
Modeling and Management of Reservoir Sedimentation
Pierre Y. Julien
Colorado State University
Training for Technical Planning of Reservoir Sedimentation
Penang, Malaysia
November 21, 2019

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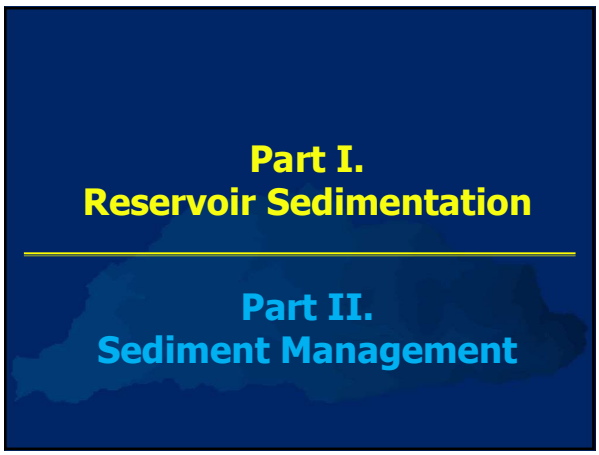
Part I.
Reservoir Sedimentation
Part II.
Sediment Management

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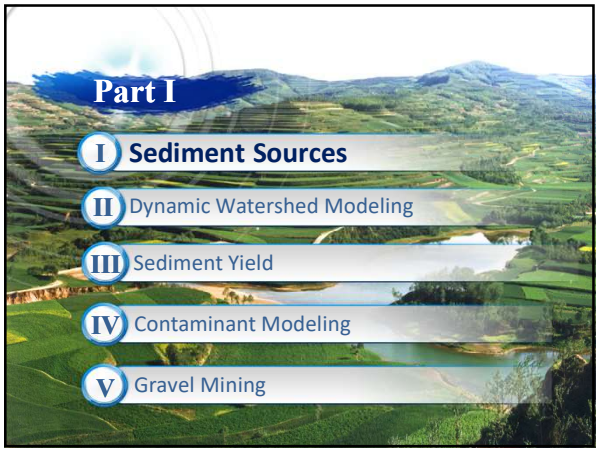
Part I
I Sediment Sources
II Dynamic Watershed Modeling
III Sediment Yield
IV Contaminant Modeling
V Gravel Mining

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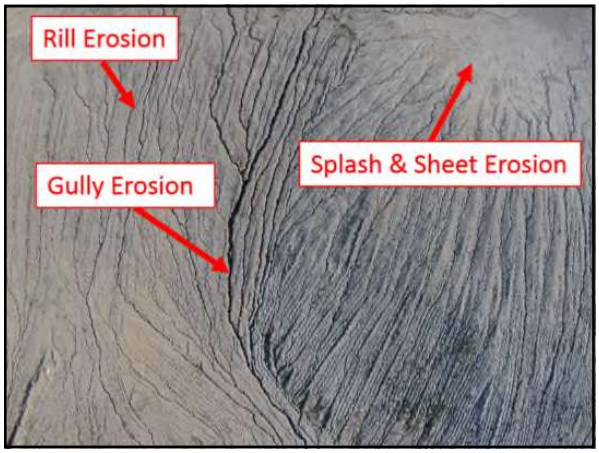


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## Revised Universal Soil-Loss Equation (RUSLE)

**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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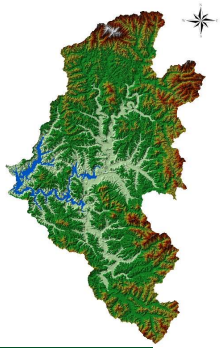
## Example, Imha Watershed, South Korea



- Watershed area: 1,361 km²
- 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

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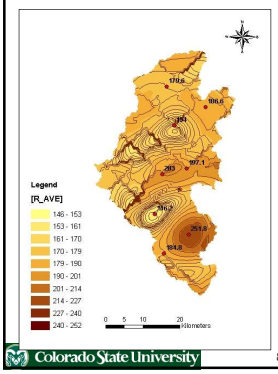
## Rainfall Erosivity "R"




- 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

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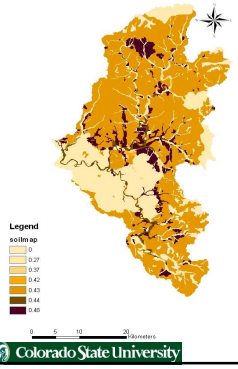
## Soil Erodibility "K"




| 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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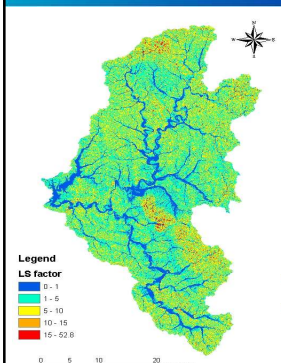
## Slope Length-Steepness "LS"




- 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 (%)

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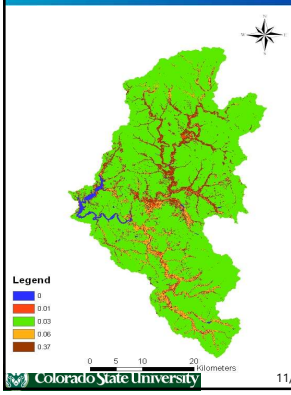
## Cropping Management "C"




| 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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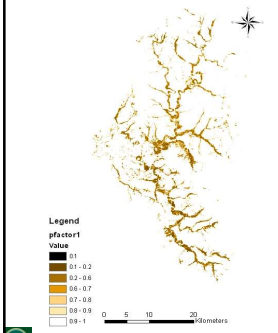
## Conservation Practice Factor "P"




| 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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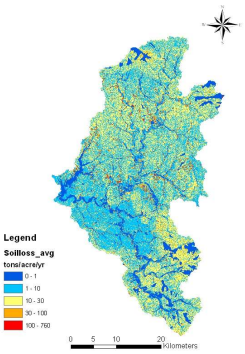
## Results: Annual Average Soil Loss Map




- **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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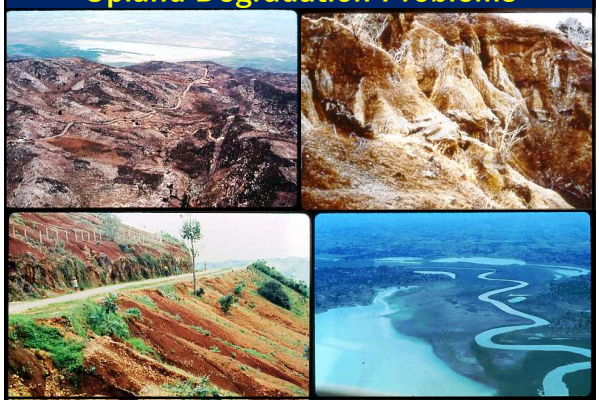
## Upland Degradation Problems



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Desirable stable landscape!

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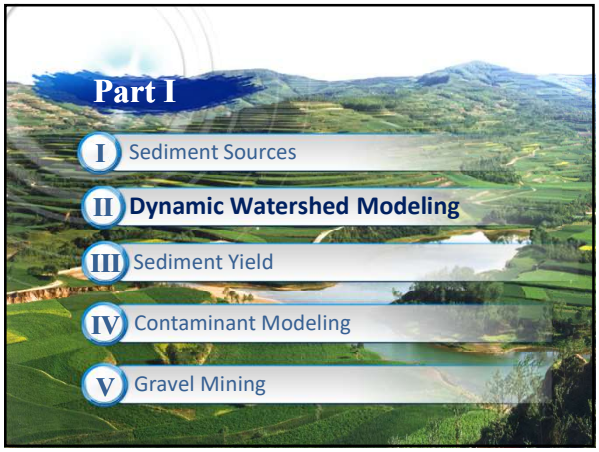
Part I
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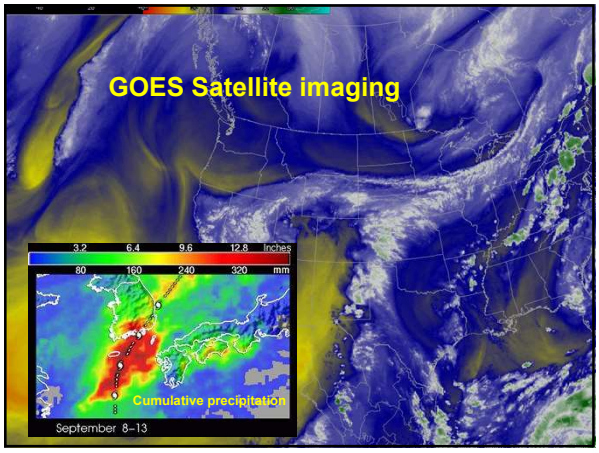
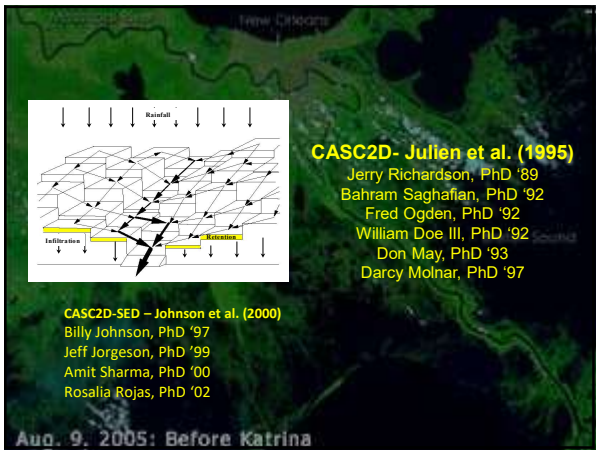

GOES Satellite imaging
3.2 6.4 9.6 12.8 Inches
80 160 240 320 mm
Cumulative precipitation
September 8–13

18


Rainfall
Infiltration
Retention
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

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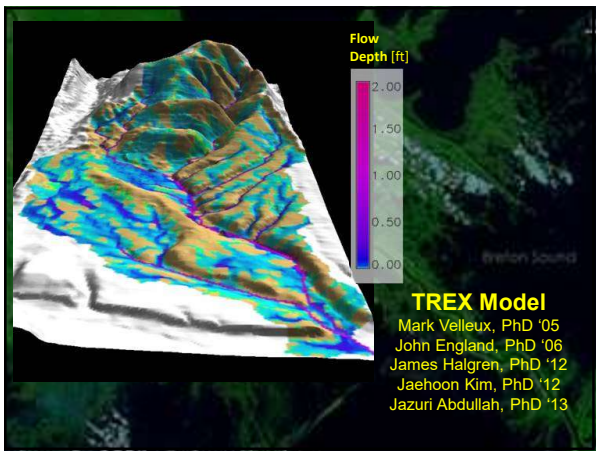
Flow
Depth [ft]
2.00
1.50
1.00
0.50
0.00
TREX Model
Mark Velleux, PhD '05
John England, PhD '06
James Halgren, PhD '12
Jaehoon Kim, PhD '12
Jazuri Abdullah, PhD '13

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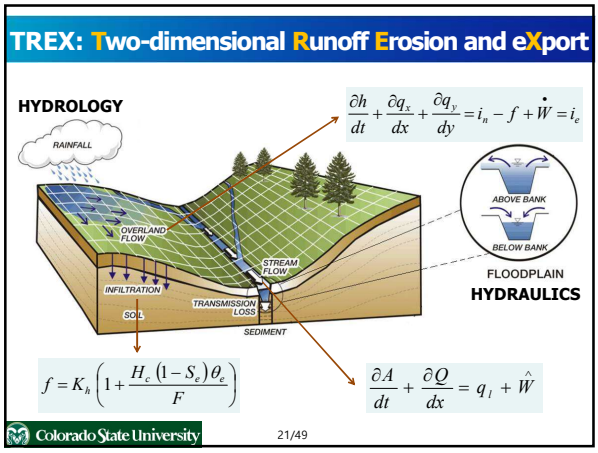
TREX: Two-dimensional Runoff Erosion and eXport
HYDROLOGY
RAINFALL
OVERLAND FLOW
INFILTRATION
SOIL
TRANSMISSION LOSS
STREAM FLOW
SEDIMENT
ABOVE BANK
BELOW BANK
FLOODPLAIN
HYDRAULICS
$\frac{\partial h}{dt} + \frac{\partial q_x}{dx} + \frac{\partial q_y}{dy} = i_n - f + \dot{W} = i_e$
$f = K_h \left(1 + \frac{H_c (1 - S_e)\theta_e}{F}\right)$
$\frac{\partial A}{dt} + \frac{\partial Q}{dx} = q_l + \hat{W}$
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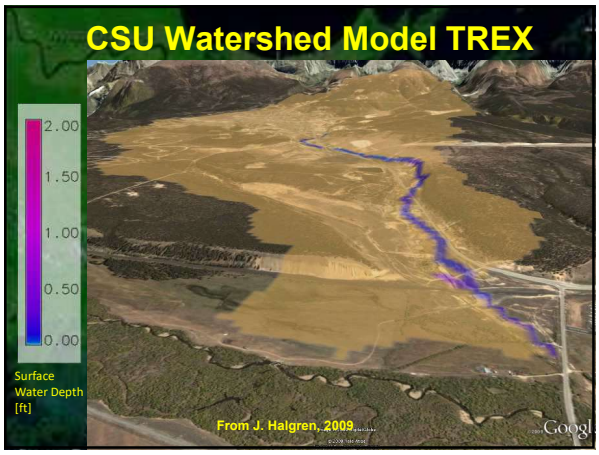
CSU Watershed Model TREX
2.00
1.50
1.00
0.50
0.00
Surface
Water Depth
[ft]
From J. Halgren, 2009

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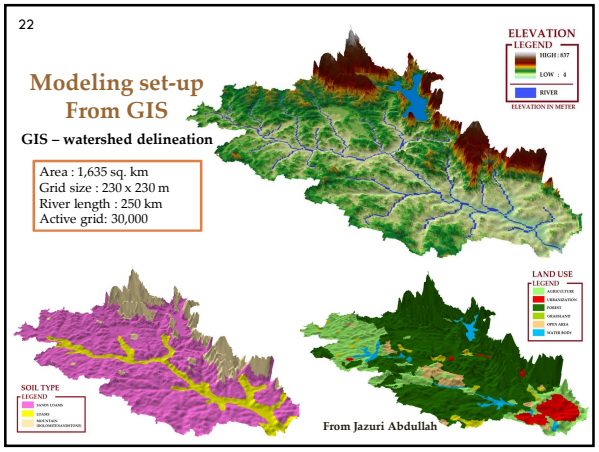
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Modeling set-up
From GIS
GIS – watershed delineation
Area : 1,635 sq. km
Grid size : 230 x 230 m
River length : 250 km
Active grid: 30,000
ELEVATION
LEGEND
HIGH : 837
LOW : 4
RIVER
ELEVATION IN METER
LAND USE
LEGEND
AGRICULTURE
URBANIZATION
FOREST
GRASSLAND
OPEN AREA
WATER BODY
SOIL TYPE
LEGEND
SANDY LOAMS
LOAMS
MOUNTAIN
(SOIL&SETTLEMENTTYPE)
From Jazuri Abdullah

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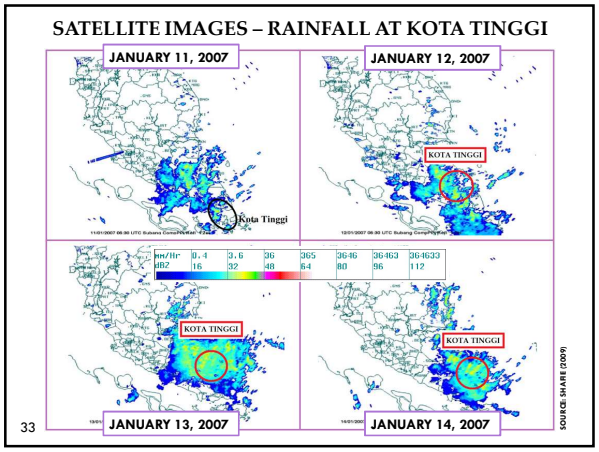
SATELLITE IMAGES – RAINFALL AT KOTA TINGGI
JANUARY 11, 2007
JANUARY 12, 2007
JANUARY 13, 2007
JANUARY 14, 2007
Kota Tinggi
KOTA TINGGI
KOTA TINGGI
KOTA TINGGI
mm/Hr
0.4
3.6
36
365
36-46
36-463
36-4633
16
32
48
64
80
96
112
SOURCE: SHAPE (2009)
33

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## 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 |

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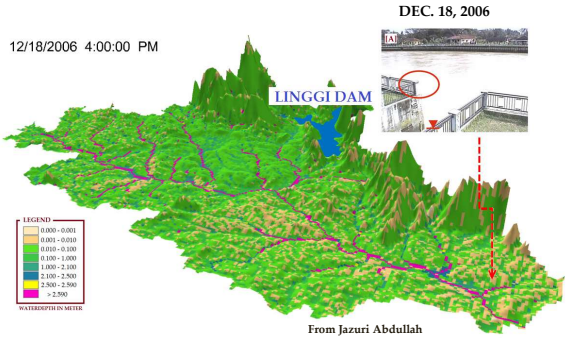
## KOTA TINGGI FLOOD

DEC. 18, 2006

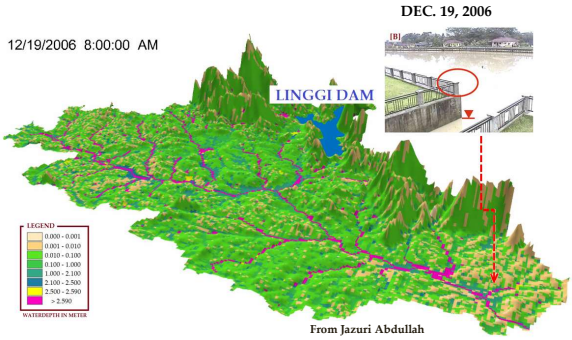



From Jazuri Abdullah

26

## KOTA TINGGI FLOOD

DEC. 19, 2006




From Jazuri Abdullah

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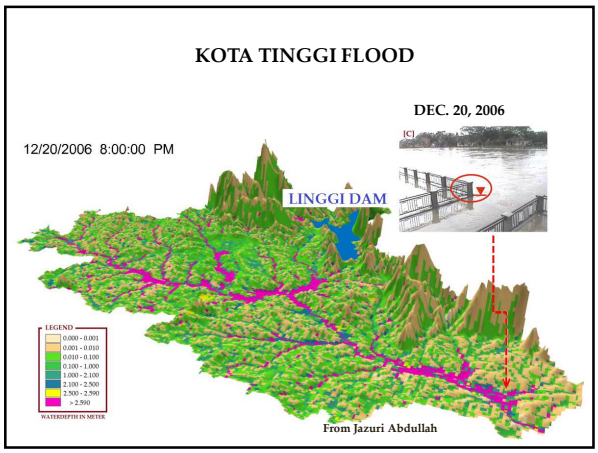
KOTA TINGGI FLOOD
DEC. 20, 2006
12/20/2006 8:00:00 PM
LINGGI DAM
[C]
LEGEND
0.000 - 0.001
0.001 - 0.010
0.010 - 0.100
0.100 - 1.000
1.000 - 2.100
2.100 - 2.500
2.500 - 2.590
> 2.590
WATERDEPTH IN METER
From Jazuri Abdullah

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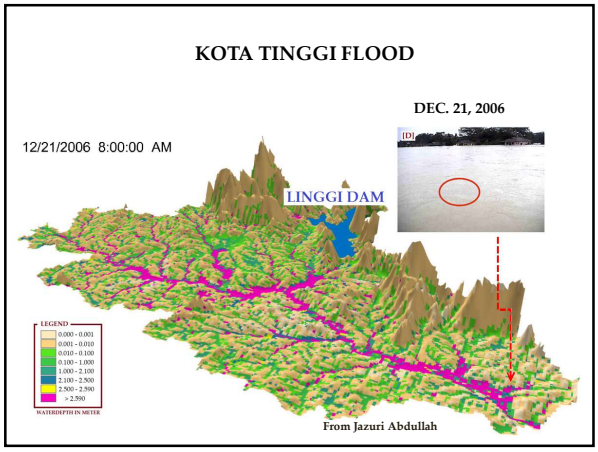
KOTA TINGGI FLOOD
DEC. 21, 2006
12/21/2006 8:00:00 AM
LINGGI DAM
[D]
LEGEND
0.000 - 0.001
0.001 - 0.010
0.010 - 0.100
0.100 - 1.000
1.000 - 2.100
2.100 - 2.500
2.500 - 2.590
> 2.590
WATERDEPTH IN METER
From Jazuri Abdullah

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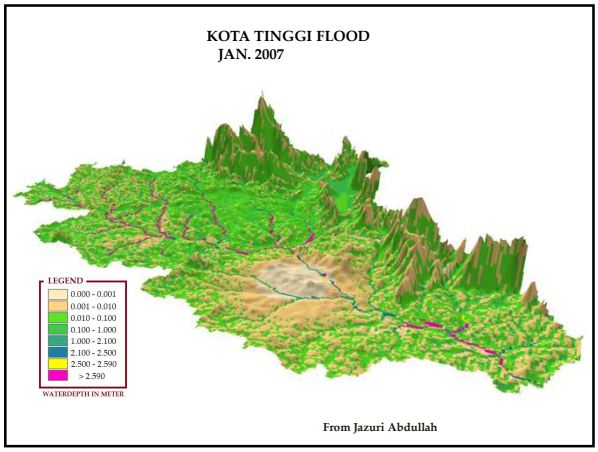
KOTA TINGGI FLOOD
JAN. 2007
LEGEND
0.000 - 0.001
0.001 - 0.010
0.010 - 0.100
0.100 - 1.000
1.000 - 2.100
2.100 - 2.500
2.500 - 2.590
> 2.590
WATERDEPTH IN METER
From Jazuri Abdullah

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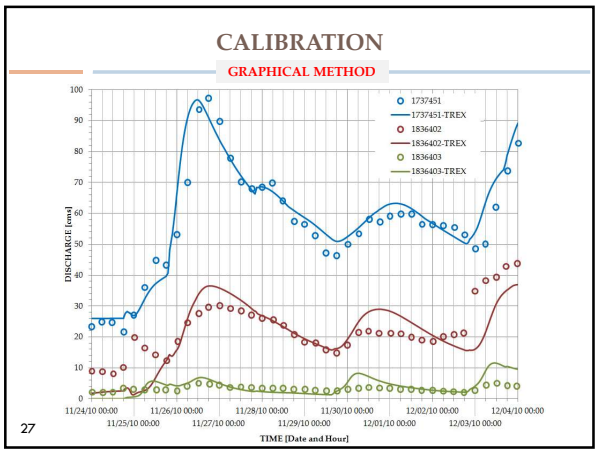
CALIBRATION
GRAPHICAL METHOD
1737451
1737451-TREX
1836402
1836402-TREX
1836403
1836403-TREX
DISCHARGE [cms]
TIME [Date and Hour]
27

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Kampung Abdullah
New Town Centre
To Labis
Jalan Pee Kang Hai
Second Bridge
Jalan Sultan
Sungai Segamat
Jalan Hassan

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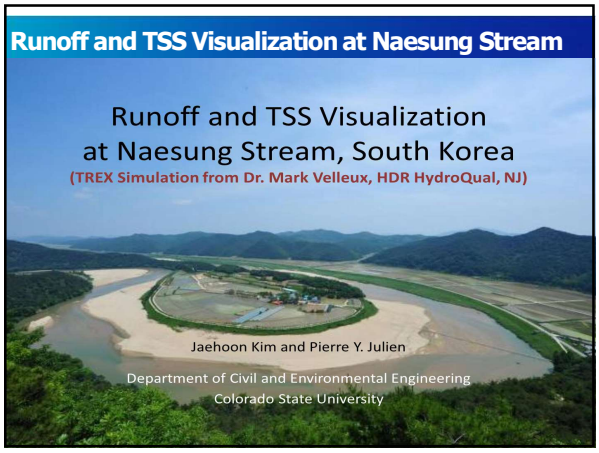
Runoff and TSS Visualization at Naesung Stream
Runoff and TSS Visualization
at Naesung Stream, South Korea
(TREX Simulation from Dr. Mark Velleux, HDR HydroQual, NJ)
Jaehoon Kim and Pierre Y. Julien
Department of Civil and Environmental Engineering
Colorado State University

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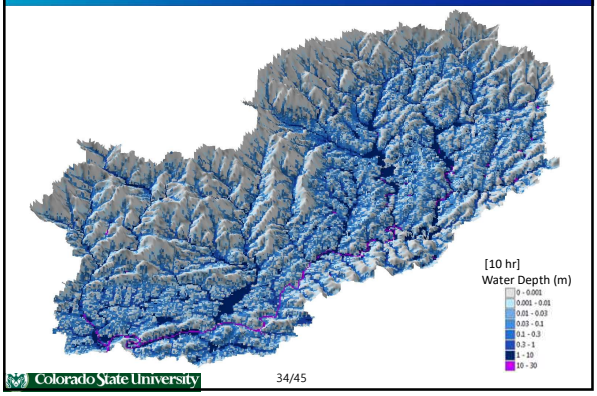
## Water Depth

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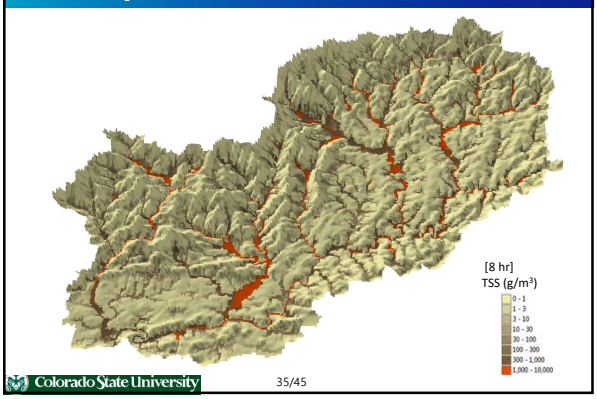
## Total Suspended Solids

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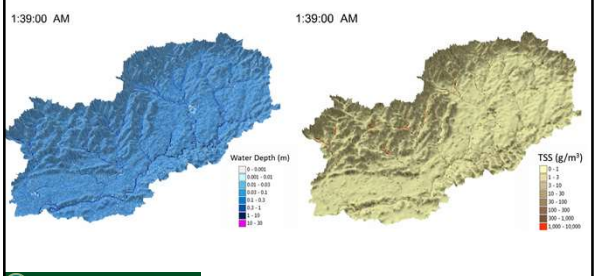
## Runoff and TSS Visualization at Naesung Stream

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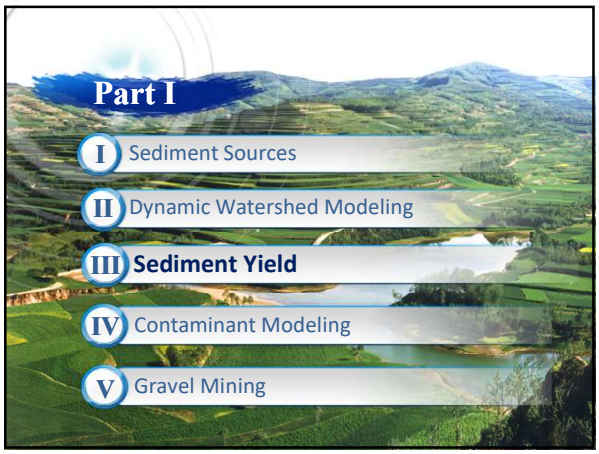
Part I
I Sediment Sources
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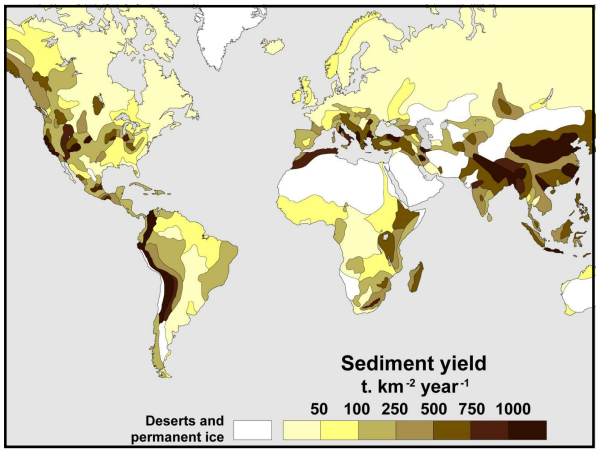
Sediment yield
t. km-2 year-1
50 100 250 500 750 1000
Deserts and permanent ice

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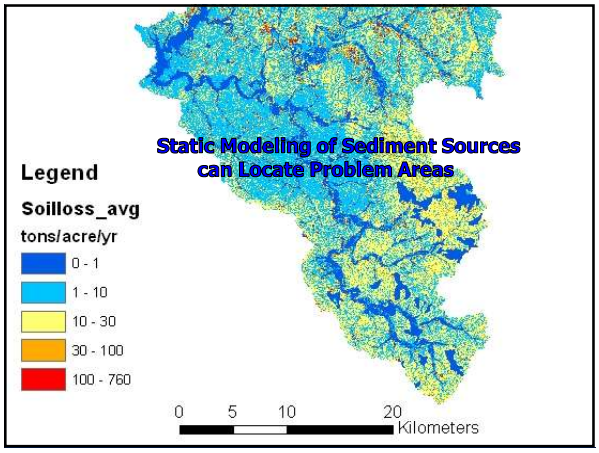
Static Modeling of Sediment Sources can Locate Problem Areas
Legend
Soilloss_avg
tons/acre/yr
0 - 1
1 - 10
10 - 30
30 - 100
100 - 760
0 5 10 20
Kilometers

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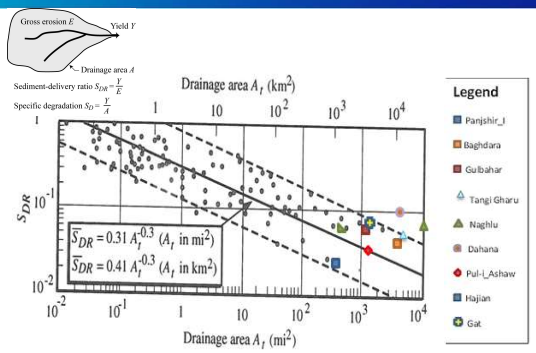
## Sediment Delivery Ratio (SDR)




New data from Afghanistan, after Sahaar, 2013



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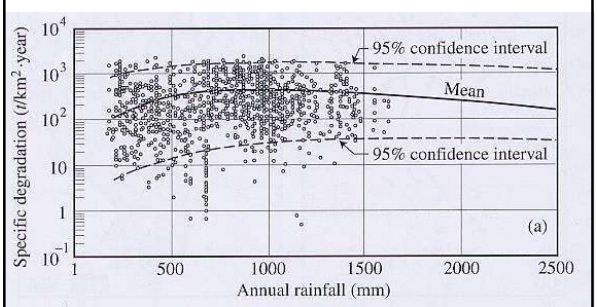
## Specific degradation and Annual rainfall




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



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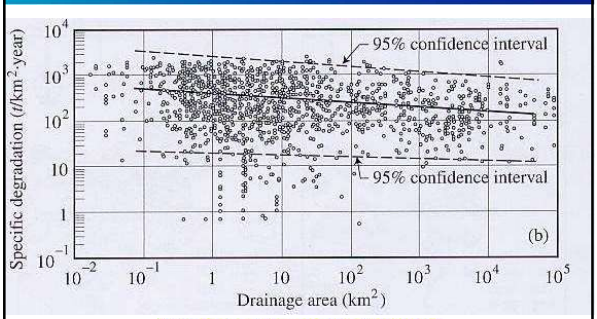
## Specific degradation and Drainage area




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



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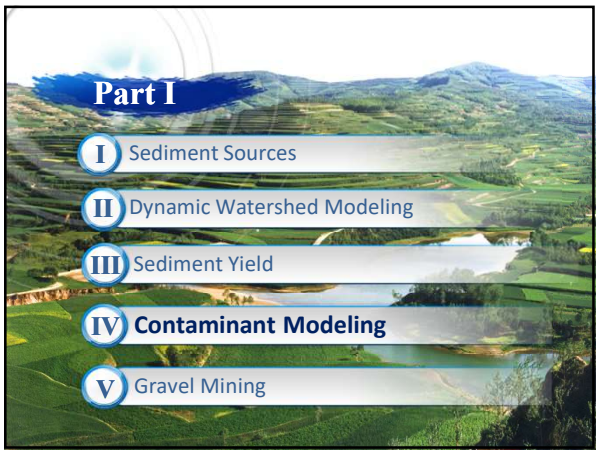


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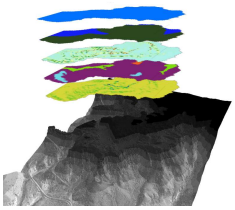
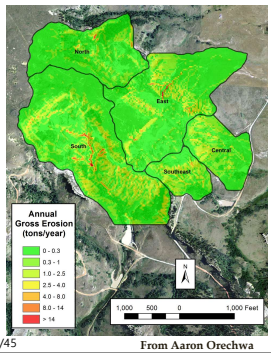
## Contaminated Mining Site



| 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 |

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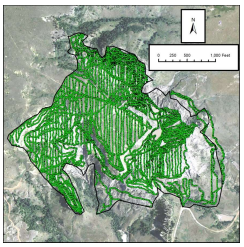
## Characterization Techniques

Gamma Radiation Survey

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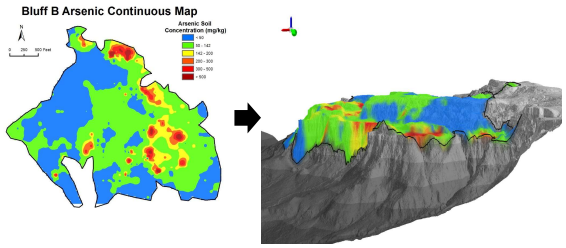
## Arsenic Mapping

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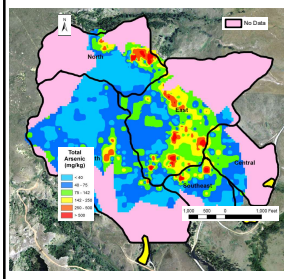
## Arsenic Concentration in Drainage Basins




| 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 | 9.19E+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 | 55 | 29 | 39 |

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## Part I

I Sediment Sources

II Dynamic Watershed Modeling

III Sediment Yield

IV Contaminant Modeling

V **Gravel Mining**

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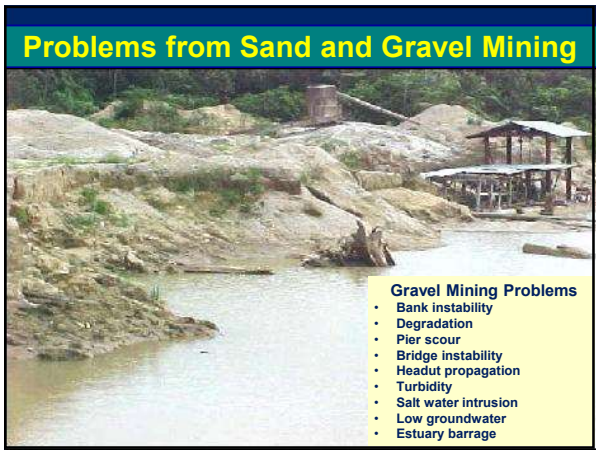
Problems from Sand and Gravel Mining
Gravel Mining Problems
• Bank instability
• Degradation
• Pier scour
• Bridge instability
• Headut propagation
• Turbidity
• Salt water intrusion
• Low groundwater
• Estuary barrage

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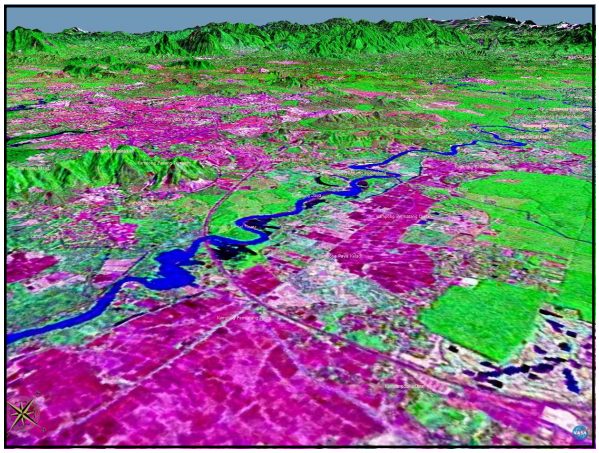

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PLUS Highway
KG. BUKIT LALANG
PEKULA
Merdeka Bridge
KG. BUMBUNG LIMA

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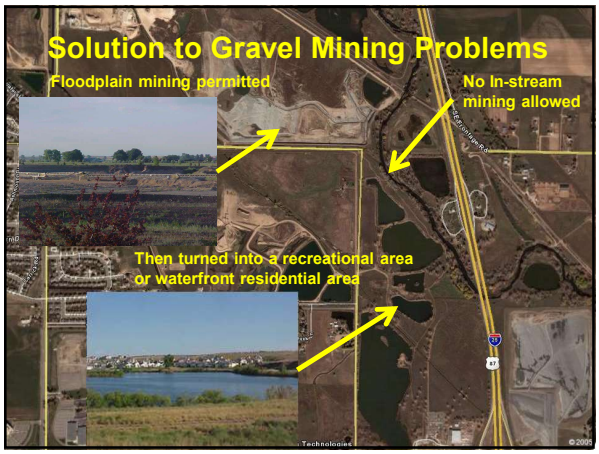
Solution to Gravel Mining Problems
Floodplain mining permitted
No In-stream mining allowed
Then turned into a recreational area or waterfront residential area

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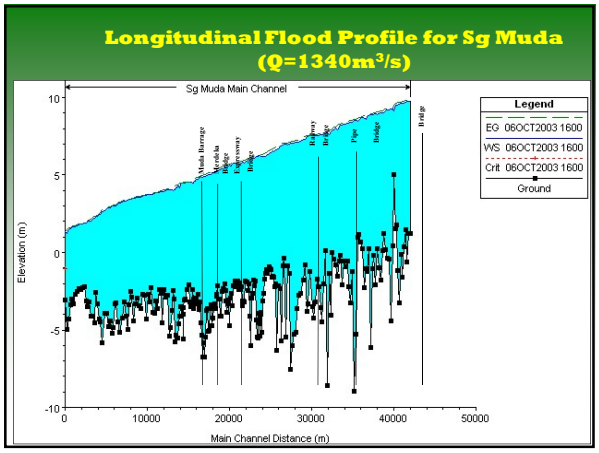
Longitudinal Flood Profile for Sg Muda (Q=1340m³/s)
Sg Muda Main Channel
Legend
EG 06OCT2003 1600
WS 06OCT2003 1600
Crit 06OCT2003 1600
Ground
Elevation (m)
Main Channel Distance (m)

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## Downstream Protection of Bridges

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## 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*

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## 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.*


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## 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.*


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