River Geometry and Mechanics

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Colorado State University
Fort Collins, Colorado

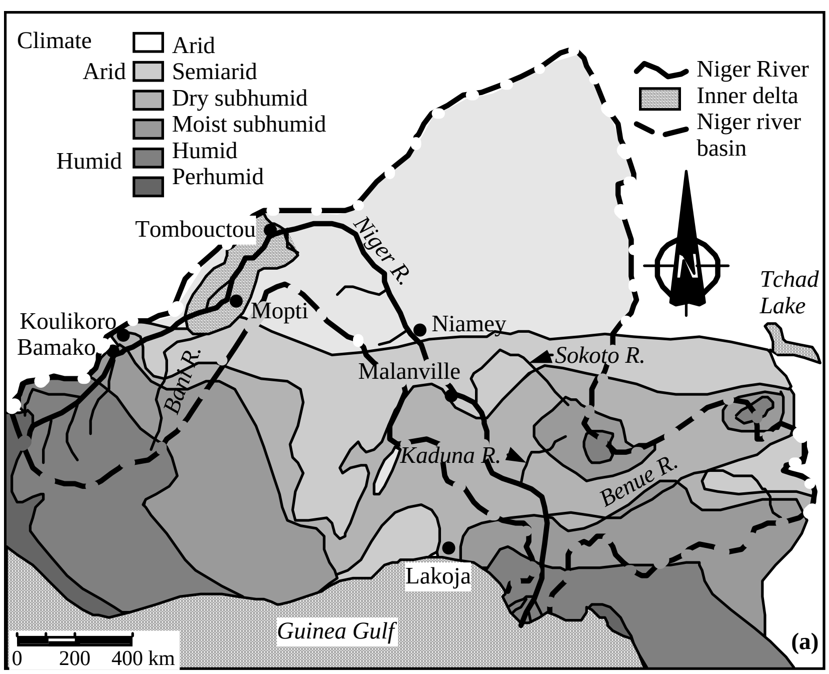
River Mechanics and Sediment Transport
Lima Peru – January 2016

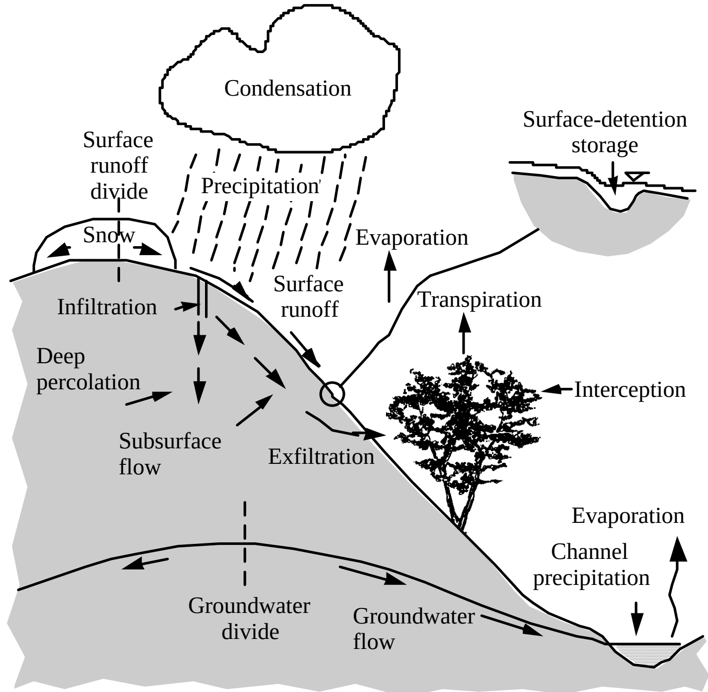
Objectives

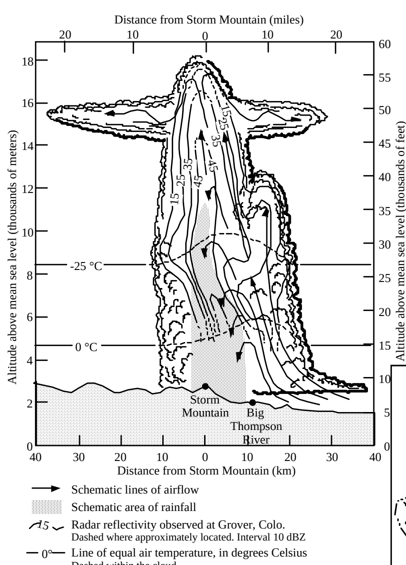
Brief overview of stream restoration and river rehabilitation guidelines:

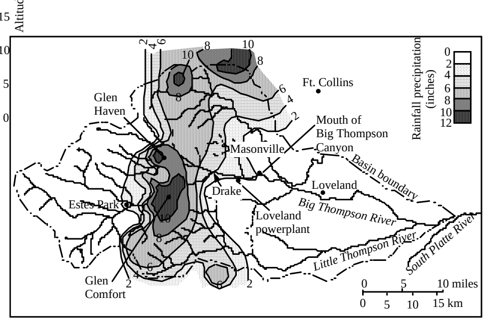
1. Hydrology and Hydraulics;
2. Extreme River Floods;
3. Climate Change Impact on Rivers;
4. River Geometry;
5. Flow Pulses Downstream of Reservoirs.

1. Hydrology and Hydraulics



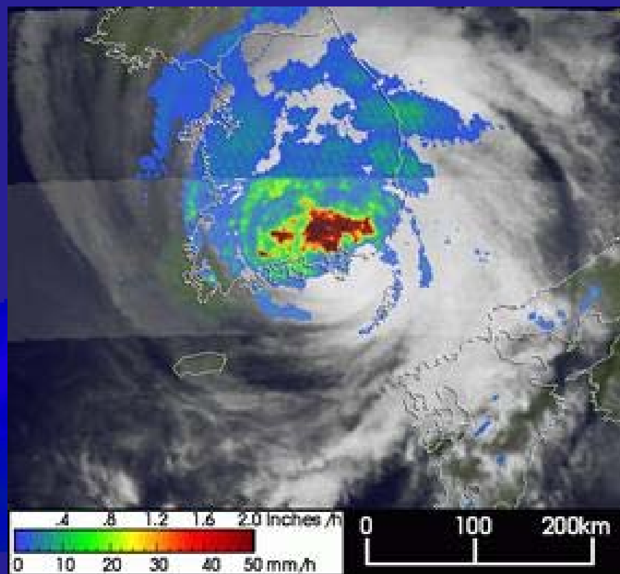

Condensation
Surface runoff divide
Precipitation
Snow
Evaporation
Surface-detention storage
Infiltration
Surface runoff
Transpiration
Deep percolation
Interception
Subsurface flow
Exfiltration
Evaporation
Channel precipitation
Groundwater divide
Groundwater flow


Distance from Storm Mountain (miles)
Altitude above mean sea level (thousands of meters)
Altitude above mean sea level (thousands of feet)
-25 °C
0 °C
Storm Mountain
Big Thompson River
Distance from Storm Mountain (km)
Schematic lines of airflow
Schematic area of rainfall
Radar reflectivity observed at Grover, Colo.
Dashed where approximately located. Interval 10 dBZ
Line of equal air temperature, in degrees Celsius
Dashed within the cloud

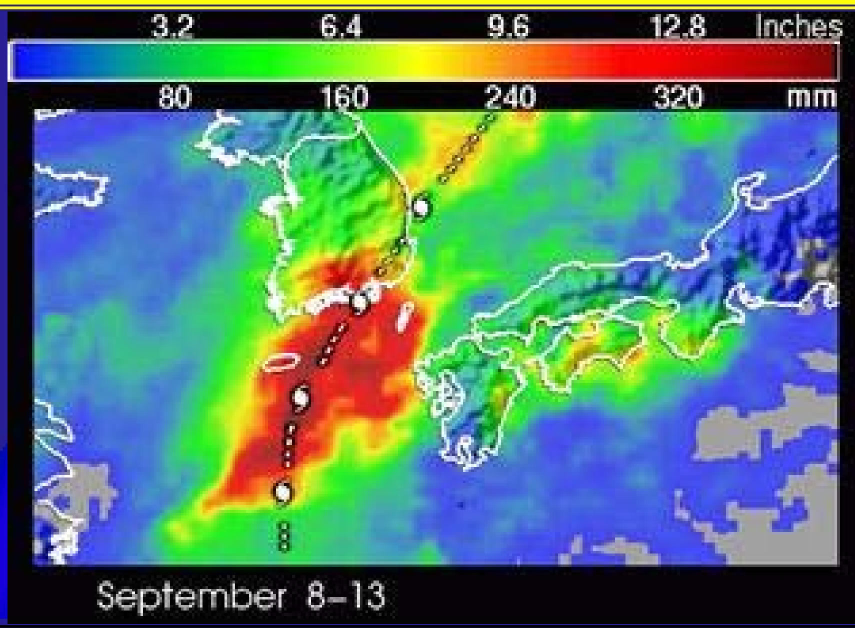

Ft. Collins
Glen Haven
Mouth of Big Thompson Canyon
Masonville
Basin boundary
Loveland
Drake
Estes Park
Big Thompson River
Loveland powerplant
Little Thompson River
South Platte River
Glen Comfort
Rainfall precipitation (inches)
10 miles
15 km

AGU Hydrology days 2005

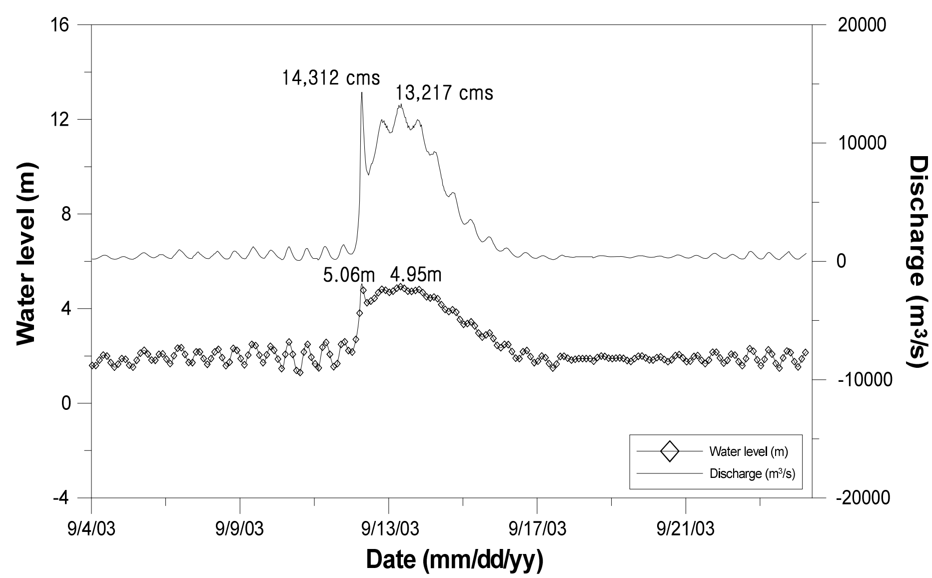
Rainfall distribution of Typhoon Maemi in Korea

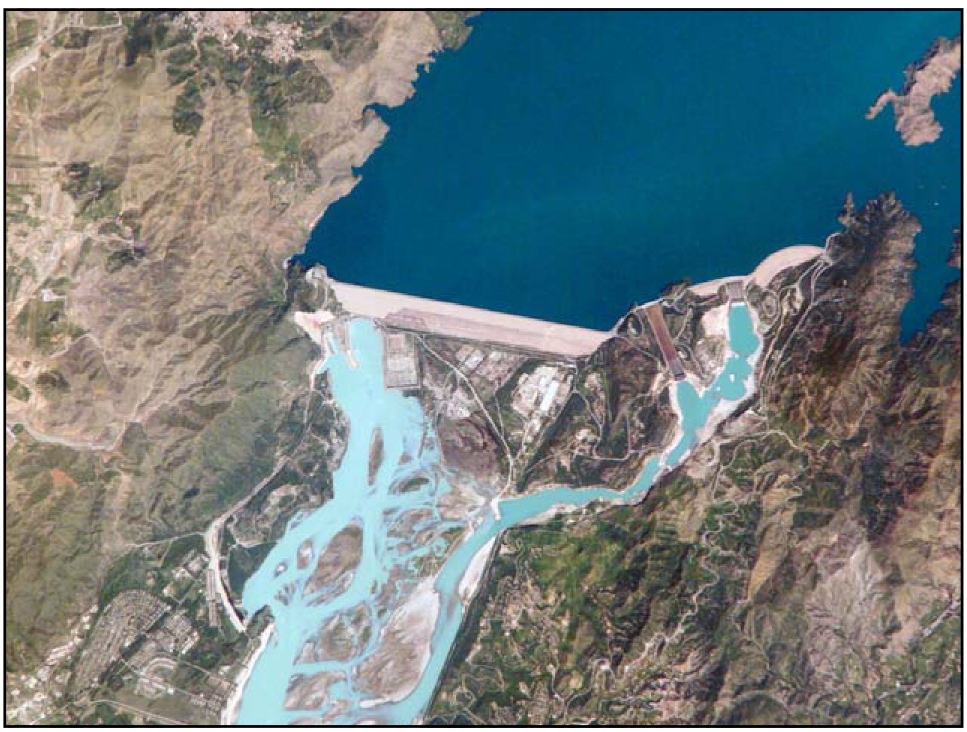


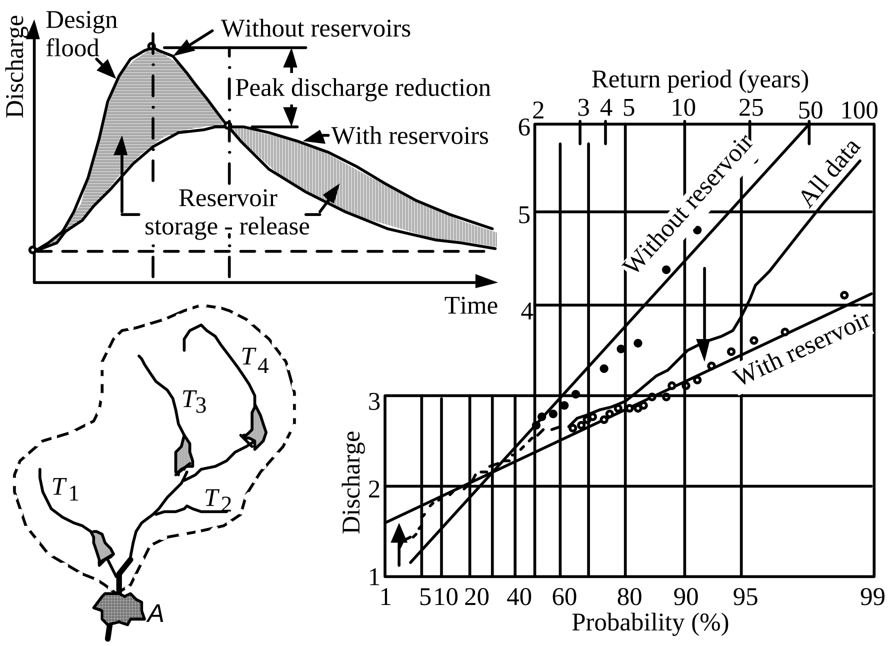
Total rainfall of Typhoon Maemi in 2003

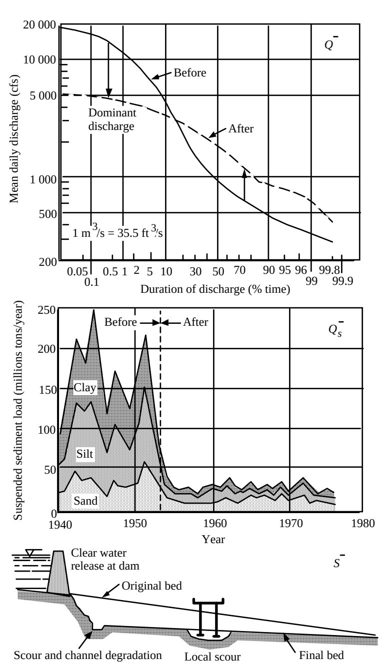


Water stage and discharge graph at Gupo bridge

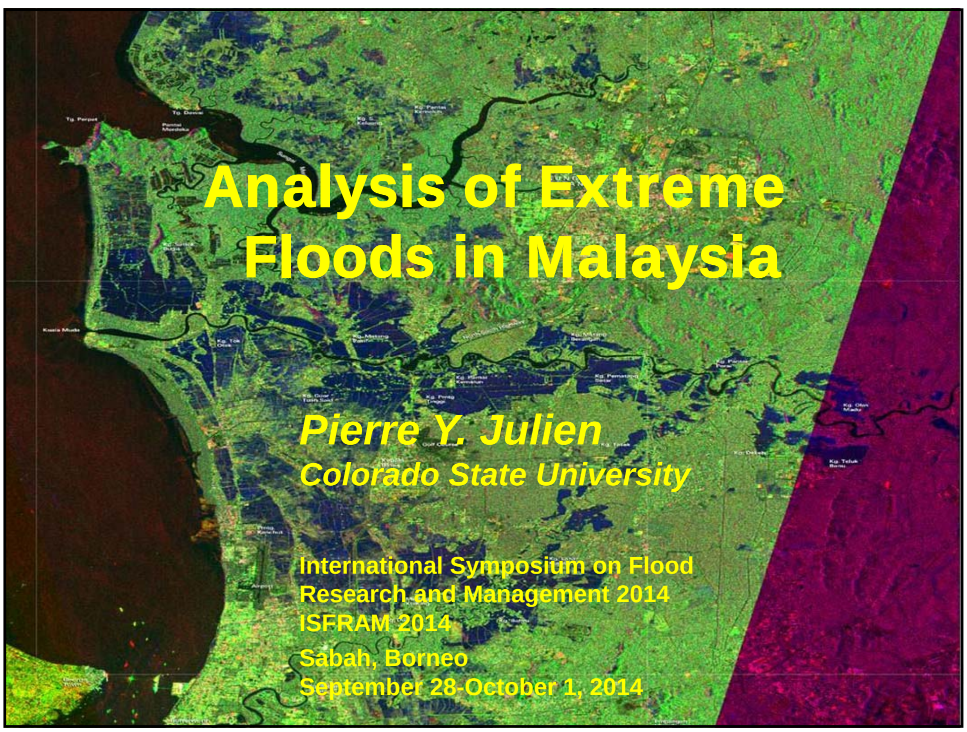





Design flood
Without reservoirs
Discharge
Peak discharge reduction
With reservoirs
Reservoir storage - release
Time
T_4
T_3
T_1
T_2
A
Return period (years)
2 3 4 5 10 25 50 100
Without reservoir
All data
With reservoir
Discharge
1 5 10 20 40 60 80 90 95 99
Probability (%)


(a)
Mean daily discharge (cfs)
Before
After
Dominant discharge
1 m³/s = 35.5 ft³/s
Duration of discharge (% time)
(b)
Suspended sediment load (millions tons/year)
Before
After
Clay
Silt
Sand
Year
(c)
Clear water release at dam
Original bed
Scour and channel degradation
Local scour
Final bed

2. Extreme River Floods



Analysis of Extreme Floods in Malaysia

Pierre Y. Julien
Colorado State University

International Symposium on Flood Research and Management 2014
ISFRAM 2014
Sabah, Borneo
September 28-October 1, 2014

Floods in Malaysia (2006/2007)

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Flooding in Peninsular Malaysia from 2007 to 2012

YEAR	STATES	NOTE	SOURCES
2007	Johor, Pahang, Kuala Lumpur, Kedah, Negeri Sembilan, Kelantan	• RM 1.2 Billion (USD 400 Million) • 260,000 people were evacuated from more than 40,000 families	Shafie (2009); MMD (2007)
2008	Negeri Sembilan, Kuala Lumpur, Pulau Pinang, Kelantan, Terengganu, Pahang	• Major roads effected • Landslide • Over 6,000 people evacuated to 40 flood evacuation centers	MMD (2008)
2009	Kuala Lumpur, Kelantan, Kedah, Selangor, Pahang	• Severe traffic congestion • Landslide • About 60 families were evacuated	MMD (2009)
2010	Most of the states in Peninsular Malaysia	• More than 70,000 people were evacuated • Traffic jams and water depth more than 1.0 m	MMD (2010)
2011	Most of the states in Peninsular Malaysia	• More than 70,000 people were evacuated • Traffic jams and water depth more than 1.0 m	Taucan et al. (2011); Utusan (2011); Maslih et al. (2011); Ismail (2011); Abdullah (2011); Md.-Noor (2011); Mohd and Perimbanayagam (2011)
2012	Most of the states in Peninsular Malaysia	• More than 5,000 people were evacuated and 600 houses were submerged • Water depth approximately reached 2.0 m at most of the places	Utusan (2012); Jamaluddin and Hassan (2012); Maslih (2012); Sinyang (2012); Wan-Alias (2012); Cameons and Wong (2012); myMetro (2012); Md.-Noor (2012)

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Extreme Floods in Malaysia

1. Extreme Rainfall Precipitation
2. Extreme Flood Modeling
3. Kota Tinggi Flood
4. Muda River Flood
5. River Management Manual

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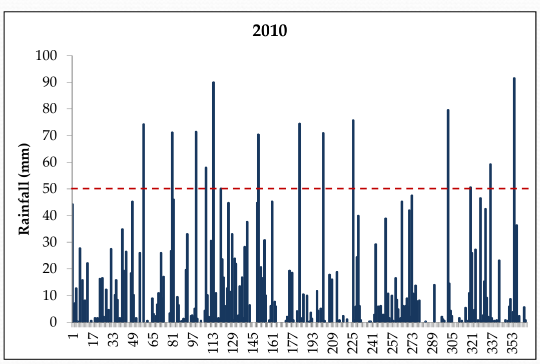
Rainfall Events in Malaysia

- Malaysia receives between **2000 and 4000 mm** of rainfall per year



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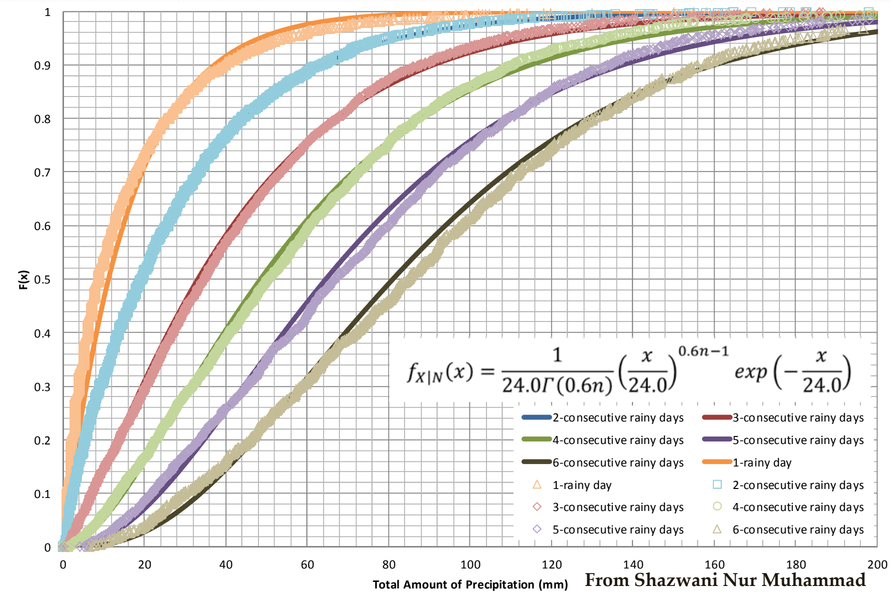
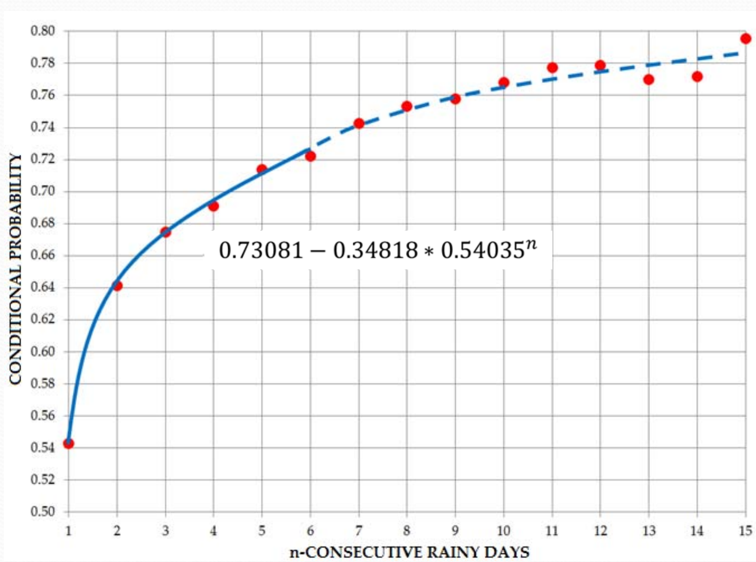
CDF for Subang Station



Conditional Probability of Multi-Day Rainfall Events at Subang Station



From Shazwani Nur Muhammad

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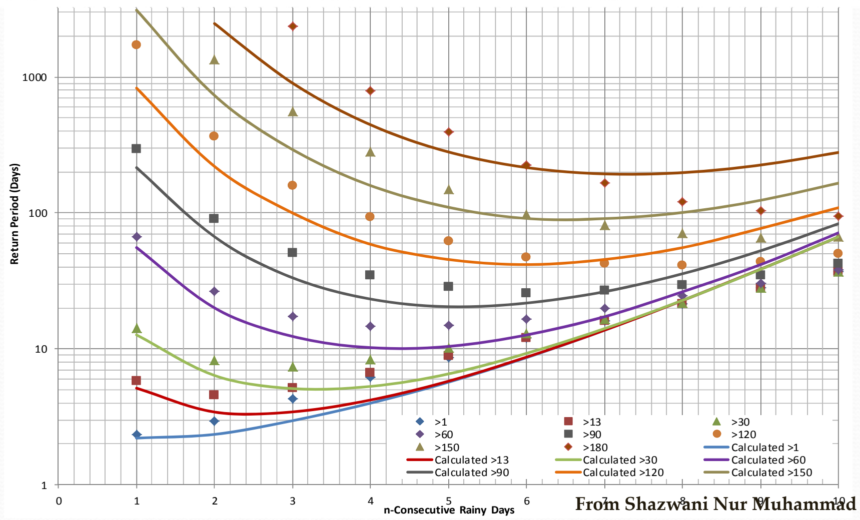
Return Period Curves from Measured & Improved Probability Structure

$$\int_{X_0}^{\infty}\sum_{n=n_0}^{\infty}\frac{1}{24.0\Gamma(0.6n)}\left(\frac{x}{24.0}\right)^{0.6n-1}exp\left(-\frac{x}{24.0}\right)\left(\prod_{n=1}^{N}0.73081-0.34818*0.54035^{n}\right)\left(\prod_{d=2}^{D}0.69064-0.38358*0.60825^{d}\right)dx$$



From Shazwani Nur Muhammad

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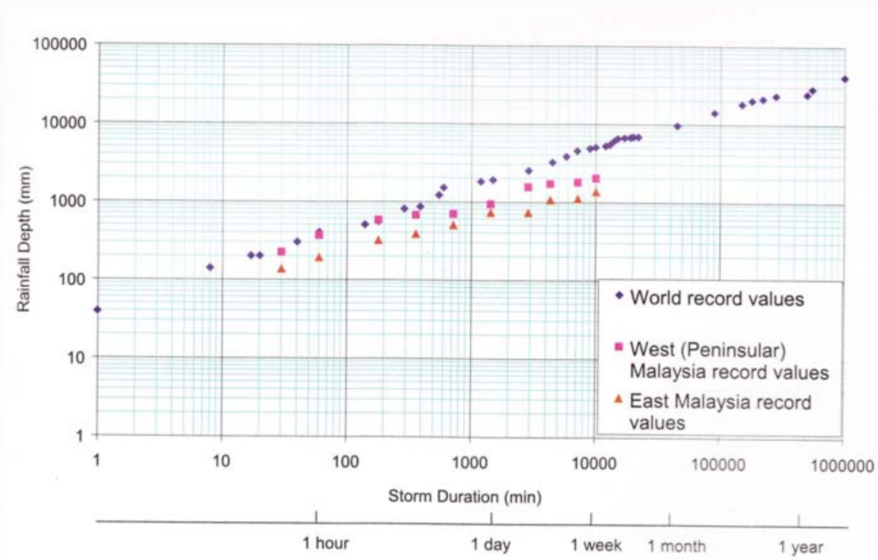
Extreme Rainfall Events



Extreme Floods in Malaysia

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TREX model (Hydrological model)

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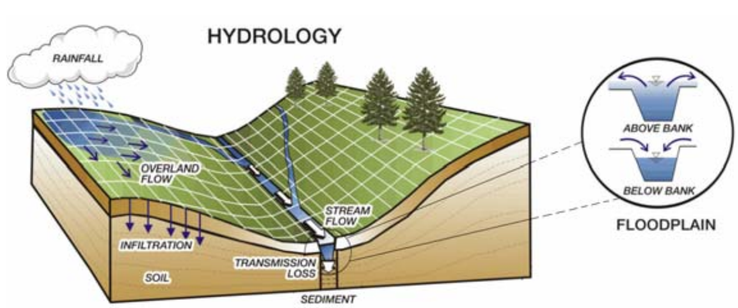
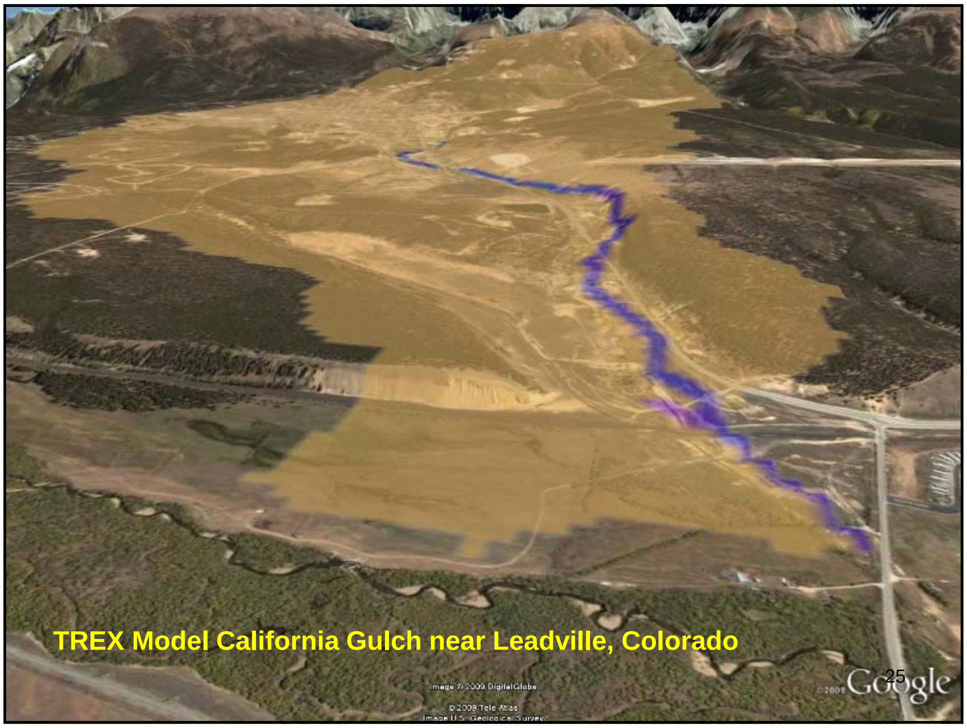
- Hydrological sub-models are:
  - Rainfall and interception
  - Depression storage and infiltration
  - Overland flow routing (2D diffusive wave approximation)
  - Channel flow (1D diffusive wave approximation)



11



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Extreme Floods in Malaysia

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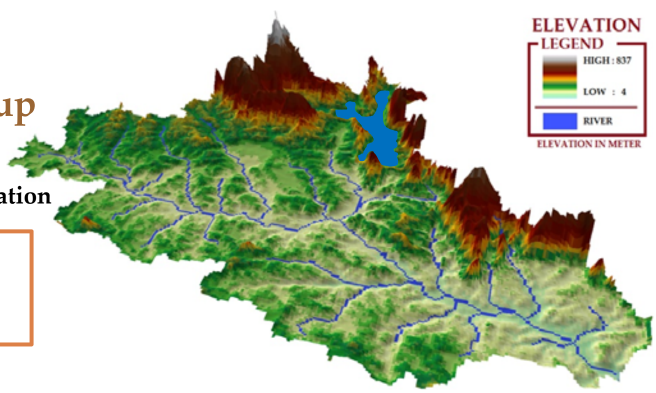
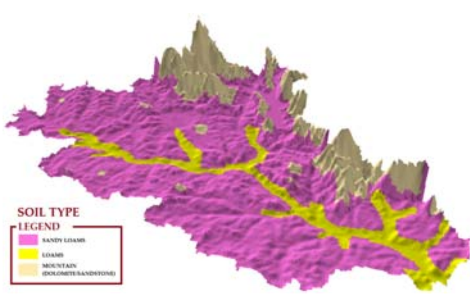
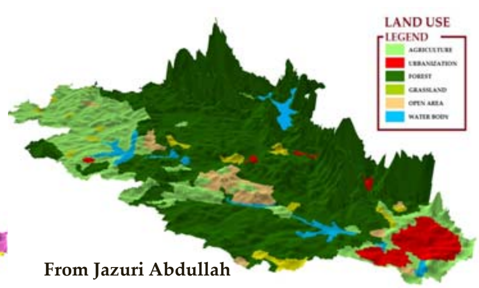
Modeling set-up From GIS

GIS – watershed delineation

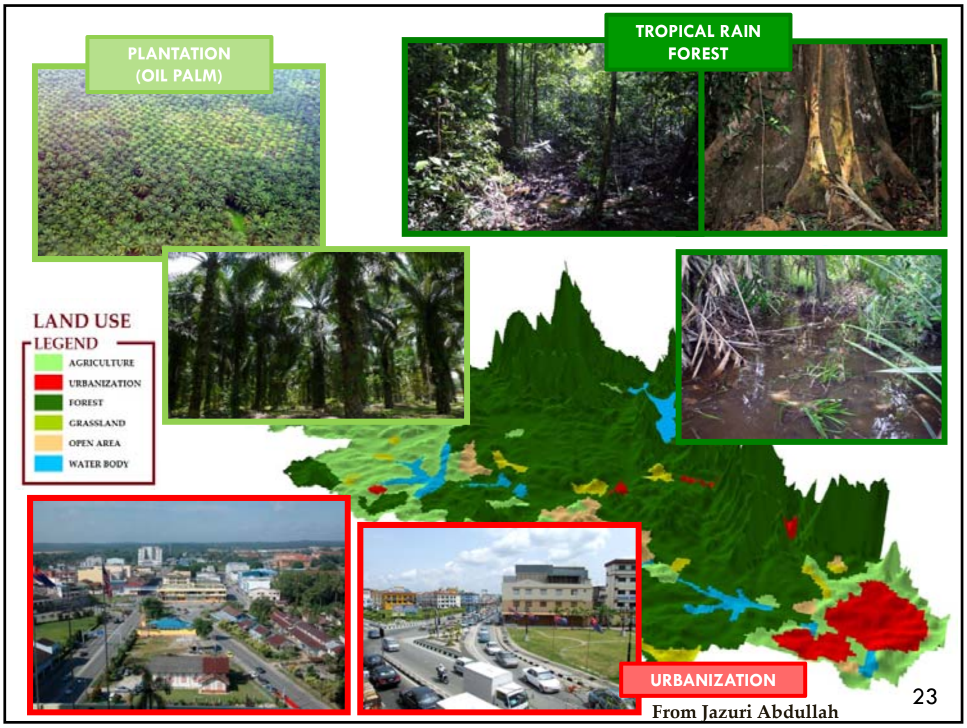
Area : 1,635 sq. km
Grid size : 230 x 230 m
River length : 250 km
Active grid: 30,000

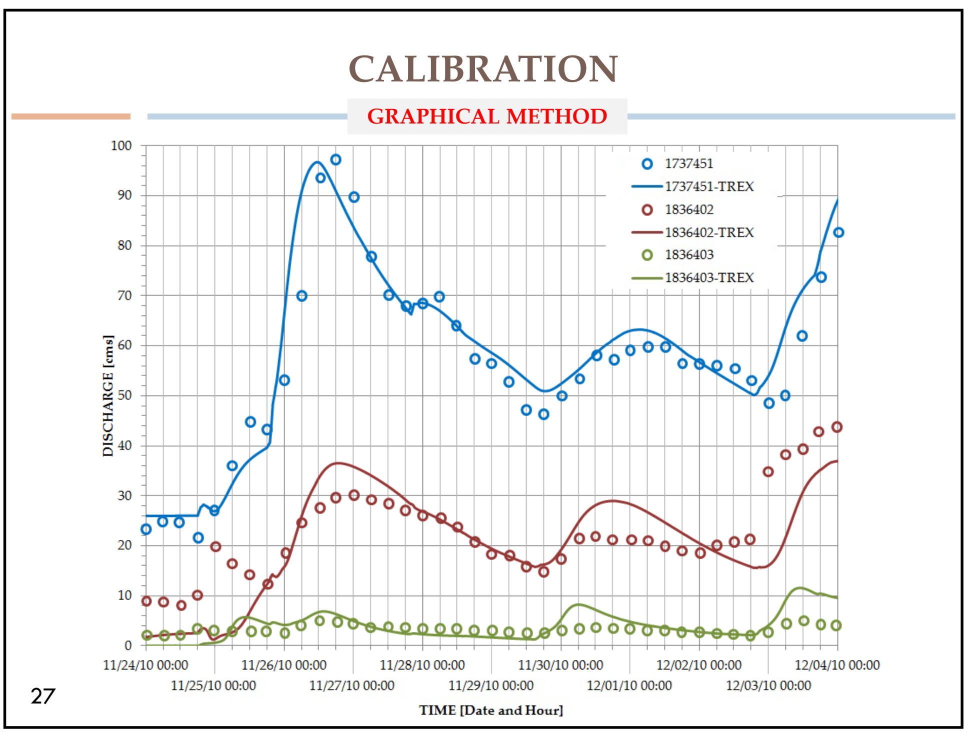




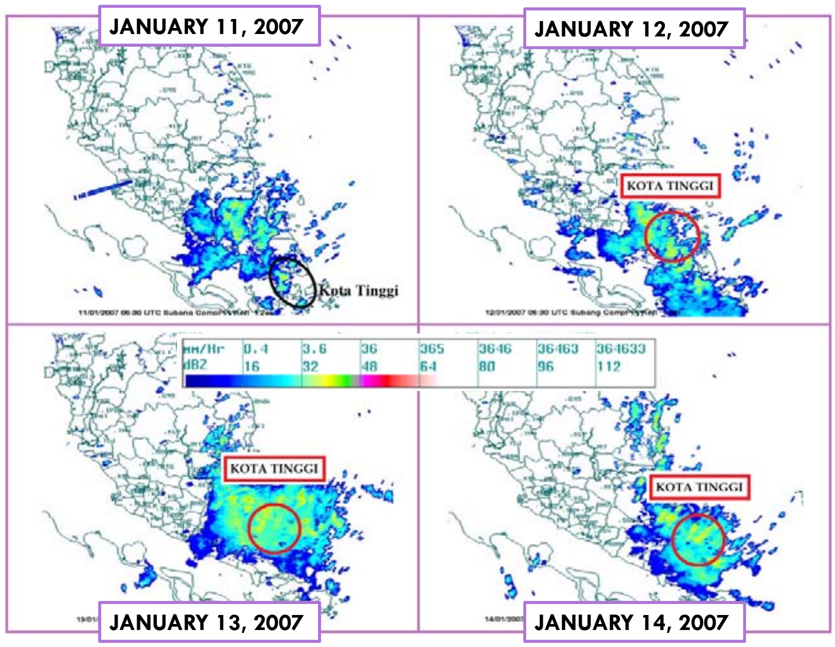


From Jazuri Abdullah


PLANTATION (OIL PALM)
TROPICAL RAIN FOREST
LAND USE
LEGEND
AGRICULTURE
URBANIZATION
FOREST
GRASSLAND
OPEN AREA
WATER BODY
URBANIZATION
From Jazuri Abdullah
23


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

SATELLITE IMAGES – RAINFALL AT KOTA TINGGI



SOURCE: SHAFIE (2009)

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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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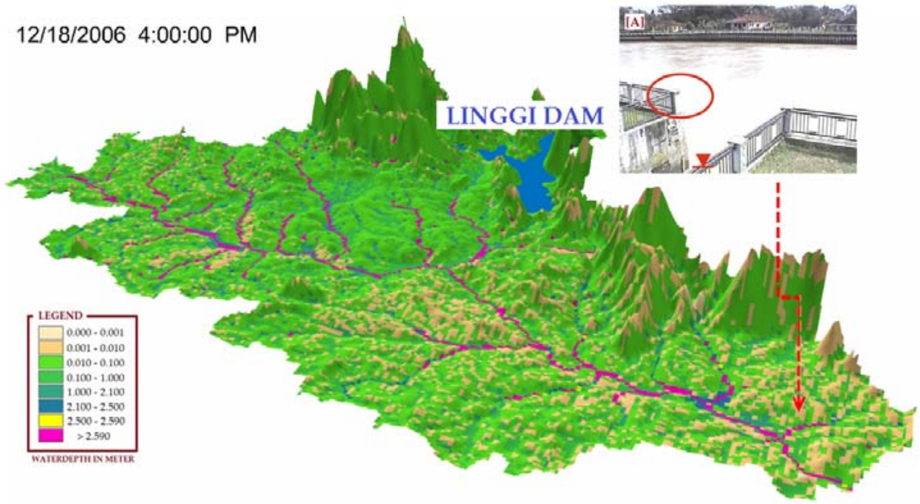
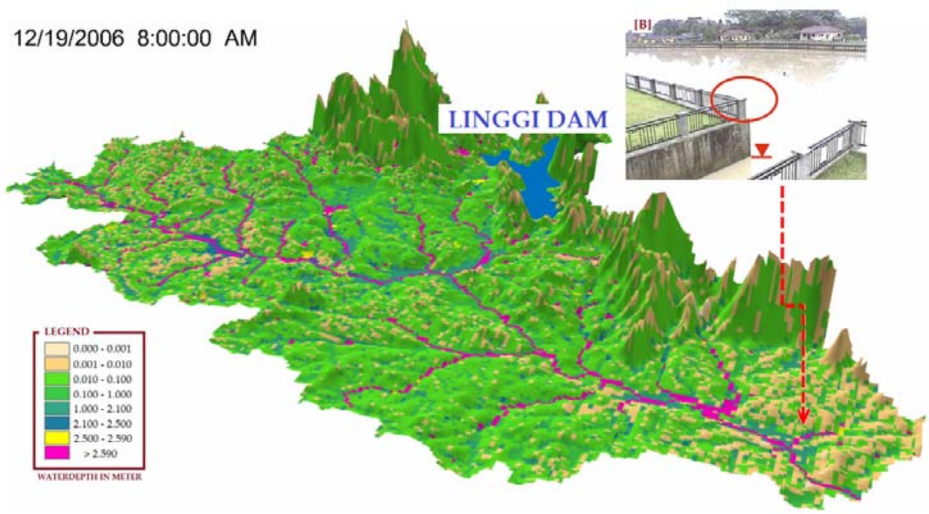
KOTA TINGGI FLOOD

DEC. 18, 2006

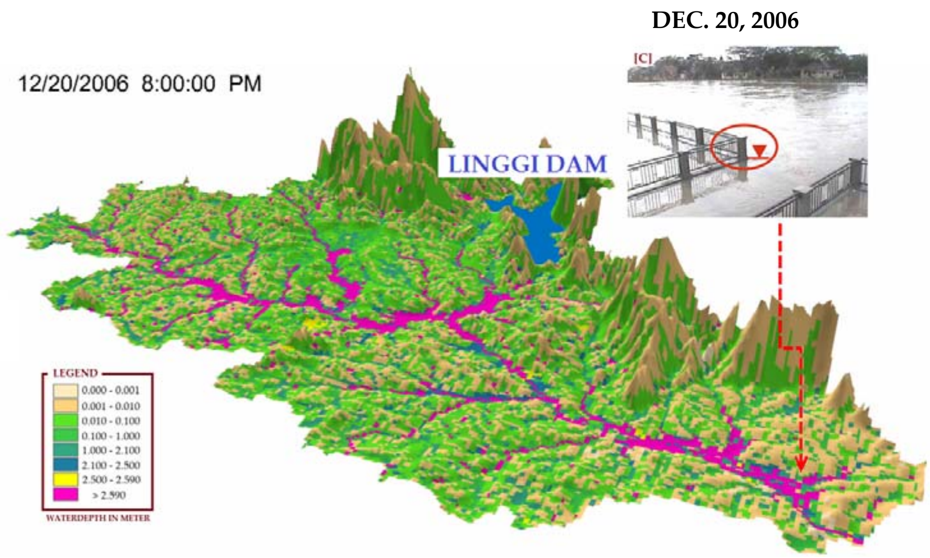


KOTA TINGGI FLOOD

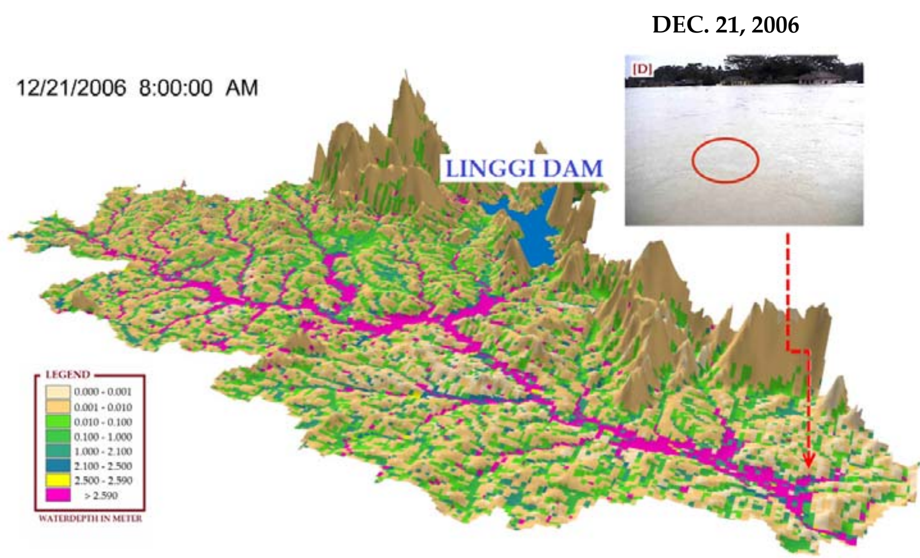
DEC. 19, 2006

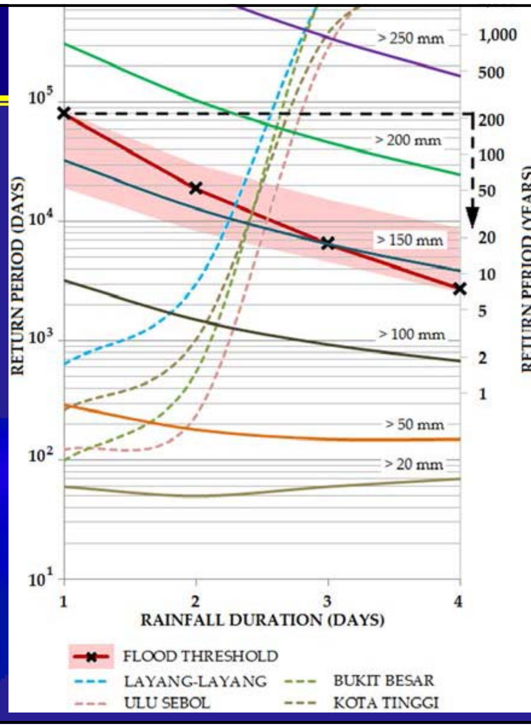


KOTA TINGGI FLOOD



KOTA TINGGI FLOOD





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Extreme Floods in Malaysia

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5. River Management Manual

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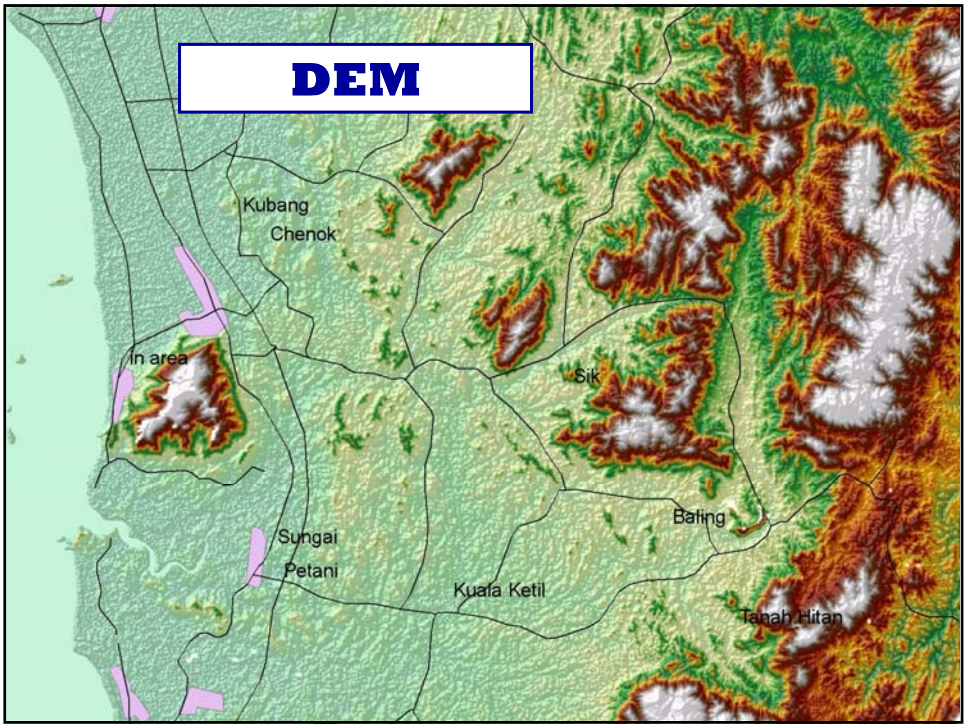
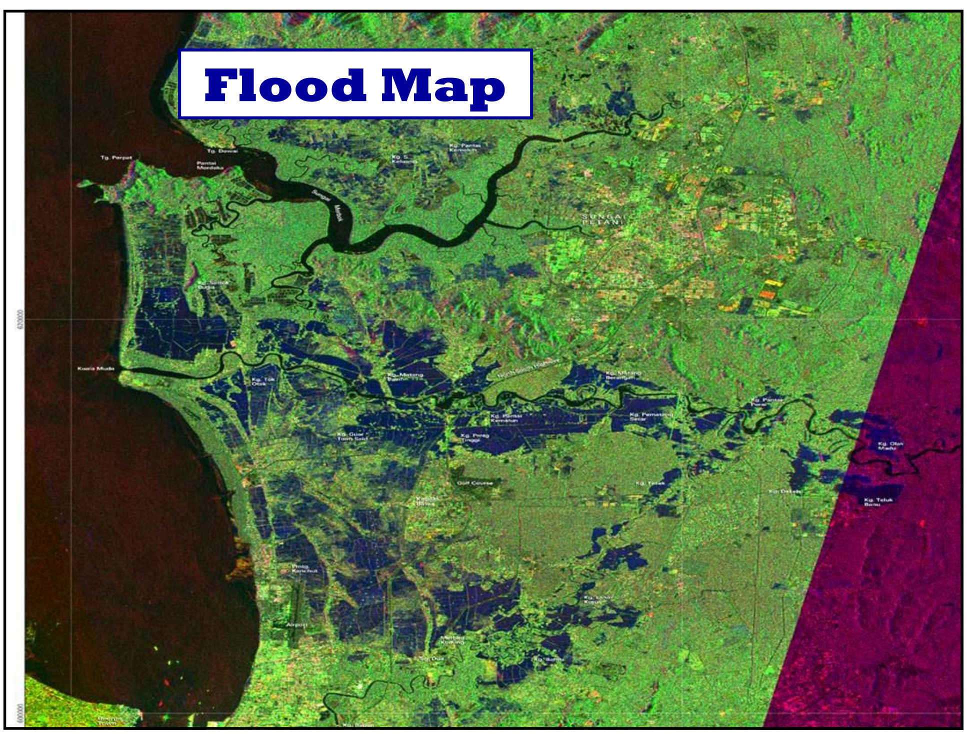
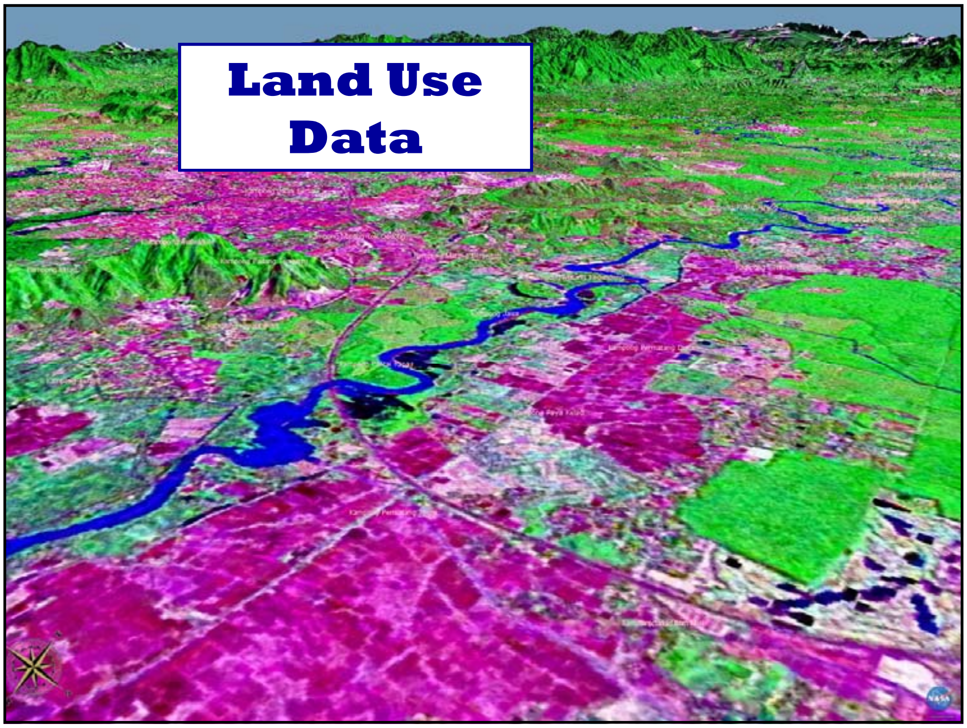
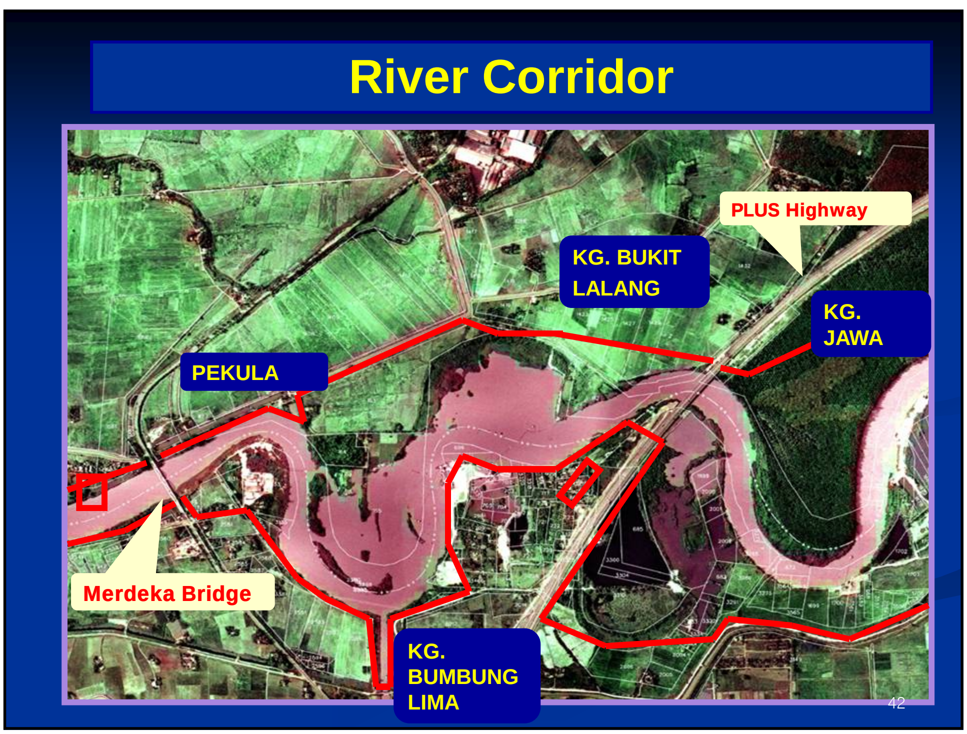
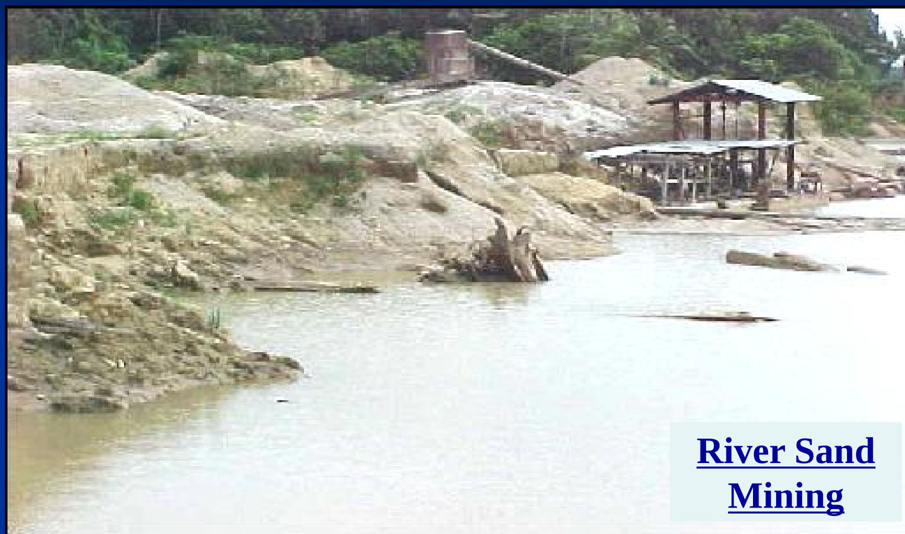

DEM
Kubang
Chenok
In area
Sik
Baling
Sungai
Petani
Kuala Ketil
Tanah Hitan


Flood Map


Land Use
Data


River Corridor
PLUS Highway
KG. BUKIT
LALANG
KG.
JAWA
PEKULA
Merdeka Bridge
KG.
BUMBUNG
LIMA
42

Sand and Gravel Mining



River Sand Mining

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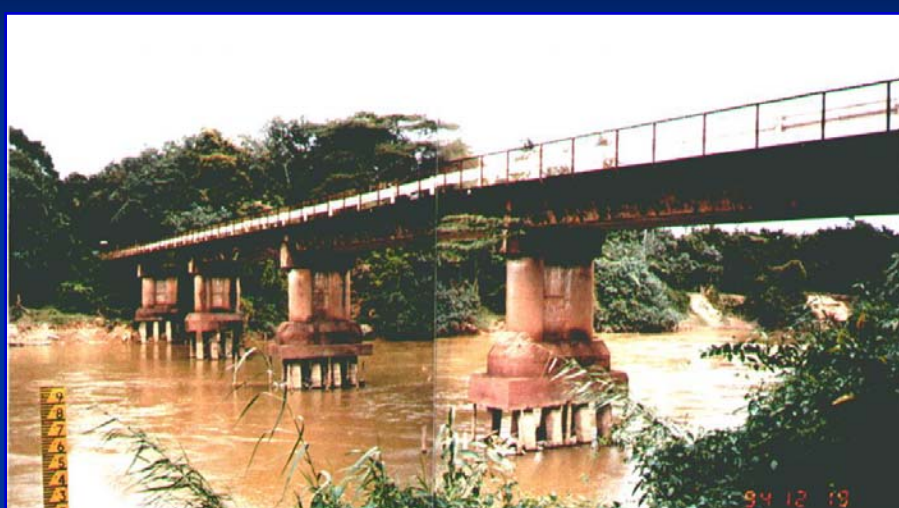
Riverbed Degradation



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Extreme Floods in Malaysia

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5. **River Management Manual**

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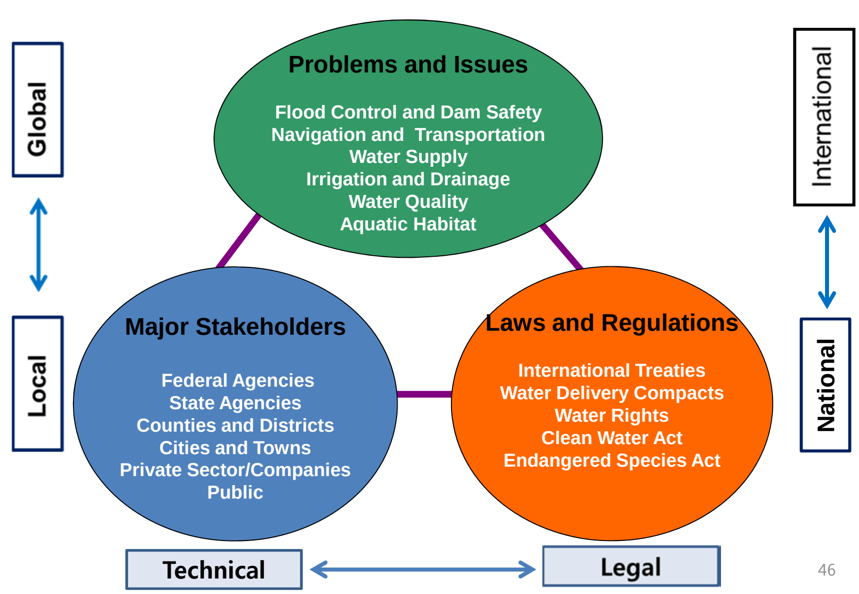
River Management



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Summary and Conclusions

1. Extreme Rainfall Precipitation

Recent advances in the frequency analysis of multi-day rainfall events

2. Extreme Flood Modeling

Distributed models like TREX can simulate extreme floods

3. Kota Tinggi Flood

Multi-day rainfall precipitation events control floods on large watersheds

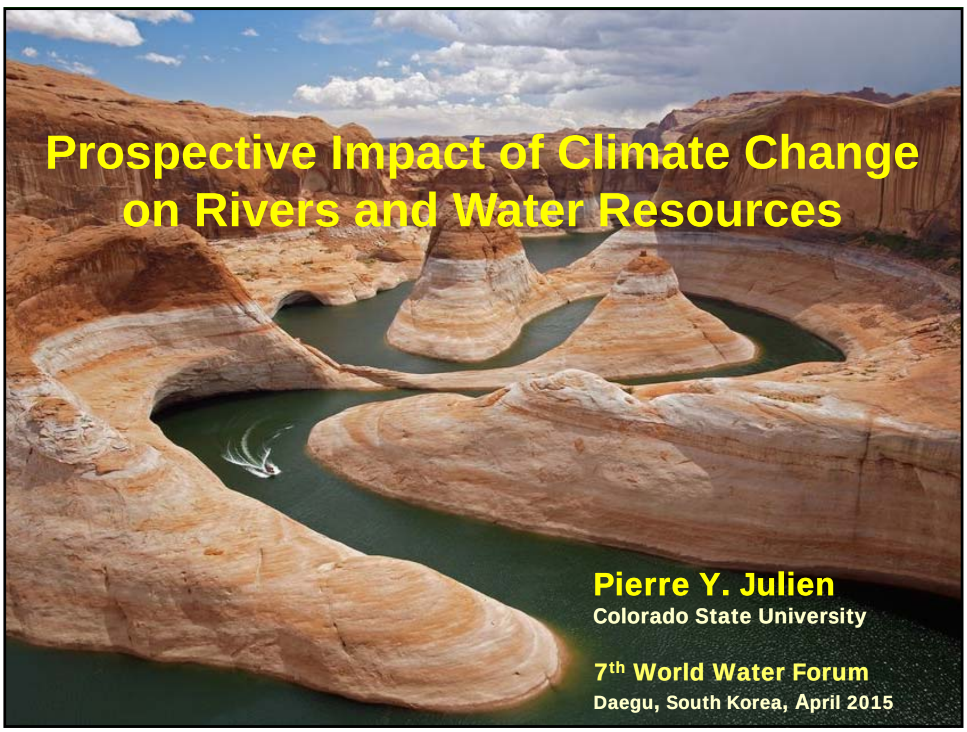
4. Muda River Flood

Concept of river corridor and problems associated with gravel mining

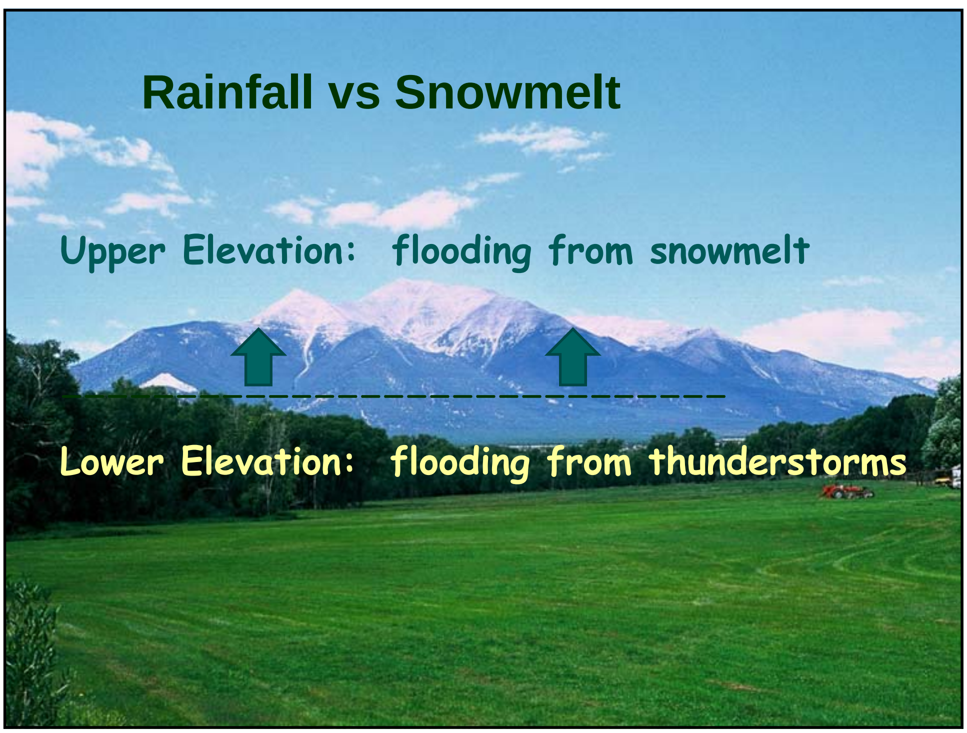
5. River Management Manual

Major step towards Integrated River Basin Management

3. Climate Change Impact on Rivers



“ … four glaciations were recognized, each lasting approximately 100,000 years…
Cordilleran Ice Sheet
Laurentide Ice Sheet
the maximum ice thickness was close to 4,000 metres”
The Canadian Encyclopedia



Rainfall vs Snowmelt
Upper Elevation: flooding from snowmelt
Lower Elevation: flooding from thunderstorms

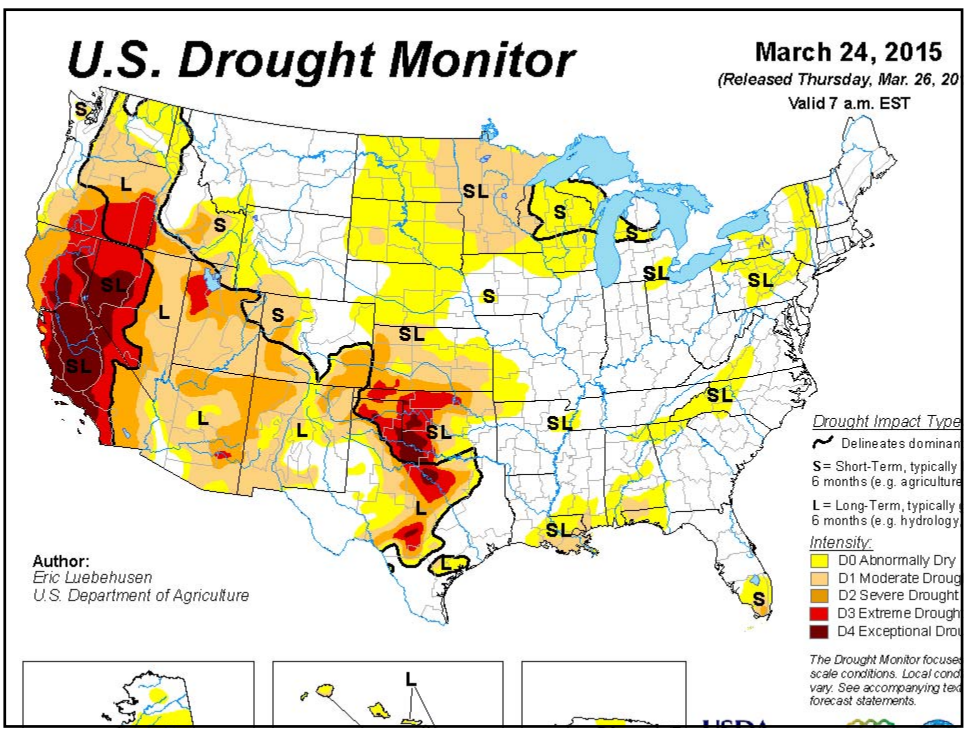

Pine beetle and the Colorado Forest

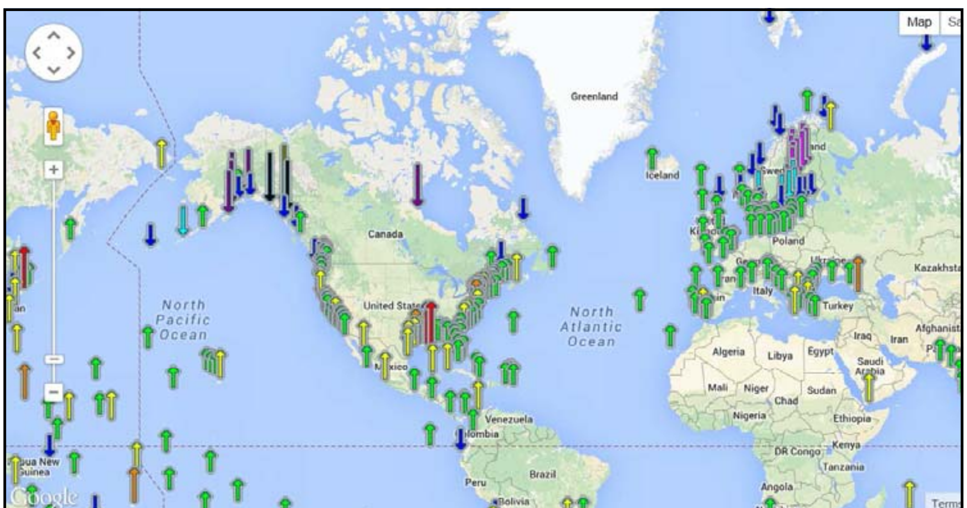

Waldo Fire
Colorado June 2012


Waldo Fire
Colorado June 2012


Impact on water quality


Sediment Plugs on the Rio Grande
Where did the water go?
From D. Baird, USBR

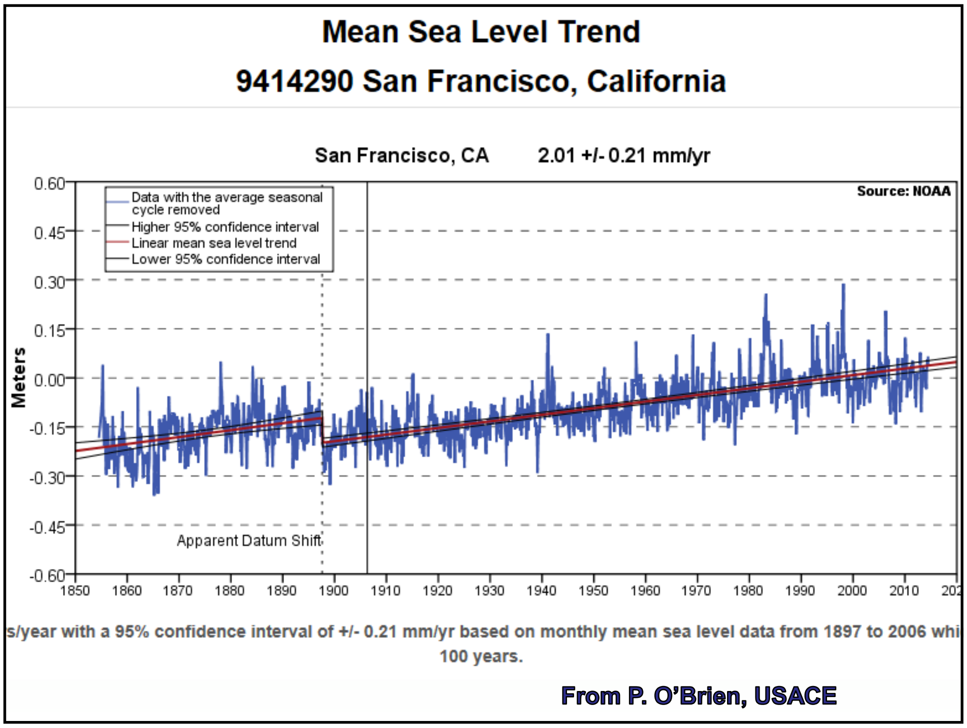

U.S. Drought Monitor
March 24, 2015
(Released Thursday, Mar. 26, 20
Valid 7 a.m. EST
Author:
Eric Luebehusen
U.S. Department of Agriculture
Drought Impact Type
Delineates dominan
S = Short-Term, typically
6 months (e.g. agriculture
L = Long-Term, typically
6 months (e.g. hydrology
Intensity:
D0 Abnormally Dry
D1 Moderate Droug
D2 Severe Drought
D3 Extreme Drough
D4 Exceptional Dro
The Drought Monitor focuse
scale conditions. Local cond
vary. See accompanying tex
forecast statements.



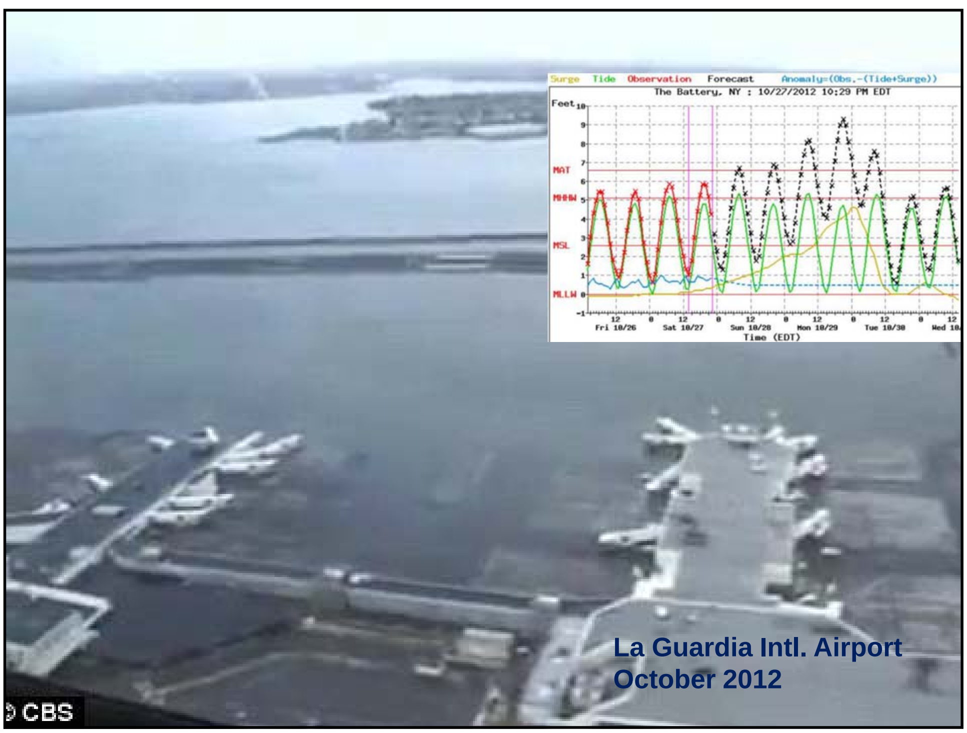
The map above illustrates regional trends in sea level, with arrows representing the direction and magnitude of change. Click on an arrow to access additional information about that station.

Sea Level Trends
mm/yr (feet/century)

15 to 21 (5 to 7)	6 to 9 (2 to 3)	-3 to 0 (-1 to 0)	-12 to -9 (-4 to -3)
12 to 15 (4 to 5)	3 to 6 (1 to 2)	-6 to -3 (-2 to -1)	-15 to -12 (-5 to -4)
9 to 12 (3 to 4)	0 to 3 (0 to 1)	-9 to -6 (-3 to -2)	-18 to -15 (-6 to -5)



Mean Sea Level Trend
9414290 San Francisco, California
San Francisco, CA 2.01 +/- 0.21 mm/yr
Source: NOAA
Data with the average seasonal cycle removed
Higher 95% confidence interval
Linear mean sea level trend
Lower 95% confidence interval
Meters
Apparent Datum Shift
s/year with a 95% confidence interval of +/- 0.21 mm/yr based on monthly mean sea level data from 1897 to 2006 whi
100 years.
From P. O'Brien, USACE



The Battery, NY : 10/27/2012 10:29 PM EDT
La Guardia Intl. Airport
October 2012
CBS

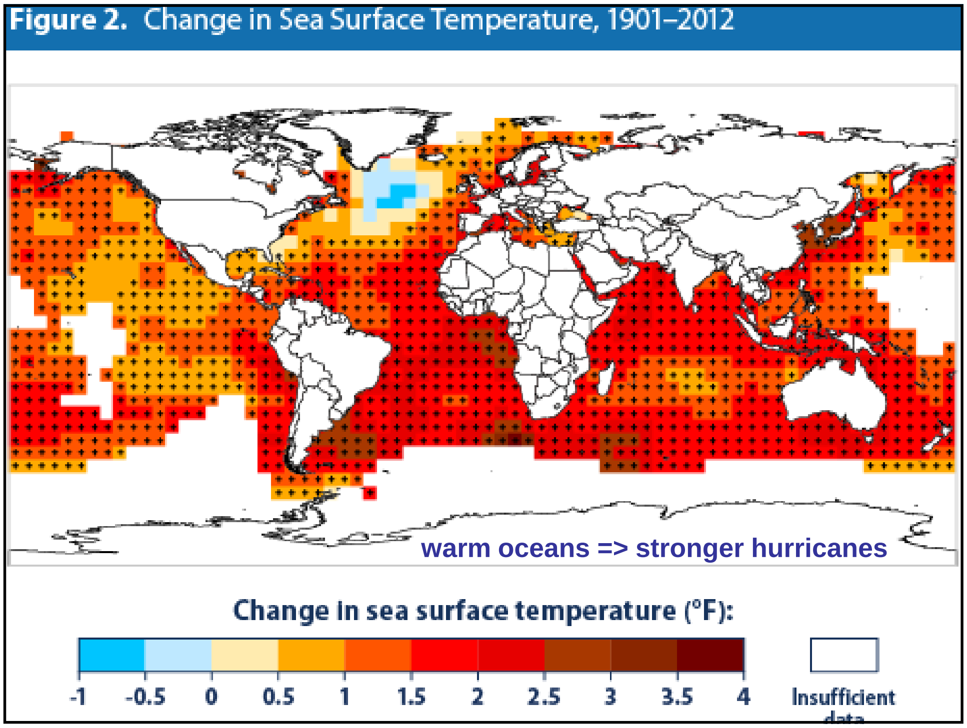
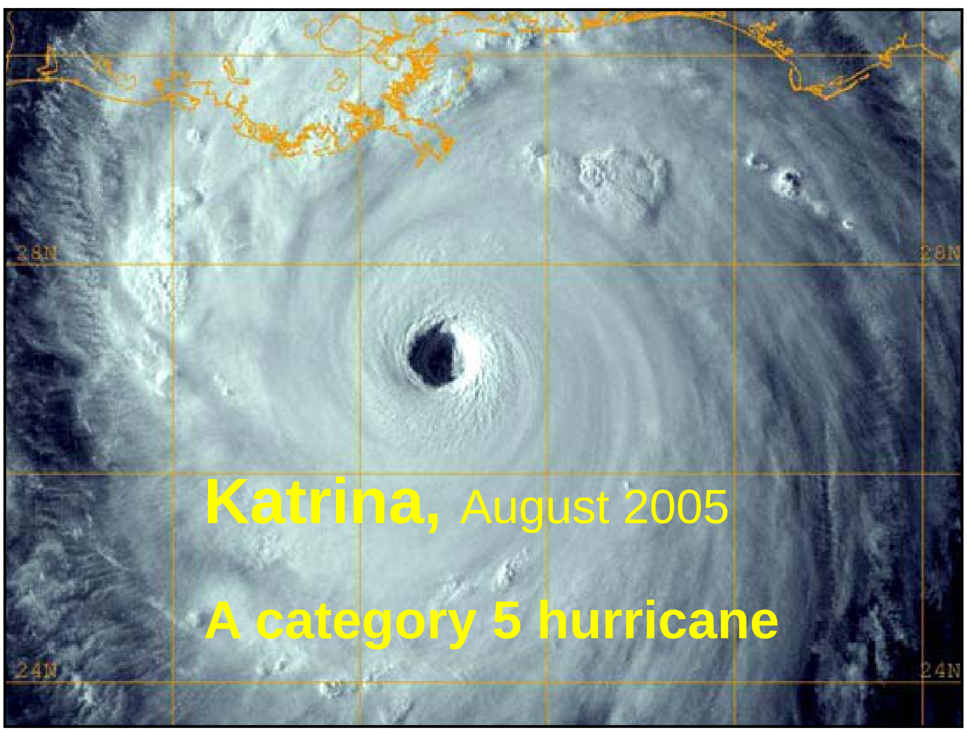
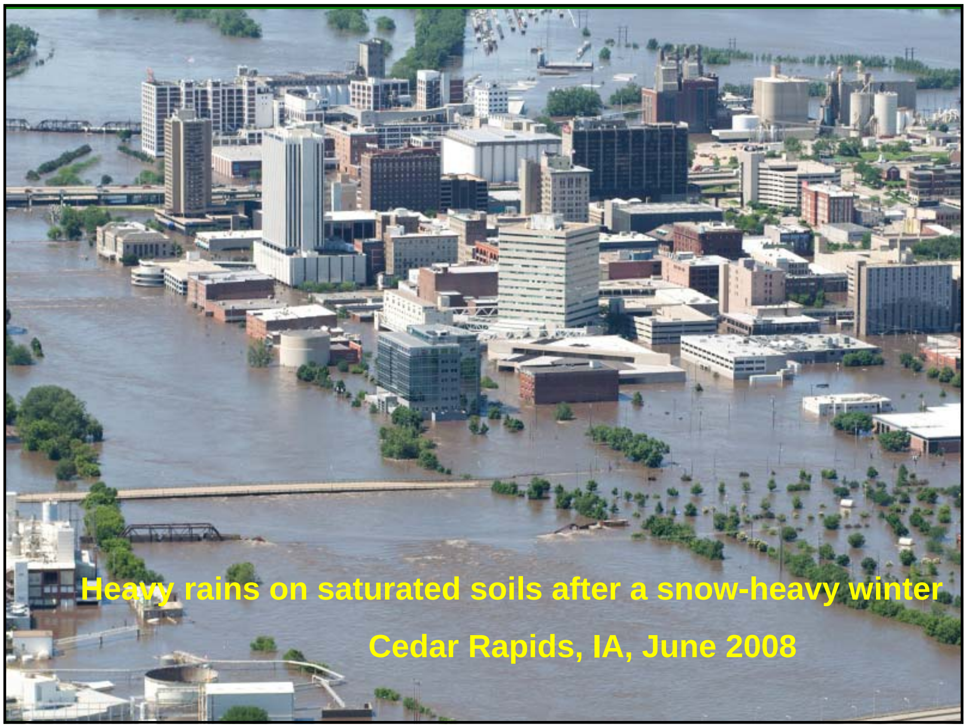


Figure 2. Change in Sea Surface Temperature, 1901–2012
warm oceans => stronger hurricanes
Change in sea surface temperature (°F):
-1
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
Insufficient data


28N
24N
Katrina, August 2005
A category 5 hurricane

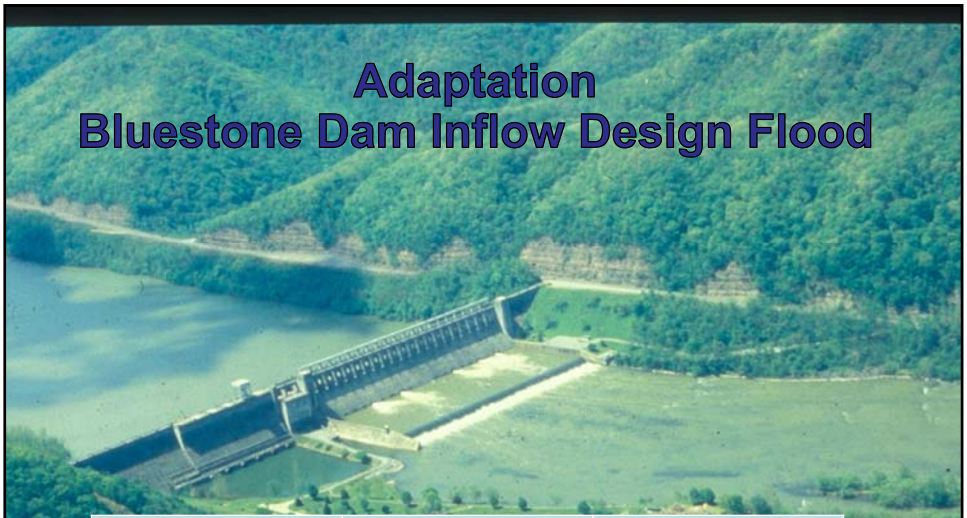

New Orleans in August 2005
after Hurricane Katrina
Damage $108 billions


Cincinnati
New Orleans
Miami
Katrina
August 2005
Saffir-Simpson Hurricane Scale
Tropical
Hurricane Category
Depr
Storm
1
2
3
4
5


Heavy rains on saturated soils after a snow-heavy winter
Cedar Rapids, IA, June 2008


Cedar Rapids, IA, June 2008

Adaptation
Bluestone Dam Inflow Design Flood



	Precipitation	Peak Inflow
1938 Design – Original	13 inches	430,000 cfs
1982 Update	20 inches	1,086,000 cfs
2014 Update	18 inches	**1,564,000 cfs**

From N. Koutsunis, USACE

Structural Measures at a Glance

GENERAL COASTAL RISK REDUCTION PERFORMANCE FACTORS:
STORM SURGE AND WAVE HEIGHT/PERIOD, WATER LEVEL

Levees

Benefits/Processes

Surge and Wave attenuation and/or dissipation

Reduce Flooding

Risk Reduction for vulnerable areas

Performance Factors

Levee height, crest width, and slope

Wave height and period

Water level

Storm Surge Barriers

Benefits/Processes

Surge and Wave attenuation

Reduced Salinity Intrusion

Performance Factors

Barrier height

Wave height

Wave period

Water level

Seawalls and Revetments

Benefits/Processes

Reduce flooding

Reduce wave overtopping

Shoreline stabilization behind structure

Performance Factors

Wave height

Wave period

Water level

Scour protection

Groins

Benefits/Processes

Shoreline stabilization

Performance Factors

Groin length, height, orientation, permeability and spacing

Depth at seaward end

Wave height

Water level

Longshore transportation rates and distribution

Detached Breakwaters

Benefits/Processes

Shoreline stabilization behind structure

Wave attenuation

Performance Factors

Breakwater height and width.

Breakwater permeability, proximity to shoreline, orientation and spacing

From K. White, USACE, ETL 1100-2-1 https://corpsclimate.us

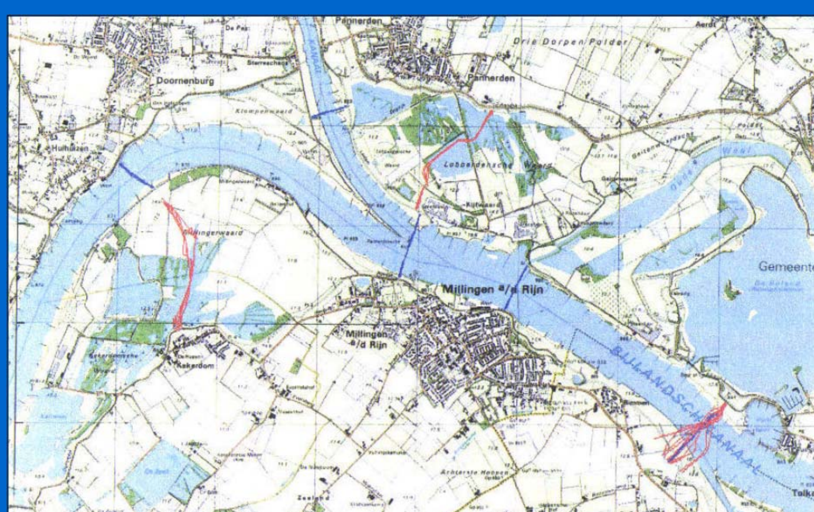
Impact of Katrina on wetlands

4. River Geometry

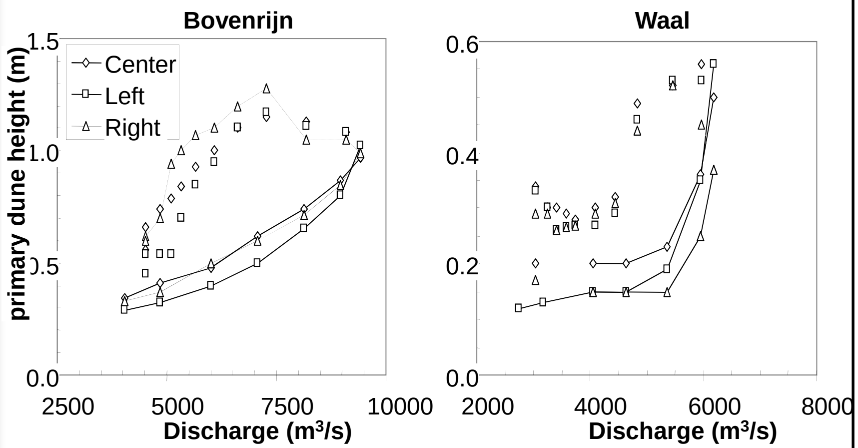
Objectives

- Bedforms and resistance to flow during floods.
- Effects of dams on hydraulic geometry.
- River response to deviations from equilibrium geometry of alluvial rivers.

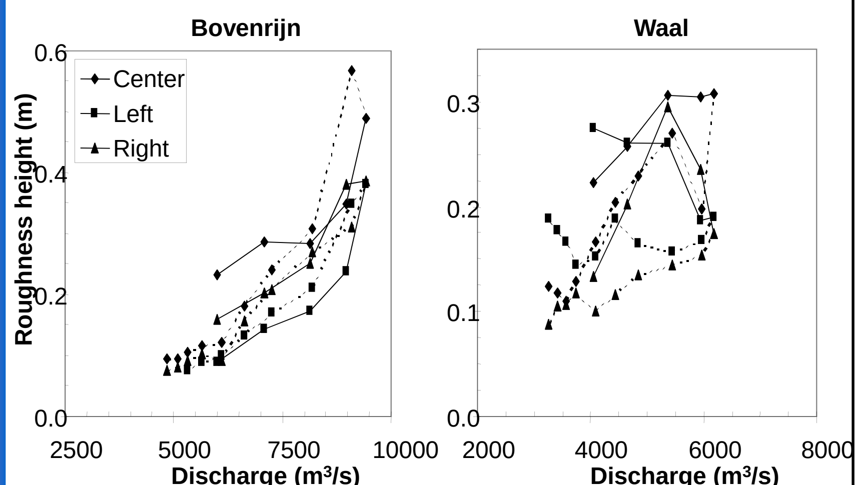
Rhine River flood in 1998



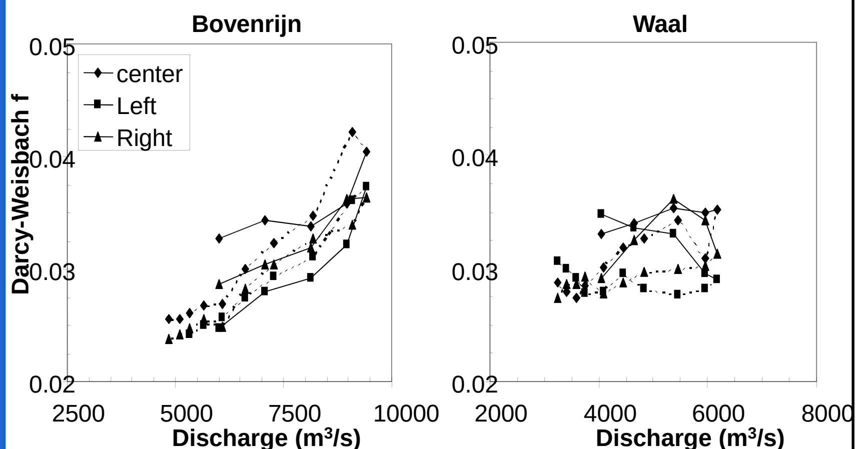
Primary dune height vs discharge



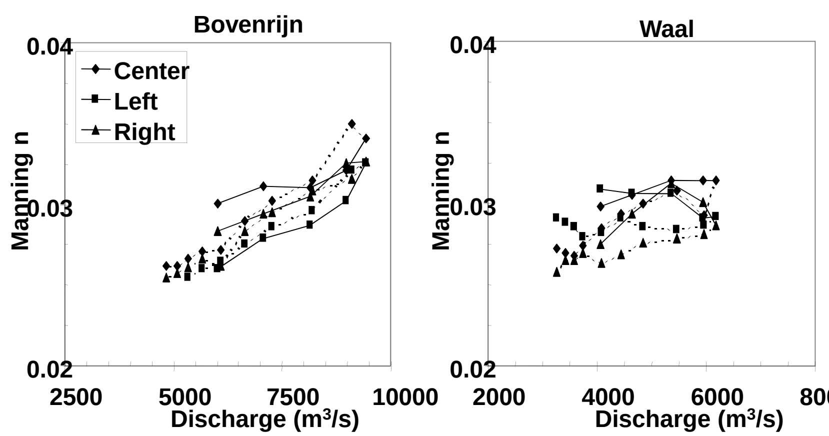
Roughness height vs discharge



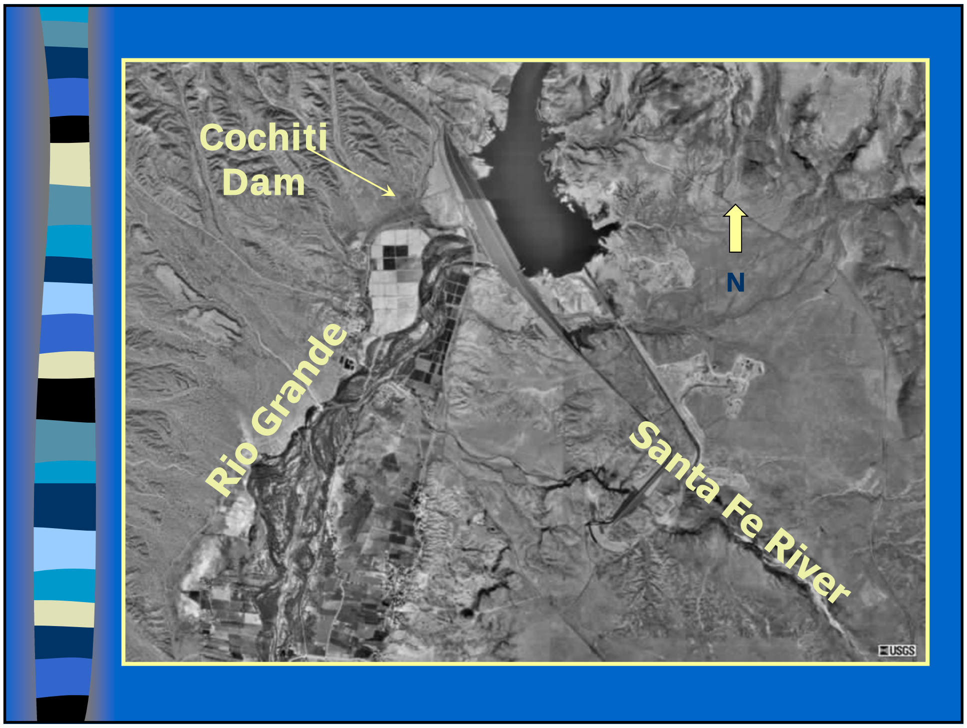
Darcy-Weisbach f vs discharge



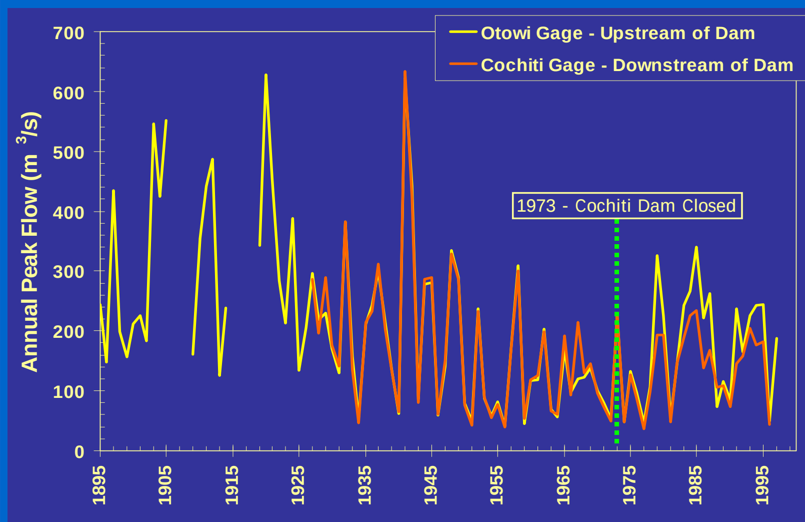
Manning n vs discharge



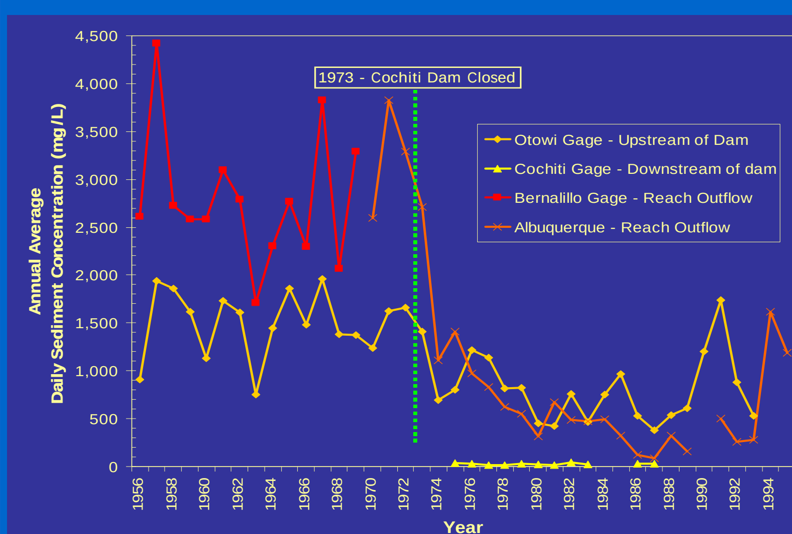
Downstream Hydraulic Geometry of the Rio Grande, New Mexico

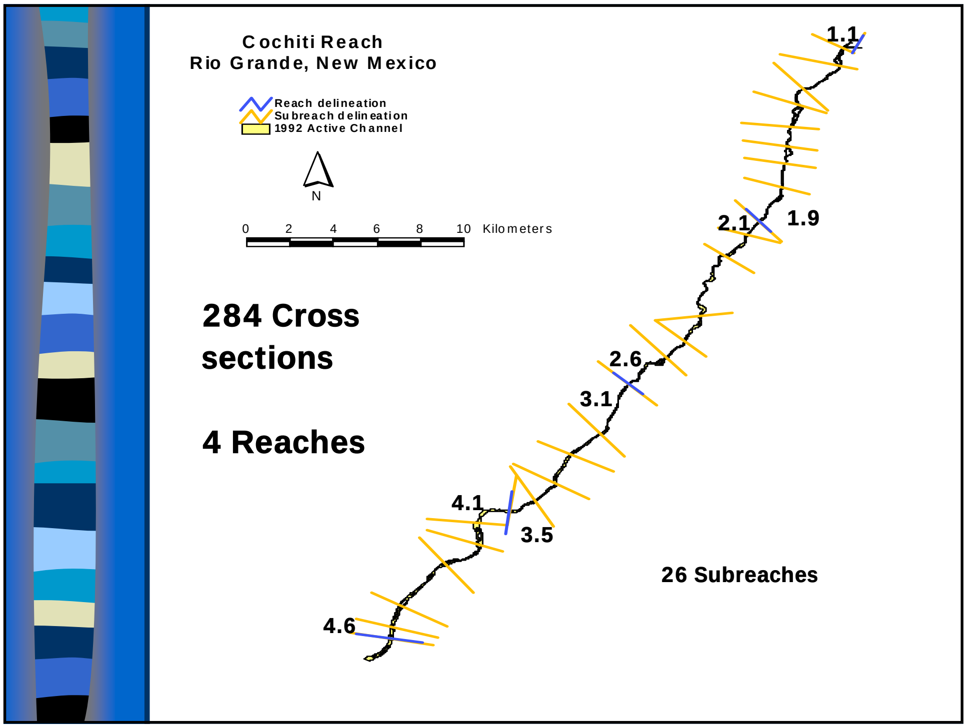

Cochiti
Dam
N
Rio Grande
Santa Fe River
USGS

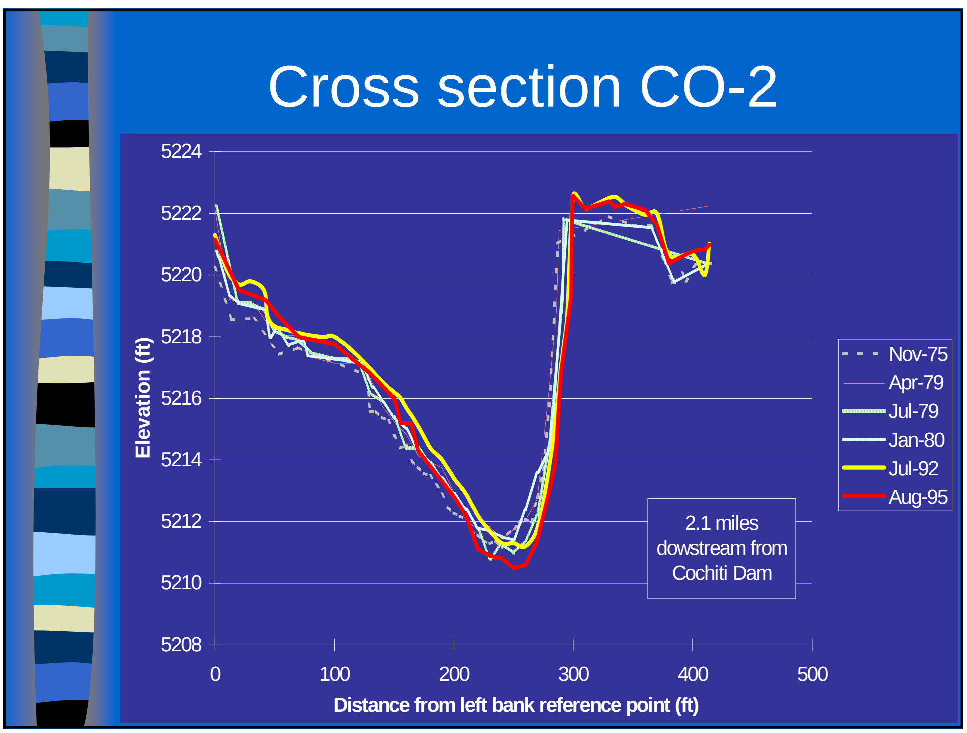
Peak Annual Discharge

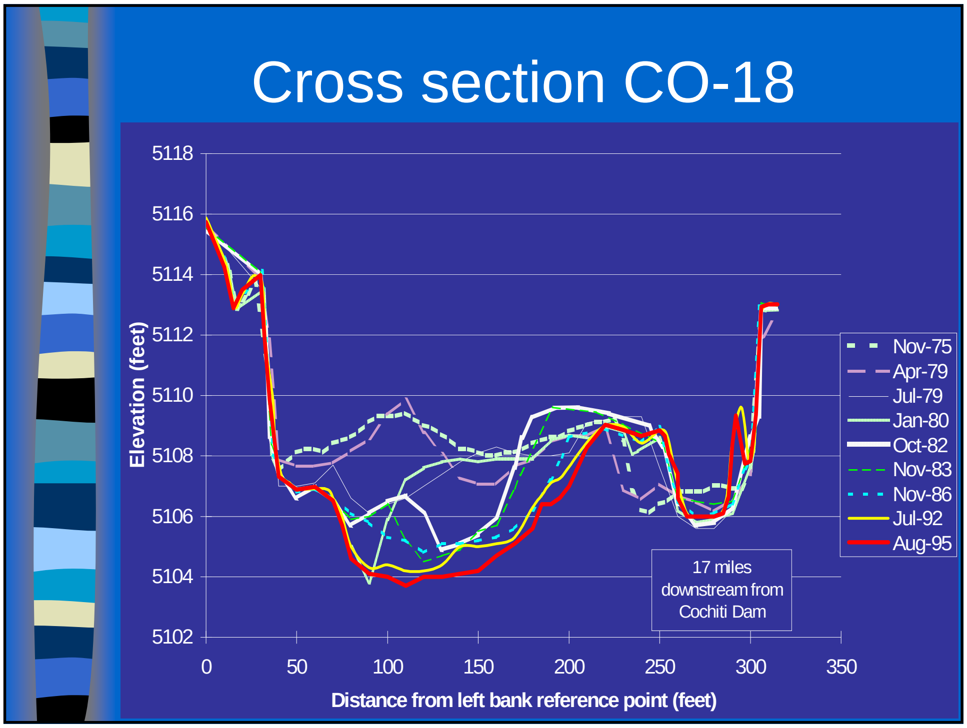


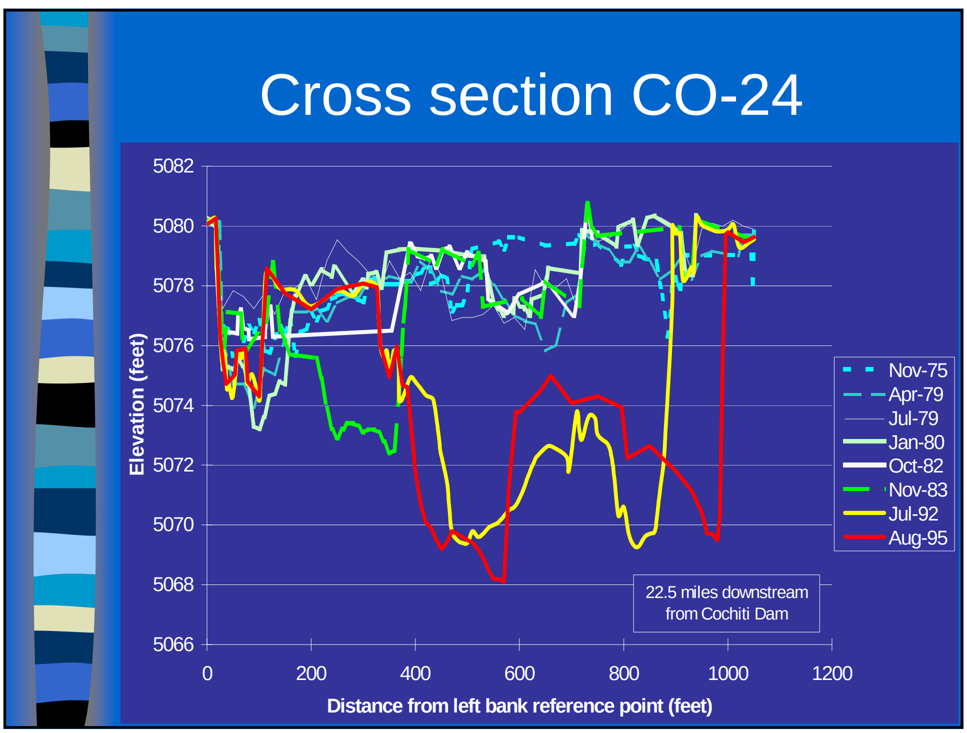
Annual Average Daily Sediment Concentration



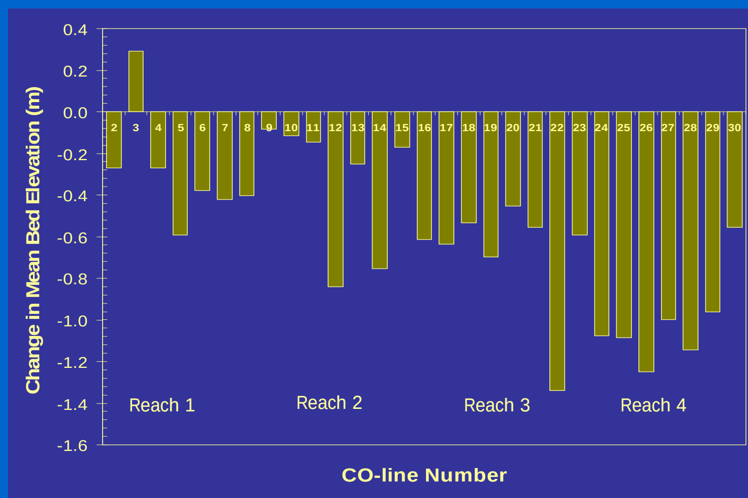

Cochiti Reach
Rio Grande, New Mexico
Reach delineation
Subreach delineation
1992 Active Channel
N
0 2 4 6 8 10 Kilometers
284 Cross sections
4 Reaches
26 Subreaches
1.1
1.9
2.1
2.6
3.1
3.5
4.1
4.6


Cross section CO-2
Elevation (ft)
5224
5222
5220
5218
5216
5214
5212
5210
5208
0
100
200
300
400
500
Distance from left bank reference point (ft)
Nov-75
Apr-79
Jul-79
Jan-80
Jul-92
Aug-95
2.1 miles dowstream from Cochiti Dam

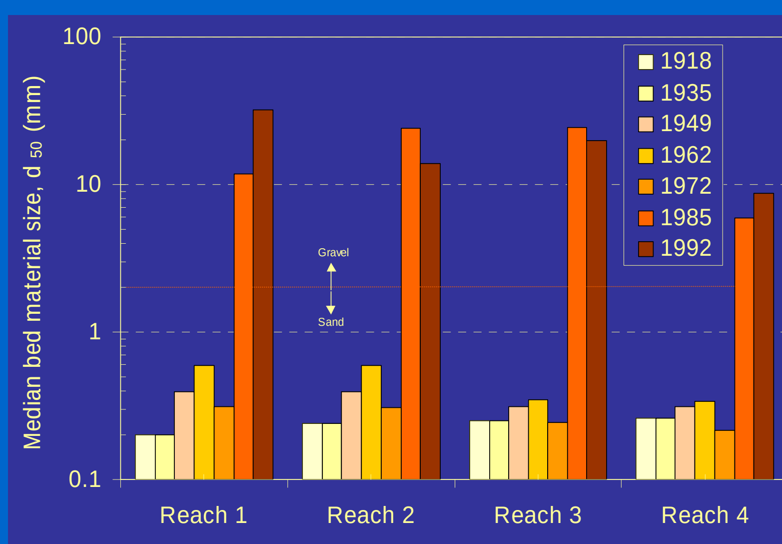

Cross section CO-18
5118
5116
5114
5112
5110
5108
5106
5104
5102
Elevation (feet)
0
50
100
150
200
250
300
350
Distance from left bank reference point (feet)
Nov-75
Apr-79
Jul-79
Jan-80
Oct-82
Nov-83
Nov-86
Jul-92
Aug-95
17 miles downstream from Cochiti Dam


Cross section CO-24
5082
5080
5078
5076
5074
5072
5070
5068
5066
Elevation (feet)
0
200
400
600
800
1000
1200
Distance from left bank reference point (feet)
Nov-75
Apr-79
Jul-79
Jan-80
Oct-82
Nov-83
Jul-92
Aug-95
22.5 miles downstream from Cochiti Dam

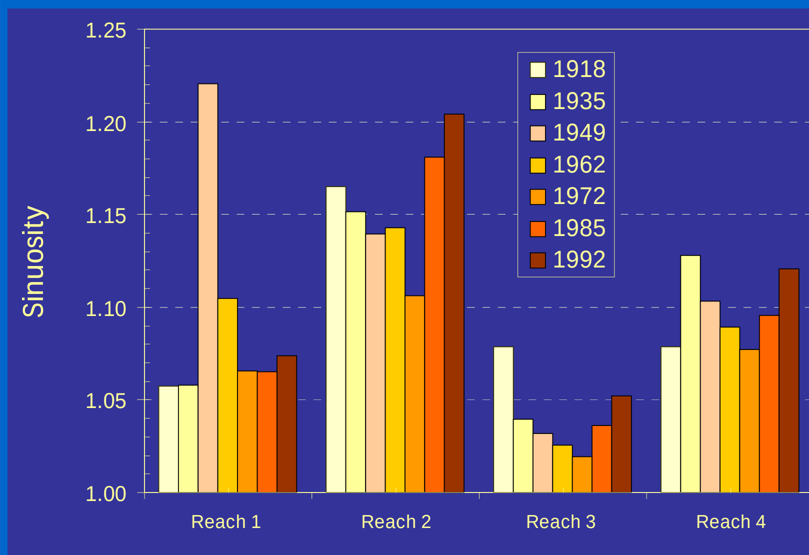
Change in Mean Bed Elevation



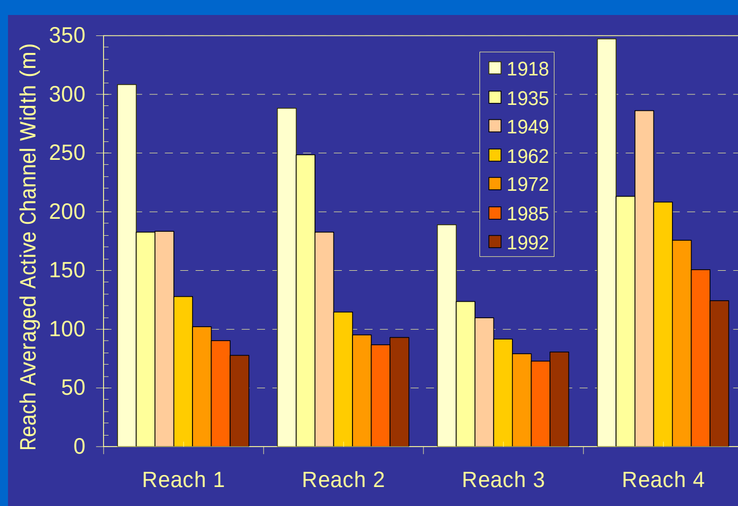
Bed material size



Sinuosity

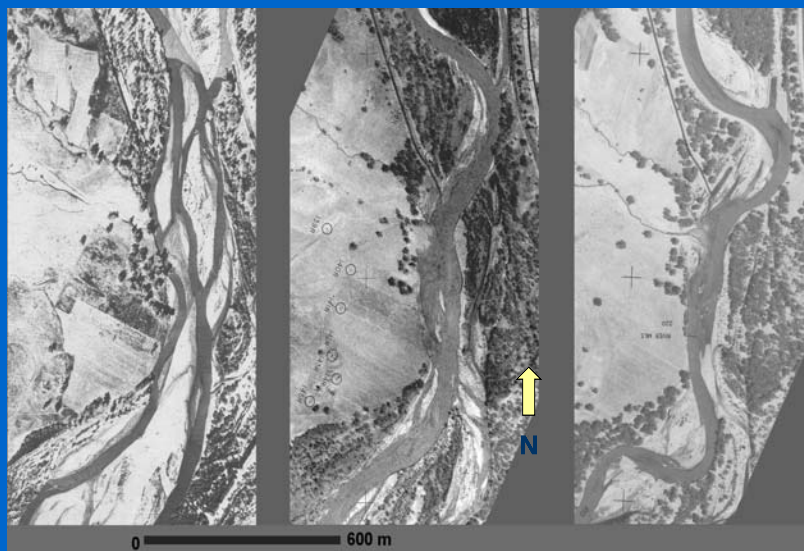


Active channel width



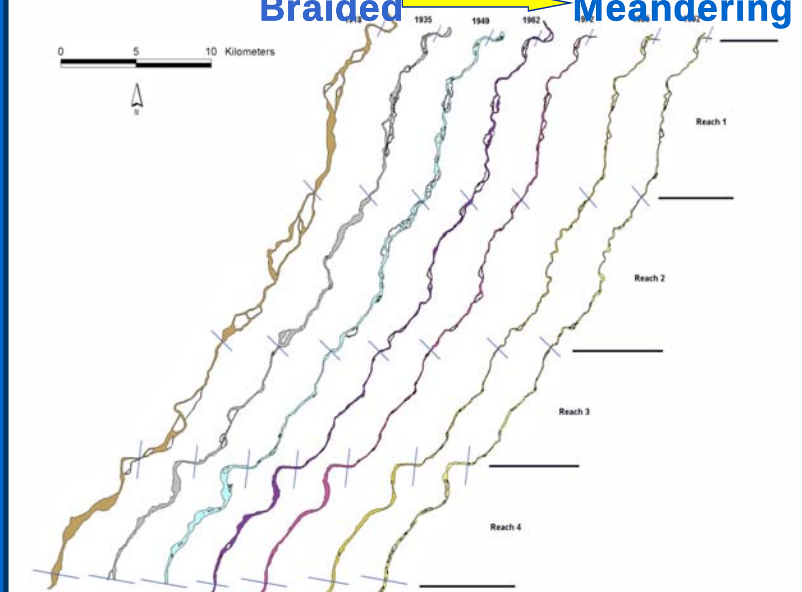
Planform geometry

1935 1972 1992

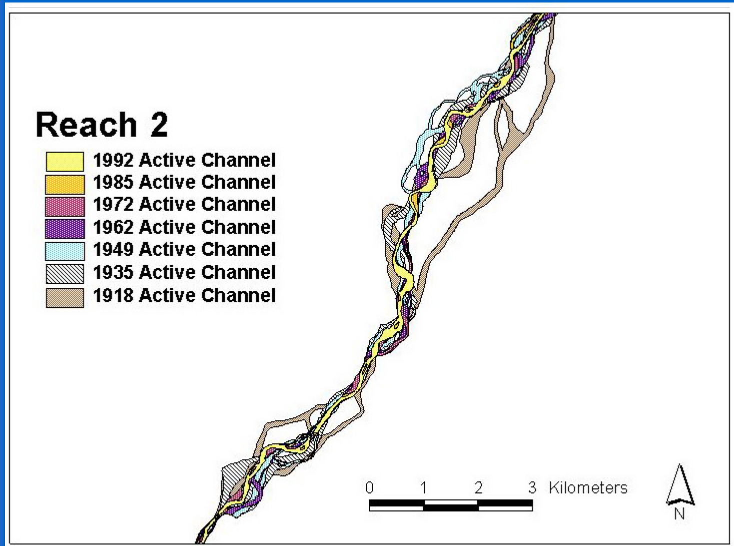


Planform Adjustments

Braided → Meandering

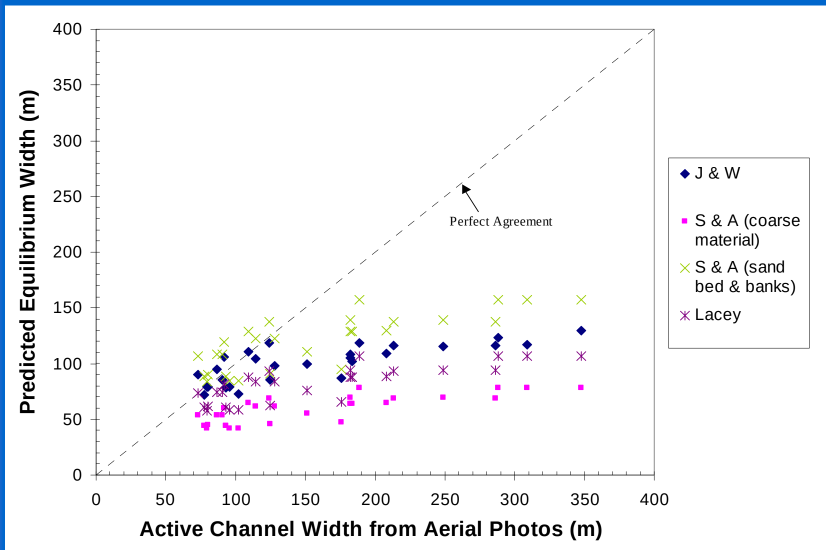


Lateral Adjustments

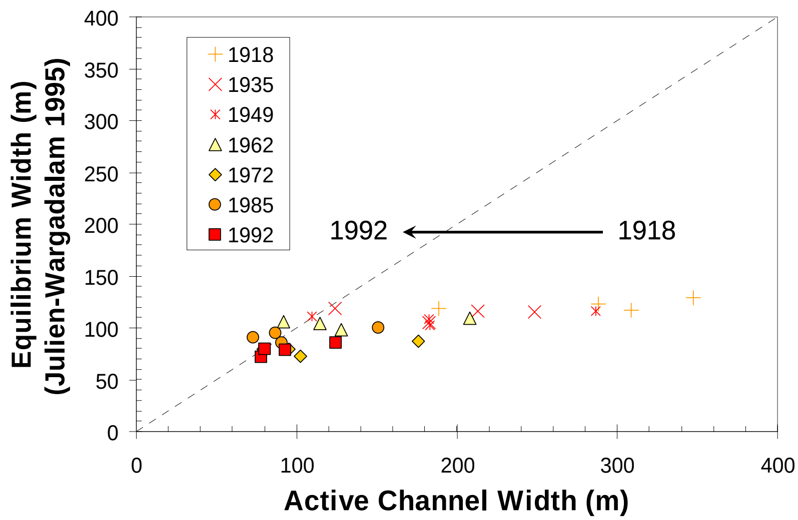


Equilibrium?

Hydraulic Geometry Equations



Hydraulic Geometry Equations (Julien & Wargadalam 1995)



Modeling Lateral Movement

Deviation from Equilibrium

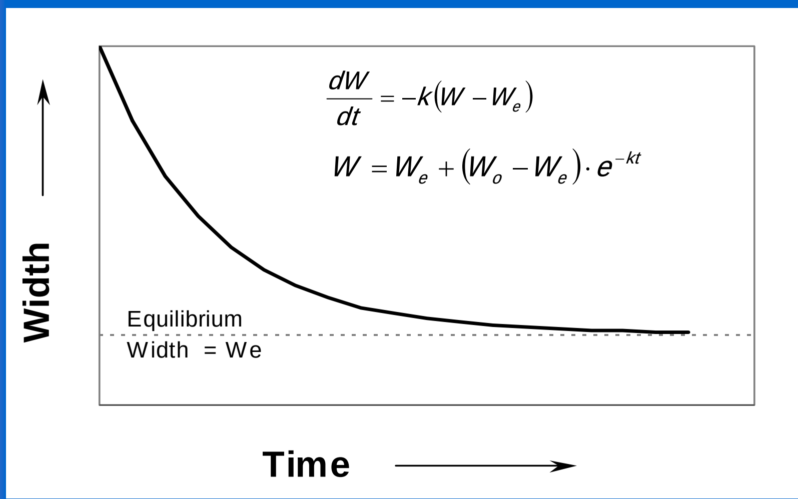
$$\frac{dW}{dt} = -k\left(W - W_e\right)$$

$$W = W_e + \left(W_o - W_e\right)\cdot e^{-kt}$$

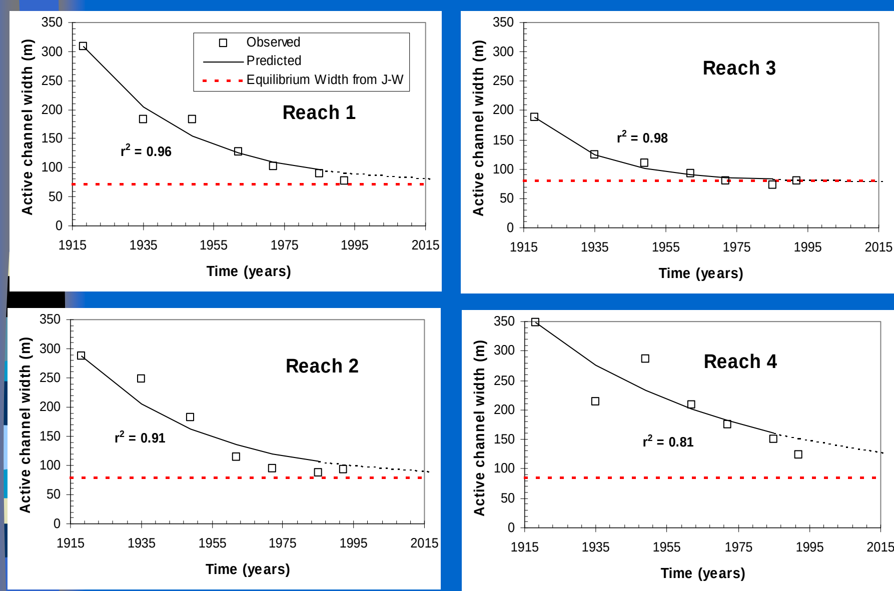
$$M = -k\left(W - W_e\right)$$

Modeling Width Change

Deviation from equilibrium width



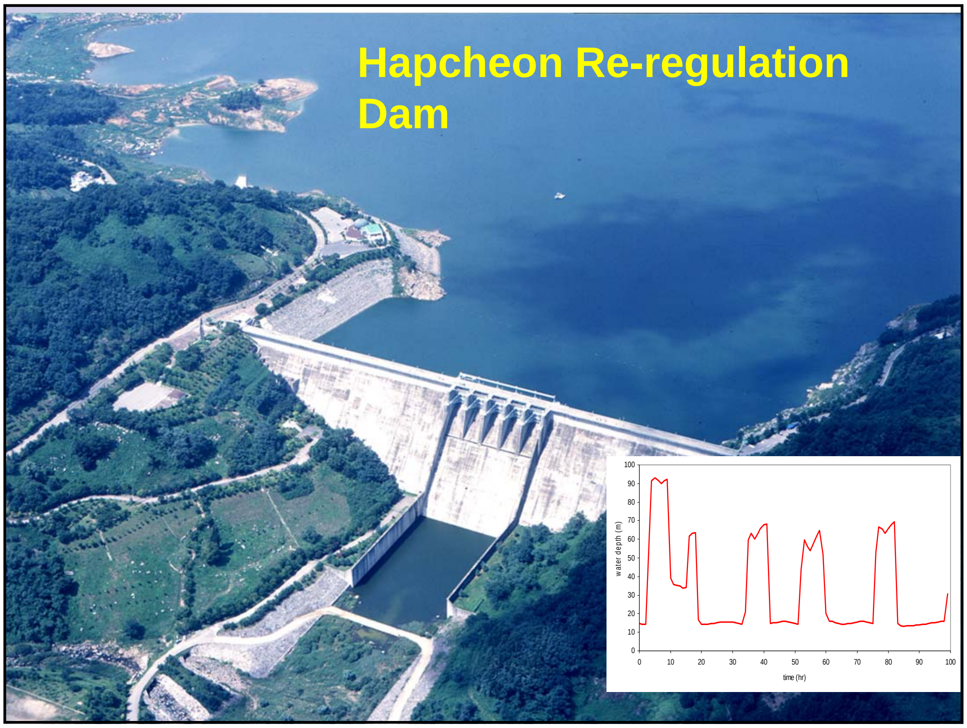
Exponential Model Results



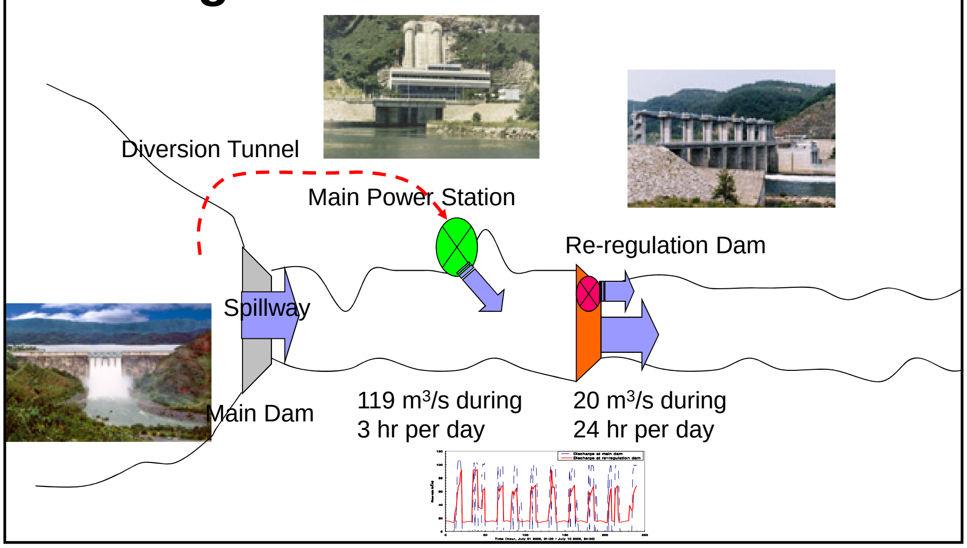
Conclusions

- Bedforms affect resistance to flow and Manning n can increase during floods.
- The effects of Cochiti Dam on the Rio Grande are primarily degradation and armouring. There is relatively little effect on channel width.
- The rate of change in channel width is proportional to the deviation from the equilibrium channel width.

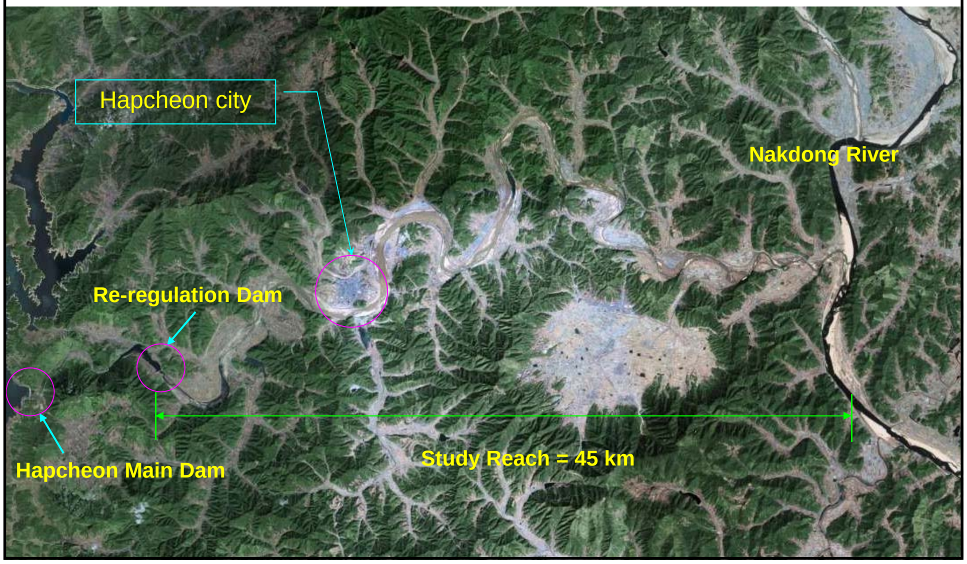
5. Flow Pulses Downstream of Reservoirs



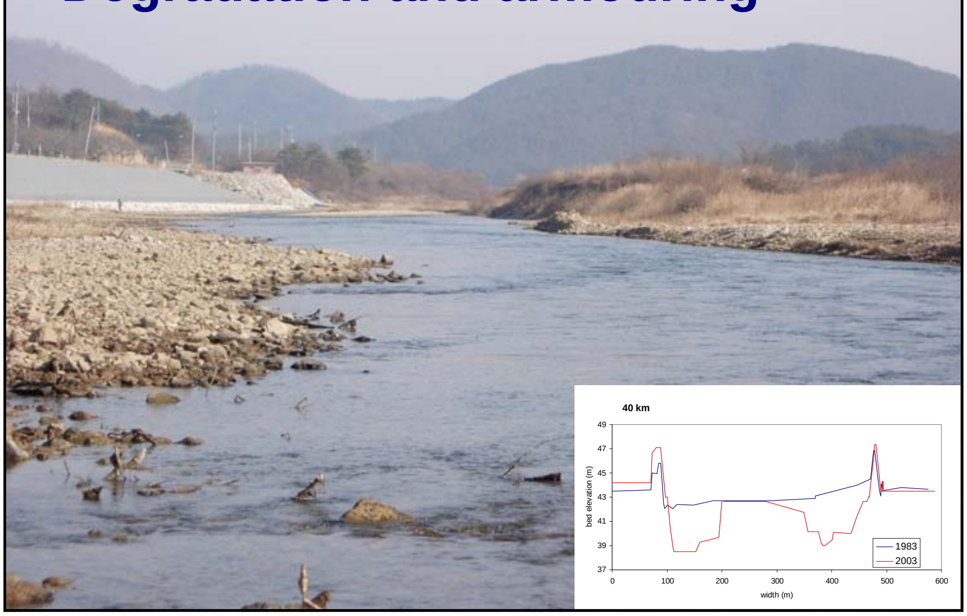
Plan view from Main dam to Re-regulation dam



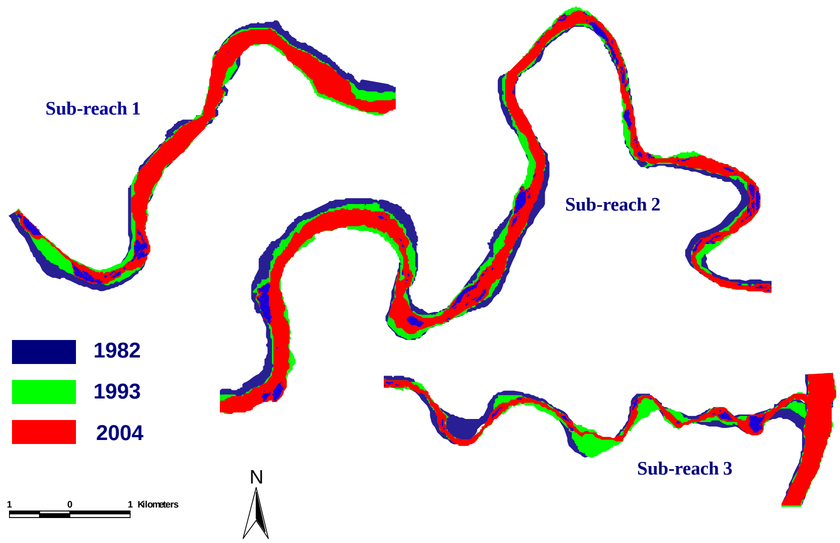
Study Reach



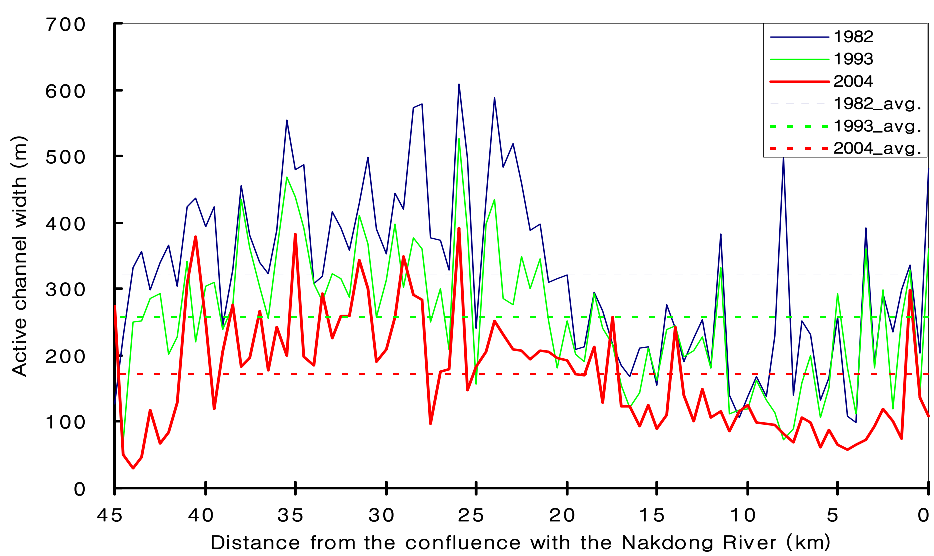
Degradation and armouring



Variation of Non-vegetated Active Channel Planform



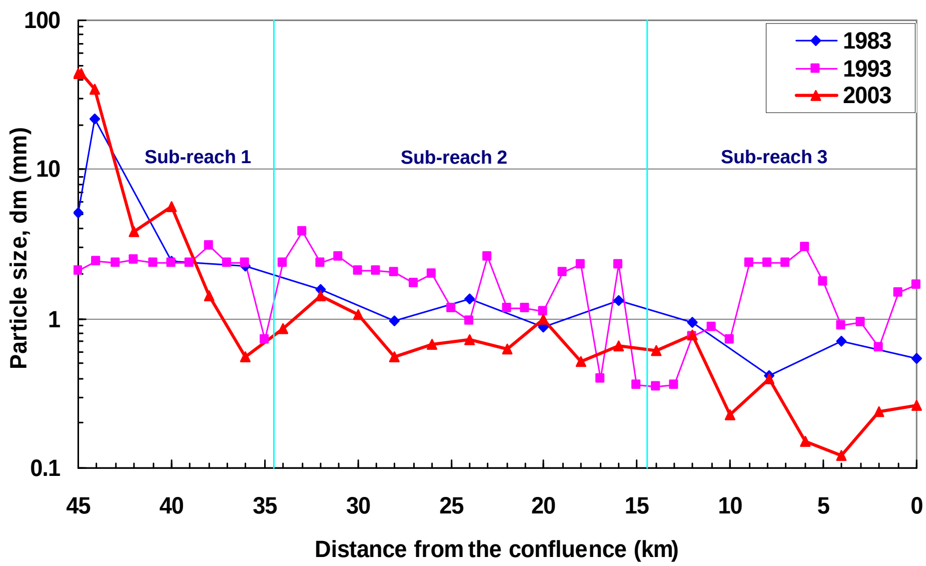
Variation of Non-vegetated Active Channel Width



River changes below Hapcheon dam

Median Bed Material Size (d_{50})

along the study reach




Lake Borgne Surge Barrier, New Orleans, LA
~ $10 billion … too much or not enough?
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Professor, Colorado State
University, U.S.A


Thank You!
pierre@engr.colostate.edu