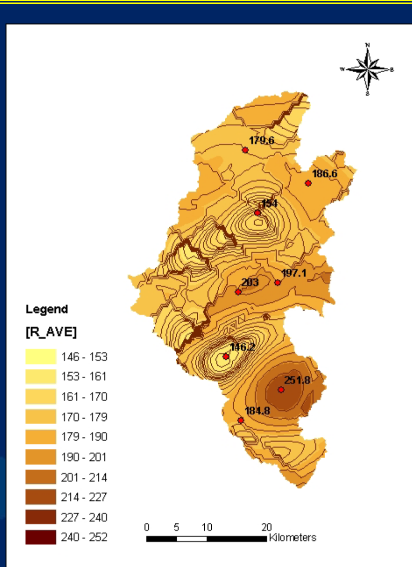
$$R = \frac{1}{n}\sum_{j=1}^{n}\left[\sum_{k=1}^{m}(E)(I_{30})_{r}\right] \qquad R = \sum EI_{30}(10^{-2})$$

- R=average annual rainfall erosivity (ft·tonf·in·acre^{-1}·h^{-1}·yr^{-1})
- E=Total storm kinetic energy (ft·tons·in·acre-1·h-1)
- I_{30}= Maximum 30-min rainfall intensity
- j=Index of number of years
- K=Index of number of storms in a year
- n=number of yrs used to obtain average R, m=number of storms

$$E = 916 + (331)\log_{10}(I), \qquad I \le 3.0 \quad in/hr$$
$$E = 1074, \qquad I > 3.0 \quad in/hr$$

- I=Rainfall intensity

Isoerodent Map



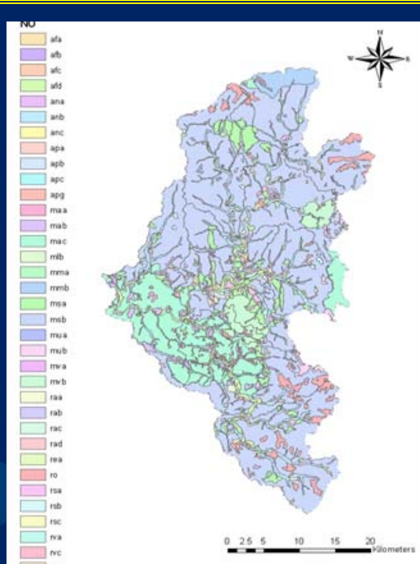
- 9 R values were transformed into spatial isoerodent lines
- Method: Kriging Ordinary Interpolation method

Soil Erodibility Factor (K)

Applied soil erodibility factor (Schwab, 1981)

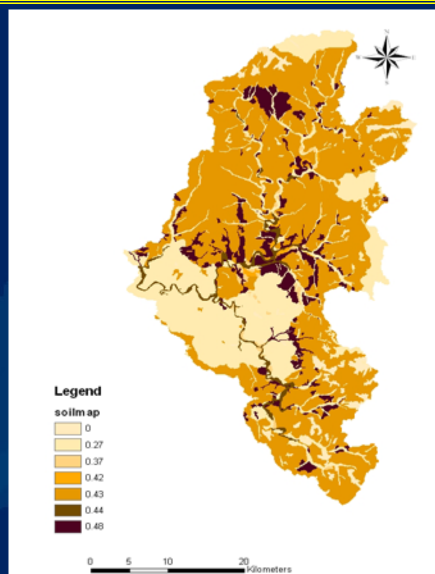
Textural Class	Organic Matter Content (%)	
	0.5	2
Fine sand	0.16	0.14
Very fine sand	0.42	0.36
Loamy sand	0.12	0.10
Loamy very fine sand	0.44	0.38
Sandy loam	0.27	0.24
Very fine sandy loam	0.47	0.41
Silt loam	0.48	0.42
Clay loam	0.28	0.25
Silty clay loam	0.37	0.32
Silty clay	0.25	0.23

Soil Classification Map



- 35 soil types
- Source: Korea National Institute agricultural and science technology

Soil Erodibility Map



Slope length/steepness factor (LS)

Basic equations (Renard, McCool, 1997)

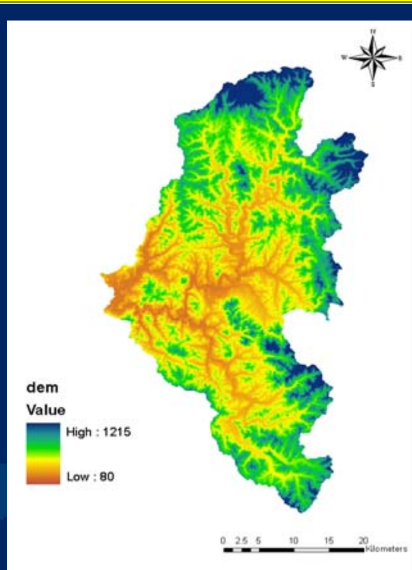
$$L = \left(X_h / 72.6 \right)^m$$

- Xh: the horizontal slope length (ft)
- m: a variable slope length factor

$$S = 10.8 \times SIN\theta + 0.03, \qquad \sigma \leq 9\%$$
$$S = 16.8 \times SIN\theta - 0.50, \qquad \sigma > 9\%$$

- θ: the slope angle (degree)
- σ: the slope gradient percentage(%)

Digital Elevation Model

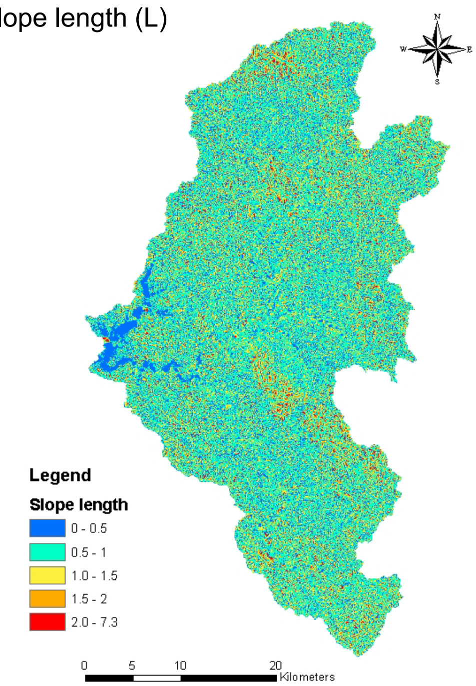


• 30 x 30m resolution.

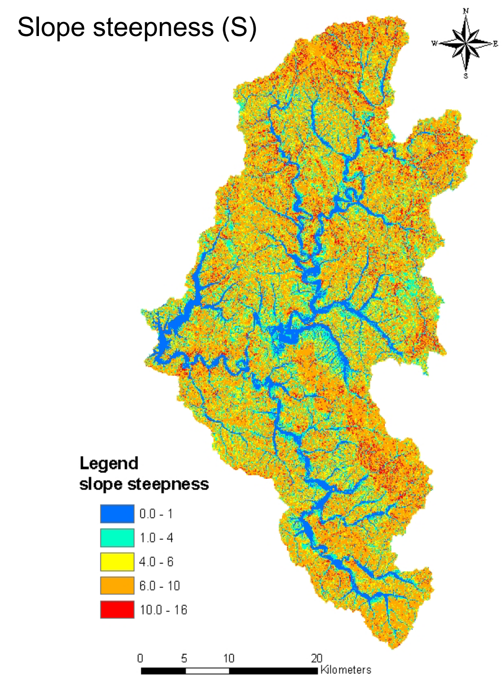
• Source: Korea Ministry of Construction and Transportation

Slope length & steepness

Slope length (L)

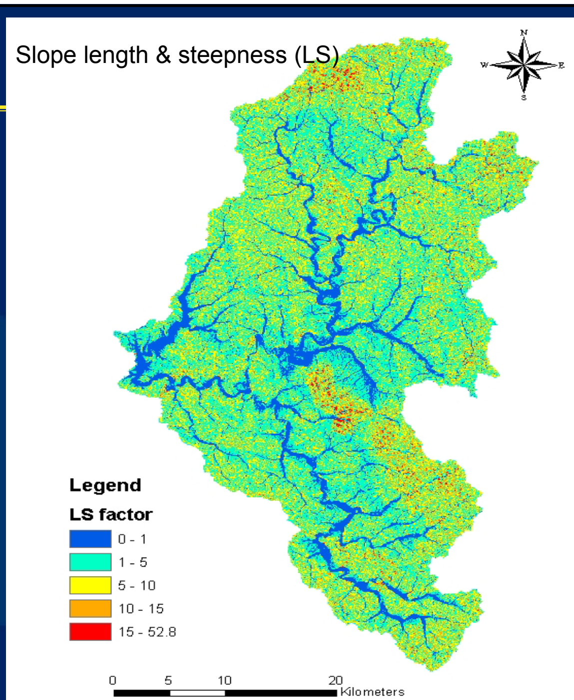


Slope length & steepness



CASC2

Slope length & steepness

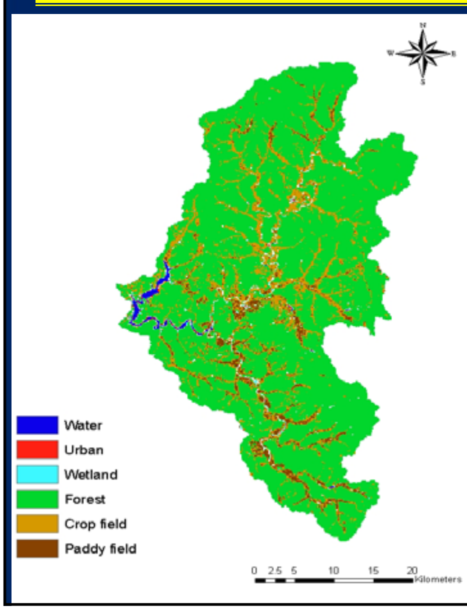


Cover Management Factor (C)

Applied cover management factor

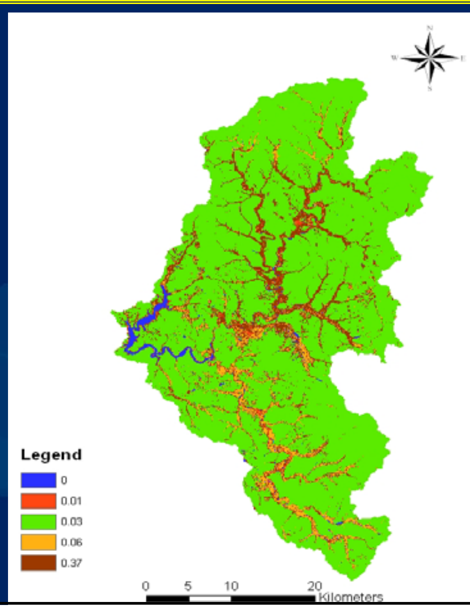
Num	Land cover type	Cover Management Factor (C)	Applied method
1	Water	0.00	
2	Urban	0.01	Urban density
3	Wetland	0.00	
4	Forest	0.03	Trial and Error
5	Paddy field	0.06	Kim, 2002
6	Crop field	0.37	NIAST, 2003

Land Cover Map



- 30 x 30m resolution.
- Source: Korea Ministry of Construction and Transportation

Cover Management Map



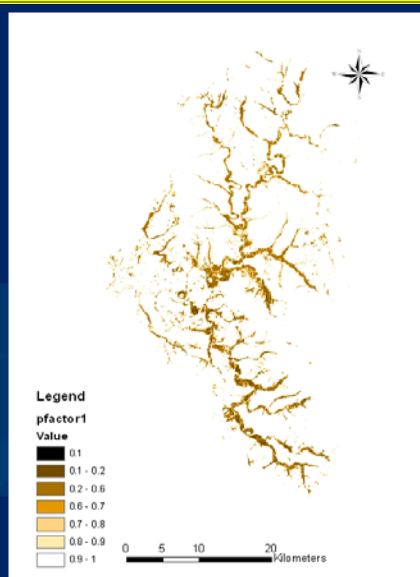
Support Practice Factor (P)

Applied support practice factor

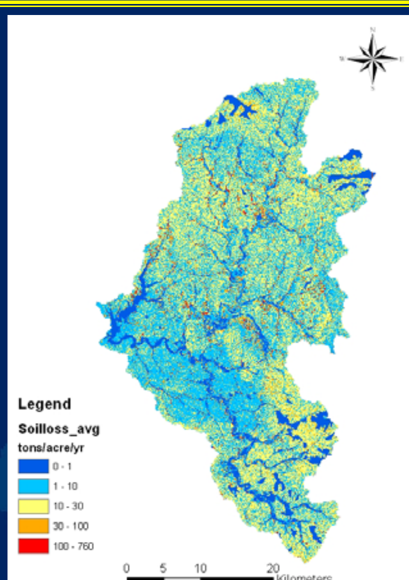
- Cultivation method and slope (Shin, 1999)

Slope (%)	Contouring	Strip Cropping	Terracing
0.0 - 7.0	0.55	0.27	0.10
7.0 - 11.3	0.60	0.30	0.12
11.3 - 17.6	0.80	0.40	0.16
17.6 - 26.8	0.90	0.45	0.18
26.8 >	1.00	0.50	0.20

Support Practice Map



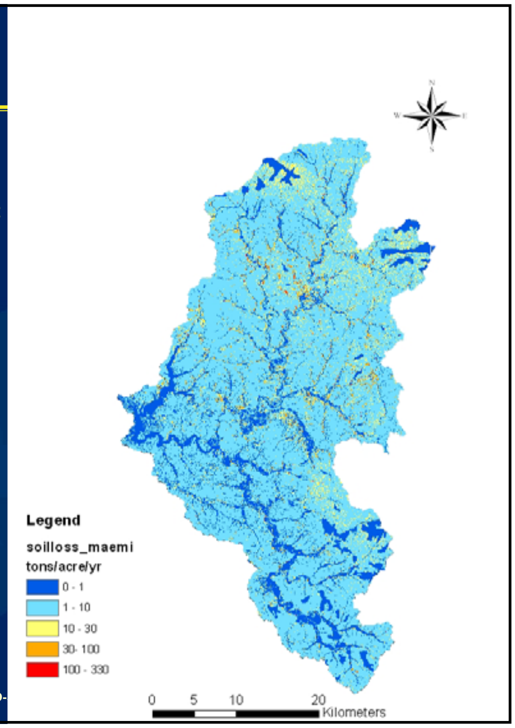
Results: Annual average soil loss map



- Annual average soil loss: 3,450 tons/km^2/year.

Soil loss map by “Maemi”

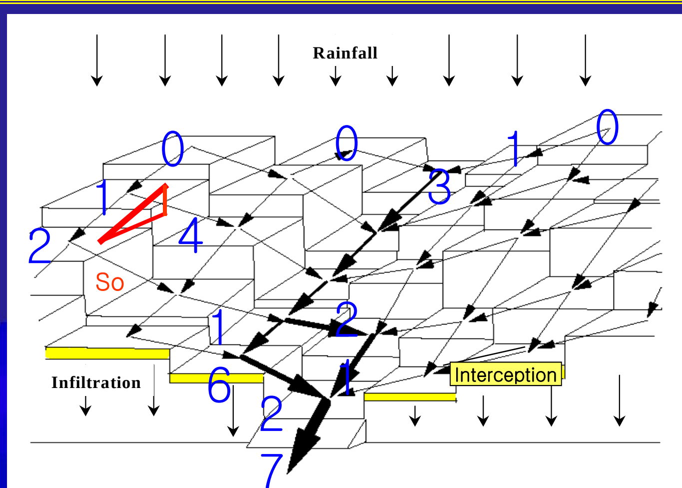
- Average soil loss: 2,920 tons/km^2 (40% of the annual average)



CASC2D-

2. Dynamic Watershed Modeling

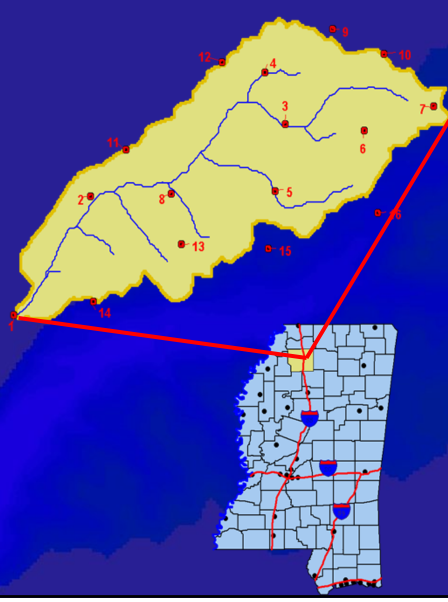
CASC2D-SED



CASC2D- Julien et al. (1995)
CASC2D-SED – Johnson et al. (2000), Rojas (2002)

Goodwin Creek Watershed

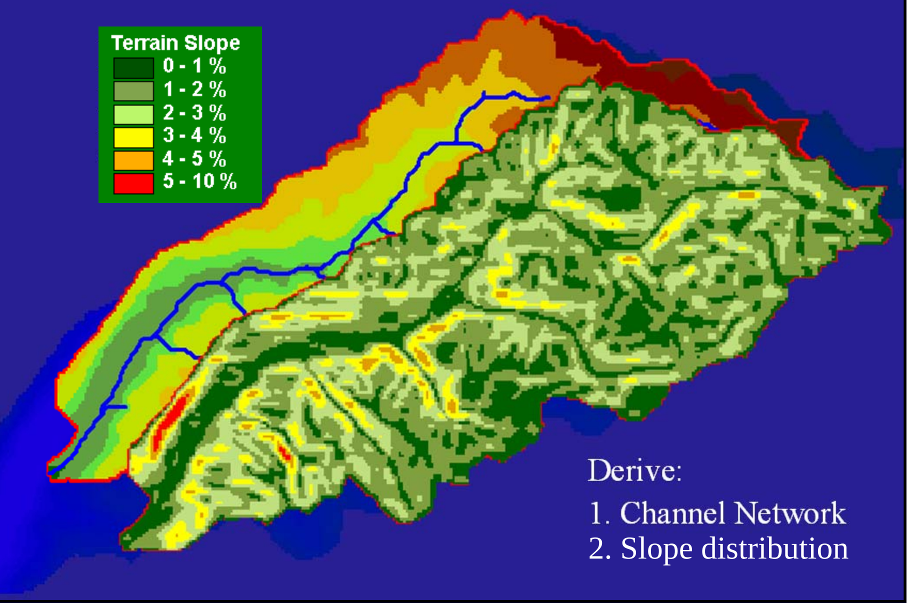
Application



- Location: Panola County (MS)
- Area: 21Km^2
- Monitored by ARS-NSL (Oxford, MS)
  - 37 rain gages
  - 14 stream gages (water and sediment)
  - Channel surveys
  - GIS data

INPUT DATA (DEM)

Application

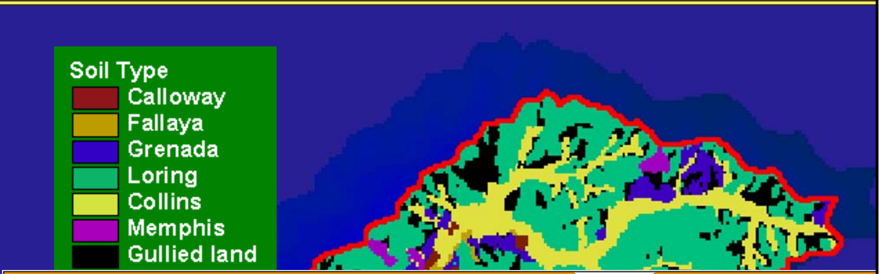


Derive:

1. Channel Network
2. Slope distribution

INPUT DATA (soil type)

Application

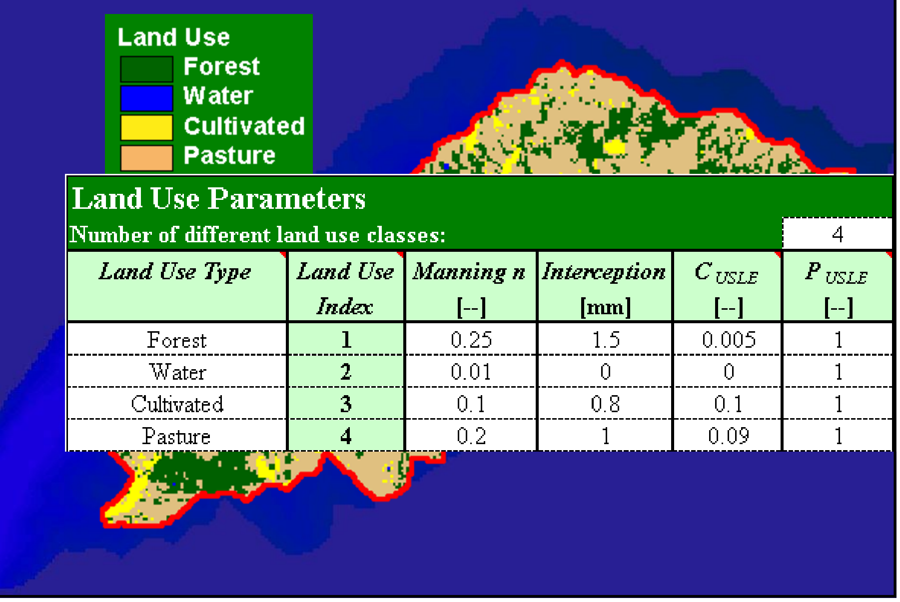


Soil Parameters — Number of different soil types: 7

		Infiltration			Erosion			
Soil Type	*Soil Index*	*Hydr. Cond.* [cm/h]	*Suction Head* [cm]	*Moisture Deficit* [cm3/cm3]	*Sand* [%]	*Silt* [%]	*Clay* [%]	*K_{USLE}* [--]
Calloway	1	0.350	22	0.34	0.25	0.55	0.20	0.4
Fallaya	2	0.320	14	0.34	0.25	0.55	0.20	0.1
Grenada	3	0.370	17	0.34	0.3	0.6	0.10	0.2
Loring	4	0.380	22	0.34	0.25	0.55	0.20	0.6
Collins	5	0.360	18	0.34	0.3	0.6	0.10	0.2
Memphis	6	0.450	22	0.34	0.3	0.6	0.10	0.5
Gullied Land	7	0.400	15	0.34	0.25	0.55	0.20	0.1

INPUT DATA (land use)

Application



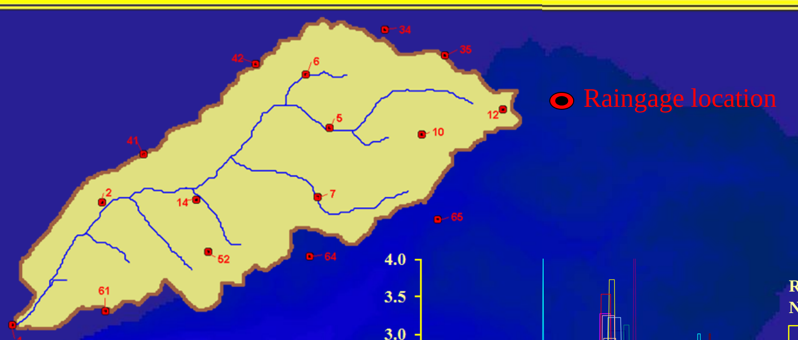
Land Use Parameters

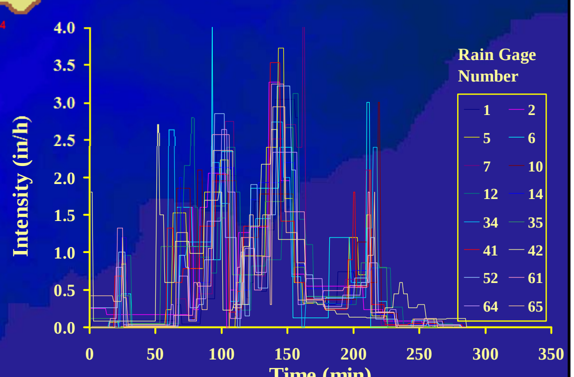
Number of different land use classes: 4

Land Use Type	*Land Use Index*	*Manning n* [--]	*Interception* [mm]	*C USLE* [--]	*P USLE* [--]
Forest	1	0.25	1.5	0.005	1
Water	2	0.01	0	0	1
Cultivated	3	0.1	0.8	0.1	1
Pasture	4	0.2	1	0.09	1

INPUT DATA (rainfall)

Application





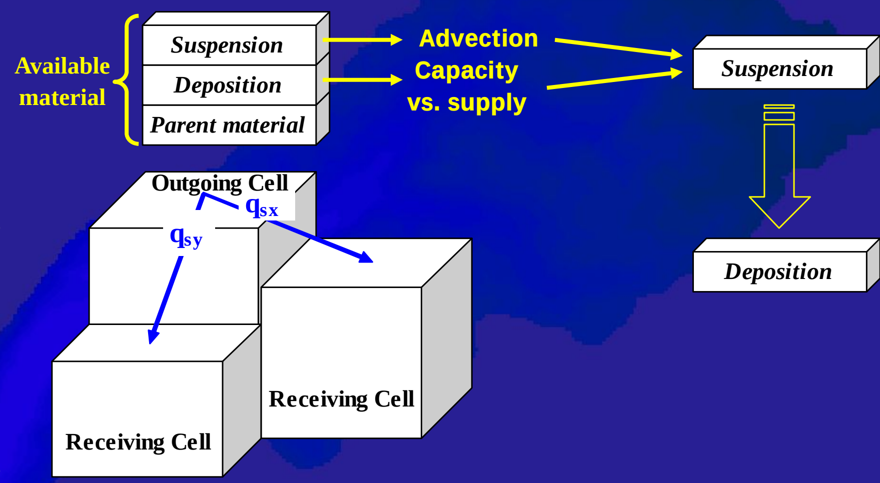
10/17/81 event:

Duration: 3.5 hr.

Depth: 73 mm.

SEDIMENT ROUTING

CASC2D-SED



UPLAND EROSION (2-D)

CASC2D-SED

Modified Kilinc and Richardson equation for the overland:

$$q_t\,(tons/m*s) = 23210\, S_o^{1.66} \left(\frac{Q}{W}\right)^{2.035} \frac{K}{0.15}\, C\, P$$

Land use (C P)

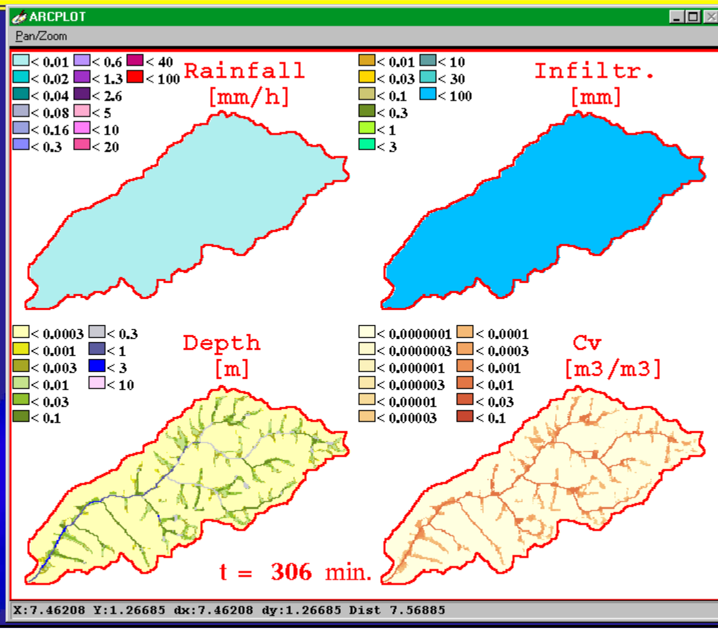
Soils (K)

DEM (S_o)

Hydraulics (Q/W)

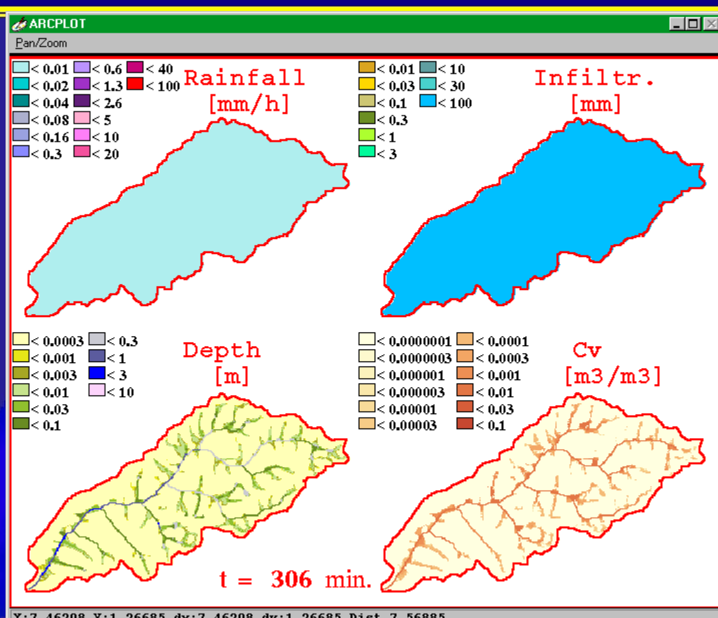
GEOVISUALIZATION rainfall-runoff

Results

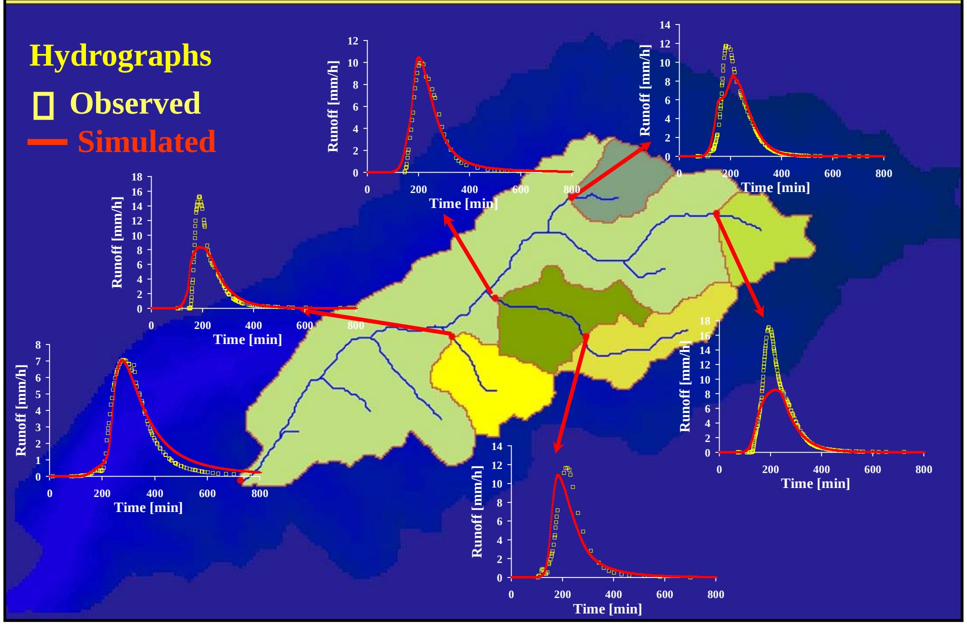


GEOVISUALIZATION rainfall-runoff

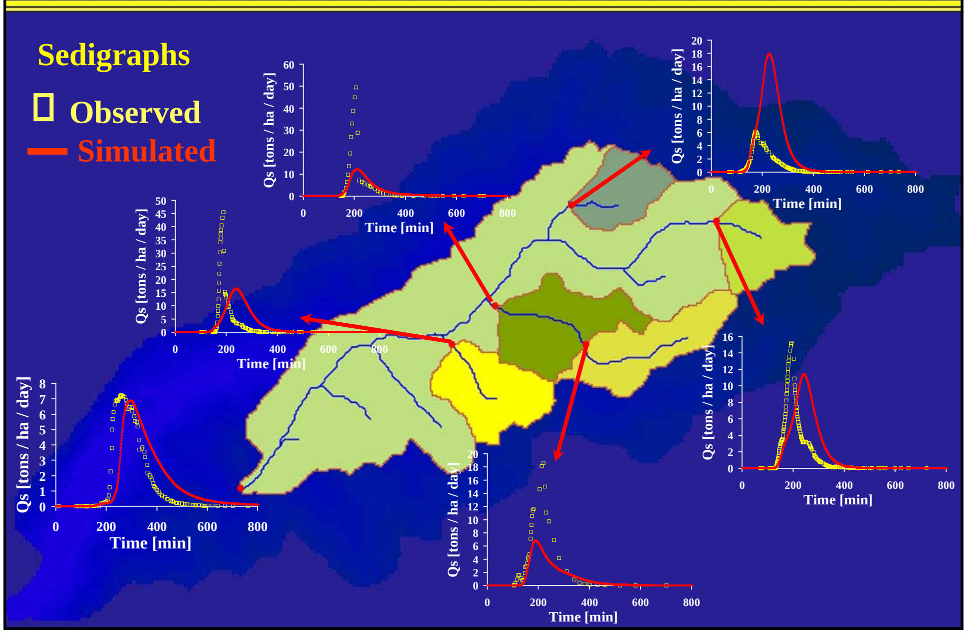
Results



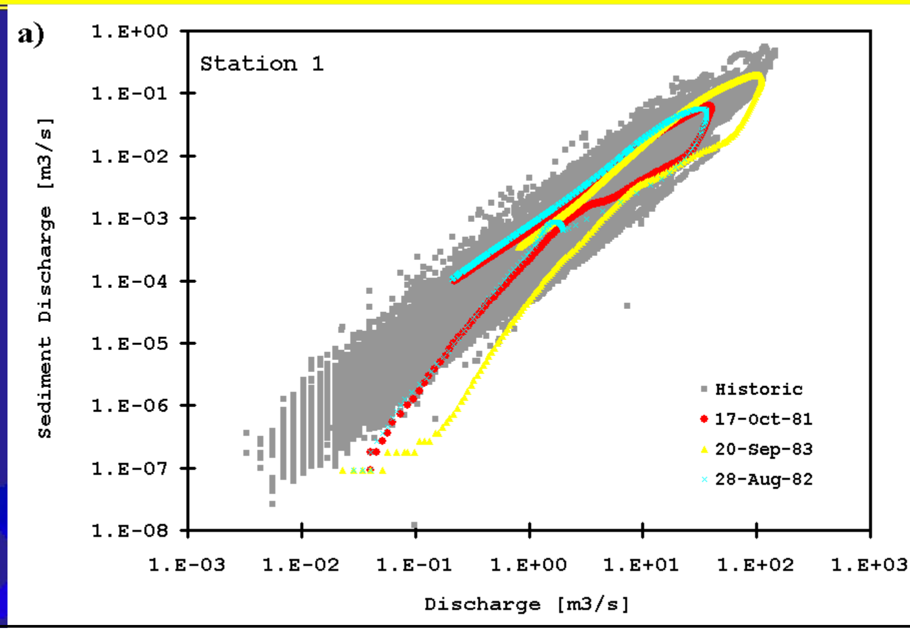
INTERNAL VALIDATION



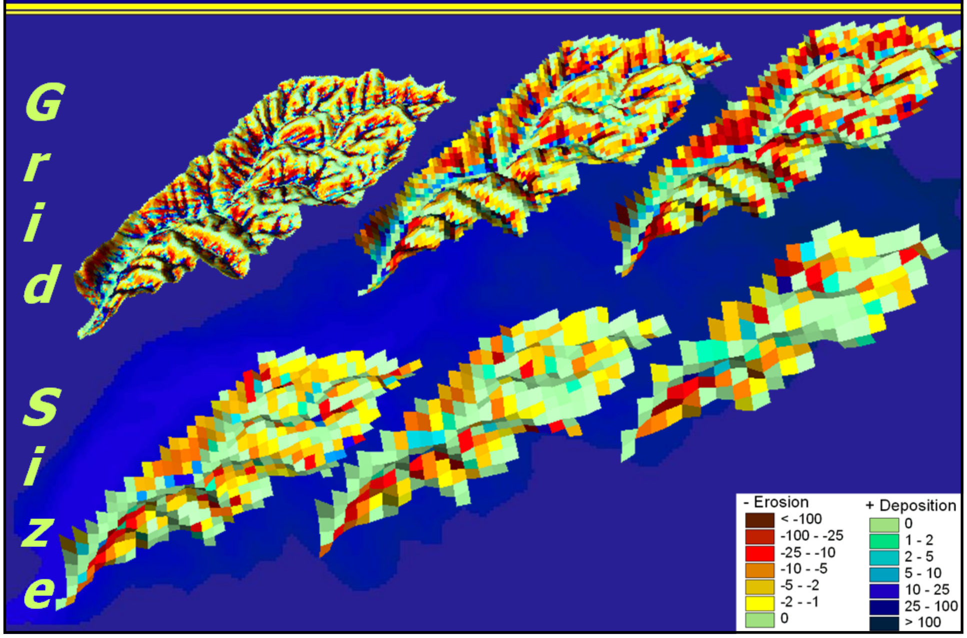
INTERNAL VALIDATION



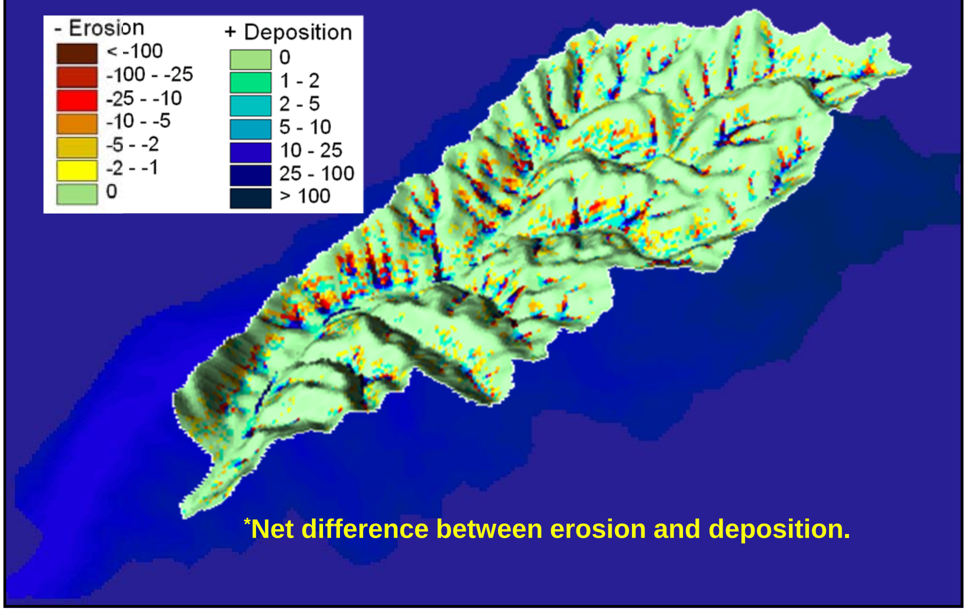
SEDIMENT RATING CURVES



NET EROSION (Uniform)

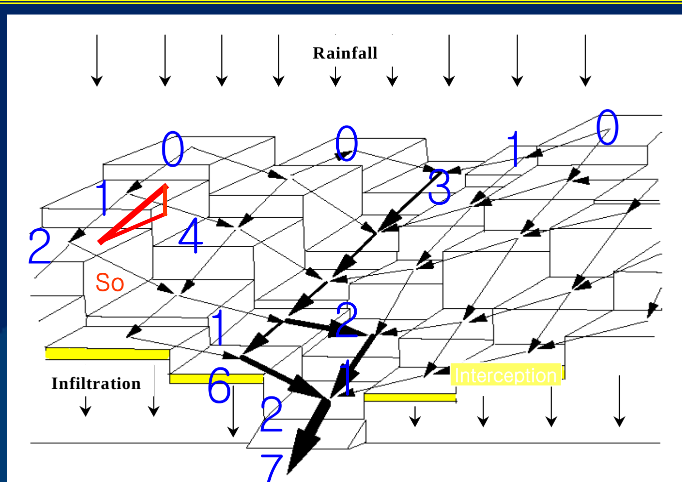


Net Erosion and Deposition*



*Net difference between erosion and deposition.

CASC2D-SED



CASC2D- Julien et al. (1995)
CASC2D-SED – Johnson et al. (2000), Rojas (2002)

CASC2D-SED Web Page

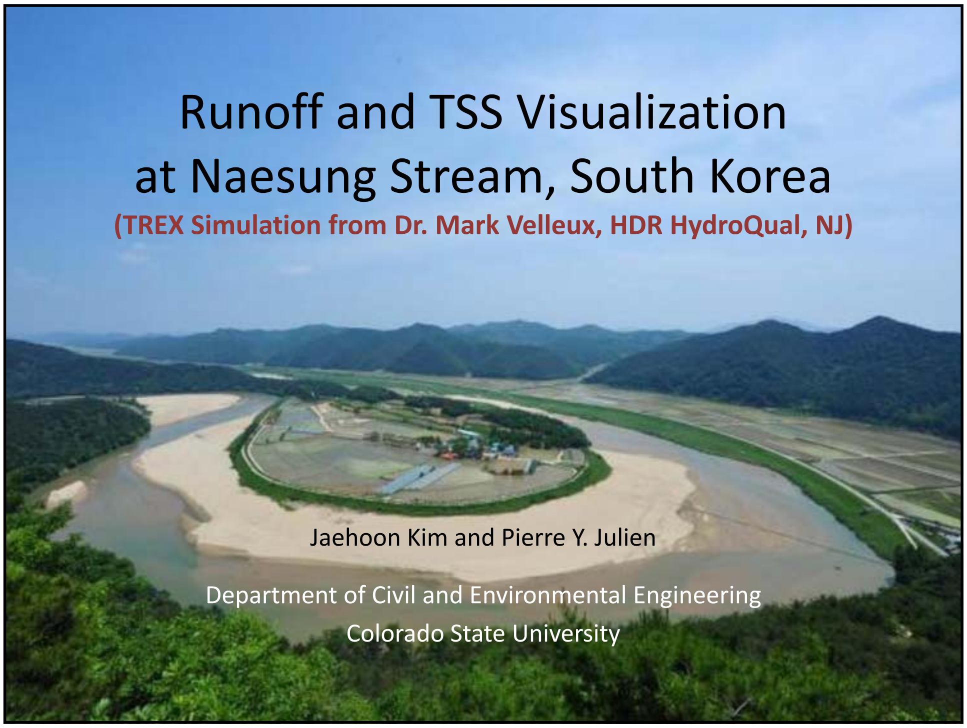
- At Colorado State University
- Under direction of Dr. Pierre Julien

pierre@engr.colostate.edu

- Current manual, source code, example, MPEG movies

http://www.engr.colostate.edu/%7epierre/ce_old/projects/casc2d-Rosalia/index.htm

3. Modeling of Naesung Stream, South Korea



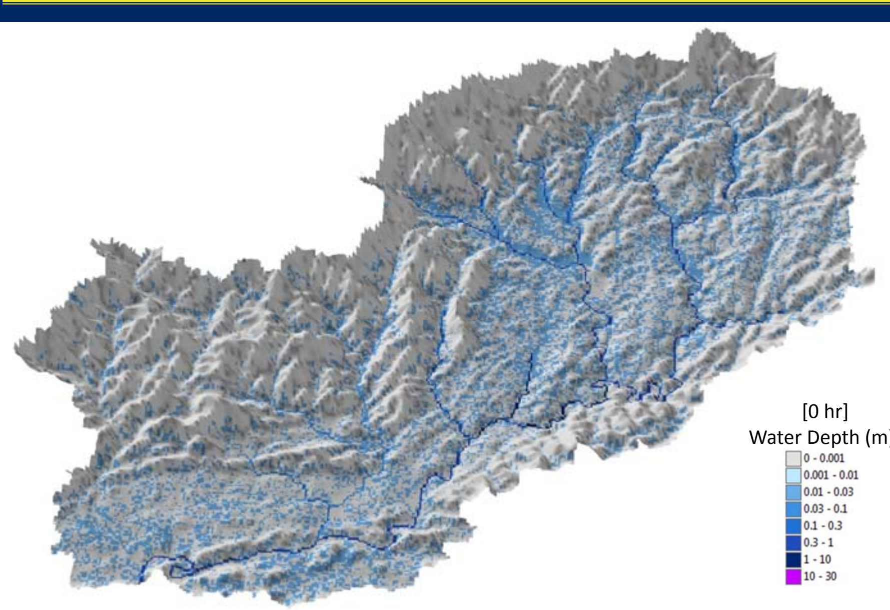
Runoff and TSS Visualization at Naesung Stream, South Korea

(TREX Simulation from Dr. Mark Velleux, HDR HydroQual, NJ)

Jaehoon Kim and Pierre Y. Julien

Department of Civil and Environmental Engineering
Colorado State University

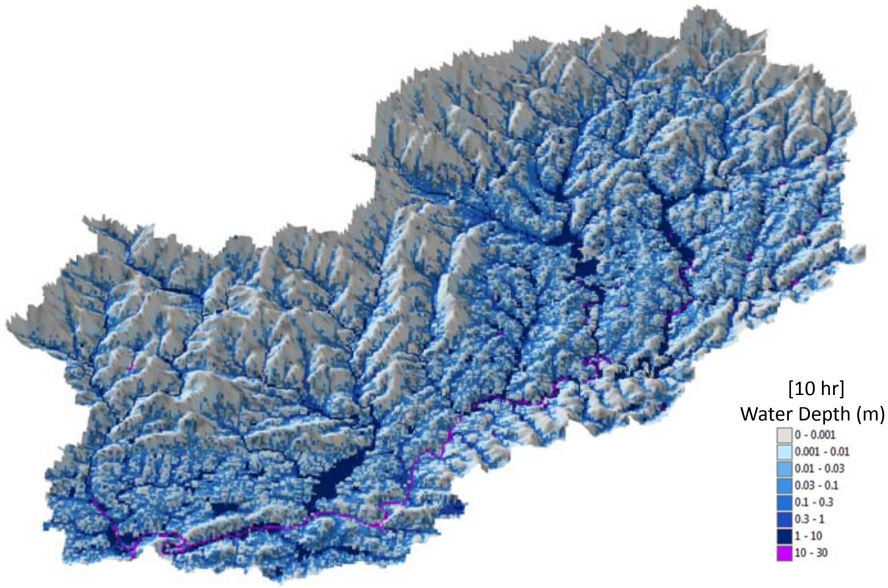
Water Depth



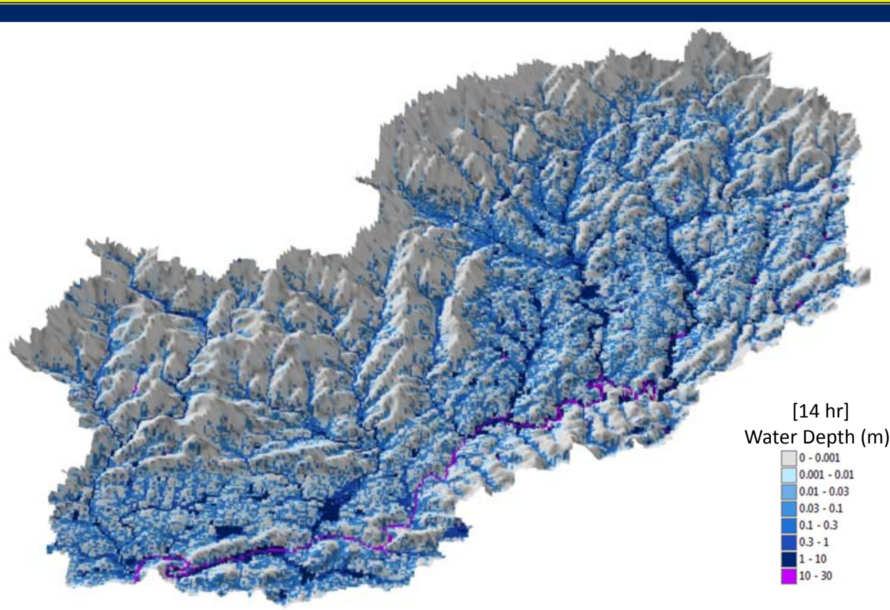
Water Depth

Water Depth

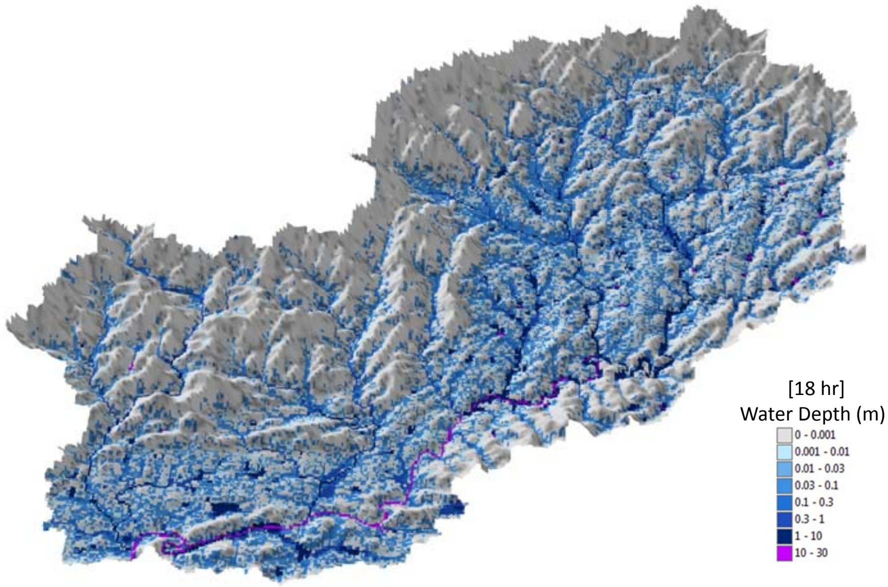
Water Depth



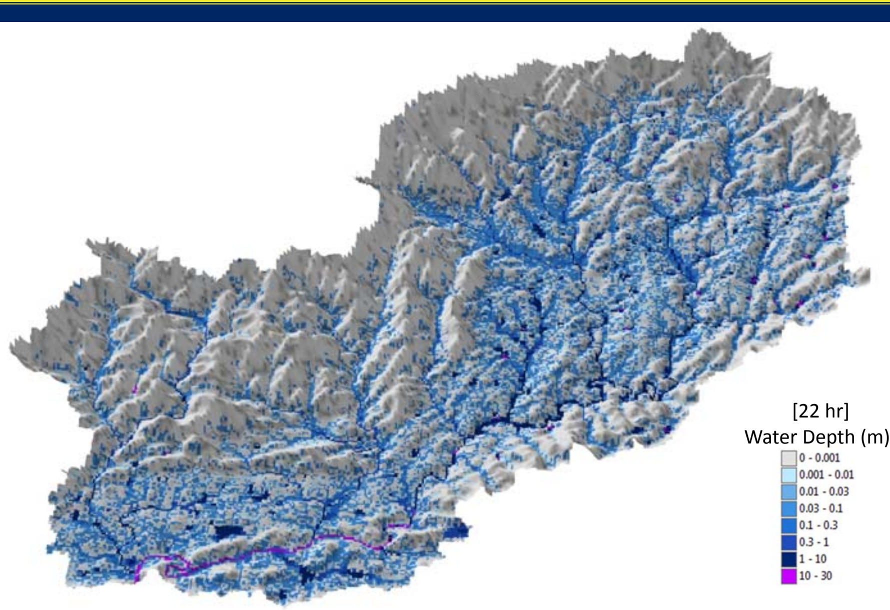
Water Depth



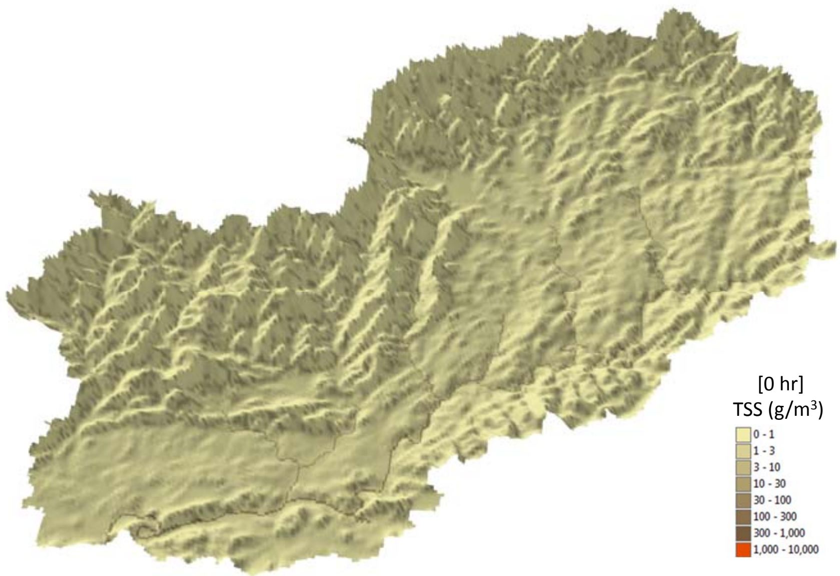
Water Depth



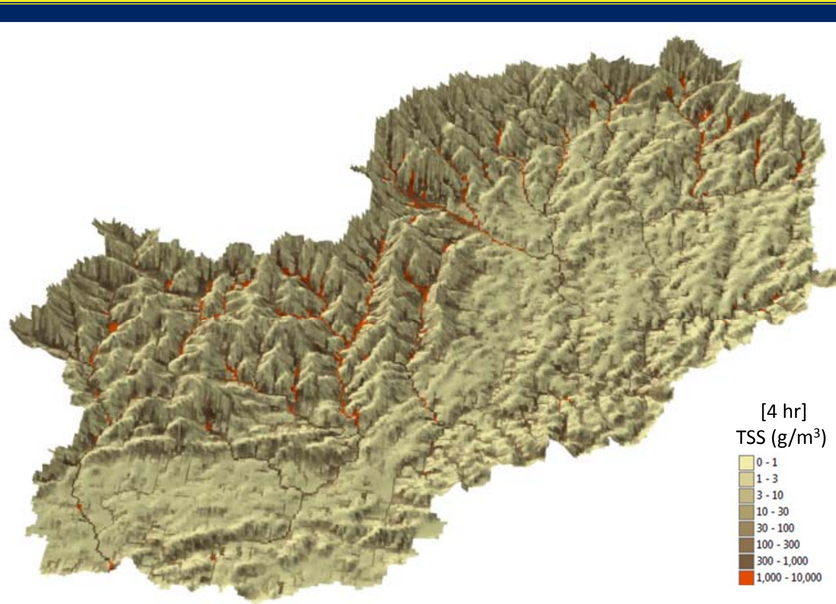
Water Depth



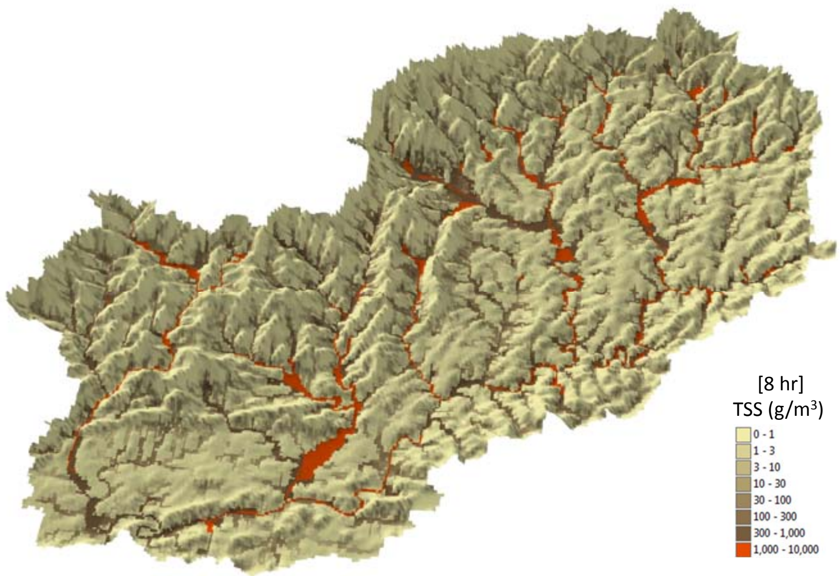
Total Suspended Solids



Total Suspended Solids



Total Suspended Solids



Total Suspended Solids

Total Suspended Solids

Total Suspended Solids

Total Suspended Solids

4. Sediment Yield

Sediment Delivery Ratio

Defined as the ratio of the sediment yield at a given stream cross section to the gross erosion from the watershed upstream

$$SDR = Y / A_T$$

- Y: sediment yield
- A_T : gross erosion

- **SDR equations**

Boyce (1975): $SDR = 0.31 A^{-0.3}$

Vanoni(1975): $SDR = 0.42 A^{-0.125}$

- A : the catchment area ($mile^2$)

Renfro (1975): $\log(SDR) = 2.94259 + 0.82362 \log(R/L)$

Williams (1977): $SDR = 1.366 \times 10^{-11} \times A^{-0.0998} \times (R/L) \times CN^{5.444}$

- A : the catchment area (Km^2)
- R : relief of a watershed (difference elevation between max. and outlet)
- L : maximum length of a watershed
- CN: the long-term average SCS curve number

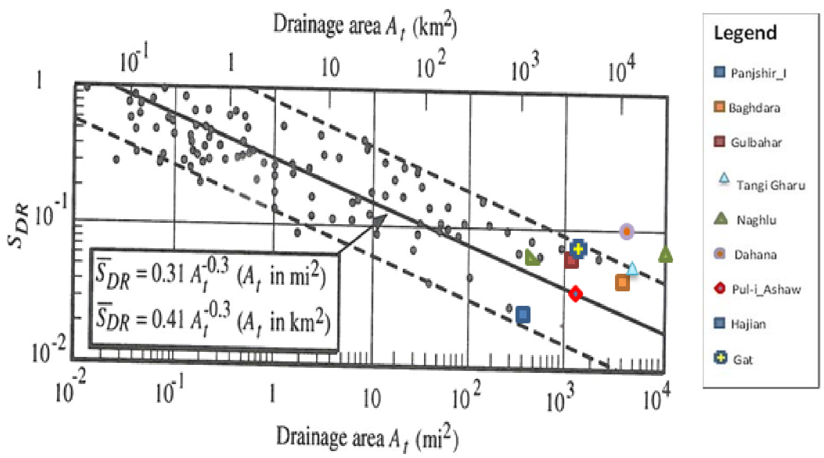
Sediment Yield …

- Sediment delivery ratio: Observed
  - $S_{DR} = \frac{sediment\ yield}{Gross\ soil\ erosion} = \frac{sediment\ degradation}{annual\ average\ soil\ loss\ rate} = \frac{Y}{A_T}$
- S_{DR}
  - Drainage Area
    - Renfro (1975)
      - $\log(S_{DR}) = 1.7935 - 0.14191 \log(A)$
    - Boyce (1975)
      - $S_{DR} = 0.41\ A_T^{-0.3}$
  - Topographic Factors
    - Williams and Berndt's (1972)
      - $\mathrm{Log}(S_{DR}) = 0.627\ SLP^{0.403}$
    - Maner (1958)
      - $\log(S_{DR}) = 2.94259 + 0.82362 \log(R/L)$

Introduction Dataset and Methodology Results and Applications Conclusions

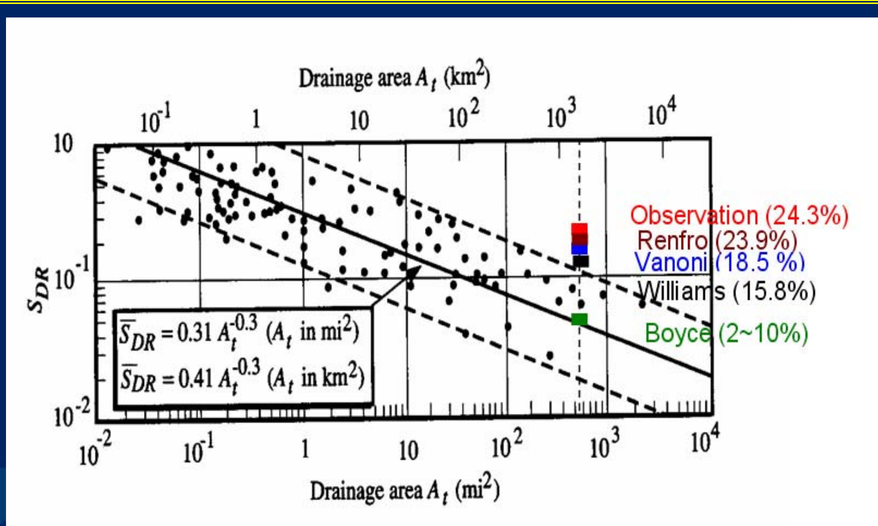
Sediment Yield…

- **Julien 2002 (modified after Boyce 1975)**



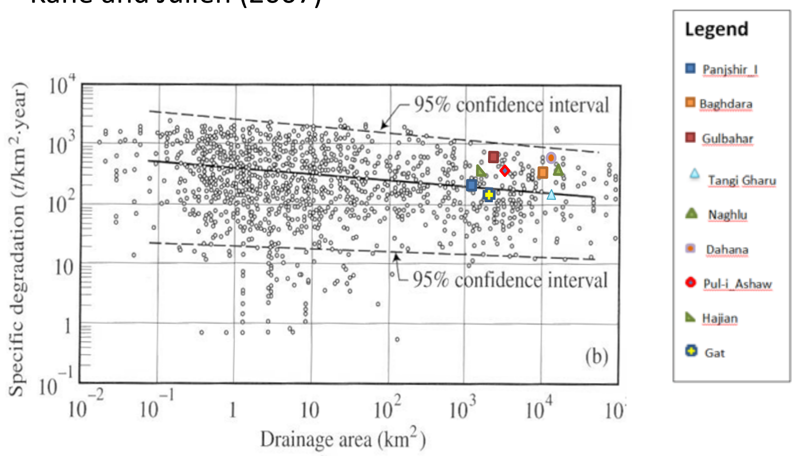
Introduction Dataset and Methodology Results and Applications Conclusions

Sediment Delivery Ratio

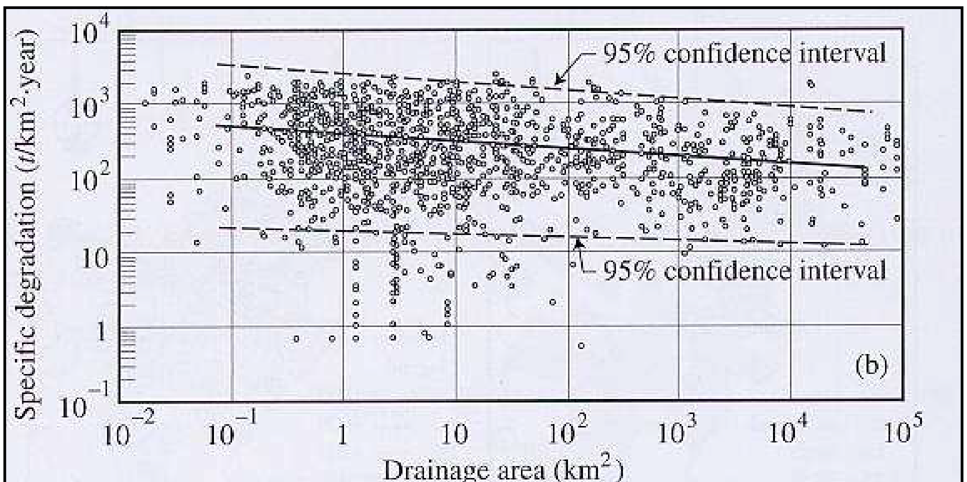


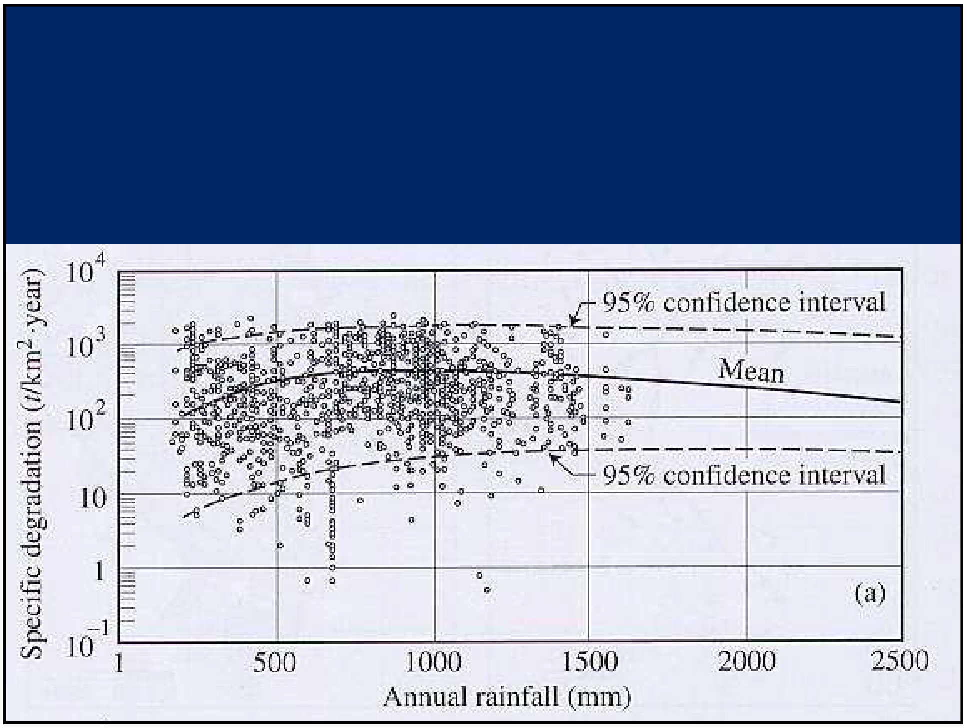
Sediment Yield…

- Kane and Julien (2007)

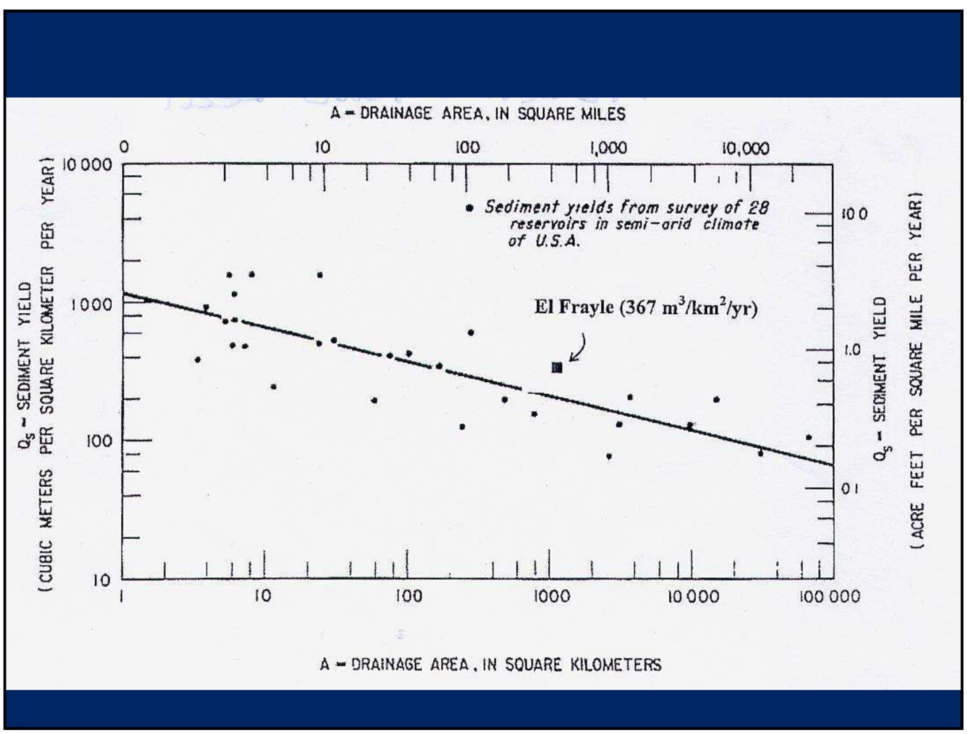


Introduction Dataset and Methodology Results and Applications Conclusions

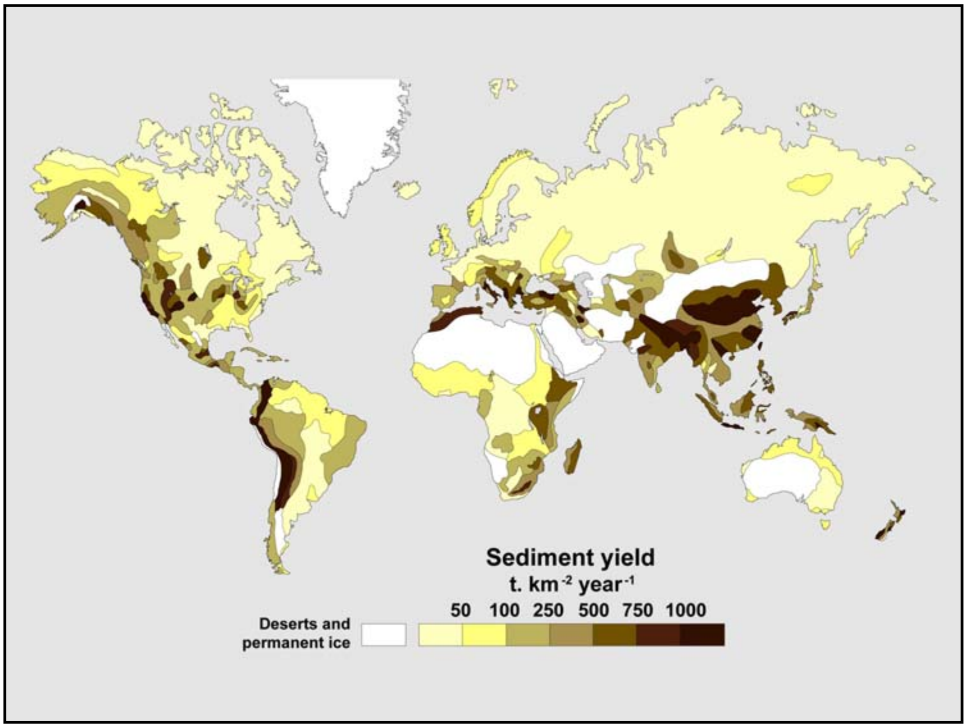




Specific degradation (t/km²·year)
95% confidence interval
Mean
95% confidence interval
(a)
Annual rainfall (mm)



A – DRAINAGE AREA, IN SQUARE MILES
• Sediment yields from survey of 28 reservoirs in semi-arid climate of U.S.A.
El Frayle (367 m³/km²/yr)
Qs – SEDIMENT YIELD (CUBIC METERS PER SQUARE KILOMETER PER YEAR)
Qs – SEDIMENT YIELD (ACRE FEET PER SQUARE MILE PER YEAR)
A – DRAINAGE AREA, IN SQUARE KILOMETERS



Sediment yield
t. km^{-2} year^{-1}
Deserts and permanent ice
50 100 250 500 750 1000

Small Checkdam (Kalong II)

5. Case Study in Haiti

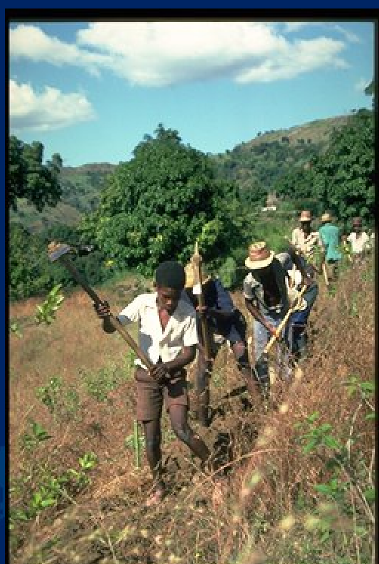
Example: Peligre Dam in Haiti

Demographic Expansion

Lowland Slash and Burn

Subsistence Farming

Farming Uphill

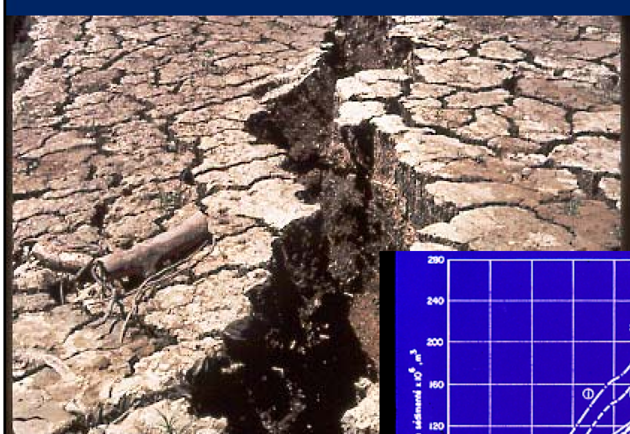


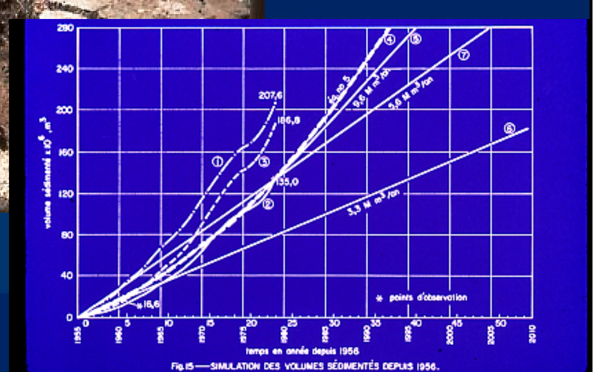
Farming Hilltops?

Watershed Deforestation

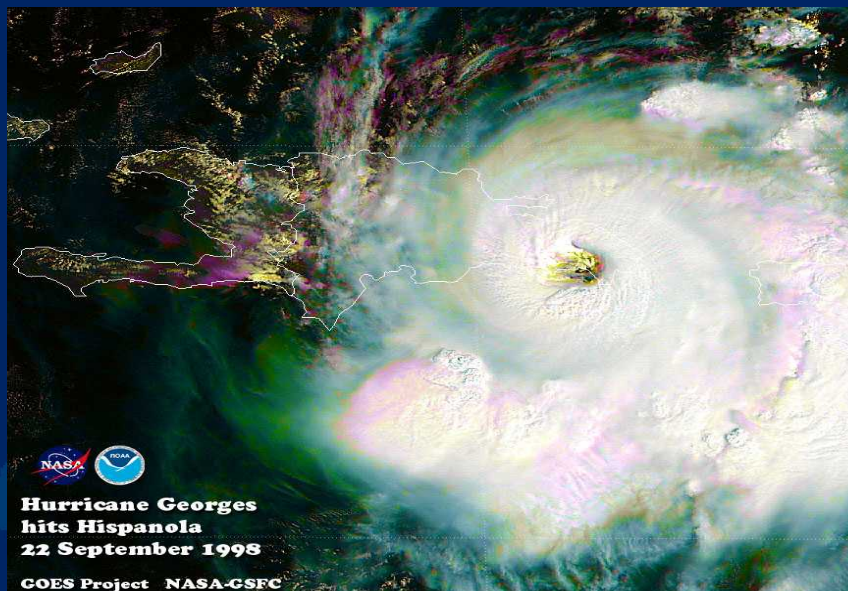
Haiti River

Peligre Dam (sedimentation)





Hurricane Impact



Emergency Spillway Operation

Flood Damages

Citizens Blame their Government

Could this be avoided?

ACKNOWLEDGMENTS

Dr. Marcel Frenette, Laval University
Dr. Mark Velleux, CSU and HDR
Dr. Boubacar Kane, CSU and Mali
Dr. Rosalia Rojas, CSU
Dr. Billy Johnson, ERDC, Mississippi
Dr. Un Ji, KICT, South Korea
Dr. Otto Stein, CSU and MSU
Hyeonsik Kim, K-water, South Korea
Shukran Sahaar, CSU
… so many others …


Muchas
Gracias!
pierre@engr.colostate.edu