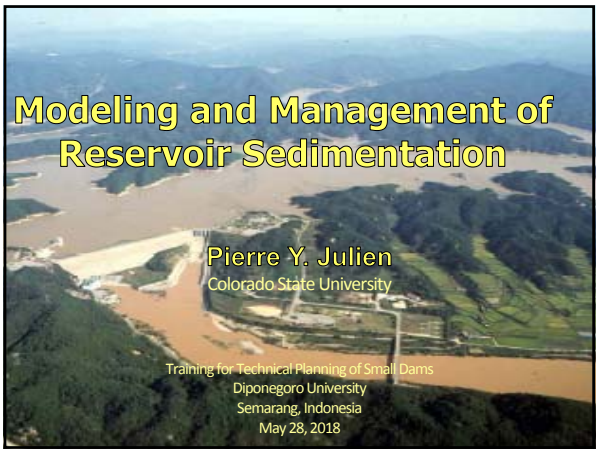
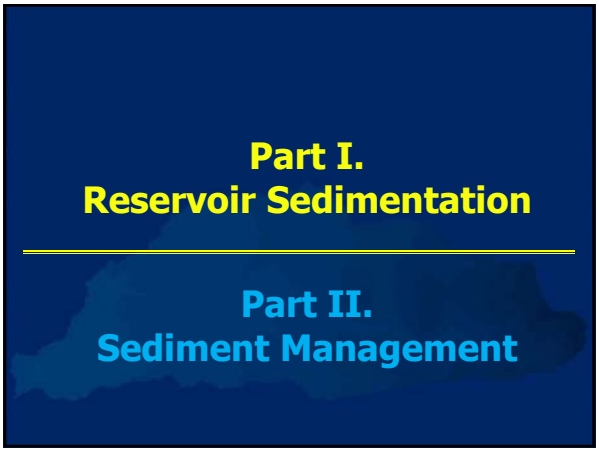
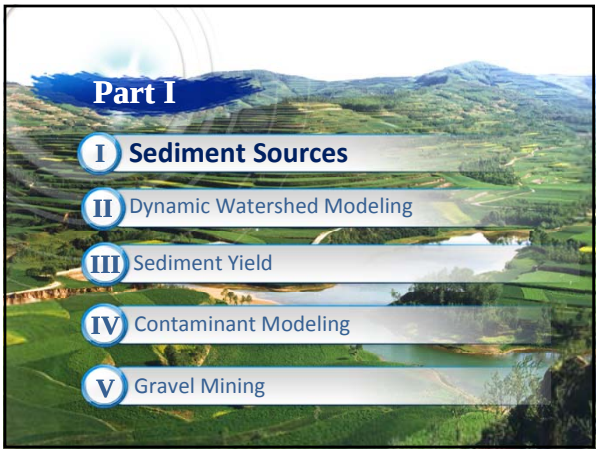
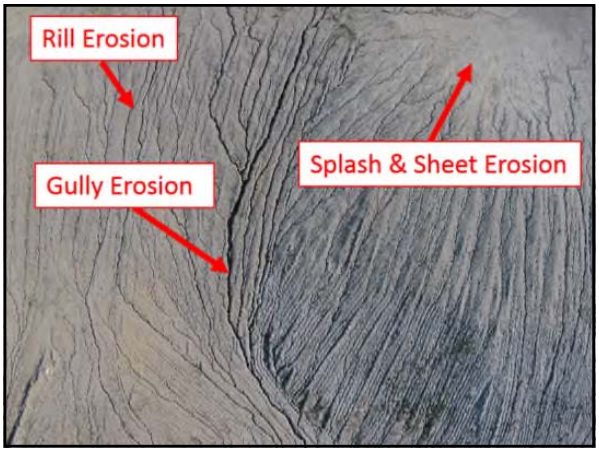

Modeling and Management of Reservoir Sedimentation
Pierre Y. Julien
Colorado State University
Training for Technical Planning of Small Dams
Diponegoro University
Semarang, Indonesia
May 28, 2018


Part I.
Reservoir Sedimentation
Part II.
Sediment Management


Part I
I Sediment Sources
II Dynamic Watershed Modeling
III Sediment Yield
IV Contaminant Modeling
V Gravel Mining



Revised Universal Soil-Loss Equation (RUSLE)

A = R K L S C P

- A : mean annual soil loss
- R : rainfall erosivity
- K : soil erodibility
- L : slope length
- S : slope steepness
- C : cropping management
- P : conservation practice

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Example, Imha Watershed, South Korea

- Watershed area: 1,361 km^2
- Channel length: 96 km
- Average watershed slope: 40%
- Fast and high peak runoff characteristics
- 30m x 30m resolution in 2006
- 5m x 5m resolution in 2018

From Kim and Julien 2006

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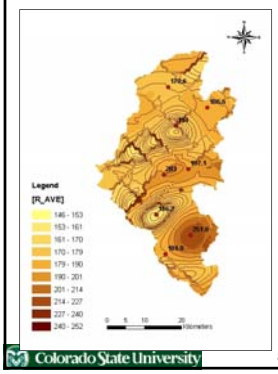
Rainfall Erosivity "R"



- Basic equation (Wischmeier, 1959)

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

$$R = \sum EI_{30}(10^{-2})$$

- R=average annual rainfall erosivity (ft·tonf·in/acre·h·yr)
- E=Total storm kinetic energy (ft·tons·in/acre·h)
- 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

From Kim and Julien 2006

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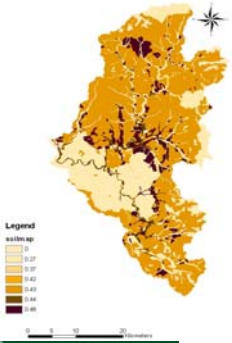
Soil Erodibility "K"



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

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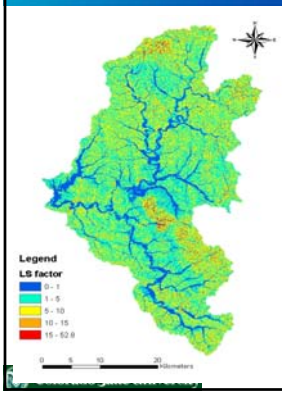
Slope Length-Steepness "LS"



- Basic equation (Renard-McCool, 1997)

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

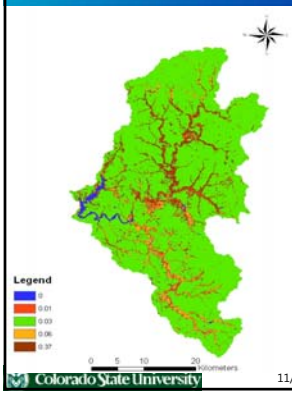
- X_h: the horizontal slope length (ft)
- m: a variable slope length factor

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

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

From Kim and Julien 2006

Cropping Management "C"



Land cover type	Cropping Management Factor (C)
Water	0.00
Urban	0.01
Wetland	0.00
Forest	0.03
Paddy field	0.06
Crop field	0.37

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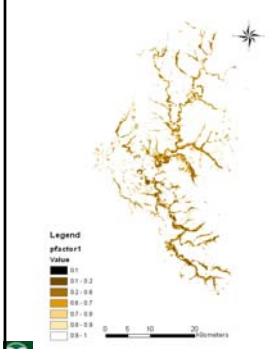
From Kim and Julien 2006

Conservation Practice Factor "P"



Slope (%)	Contour	Strip Crop	Terrace
0-7	0.55	0.27	0.10
7-11	0.60	0.30	0.12
11-18	0.80	0.40	0.16
18-27	0.90	0.45	0.18
>27	1.00	0.50	0.20

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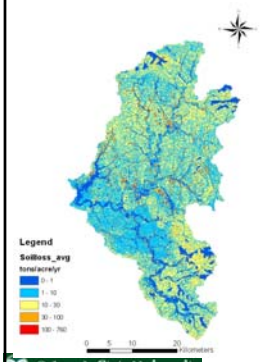
From Kim and Julien 2006

Results: Annual Average Soil Loss Map



- **Annual average soil loss:**
  A=3,450 tons/km^2/year
- Yield = A x SDR
- SDR: Sediment Delivery Ratio
- Boyce (1975):
  $SDR=0.31\ A^{-0.3}$

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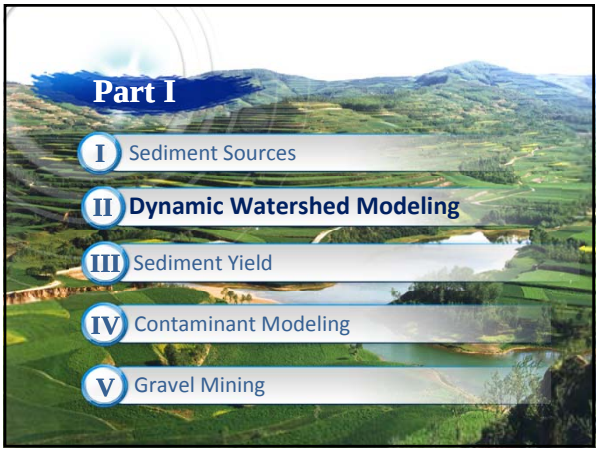
From Kim and Julien 2006

Upland Degradation Problems

Desirable stable landscape!


Part I
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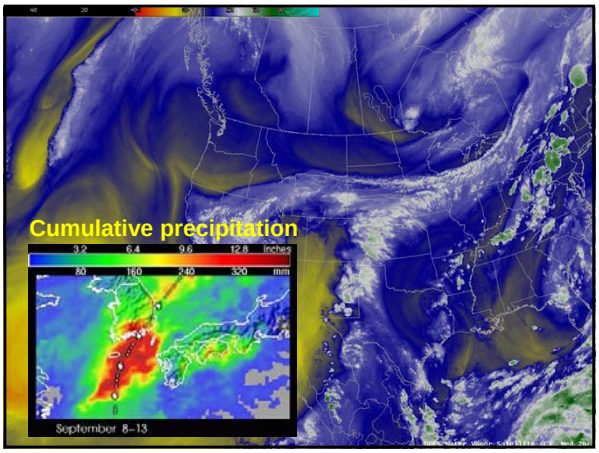
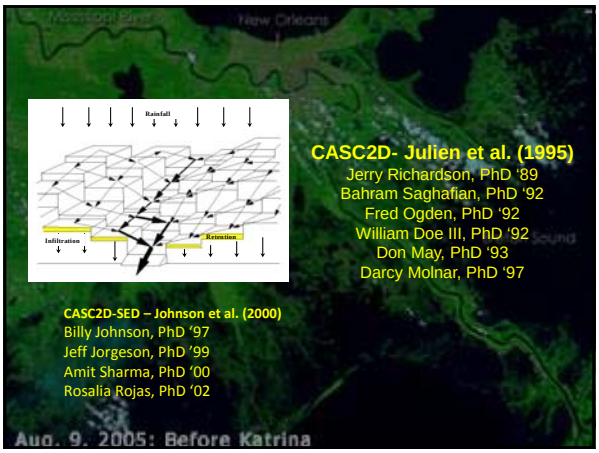
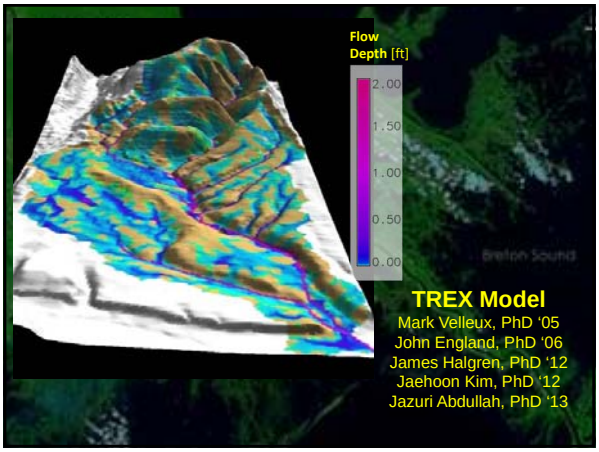
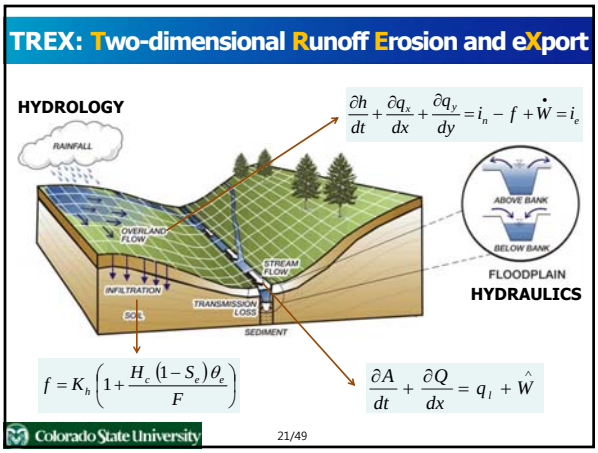
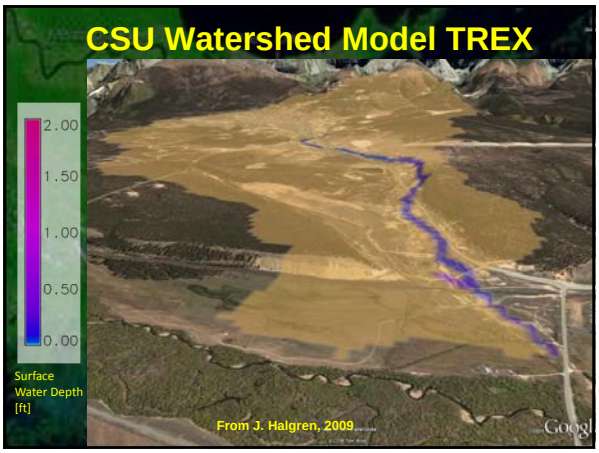
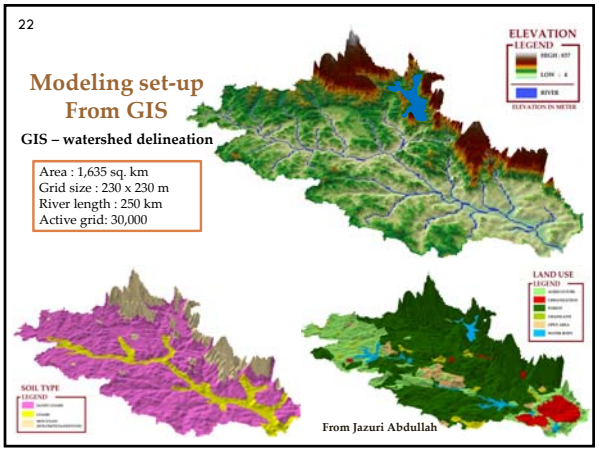

Cumulative precipitation
3.2 6.4 9.6 12.8 inches
80 160 240 320 mm
September 8–13

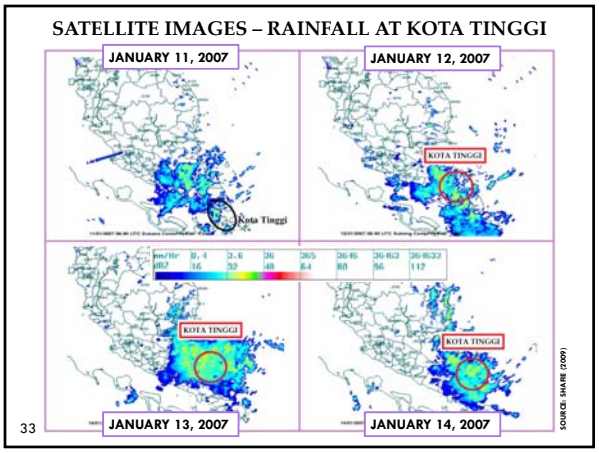

Rainfall
Infiltration
Retension
CASC2D- Julien et al. (1995)
Jerry Richardson, PhD '89
Bahram Saghafian, PhD '92
Fred Ogden, PhD '92
William Doe III, PhD '92
Don May, PhD '93
Darcy Molnar, PhD '97
CASC2D-SED – Johnson et al. (2000)
Billy Johnson, PhD '97
Jeff Jorgeson, PhD '99
Amit Sharma, PhD '00
Rosalia Rojas, PhD '02
Aug. 9, 2005: Before Katrina


Flow
Depth [ft]
2.00
1.50
1.00
0.50
0.00
TREX Model
Mark Velleux, PhD '05
John England, PhD '06
James Halgren, PhD '12
Jaehoon Kim, PhD '12
Jazuri Abdullah, PhD '13


TREX: Two-dimensional Runoff Erosion and eXport
HYDROLOGY
$\frac{\partial h}{dt} + \frac{\partial q_x}{dx} + \frac{\partial q_y}{dy} = i_n - f + \dot{W} = i_e$
RAINFALL
OVERLAND FLOW
INFILTRATION
SOIL
TRANSMISSION LOSS
STREAM FLOW
SEDIMENT
ABOVE BANK
BELOW BANK
FLOODPLAIN
HYDRAULICS
$f = K_h\left(1 + \frac{H_c(1-S_e)\theta_e}{F}\right)$
$\frac{\partial A}{dt} + \frac{\partial Q}{dx} = q_l + \hat{W}$
Colorado State University
21/49


CSU Watershed Model TREX
2.00
1.50
1.00
0.50
0.00
Surface
Water Depth
[ft]
From J. Halgren, 2009


22
Modeling set-up
From GIS
GIS – watershed delineation
Area : 1,635 sq. km
Grid size : 230 x 230 m
River length : 250 km
Active grid: 30,000
ELEVATION
LEGEND
LAND USE
LEGEND
SOIL TYPE
LEGEND
From Jazuri Abdullah


SATELLITE IMAGES – RAINFALL AT KOTA TINGGI
JANUARY 11, 2007
JANUARY 12, 2007
JANUARY 13, 2007
JANUARY 14, 2007
Kota Tinggi
KOTA TINGGI
KOTA TINGGI
KOTA TINGGI
33
SOURCE: SHAFIE (2009)

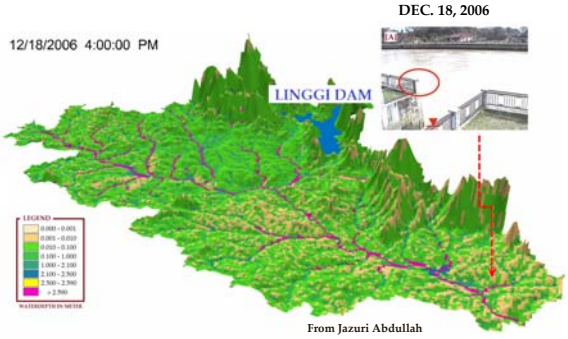
Rainfall near Kota Tinggi

Date	Layang-Layang	Ulu Sebol	Bukit Besar	Kota Tinggi
December 2006				
17-Dec	66 mm	33 mm	29 mm	48 mm
18-Dec	52 mm	23 mm	47 mm	43 mm
19-Dec	156 mm	189 mm	200 mm	161 mm
20-Dec	73 mm	78 mm	69 mm	39 mm
4 days total	367 mm	353 mm	345 mm	287 mm
January 2007				
11-Jan	145 mm	124 mm	147 mm	167 mm
12-Jan	135 mm	290 mm	234 mm	122 mm
13-Jan	84 mm	76 mm	42 mm	49 mm
14-Jan	20 mm	44 mm	35 mm	-
4 days total	384 mm	534 mm	458 mm	338 mm

25

KOTA TINGGI FLOOD

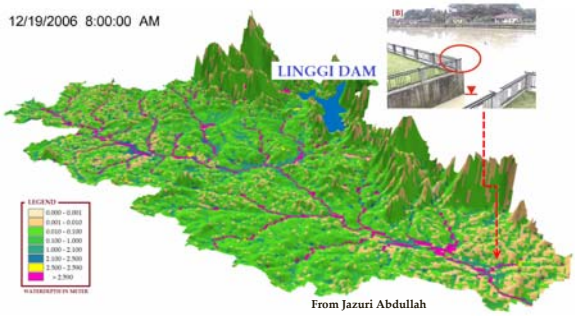
DEC. 18, 2006



From Jazuri Abdullah

KOTA TINGGI FLOOD

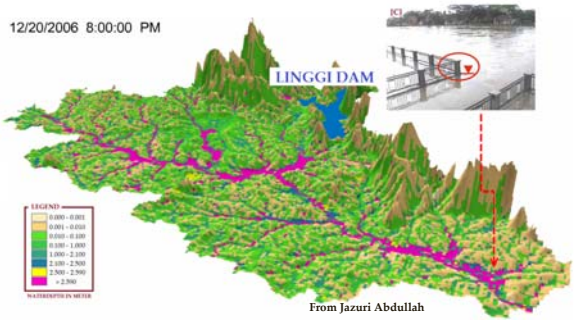
DEC. 19, 2006



From Jazuri Abdullah

KOTA TINGGI FLOOD

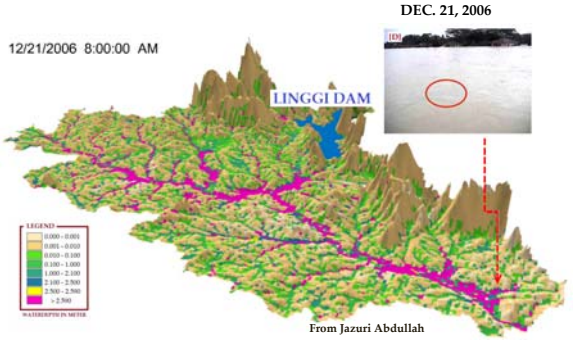
DEC. 20, 2006



From Jazuri Abdullah

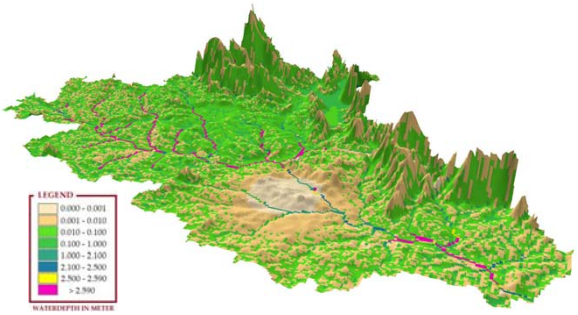
KOTA TINGGI FLOOD

DEC. 21, 2006



From Jazuri Abdullah

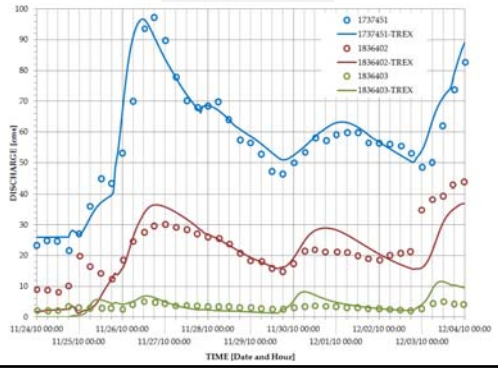
KOTA TINGGI FLOOD
JAN. 2007



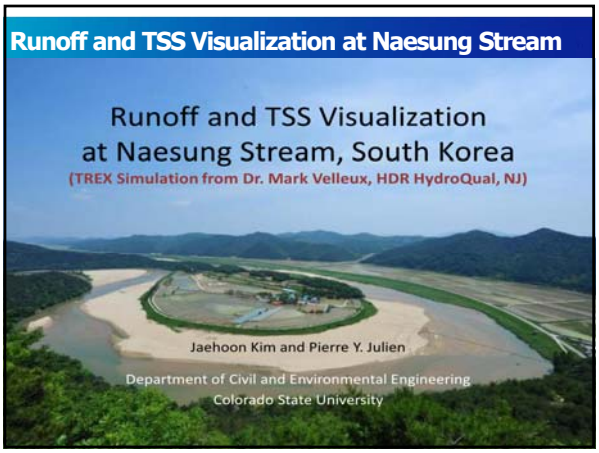
From Jazuri Abdullah

CALIBRATION

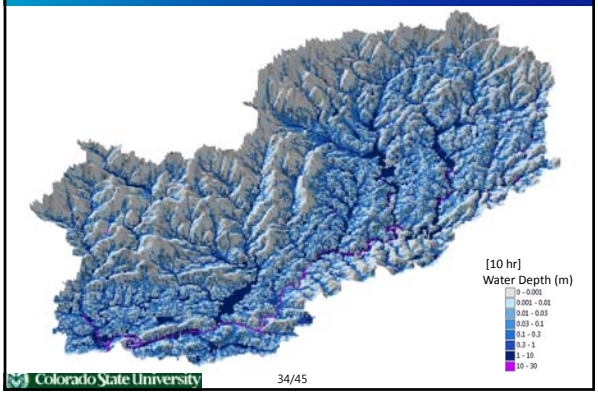
GRAPHICAL METHOD



27



Water Depth



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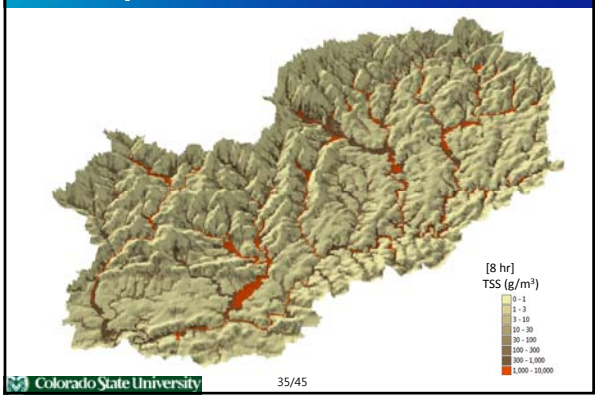
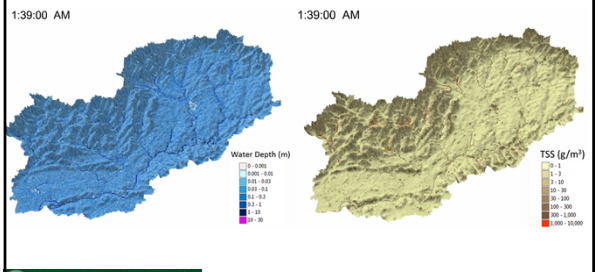
Total Suspended Solids

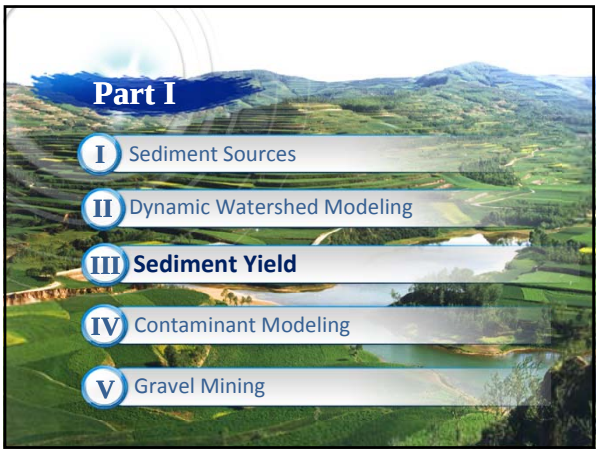


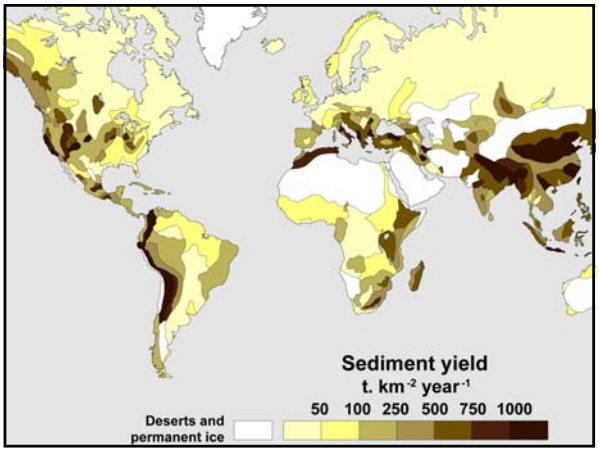
Colorado State University 35/45

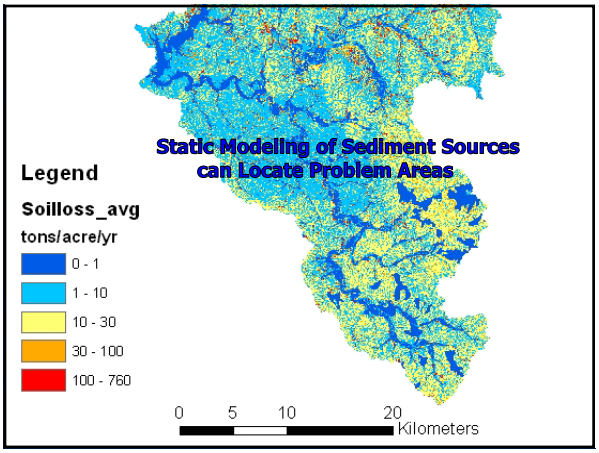
Runoff and TSS Visualization at Naesung Stream



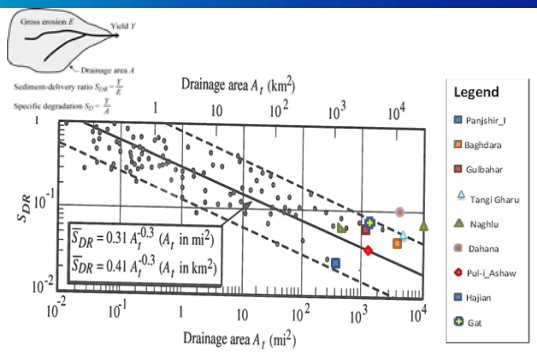
Colorado State University 36/45 Dynamic Watershed Modeling


Part I
I Sediment Sources
II Dynamic Watershed Modeling
III Sediment Yield
IV Contaminant Modeling
V Gravel Mining


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

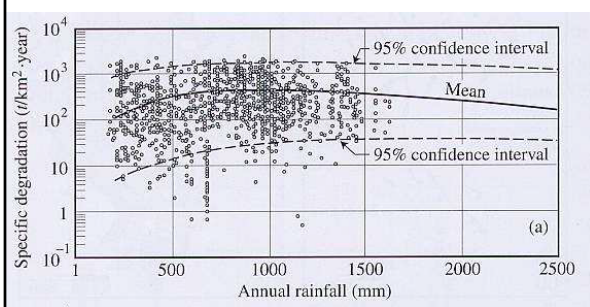

Static Modeling of Sediment Sources can Locate Problem Areas
Legend
Soilloss_avg
tons/acre/yr
0 - 1
1 - 10
10 - 30
30 - 100
100 - 760
0 5 10 20
Kilometers

Sediment Delivery Ratio (SDR)



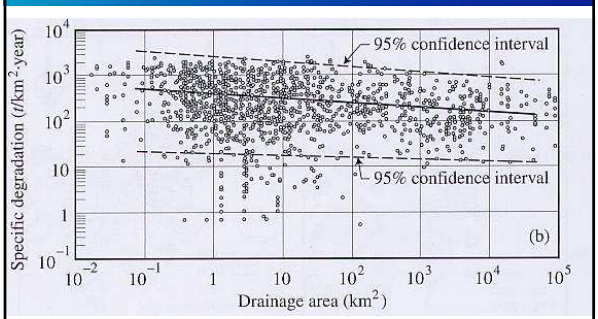
New data from Afghanistan, after Sahaar, 2013

Specific degradation and Annual rainfall

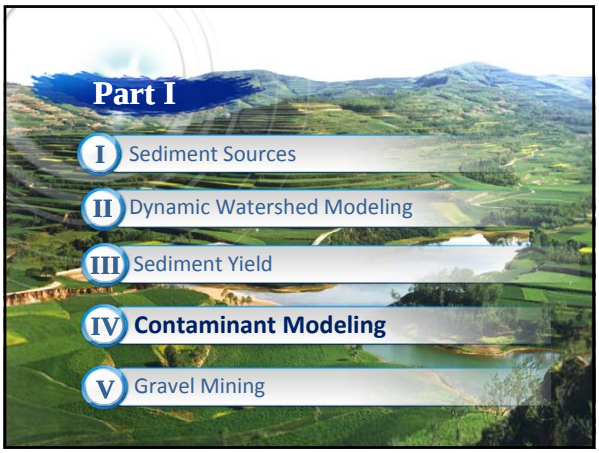


Data from all reservoirs in the US
From Kane and Julien (2007)

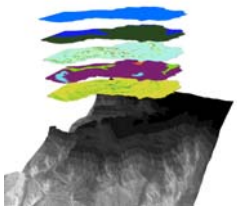
Specific degradation and Drainage area



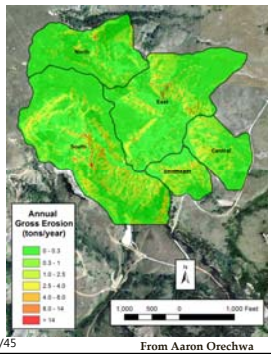
Data from all reservoirs in the US
From Kane and Julien (2007)



Contaminated Mining Site



Watershed ID	Area	Gross Erosion, A_T	
	[acres]	tons/year	kg/year
North	43	713	646,462
East	72	1,836	1,665,793
Southeast	16	587	532,348
Central	25	708	642,444
South	94	3,366	3,053,933



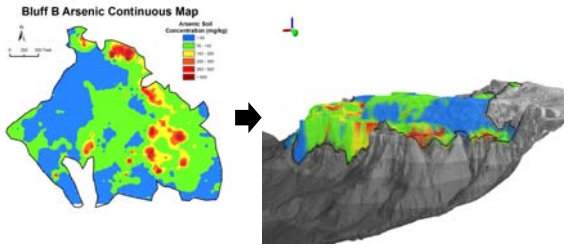
Colorado State University 44/45 From Aaron Orechwa

Characterization Techniques

Gamma Radiation Survey

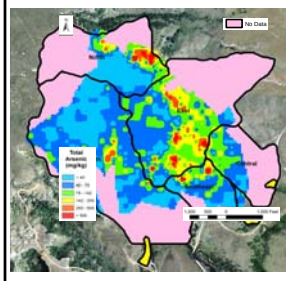
Colorado State University 45/45 From Aaron Orechwa

Arsenic Mapping



Colorado State University 46/45 From Aaron Orechwa

Arsenic Concentration in Drainage Basins



Watershed ID	Sediment Yield (Total Sediment) (kg/year)	Sediment Yield (Arsenic) (mg/year)	Predicted Sediment Concentration (Uranium) (mg/kg)
North	3.81E+05	1.4.E+07	37
East	9.15E+05	6.8.E+07	74
Southeast	3.54E+05	2.1.E+07	59
Central	4.05E+05	2.1.E+07	53
South	1.63E+06	6.3.E+07	39

Sediment Pond ID	Observed Arsenic in Sediment			Predicted Arsenic in Sediment (mg/kg)
	Minimum (mg/kg)	Maximum (mg/kg)	Average (mg/kg)	
SP1	29	99	56	53
SP2	25	77	62	59
SP3	25	33	29	39

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Part I

I Sediment Sources

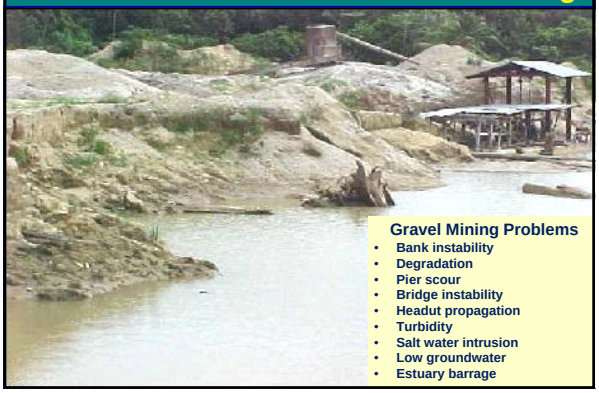
II Dynamic Watershed Modeling

III Sediment Yield

IV Contaminant Modeling

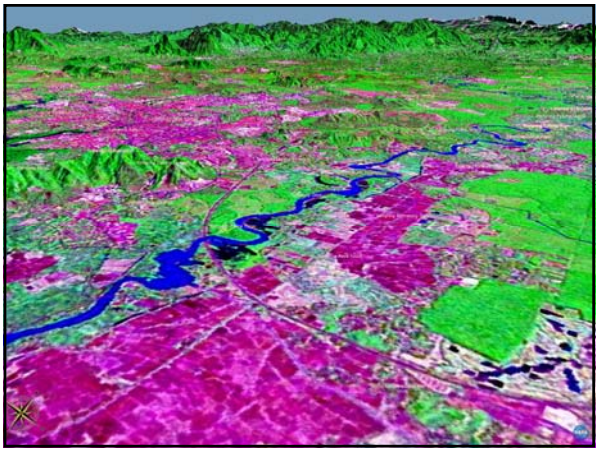
V **Gravel Mining**

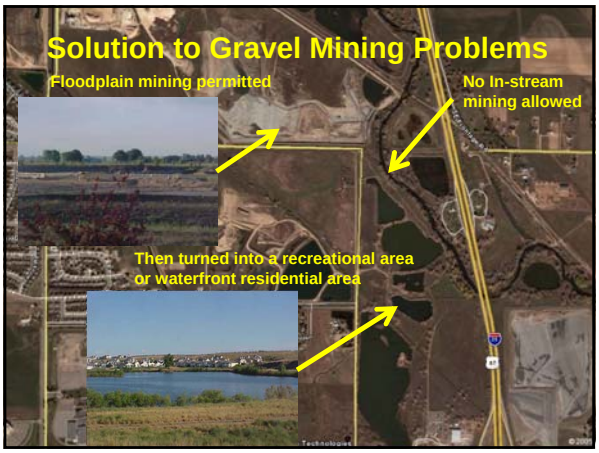
Problems from Sand and Gravel Mining

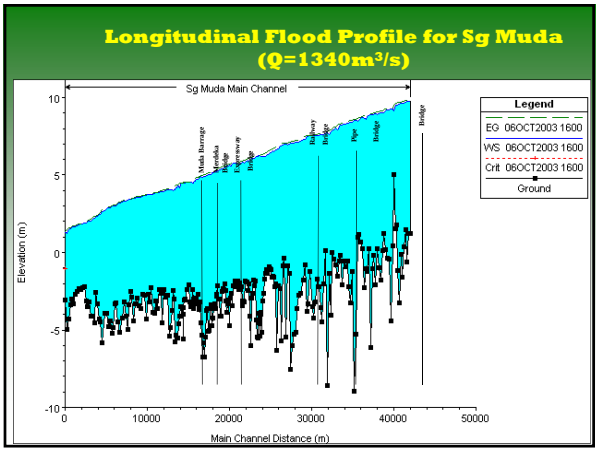


Gravel Mining Problems

- Bank instability
- Degradation
- Pier scour
- Bridge instability
- Headut propagation
- Turbidity
- Salt water intrusion
- Low groundwater
- Estuary barrage




Solution to Gravel Mining Problems
Floodplain mining permitted
No In-stream mining allowed
Then turned into a recreational area or waterfront residential area


Longitudinal Flood Profile for Sg Muda (Q=1340m³/s)
Sg Muda Main Channel
Legend
EG 06OCT2003 1600
WS 06OCT2003 1600
Crit 06OCT2003 1600
Ground
Elevation (m)
Main Channel Distance (m)

Downstream Protection of Bridges

Part I - Summary and Conclusions

1. Sediment Sources

Erosion mapping locates problem source areas

2. Dynamic Watershed Modeling

Dynamic models like TREX can simulate extreme floods

3. Sediment Yield

Typically less than 2,000 metric tons/km2-yr

4. Contaminant Modeling

New remote-sensing techniques for contaminant modeling

5. Gravel Mining

Allow off-stream mining turned into recreational areas

Reservoir Sedimentation References

1. Sediment Sources

Kim, H.S. and P.Y. Julien, "Soil Erosion Modeling using RUSLE and GIS on the Imha Watershed, South Korea", Water Eng. Res., J. Korean Water Res. Ass., 7(1), 2006, 29-41.

Rojas, R., P.Y. Julien, M. Velleux and B.E. Johnson, "Grid Size Effect on Watershed Soil Erosion Models", J. Hydrologic Eng., ASCE, 134(9), 2008, 793-802.

2. Dynamic Watershed Modeling

Abdullah, J. et al., "Flood Flow Simulations and Return Period Calculation for the Kota Tinggi Watershed, Malaysia", J. Flood Risk Manag., 2016, DOI: 10.1111/jfr3.12256

Ji U., M. Velleux, P.Y. Julien and M. Hwang, "Risk Assessment of Watershed Erosion at Naesung Stream, South Korea", J. Environmental Management, 136, 2014, 16-26.

Reservoir Sedimentation References

3. Sediment Yield

Kane, B. and P.Y. Julien, "Specific Degradation of Watersheds", Intl, J. Sediment Res., 22(2), 2007, 114-119.

4. Contaminant Modeling

Velleux, M.L., J.F. England Jr. and P.Y. Julien, "TREX: Spatially Distributed Model to Assess Watershed Contaminant Transport and Fate", J. Sci. Total Environ., 404, 2008, 113-128.

Velleux, M., et al. "Simulation of Metals Transport and Toxicity at a Mine-Impacted Watershed: California Gulch Colorado", Environ. Sci. Tech., 40(22), 2006, 6996-7004.

5. Gravel Mining

Julien, P.Y., A. Ab. Ghani, N.A. Zakaria, R. Abdullah and C.K. Chang, "Case- Study: Flood Mitigation of the Muda River, Malaysia," J. Hydraulic Eng., ASCE, 136(4), 2010, 251-261.