Catchment Processes and Modeling

Pierre Y. Julien
Department of Civil Engineering
Colorado State University
Fort Collins, Colorado

UNITEN-TNBR Short Course
Kuala Lumpur – July 20 2006

Objectives

Brief overview of catchment modeling and trap efficiency of reservoirs:

1. Upland Erosion Modeling;
2. Dynamic Watershed Modeling;
3. Sediment Delivery Ratio;
4. Trap Efficiency.

1. Upland Erosion Modeling

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

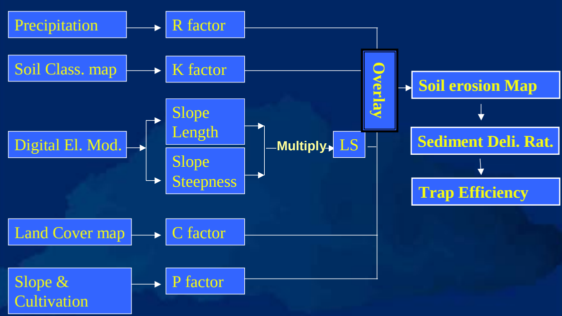
$$A = R\ K\ L\ S\ C\ P$$

- 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)

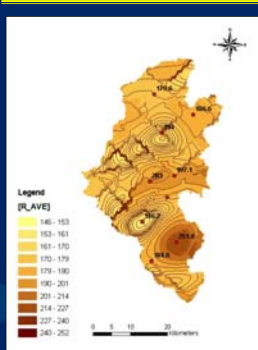
$$R = \frac{1}{n}\sum_{j=1}^{n}\left[\sum_{k=1}^{m}(E)(I_{30})_r\right] \qquad R=\sum EI_{30}(10^{-2})$$

- 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

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

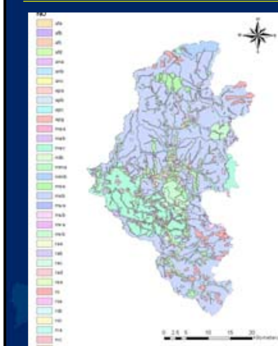
- I=Rainfall intensity

Isoerodent Map



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

Soil Classification Map



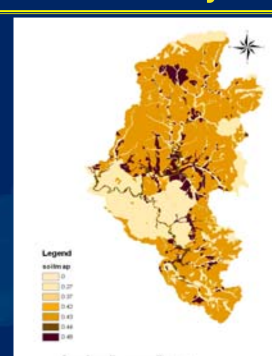
- 35 soil types
- Source: Korea National Institute agricultural and science technology

Soil Erodibility Factor (K)

Applied soil erodibility factor (Schwab, 1981)

Textural Class	Organic Matter Content (%) 0.5	Organic Matter Content (%) 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 Erodibility Map



Slope length/steepness factor (LS)

Basic equations (Renard, McCool, 1997)

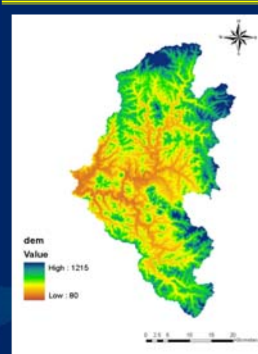
$$L = \left(\frac{X_h}{72.6}\right)^m$$

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

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

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

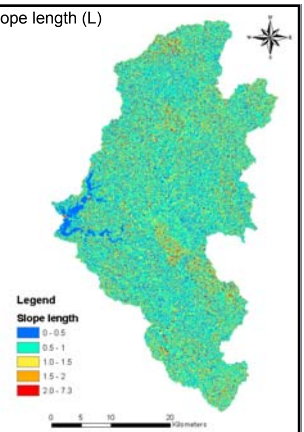
Digital Elevation Model



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

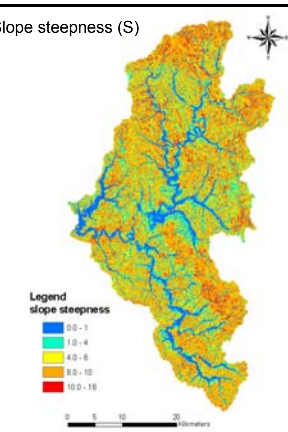
Slope length & steepness

Slope length (L)



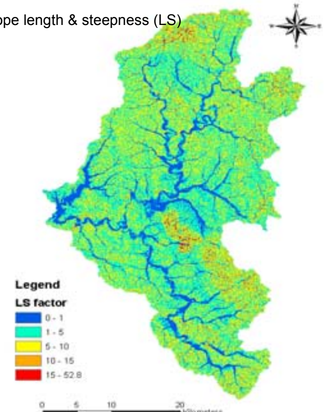
Slope length & steepness

Slope steepness (S)



Slope length & steepness

Slope length & steepness (LS)

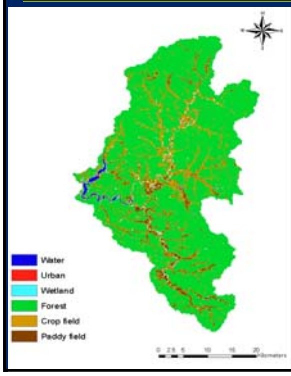


Cover Management Factor (C)

Applied cover management factor

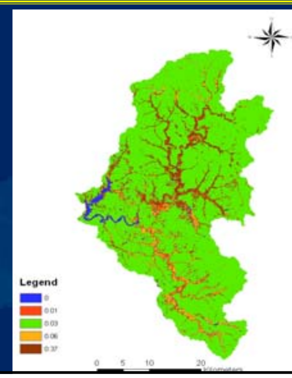
Num	Land cover type	Cover Management Factor (C)	Applied method
1	Water	0.00	
2	Urban	0.01	Urban density
3	Wetland	0.00	
4	Forest	0.03	Trial and Error
5	Paddy field	0.06	Kim, 2002
6	Crop field	0.37	NIAST, 2003

Land Cover Map



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

Cover Management Map



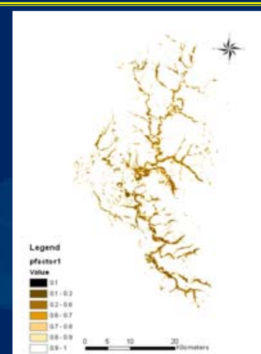
Support Practice Factor (P)

Applied support practice factor

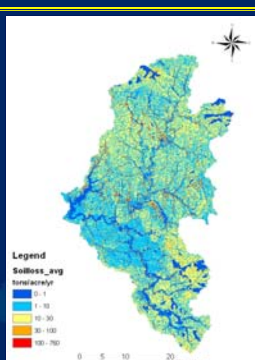
- **Cultivation method and slope (Shin, 1999)**

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



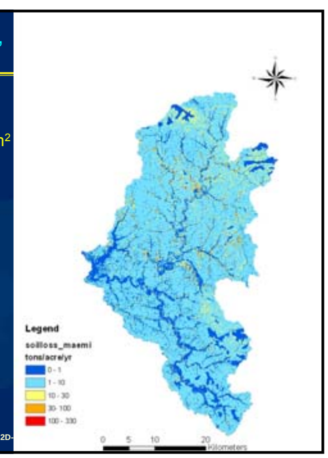
Results: Annual average soil loss map



- 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)

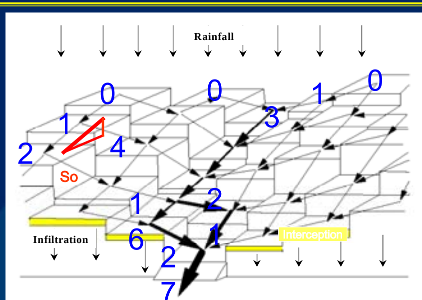


2. Dynamic Watershed Modeling with CASC2D-SED

CASC2D-SED

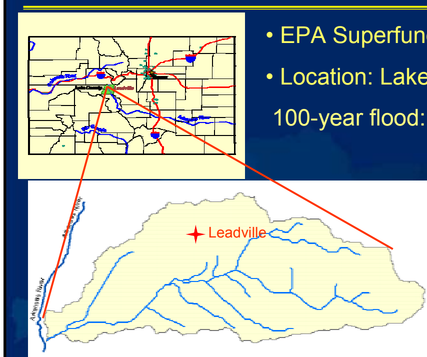
- **Water**
  1. Rainfall
  2. Infiltration
  3. Overland and Channel Flow
- **Sediment**
  1. Upland Erosion and Deposition
  2. Channel Processes
  3. Sediment yield

CASC2D-SED



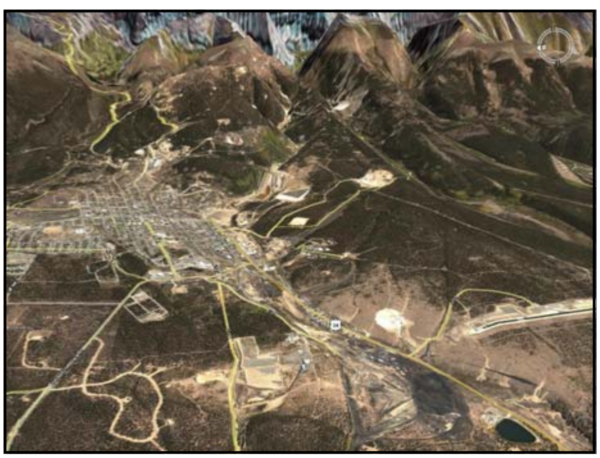
CASC2D- Julien et al. (1995)
CASC2D-SED – Johnson et al. (2000), Rojas (2002)

California Gulch Watershed

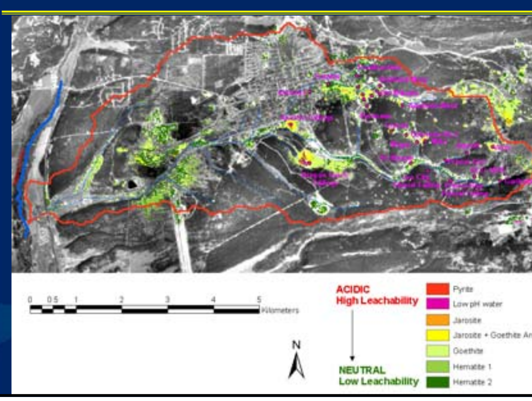


- EPA Superfund Site
- Location: Lake County (CO)

100-year flood: 2-h: 1.73 in

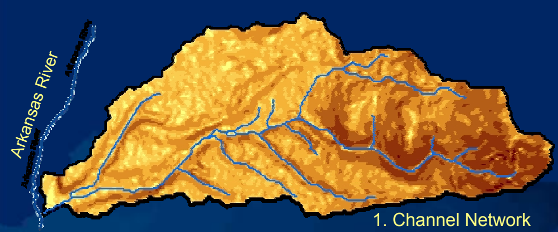


California Gulch Watershed

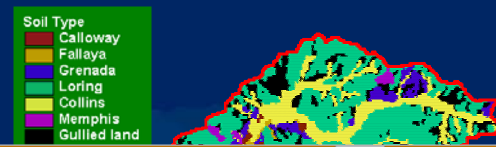


Input Data (DEM)

Digital Elevation Model

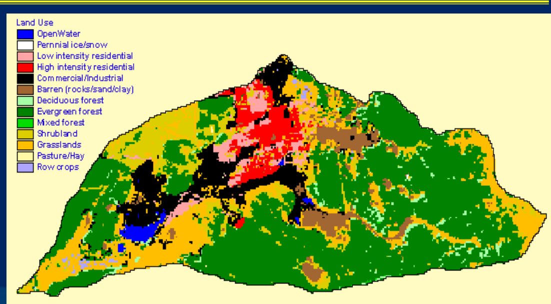


Input data (soil type)

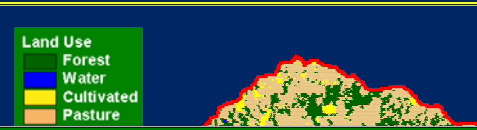


Soil Parameters		Number of different soil types:			7			
		Infiltration			Erosion			
Soil Type	Soil Index	Hydr. Cond. [cm/h]	Suction Head [cm]	Moisture Deficit [cm3/cm3]	Sand [%]	Silt [%]	Clay [%]	K_{USLE} [--]
Calloway	1	0.350	22	0.34	0.25	0.55	0.20	0.4
Fallaya	2	0.320	14	0.34	0.25	0.55	0.20	0.1
Grenada	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

Land Use Data

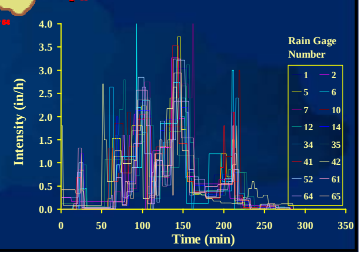


Input data (land use)



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)

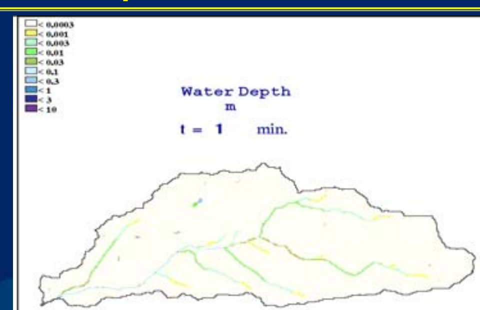


10/17/81 event:

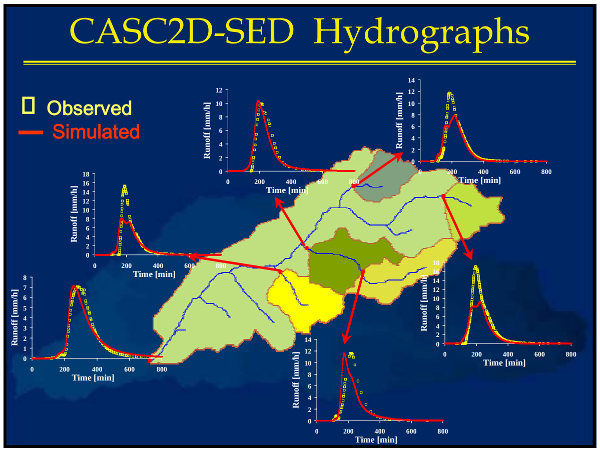
Duration: 3.5 hr.

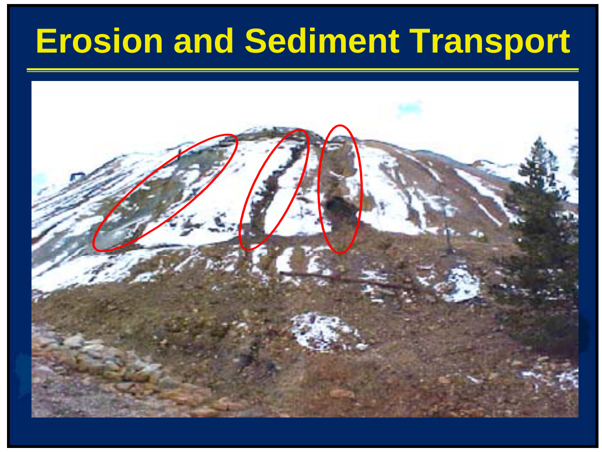
Depth: 73 mm.

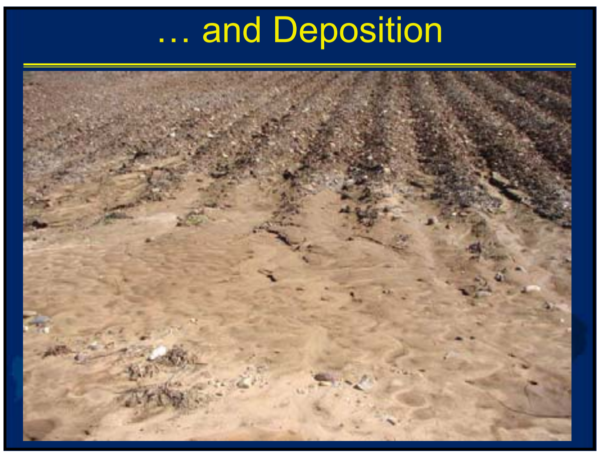
Water depths from a rainfall event*

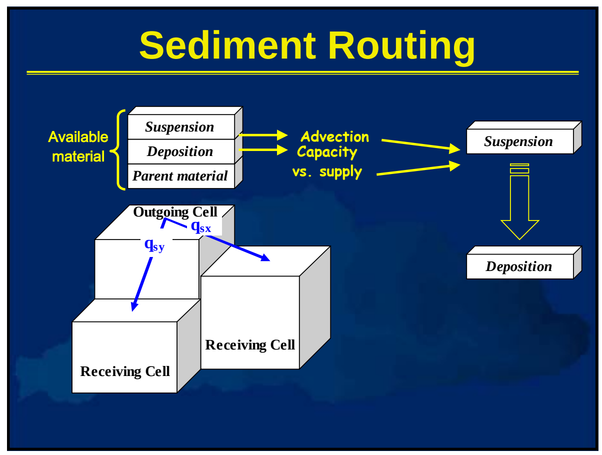


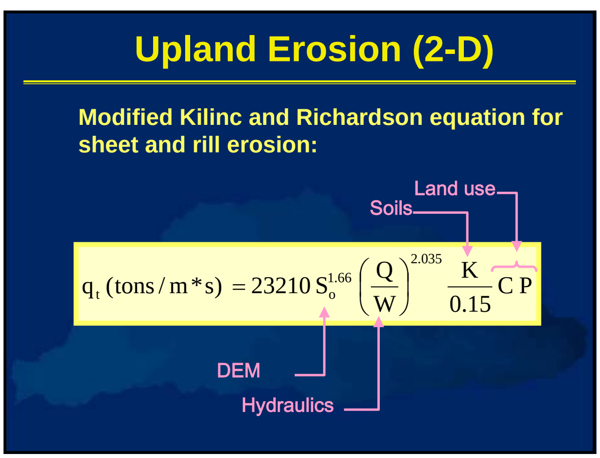
*1-in-100 year intensity, 2 hour duration uniform rainfall event.

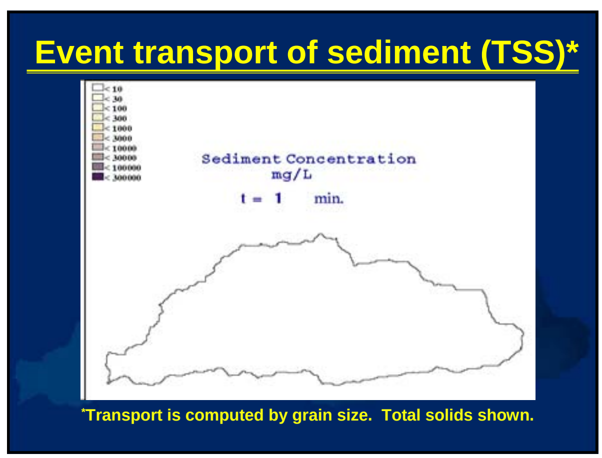

CASC2D-SED Hydrographs
Observed
Simulated
Runoff [mm/h]
Time [min]


Erosion and Sediment Transport

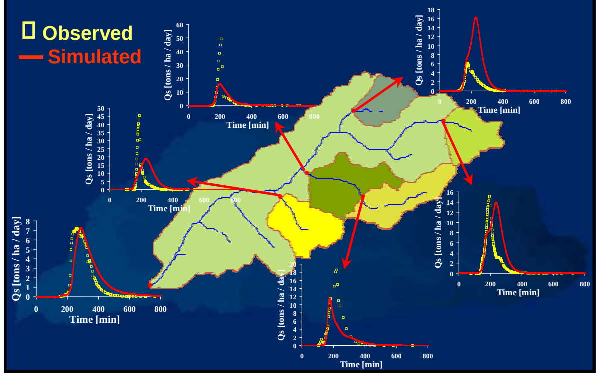

… and Deposition


Sediment Routing
Available material
Suspension
Deposition
Parent material
Advection Capacity vs. supply
Suspension
Deposition
Outgoing Cell
q_{sx}
q_{sy}
Receiving Cell
Receiving Cell

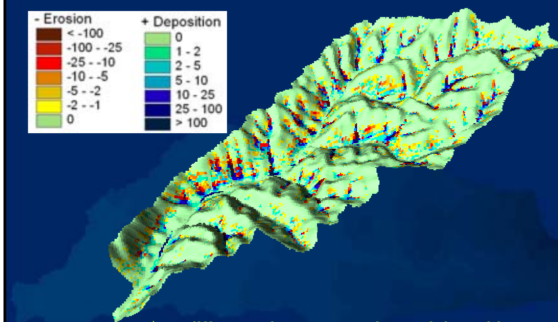

Upland Erosion (2-D)
Modified Kilinc and Richardson equation for sheet and rill erosion:
Land use
Soils
$q_t\,(tons/m*s) = 23210\,S_o^{1.66}\left(\frac{Q}{W}\right)^{2.035}\frac{K}{0.15}\,C\,P$
DEM
Hydraulics


Event transport of sediment (TSS)*
Sediment Concentration
mg/L
t = 1 min.
*Transport is computed by grain size. Total solids shown.

CASC2D-SED Sediment graphs



Net Erosion and Deposition*



*Net difference between erosion and deposition.

3. Sediment Delivery Ratio

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): $SDR = 0.42\,A^{-0.125}$

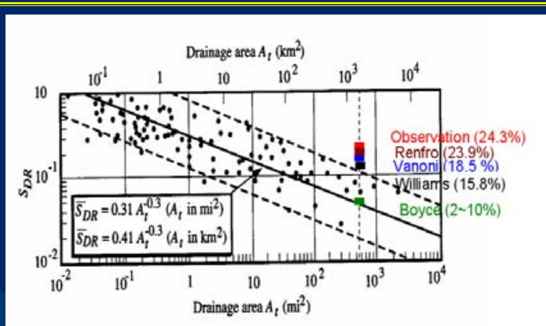
- A : the catchment area (mile^2)

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 Delivery Ratio



4. Trap Efficiency of Reservoirs

Imha reservoir

Trap Efficiency

Defined as the percentage of the total inflowing sediment that is retained in the reservoir

$$TE = \frac{Y_s(in) - Y_s(out)}{Y_s(in)}$$

- Ys (in) : sediment yield in inflow
- Ys (out) : sediment yield in outflow

TE equations

Julien (1998): $TE = 1 - e^{\frac{-X\omega_i}{Vh}}$ - Vh = q (unit discharge)

Brown (1943): $TE = 1 - \left[1 / (1 + KC / W) \right]$

Brune (1953): $TE = 0.97^{0.19^{\log\left(\frac{C}{I}\right)}}$

- K : coefficient k ranges from 0.046 to 1.0
- C : reservoir capacity (acre-ft)
- W: watershed area (miles^2), I : inflow rate (acre-ft/year)

Results of trap efficiency

Methods	Julien(1998)	Brown(1943)	Brune(1953)
TE (%)	99	96	98

- Results of TE range from 96 to 99% at the Imha reservoir.
- Considering the spillway discharge for flood season, TE of Imha reservoir might be around 95%

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

Acknowledgments

Dr. Mark Velleux, CSU, now Hydroqual
Dr. John England, CSU, also US Bureau of Reclamation
Dr. Rosalia Rojas, CSU
Hyeon Sik Kim, CSU, also KOWACO

pierre@engr.colostate.edu

THANK YOU for your attention!