RECLAMATION

Managing Water in the West

GSTAR-1D: A ONE-DIMENSIONAL HYDRAULIC AND SEDIMENT TRANSPORT MODEL

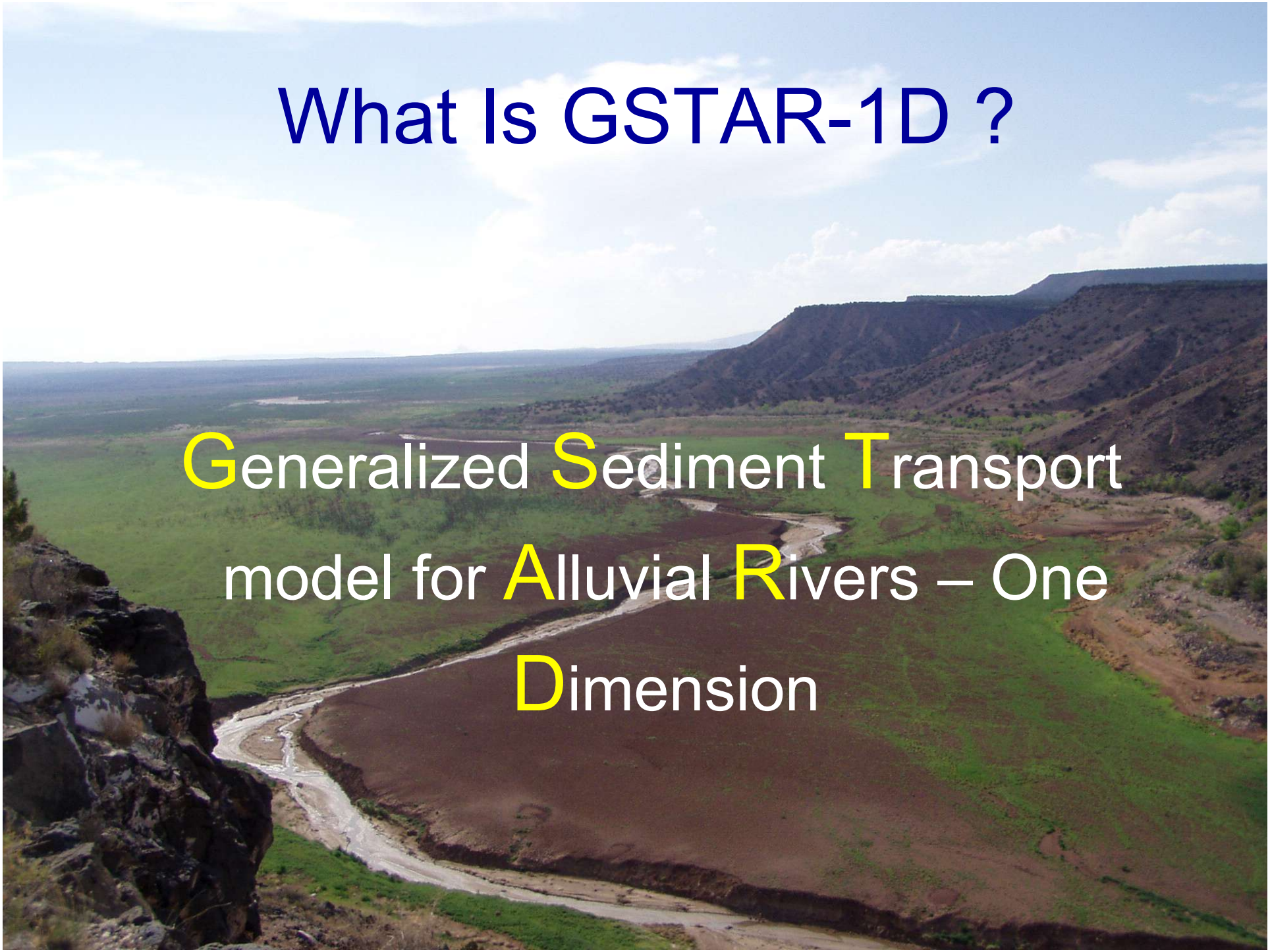
Jianchun Huang, Ph.D., Colorado State University, Fort Collins, CO

Blair Greimann, Ph.D., P.E., Technical Service Center, Sedimentation and River Hydraulics Group, Denver, CO

Prepared for FISC 2006, Reno, NV

U.S. Department of the Interior
Bureau of Reclamation

What Is GSTAR-1D ?



Generalized Sediment Transport model for Alluvial Rivers – One Dimension

Why GSTAR-1D?

- Why did Reclamation develop GSTAR-1D?
  - Full Flexibility for Research and Development
  - Specialized Applications
  - Lack of flexible tools available
- We do not try to compete with commercial codes

History

- 1980s – STARS (Randle)
- 1986 – GSTARS (Molinas and Yang)
- 1998 – GSTARS2.0 (Yang, Trevino and Simões)
- 2000 – GSTARS2.1 (Yang and Simões)
- 2003 – GSTARS3 (Yang and Simões)
- 2006 – GSTAR-1D 1.1 (Huang and Greimann)
- Current Work in Progress: GSTAR-W (Lai)

Scale Issues in Modeling

- Spatial Scale:
  - Three-dimensional (3D) model (most comprehesive, smallest scales)
  - Two-dimensional (2D) model (depth-averaged or laterally averaged)
  - One-dimensional (1D) model (cross-sectional averaged)
- Time Scale:
  - Event based small time scale analysis
  - Long term simulation

GSTAR-1D Methods

- 1D hydraulic model
- Quasi-3D model for sediment routing
- Single channel and channel network
- Steady and unsteady hydraulic and sediment transport models
- Cohesive and non-cohesive sediment transport
- Large spatial scale application and long term simulation

Major Features (1/2)

- Flow Regimes
  - subcritical flow computation for steady flow
  - subcritical, critical, and supercritical flow computation for unsteady flow
- Network
  - simple channel, simple channel network, and complex channel network
- Cohesive and non-cohesive sediment transport
  - cohesive sediment aggregation, deposition, erosion, and consolidation
  - many sediment transport equations for non-cohesive sediment
- Different sediment size fractions
  - separate routing of different size fractions to simulate sorting and armoring

Major Features (2/2)

- Floodplains
  - separate subchannels for main channel and floodplains, exchange of water and sediment between main channel and floodplains
- Point and non-point sources
  - allowing lateral flow and sediment input from tributary and water shield
- Internal boundary conditions
  - time-stage table, rating curve, weir, bridge, and radial gate

Limits of Application (or Keeping Your Expectations Low)

- GSTAR-1D is a 1D model. It should not be applied to situations where a truly 2D or truly 3D model is needed for detailed simulation of local conditions.

- The phenomena of secondary currents, transverse movement, diffusion, and super elevation are **ignored**.

Limits of Application (or Keeping Your Expectations Low)

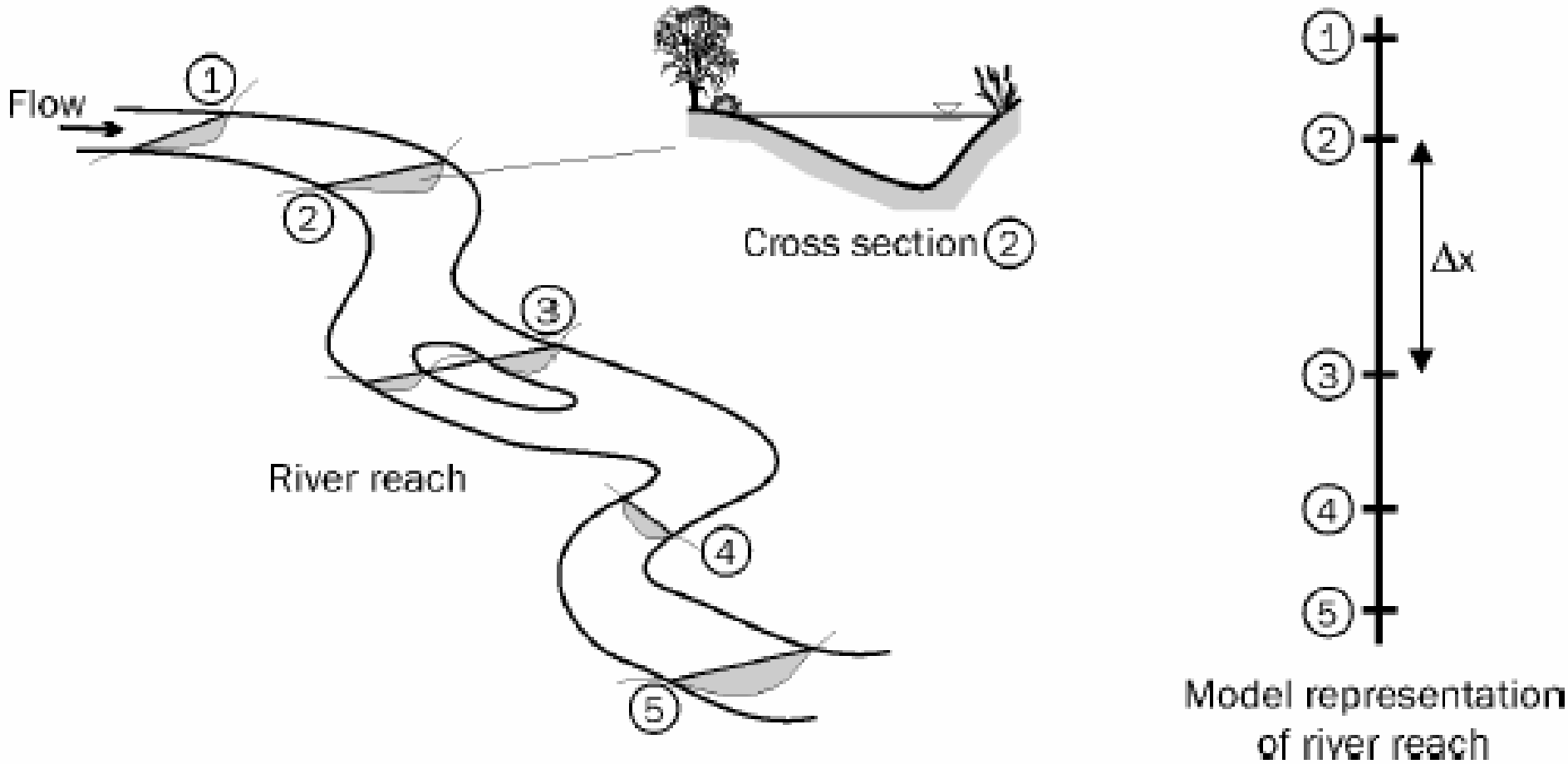
1D Problem areas:

- Lateral sorting (a cross section armors before you think it will)
- Pool-riffle sequences (pools fill up and are not scoured)
- Changes in plan form (cannot simulate transitions from braided to meandering)
- Bank erosion (hydraulics are not resolved adequately to predict bank erosion)

Limits of Application (or Keeping Your Expectations Low)

- General problems:
  - Transport and mixing of gravel-sand mixtures
  - Sediment supply prediction
  - Channel modifications (the D9 factor)

Model Representation



RECLAMATION

Steady Flow Computation

Energy equation for steady gradually varied flow

$$Z_2 + \beta_2 \frac{V_2^2}{2g} - Z_1 - \beta_1 \frac{V_1^2}{2g} = h_f + h_c$$

$$h_f = \left[\frac{2Q}{(K_1 + K_2)}\right]^2 (x_2 - x_1) \qquad h_c = C_c \left|\frac{V_1^2}{2g} - \frac{V_2^2}{2g}\right|$$

where z = water surface elevation

β = velocity distribution coefficients

V = flow velocity

h_f = friction loss

h_c = contraction or expansion losses

K = conveyance computed from Manning's equation

RECLAMATION

Steady Flow Computation -Network

- The energy equation and the continuity equation

$$F_i = Z_{i+1} - Z_i + \frac{1}{2g}\left(\frac{\beta_{i+1}Q_{i+1}|Q_{i+1}|}{A_{i+1}^2} - \frac{\beta_i Q_i |Q_i|}{A_i^2}\right) + h_f + h_c = 0$$

$$G_i = Q_{i+1} - Q_i - Q_{Lat_i} = 0$$

- Upstream B.C. $BU = f(Q_1, Z_1) = 0$
- Downstream B.C. $BD = f'(Q_{N+1}, Z_{N+1}) = 0$

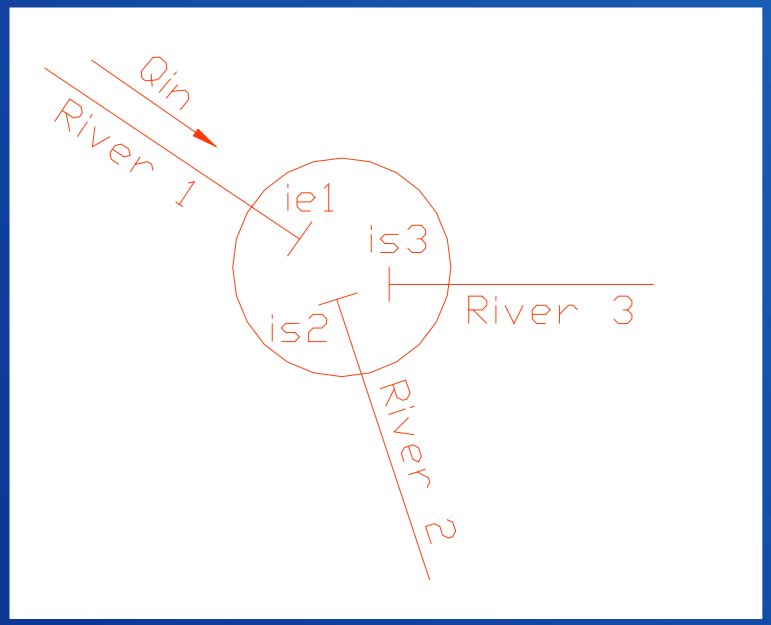
- Final equation:

$$\begin{bmatrix} \frac{\partial BU}{\partial Z_1} & \frac{\partial BU}{\partial Q_1} & & & & & & \\ \frac{\partial F_1}{\partial Z_1} & \frac{\partial F_1}{\partial Q_1} & \frac{\partial F_1}{\partial Z_2} & \frac{\partial F_1}{\partial Q_2} & & & & \\ \frac{\partial G_1}{\partial Z_1} & \frac{\partial G_1}{\partial Q_1} & \frac{\partial G_1}{\partial Z_2} & \frac{\partial G_1}{\partial Q_2} & & & & \\ & & \vdots & \vdots & \ddots & \vdots & \vdots & \\ & & & & & \frac{\partial G_N}{\partial Z_N} & \frac{\partial G_N}{\partial Q_N} & \frac{\partial G_N}{\partial Z_{N+1}} & \frac{\partial G_N}{\partial Q_{N+1}} \\ & & & & & \frac{\partial G_N}{\partial Z_N} & \frac{\partial G_N}{\partial Q_N} & \frac{\partial G_N}{\partial Z_{N+1}} & \frac{\partial G_N}{\partial Q_{N+1}} \\ & & & & & & & \frac{\partial BD}{\partial Z_{N+1}} & \frac{\partial BD}{\partial Q_{N+1}} \end{bmatrix} \begin{bmatrix} \Delta Z_1 \\ \Delta Q_1 \\ \Delta Z_2 \\ \vdots \\ \Delta Q_N \\ \Delta Z_{N+1} \\ \Delta Q_{N+1} \end{bmatrix} = -\begin{bmatrix} BU \\ F_1 \\ G_1 \\ \vdots \\ F_N \\ G_N \\ BD \end{bmatrix}$$

RECLAMATION

Steady Flow Computation -Network

- Example:



- Downstream B.C. for River 1: $BD_1 = Z_{ie} + \frac{\beta_{ie} Q_{ie}^2}{2gA_{ie}^2} - Z_{is} - \frac{\beta_{is} Q_{is}^2}{2gA_{is}^2} = 0$
- Upstream B.C. for River 2: $BU_2 = Q_{is2} + Q_{is3} - Q_{in} = 0$
- Upstream B.C. for River 3: $BU_3 = Z_{is3} + \frac{\beta_{is3} Q_{is3}^2}{2gA_{is3}^2} - Z_{is2} - \frac{\beta_{is2} Q_{is2}^2}{2gA_{is2}^2} = 0$

RECLAMATION

Unsteady Flow Computation

de St Venant equations

Continuity: $$\frac{\partial(A + A_d)}{\partial t} + \frac{\partial Q}{\partial x} = q_{lat}$$

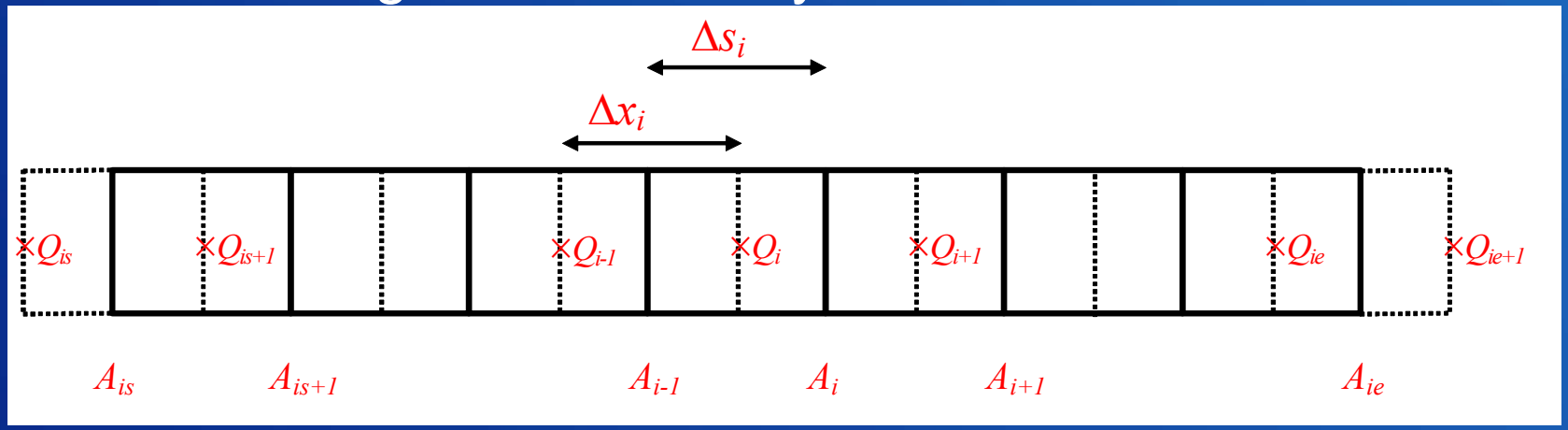
Momentum: $$\frac{\partial Q}{\partial t} + \frac{\partial(\beta Q^2 / A)}{\partial x} + gA\frac{\partial Z}{\partial x} = -gAS_f$$

where Q = discharge (m^3/s),
A = cross section area (m^2),
A_d = ineffective cross section area (m^2),
q_{lat} = lateral inflow per unit length of channel (m^2/s),
t = time independent variable (s),
x = spatial independent variable (m),
β = velocity distribution coefficients,
Z = water surface elevation (m), and
S_f = energy slope

RECLAMATION

Unsteady Flow Computation

- Discretized grid for unsteady flow simulation



- Discretized equations

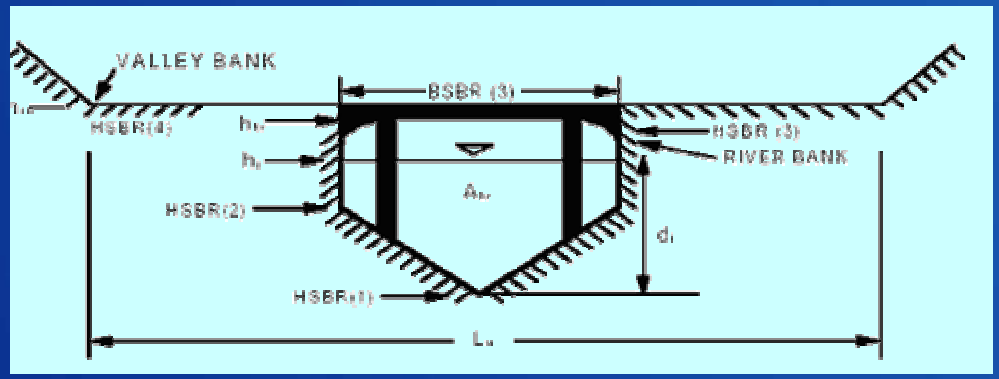
$$a_i \Delta Q_{i-1}^m + b_i \Delta Q_i^m + c_i \Delta Q_{i+1}^m = d_i$$

$$\Delta A_i^m = \alpha_i \Delta Q_i^m + \delta_i \Delta Q_{i+1}^m + \gamma_i$$

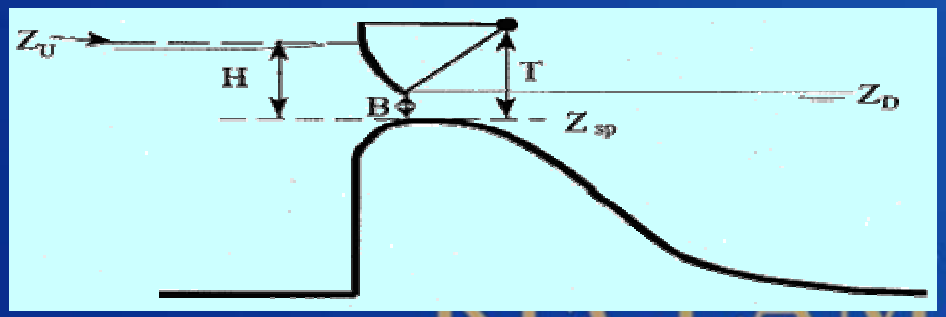
RECLAMATION

Internal Boundary Conditions

- Time Stage Table $H = H(t)$
- Rating Curve $H = H(Q)$
- Weir $Q = CB(Z - Z_0)^{\frac{3}{2}}$
- Bridge

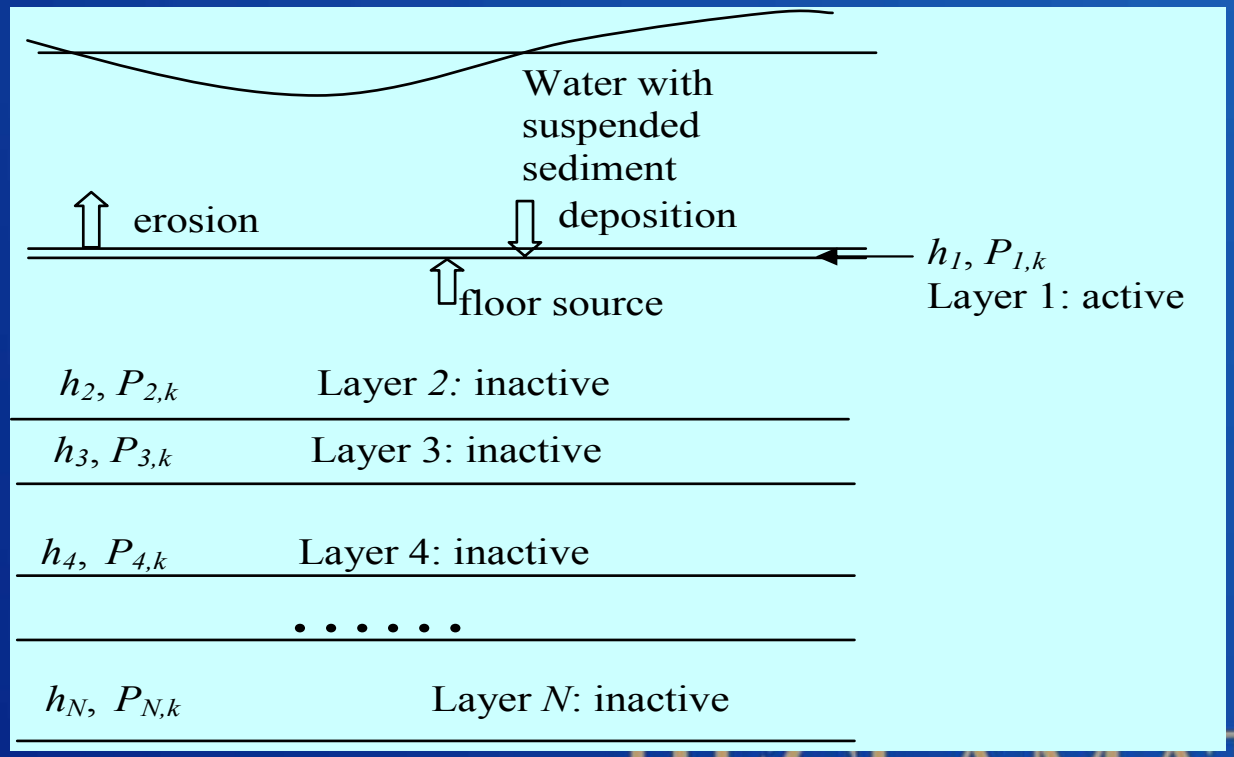


- Radial Gate



Sediment Computation

- Conceptual model



RECLAMATION

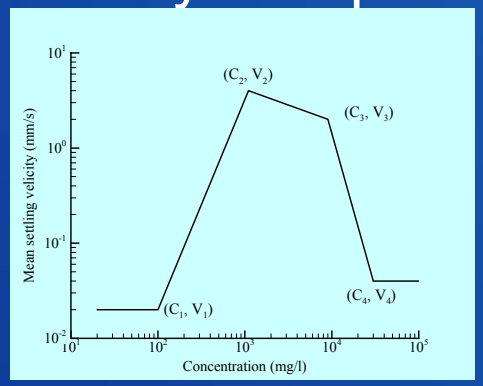
Sediment Computation

- Non-Cohesive Sediment Transport Capacity Functions

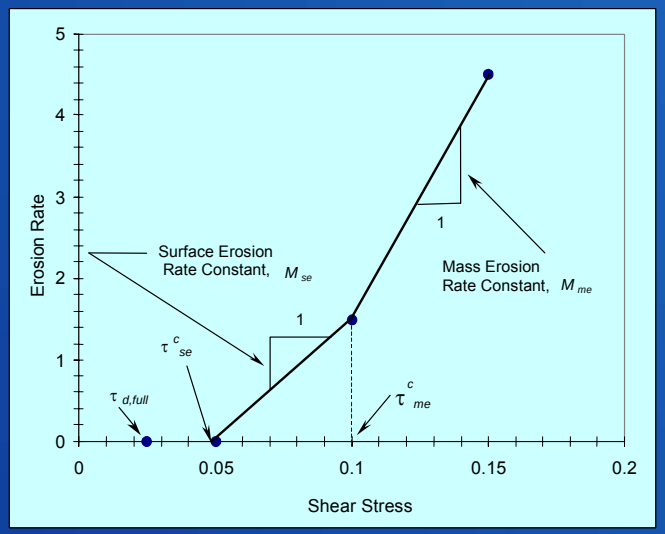
Equations	Type
DuBoys (1879)	B
Meyer-Peter and Müller (1948)	B
Laursen (1958)	BM
Midified Laursen's Formula (Madden, 1993)	BM
Toffaleti (1969)	BM
Engelund and Hansen (1972)	BM
Ackers and White (1973)	BM
Ackers and White (1990)	BM
Yang (1973) + Yang (1984)	BM
Yang (1979) + Yang (1984)	BM
Parker (1990)	B
Brownlie (1981)	BM
Yang et al. (1996)	BM

Sediment Computation

- Cohesive Sediment Physical processes
  - Aggregation



  - Deposition
    - Partial deposition
    - Full deposition
  - Erosion
    - Surface erosion
    - Mass erosion



  - Consolidation

$$\varepsilon = \varepsilon_f - (\varepsilon_f - \varepsilon_i)e^{-\beta t}$$

RECLAMATION

Uniform Sediment or Non-Uniform Sediment Model

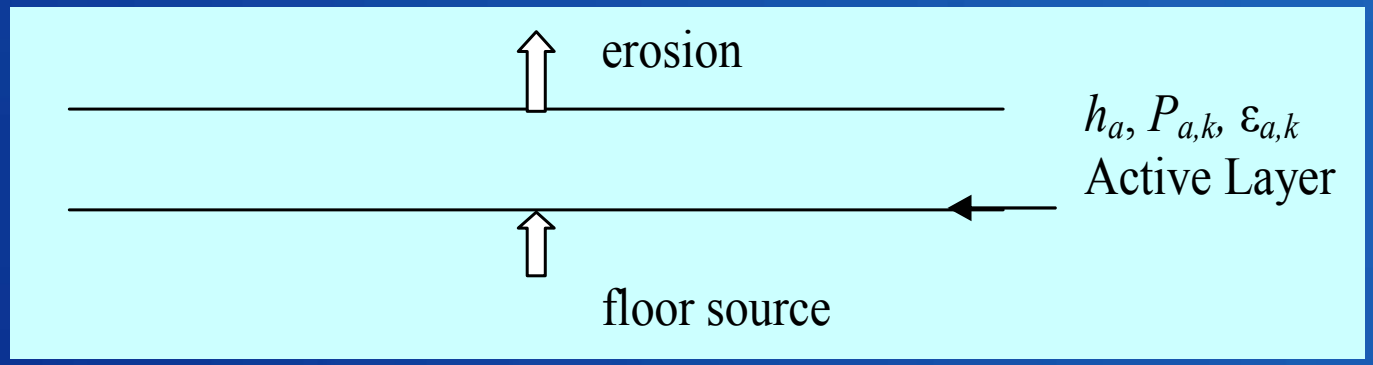
- A uniform model uses a representative particle size for sediment routing.
- A non-uniform model routes sediment by size fraction to more realistically reflect the phenomenon of sediment sorting and the formation and destruction of an armor layer on a river bed.
- GSTAR-1D is non-uniform model

Bed Sorting and Armoring

- GSTAR-1D computes sediment transport by size fraction; it will show particles of different sizes being transported at different rates. Some particle sizes may be eroded, while others may be deposited or may be immovable

- GSTAR-1D computes the carrying capacity for each size fraction present in the bed, but the amount of material actually moved is computed by the sediment routing equation. Consequently, sorting and armoring are simulated

Bed Sorting and Armoring



- Both the sediment size fraction and porosity are unknowns.
  - kinematic condition

$$h_a \frac{dP_{a,k}}{dt} = -\frac{S_{e,k}}{\overline{\varepsilon}_k} + \widetilde{P}_k \sum_k \frac{S_{e,k}}{\overline{\varepsilon}_k}$$

$$\frac{d}{dt}(\varepsilon_{a,k} P_{a,k} h_a) = -S_{e,k} + S_{f,k}$$

  - mass-conservation equation

RECLAMATION

Steady Model
- non-equilibrium

- Equilibrium Model: there is an instantaneous exchange between suspended and bed sediments when there is a difference between sediment supply and a river's sediment transport capacity
- For fine sediments, there is usually a time lag. GSTAR-1D provides a non-equilibrium model (based on Han, 1990) which takes this phenomenon into consideration

Assumptions

- Change in suspended sediment concentration at a cross section is much smaller than change of a river bed, i.e.,

$$\frac{\partial A_s}{\partial t} << (1 - p_s)\frac{\partial A_d}{\partial t}$$

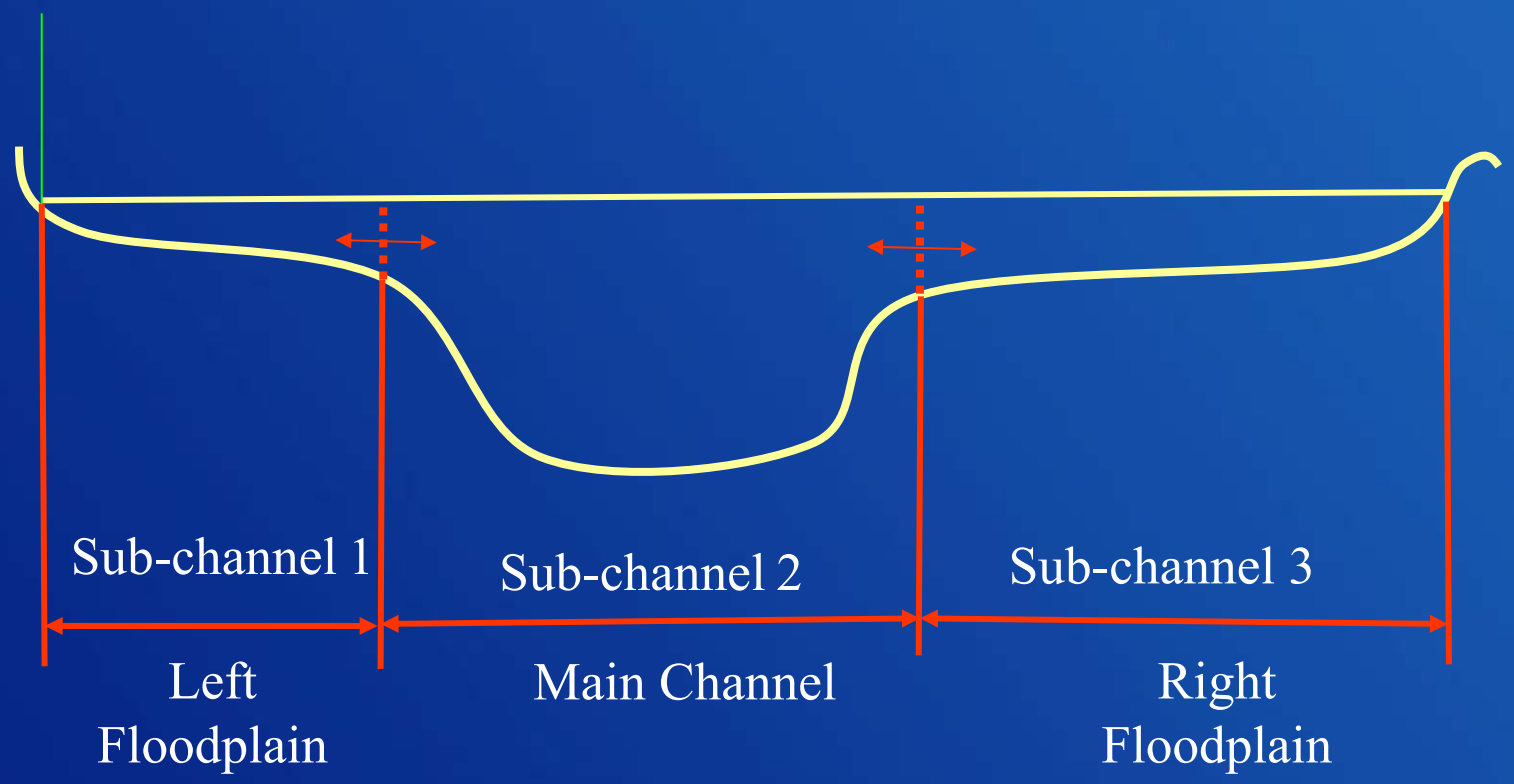
- During a time step, parameters for a cross section remain constant

$$\frac{\partial Q_s}{\partial t} = \frac{dQ_s}{dt}$$

(This allows decoupling of water and sediment computations)

RECLAMATION

Floodplain Simulation (still under development…)



RECLAMATION

Unsteady Sediment Model

- The 2D depth-averaged convection-diffusion equation for unsteady sediment transport is

$$\underbrace{\frac{\partial(hc)}{\partial t}}_{\text{Unsteady Term}} + \underbrace{\frac{\partial(huc)}{\partial x} + \frac{\partial(hvc)}{\partial y}}_{\text{Convective Term}} = \underbrace{\frac{\partial}{\partial x}\left(D_x h \frac{\partial c}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_y h \frac{\partial c}{\partial y}\right)}_{\text{Diffusion Term}} + \underbrace{s}_{\text{Source Term}}$$

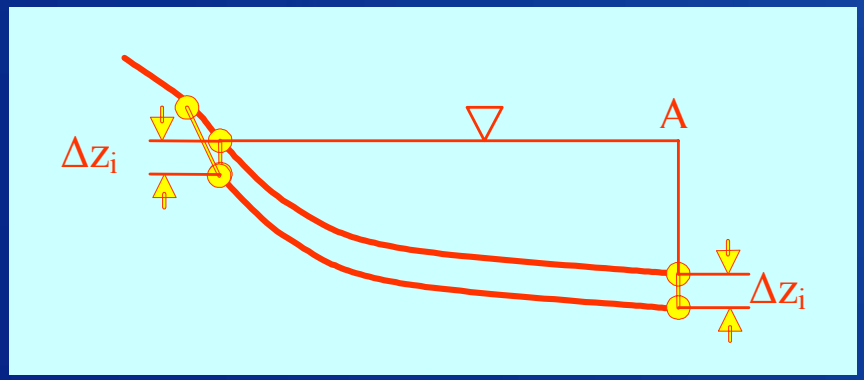
Convective Term ⇩ Lax-Wendroff TVD Scheme

Diffusion Term ⇩ CDS Scheme

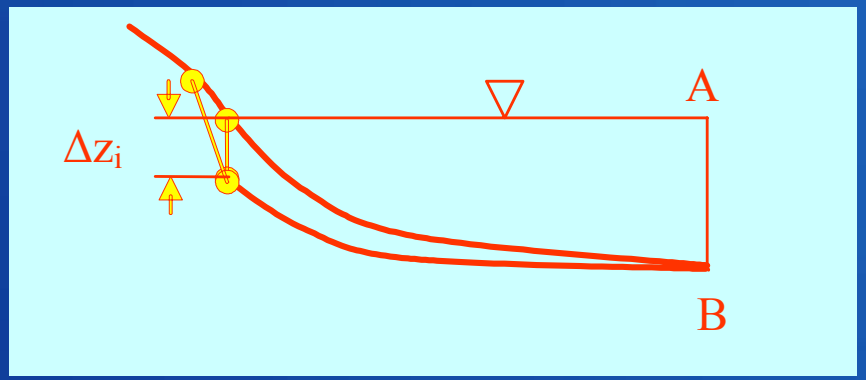
RECLAMATION

Channel Width Changes

- GSTAR-1D channel geometry adjustments can be vertical or lateral depends on a minimization theory
  - No Minimization
  - Minimization With Maximum Conveyance (Not Recommended)
  - Minimization With Total Stream Power (Not Recommended)
  - Minimization With Energy Slope
  - Minimization With Bed Slope (Not Recommended)



Vertical adjustment



Lateral adjustment

RECLAMATION

Channel Side Slope Computation

- GSTAR-1D can check whether the angle of repose exceeds a known critical slope. A user is allowed the option of specifying one critical angle above the water surface, and a different critical angle for submerged points.
- GSTAR-1D scans each cross section at the end of each time step to determine if any vertical or horizontal adjustments have caused the banks to become too steep.
- Bank erosion is added as lateral inflow.

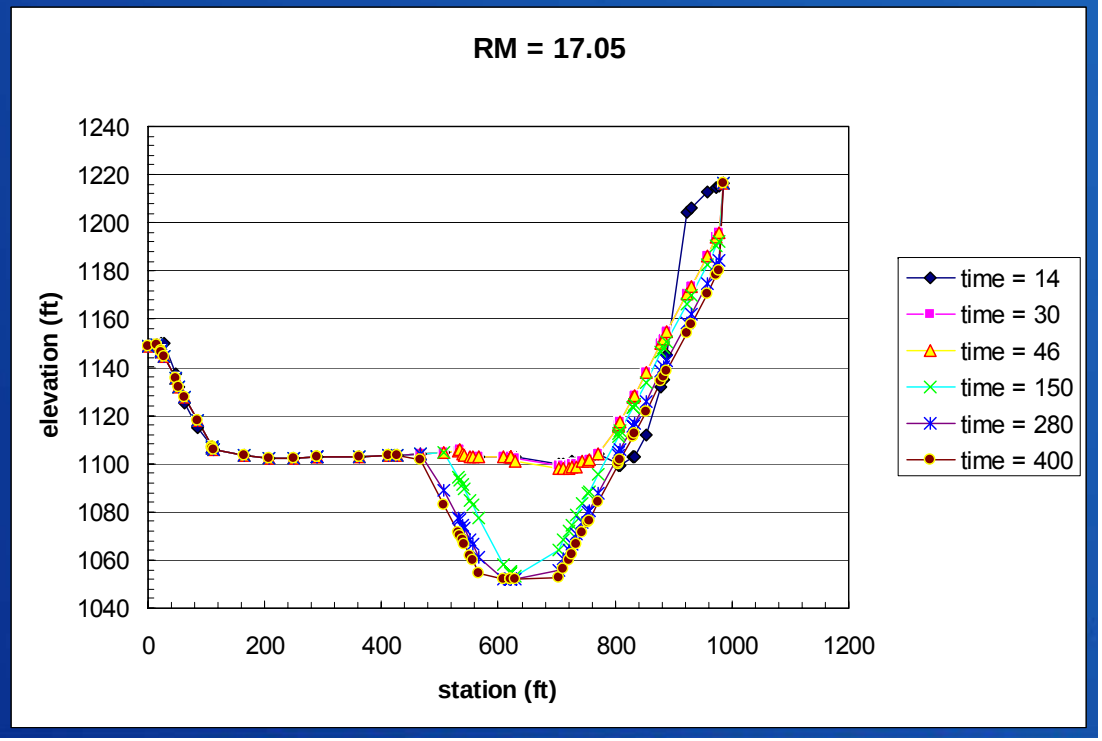
Channel Incision

- GSTAR-1D uses an equation related to flow rate to determine erosion width:

  Erosion Width = $a\ Q^b$

  a and b are user defined.

- The erosion width can be much smaller than the wetted width (e.g. delta erosion during dam removal

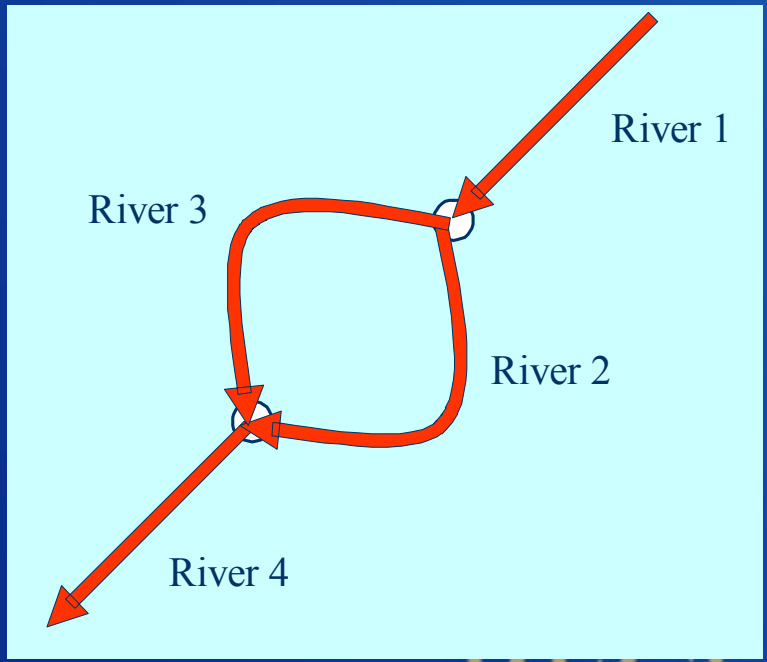


Test and Applications

- Simulation of Networks
- Canal Sedimentation (San Luis Canal)
- Dam Removal (Matilija Dam Removal)
- Reservoir Sediment Management (Black Canyon Diversion Dam)
- River Restoration (Rio Grande, Trinity River)
- River Aggradation for Flood Protection (Little Colorado River)

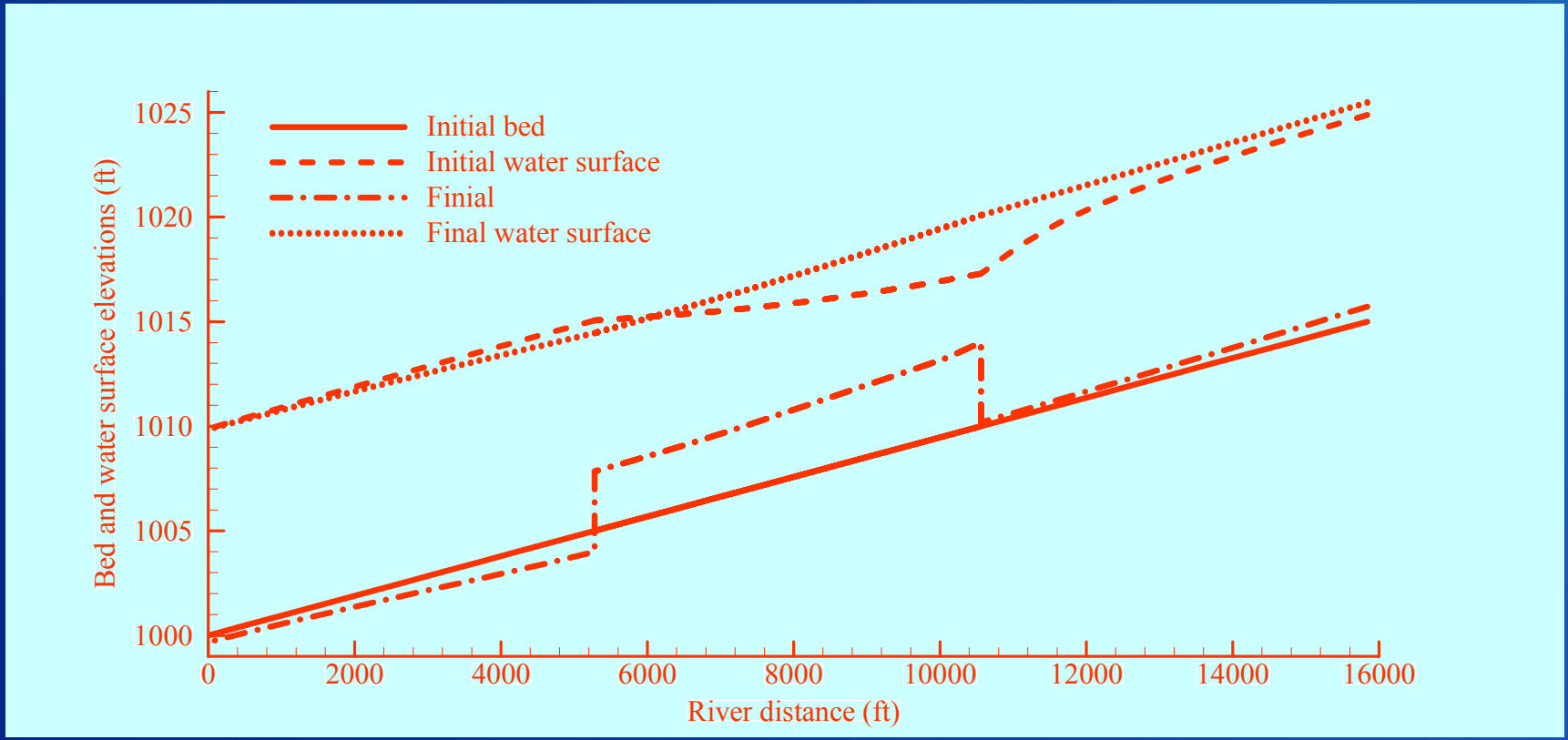
1. Network Simulation

Simulation of a simple network channel with sediment transport. The network is composed of 4 trapezoidal channels. Rivers are numbered ascending from upstream to downstream



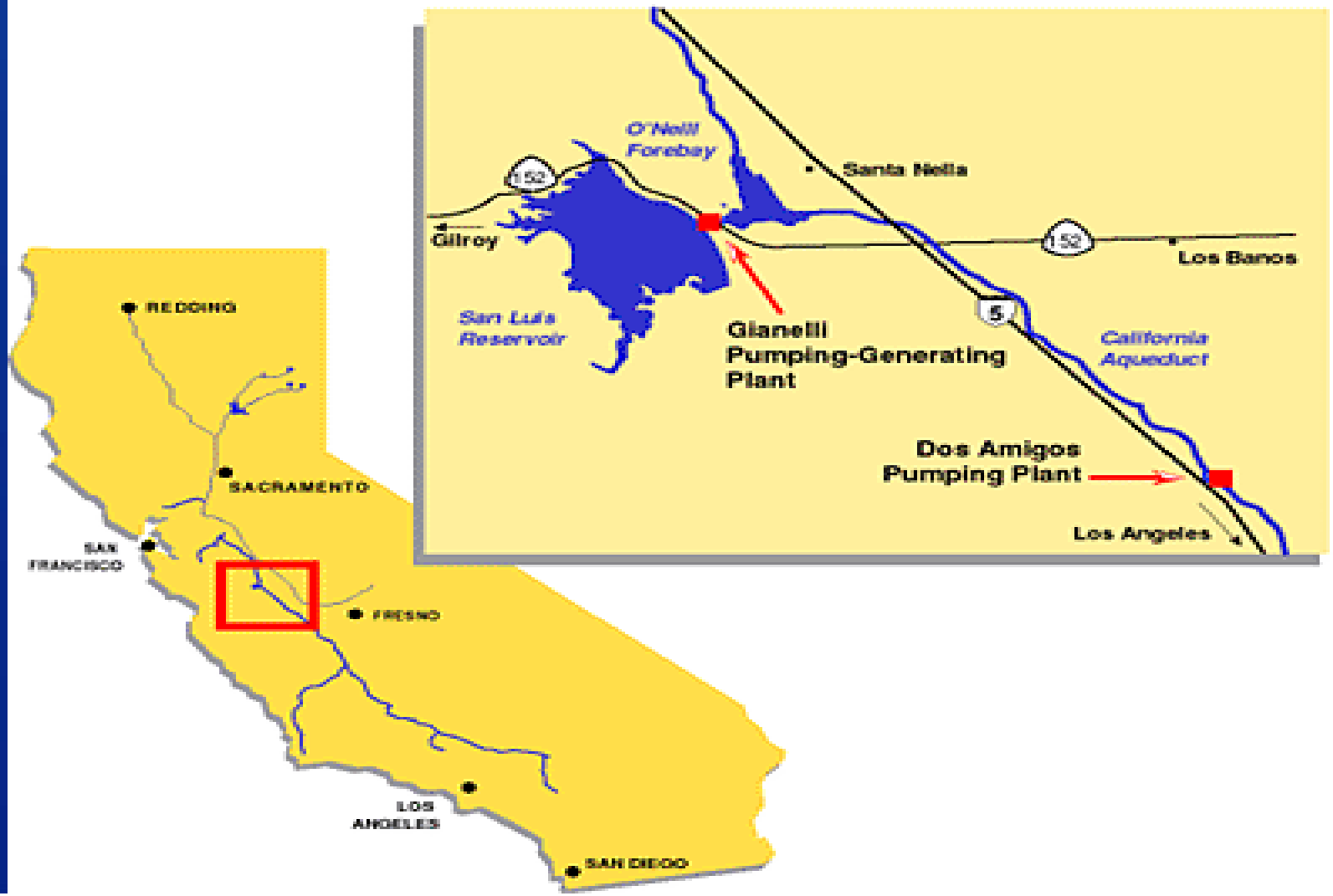
RECLAMATION

Simulation of a simple network channel with sediment transport. Bed elevation and water surface elevation

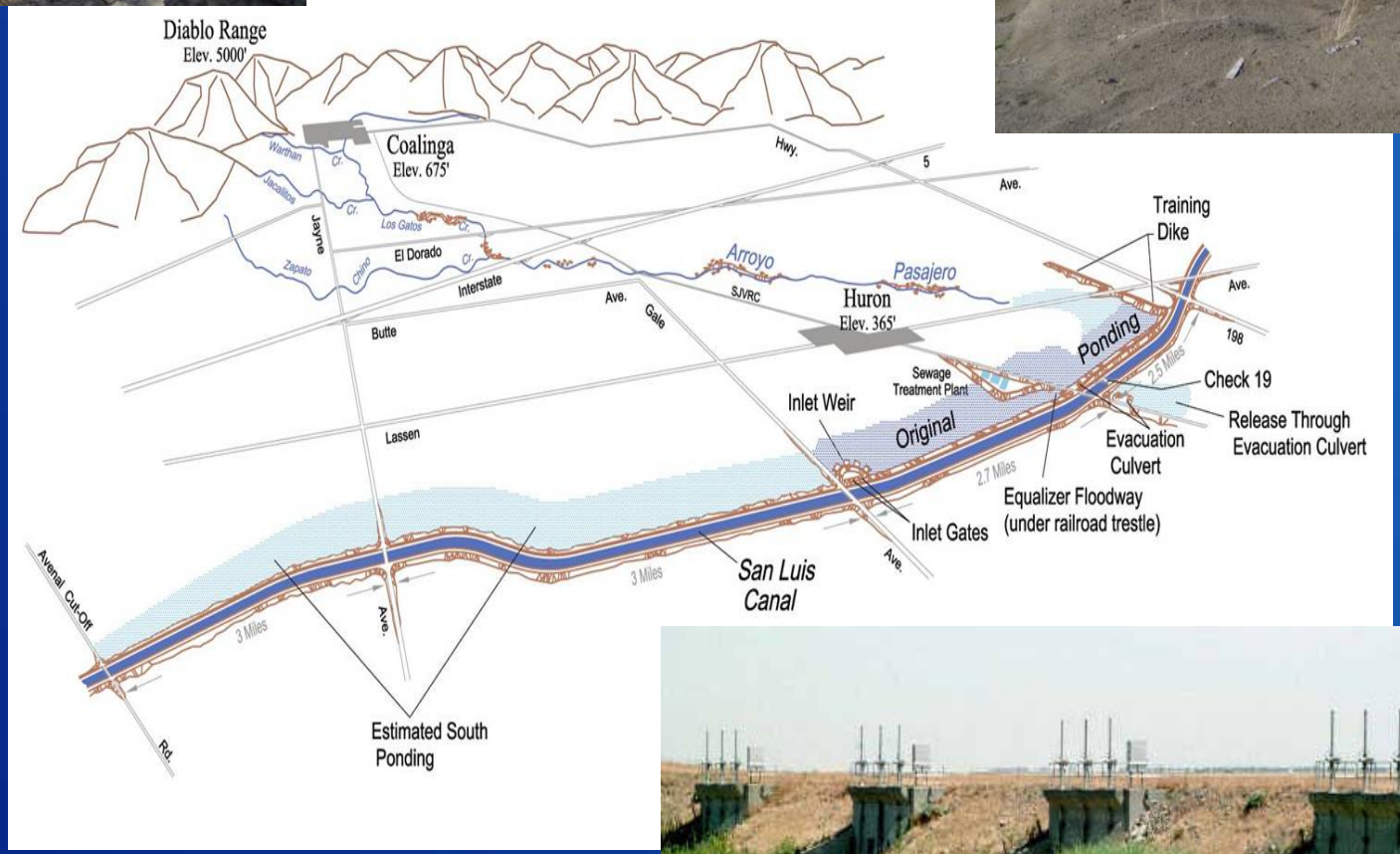


RECLAMATION

2. San Luis Canal (SLC), a reach of the California Aqueduct, extends 75 miles from Check Structure 15 to Check Structure 21

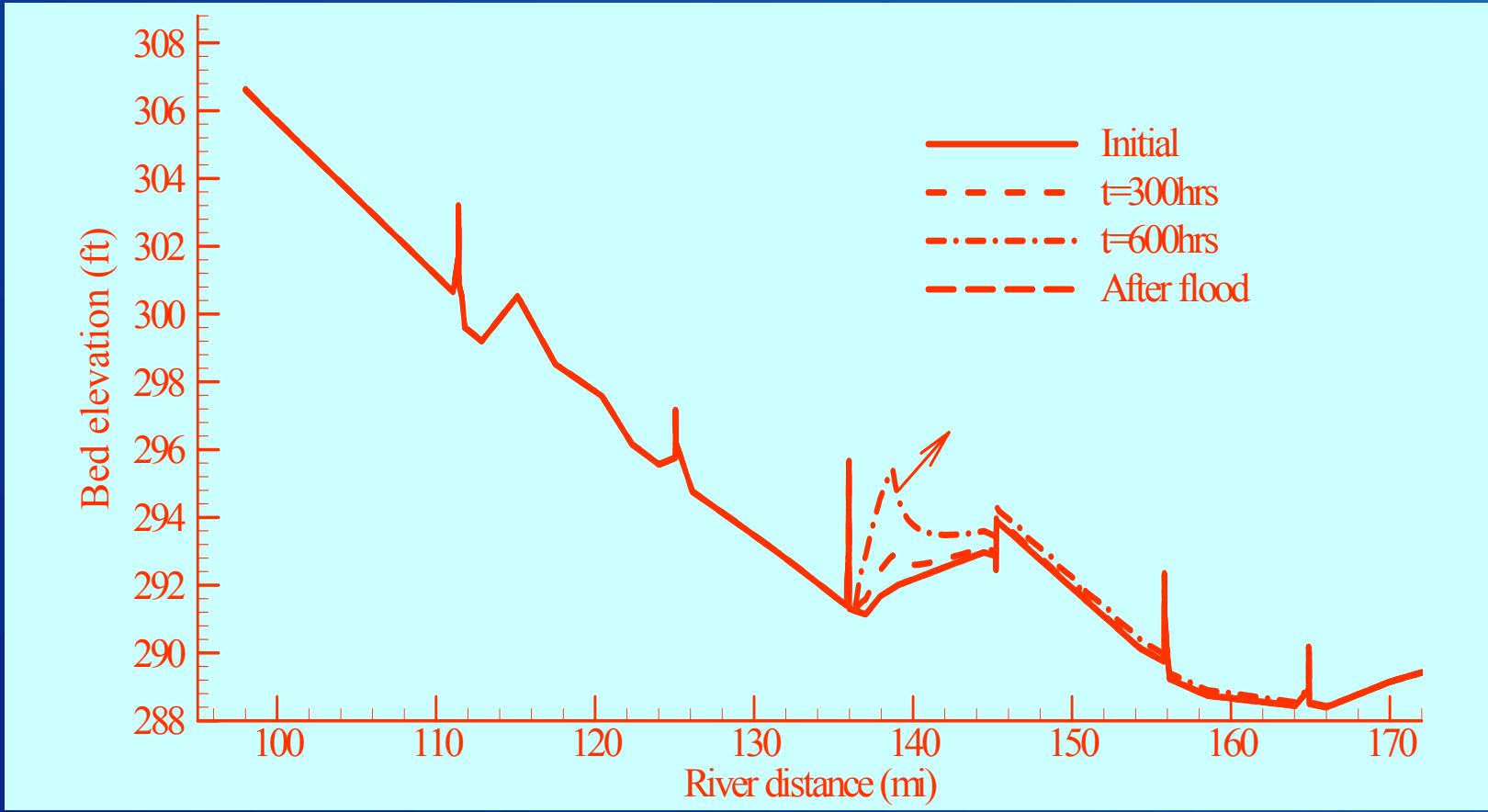


The Arroyo Pasaje



Radial Gates

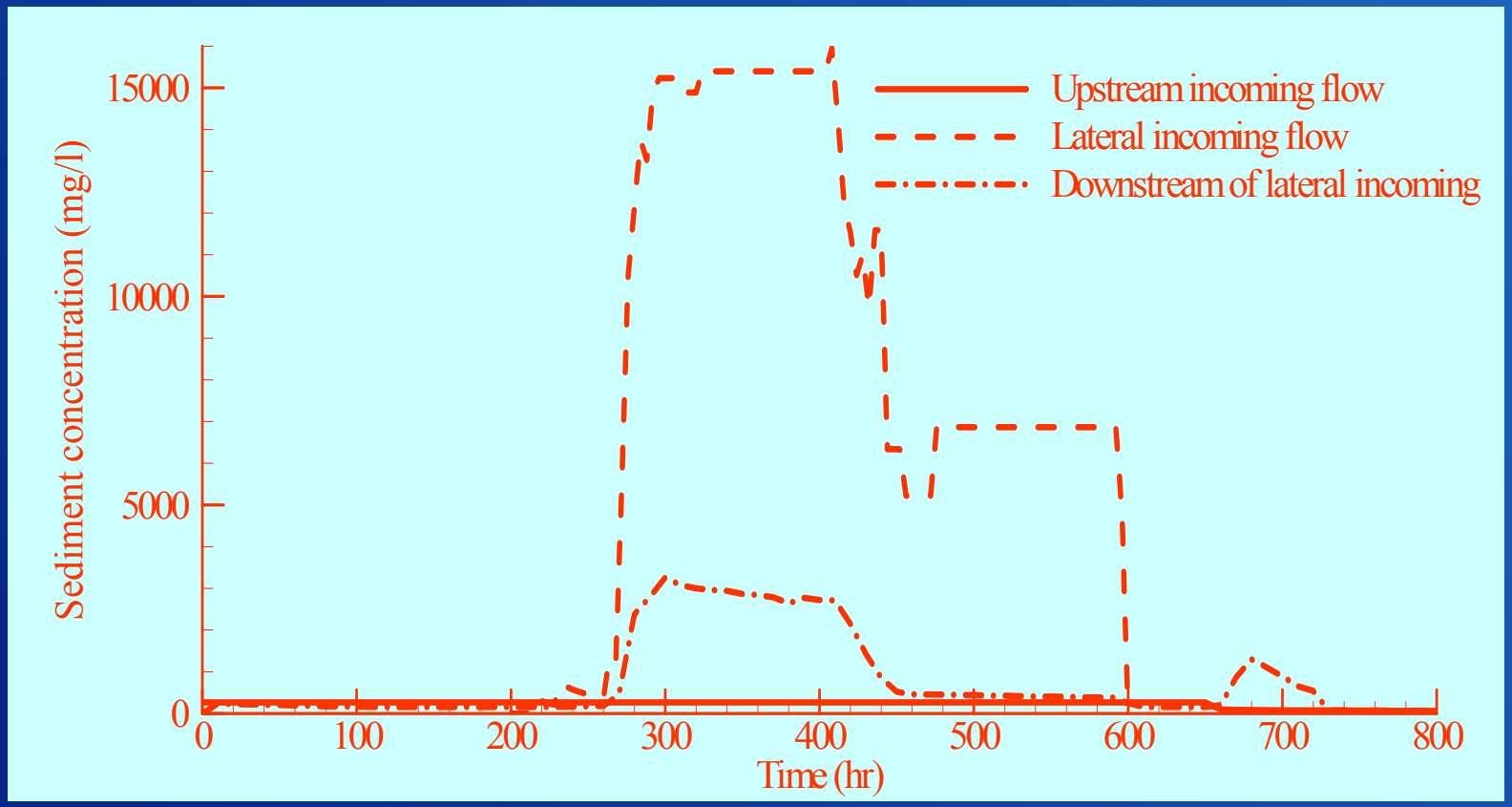
A reach of the California Aqueduct, or San Luis Canal (SLC), extends 75 miles from Check Structure 15 to Check Structure 21



Bed elevation change of the SLC before and after a flood event

RECLAMATION

A reach of the California Aqueduct, or San Luis Canal (SLC), extends 75 miles from Check Structure 15 to Check Structure 21



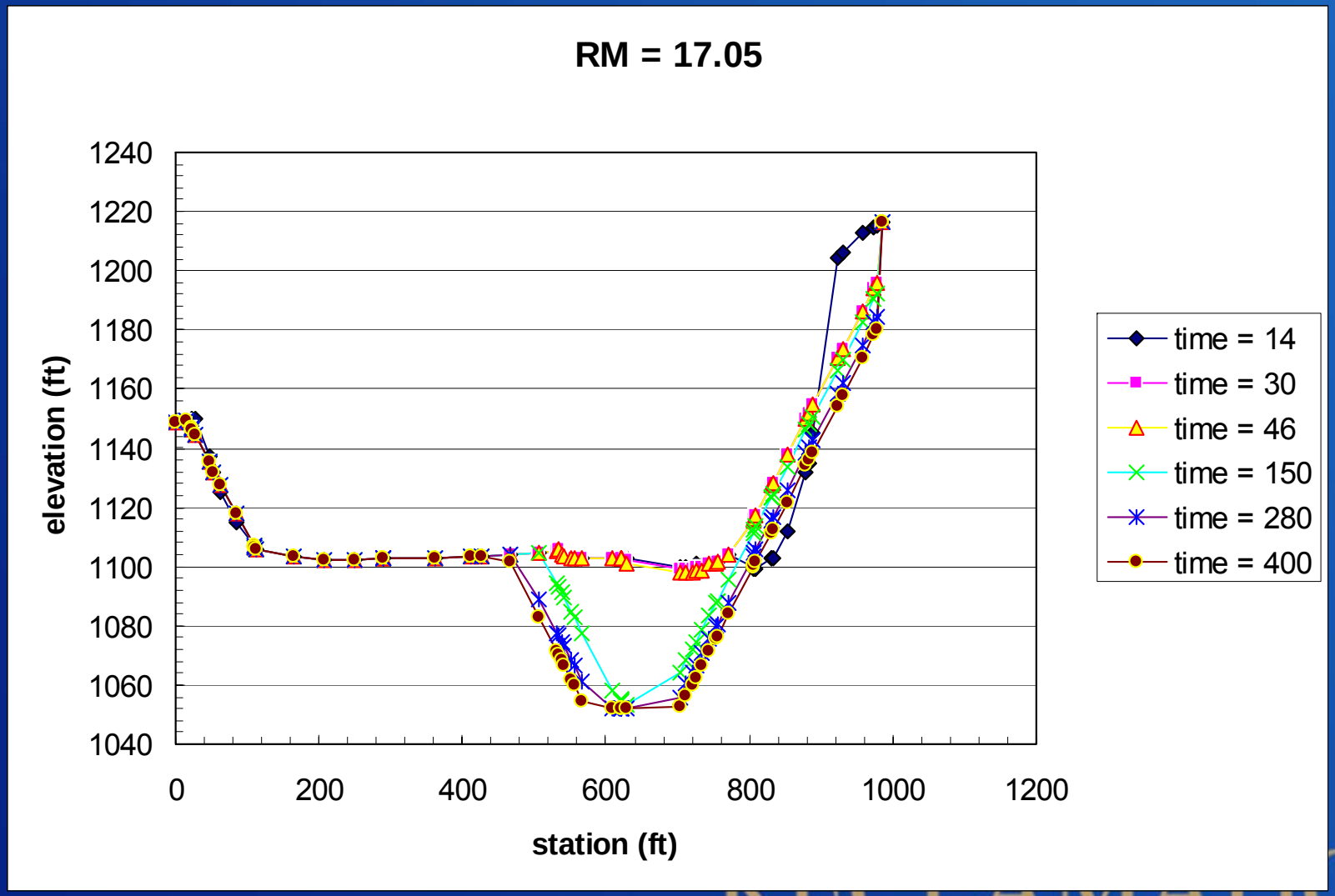
RECLAMATION

3. Matilija Dam Removal

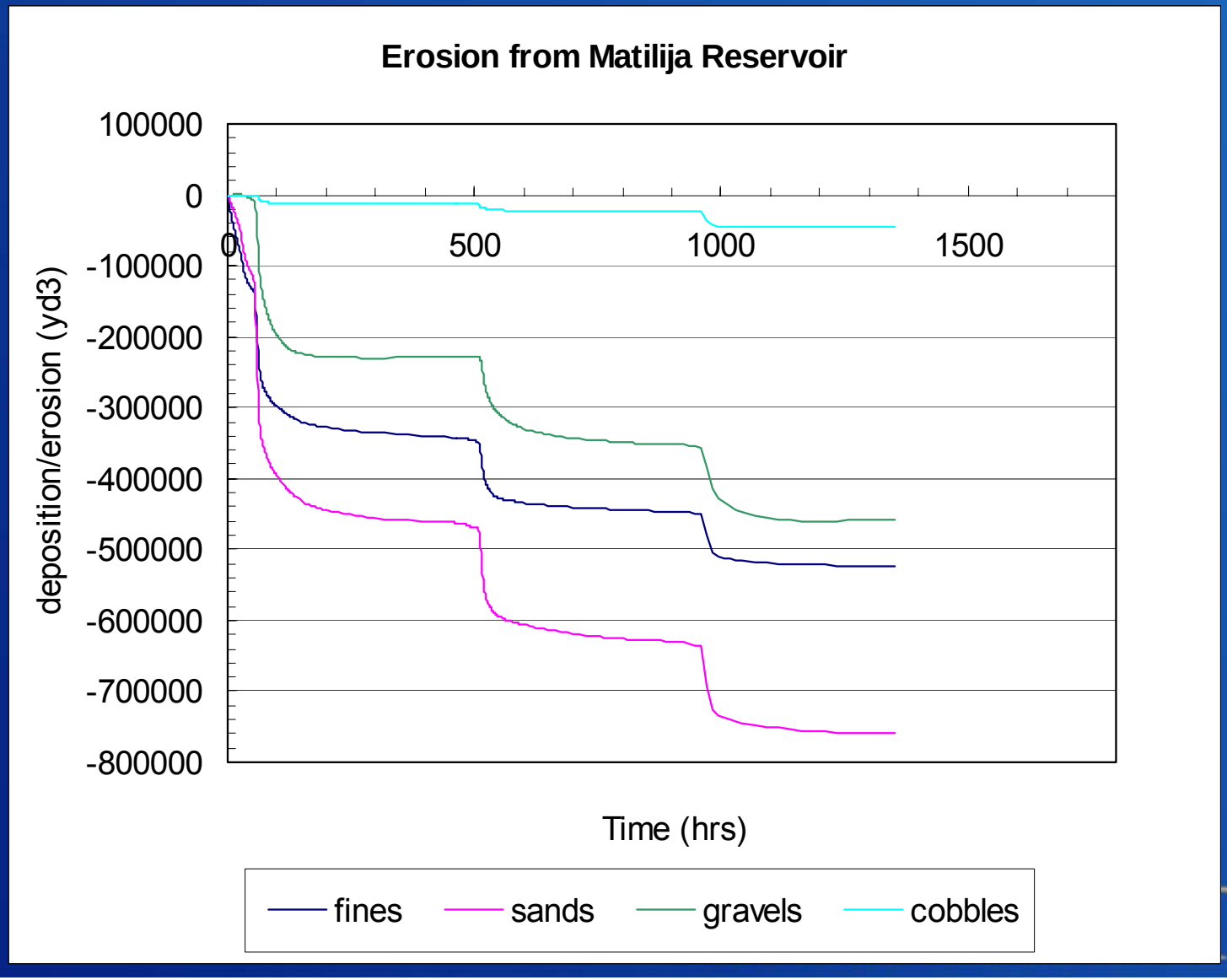
- Matilija Dam is located on the Ventura River and now has only 500 ac-ft left of its original 7000 ac-ft capacity
- GSTAR-1D is being used to quantify downstream impacts associated with dam removal
- It is being used to predict: sediment concentrations, river bed aggradation, sediment inputs to diversion, sediment delivery to ocean, reservoir erosion

Wyoming
Salt Lake City
Carson City
Sacramento
San Francisco
Oakland
San Jose
Nevada
Utah
Pacific Ocean
California
Ventura River Watershed
Los Angeles
Arizona
San Diego
Phoenix
Mexicali
New Mexico
Legend
cities
Capital Cities
Lake; Ocean
Land
Interstate Hwy
State Bnd
urban
Ventura River Watershed
0 25 50 100 150 200
Miles

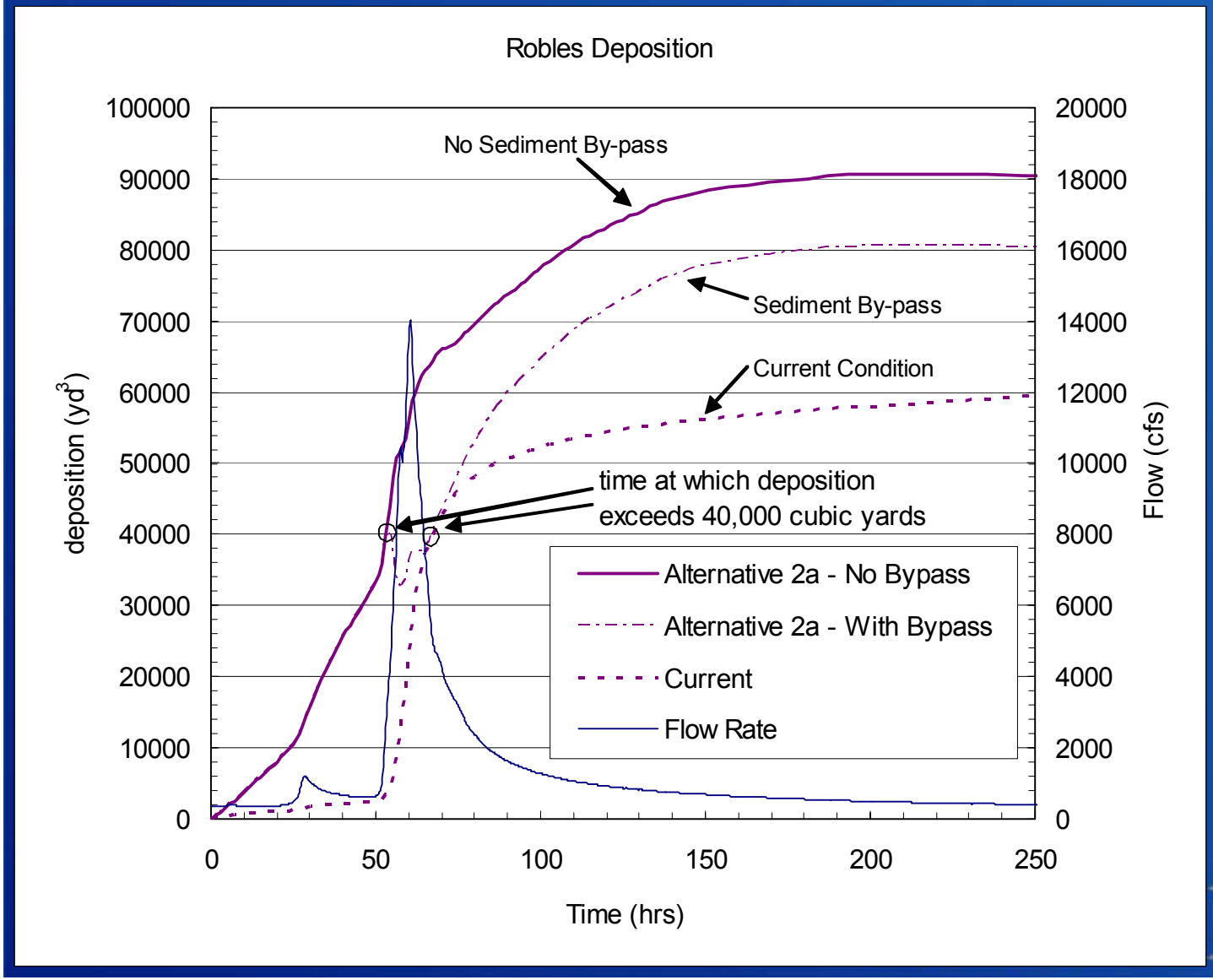
Erosion From Matilija Reservoir



Erosion From Matilija Reservoir



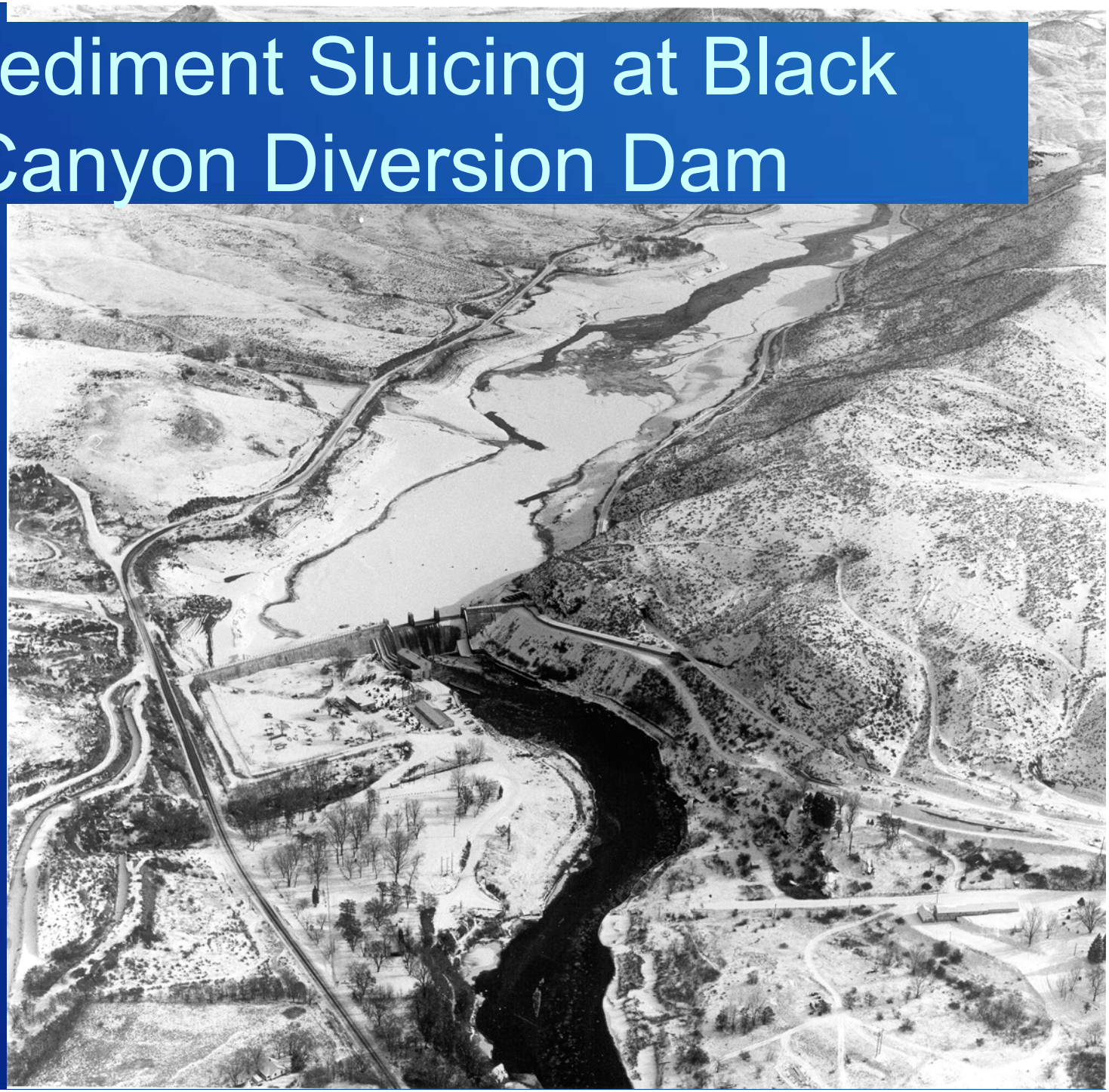
Deposition at Downstream Diversion



GSTAR-1D was used to assess the ability to pass sediment through the diversion using additional radial gates

MATION

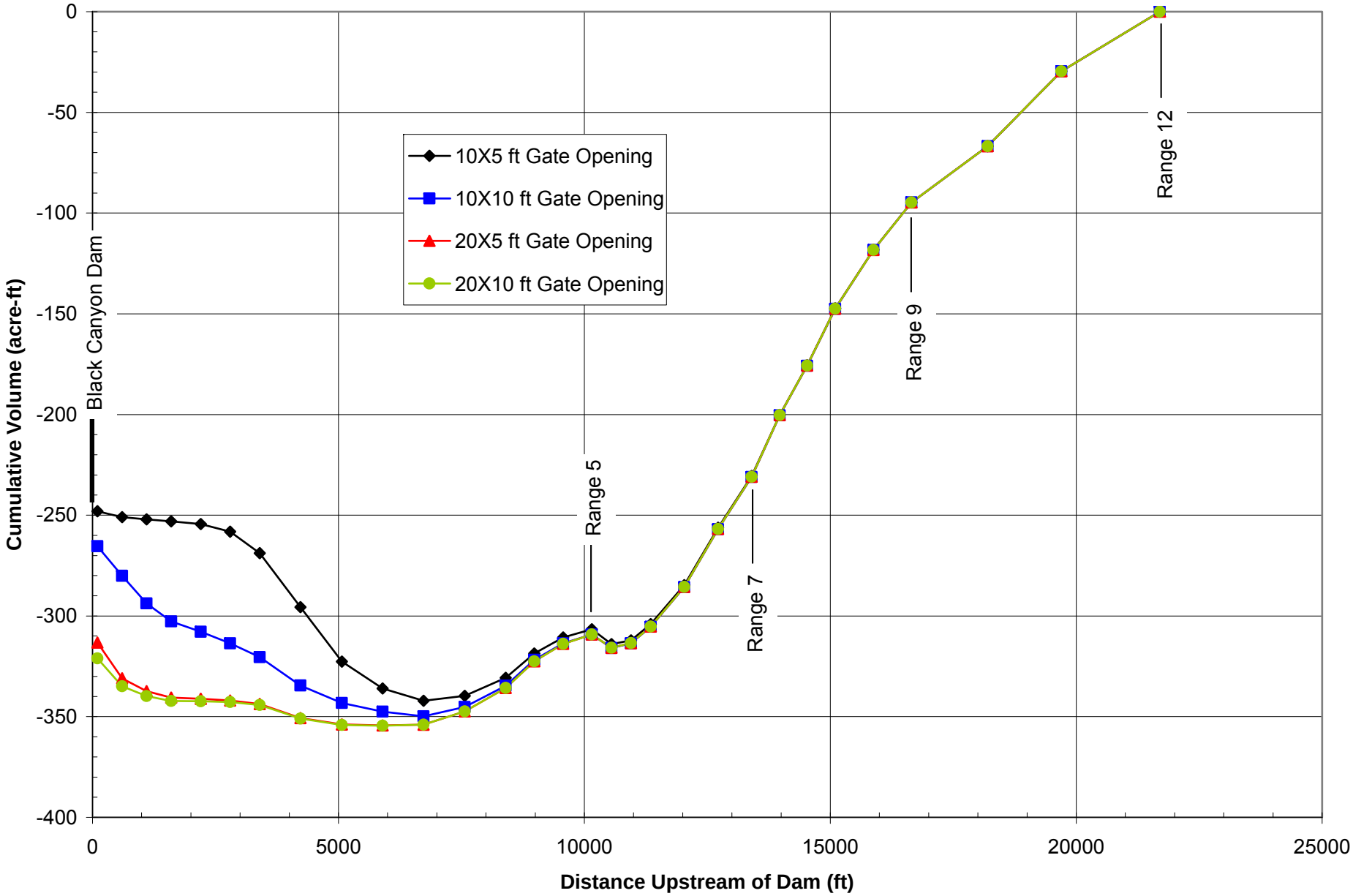
4. Sediment Sluicing at Black Canyon Diversion Dam



Sluicing Experiment at Black Canyon

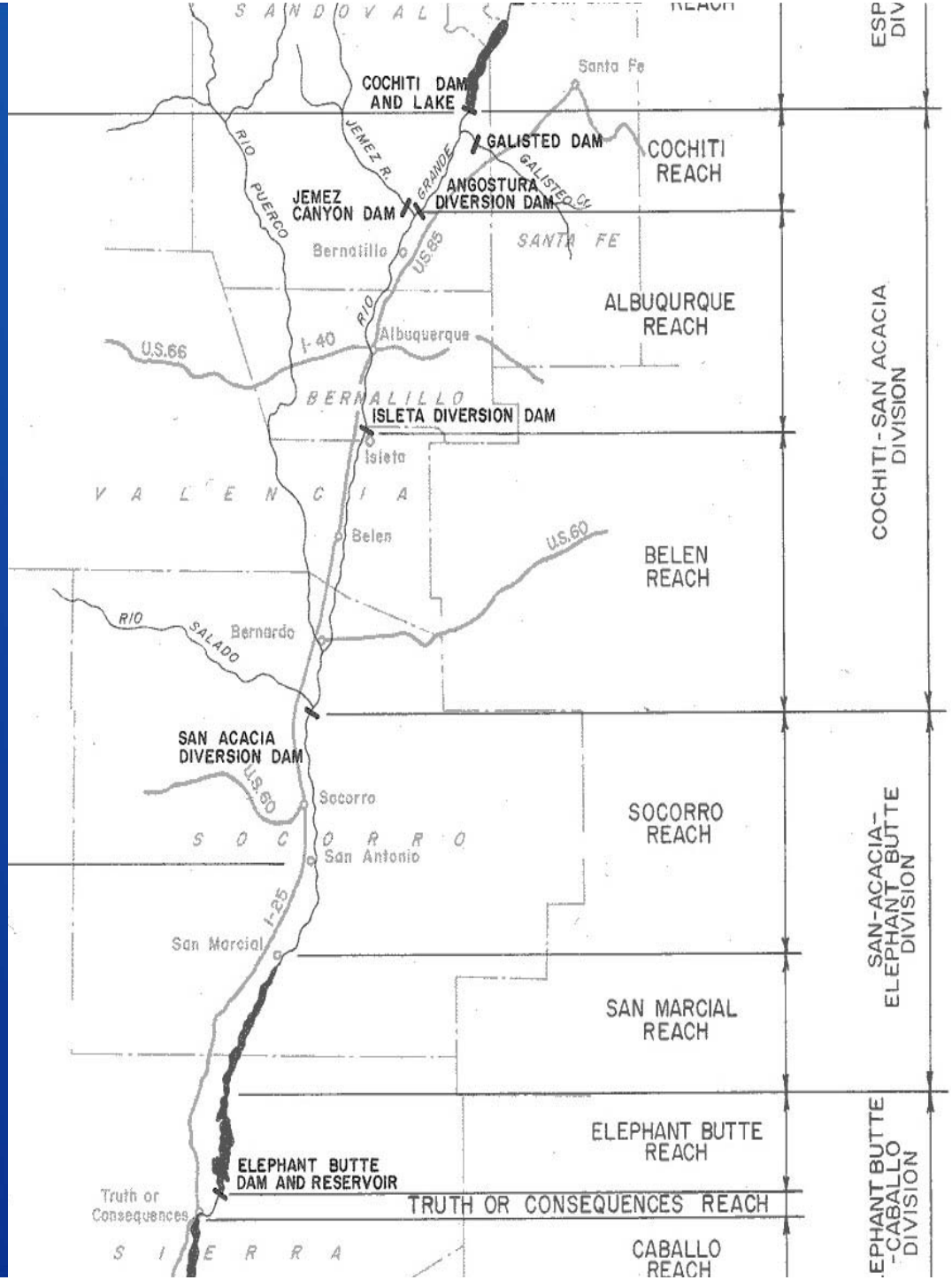
- Dam height of 111.5 ft
- Reservoir capacity of 26,860 ac-ft in 1984
- Sluice gates open from Dec 1 – Dec 27, 1984
- Mean daily outflows ranged from 980 cfs to 1630 cfs
- Removed 89 ac-ft of sediment, approx. 30 % of annual inflow
- Sediment removal limited by sluice gate capacity
- Deposition and concentrations were monitored downstream

Modeling of Sediment Sluicing



5. Middle Rio Grande

- Much of the Middle Rio Grande has been degrading in the last several decades resulting in:
  - Channel narrowing
  - Bed material coarsening
  - Increased meandering
- Resulting in:
  - Reduced habitat
  - More vegetation encroachment
- Necessary to predict future condition of the Rio Grande to assess reservoir operations



Summary

- Computation of water surface profiles in a single channel or channel networks.
- Steady and unsteady flows.
- Subcritical flows in steady hydraulic simulation.
- Subcritical, supercritical, and transcritical flows in unsteady hydraulic simulation
- Steady and unsteady sediment transport models.
- Transport of cohesive and non-cohesive sediments simultaneously.
- Cohesive sediment aggregation, deposition, erosion, and consolidation.
- Many different non-cohesive sediment transport equations that are applicable to a wide range of hydraulic and sediment conditions.

Summary

- Floodplain simulation.
- Exchange of water and sediment between main channel and floodplains.
- Fractional sediment transport, bed sorting, and armoring.
- Computation of width changes using the theory of stream power minimization and other minimizations.
- Point and non-point sources of flow and sediments.
- Internal boundary conditions, such as time-stage tables, rating curves, weirs, bridges, and radial gates.

Acknowledgement

The development and testing of GSTAR-1D was partially funded by Environmental Protection Agency and the Bureau of Reclamation Science and Technology Research Program

RECLAMATION

Example: Matilija Dam Removal

Example: Matilija Dam Removal

www.matilijadam.org

Example: Matilija Dam Removal

Example: Matilija Dam Removal

- What are the issues:
  - Flooding
  - Channel aggradation
  - Bank Erosion
  - Water Diversion Reliability
  - Fish Passage
  - Reservoir Erosion

Example: Matilija Dam Removal

- What can we estimate from the model:
  - Volume of material eroded from reservoir
  - Vertical channel aggradation in downstream reach
  - Change in particle size in downstream reach
  - Deposition in diversion pool

Example: Matilija Dam Removal

- What we cannot estimate from the model:
  - Quantification of bank erosion
  - Details of reservoir erosion
  - Deposition in estuary reach

Example: Matilija Dam Removal

- What we cannot estimate from the model:
  - Quantification of bank erosion
  - Details of reservoir erosion
  - Deposition in estuary reach

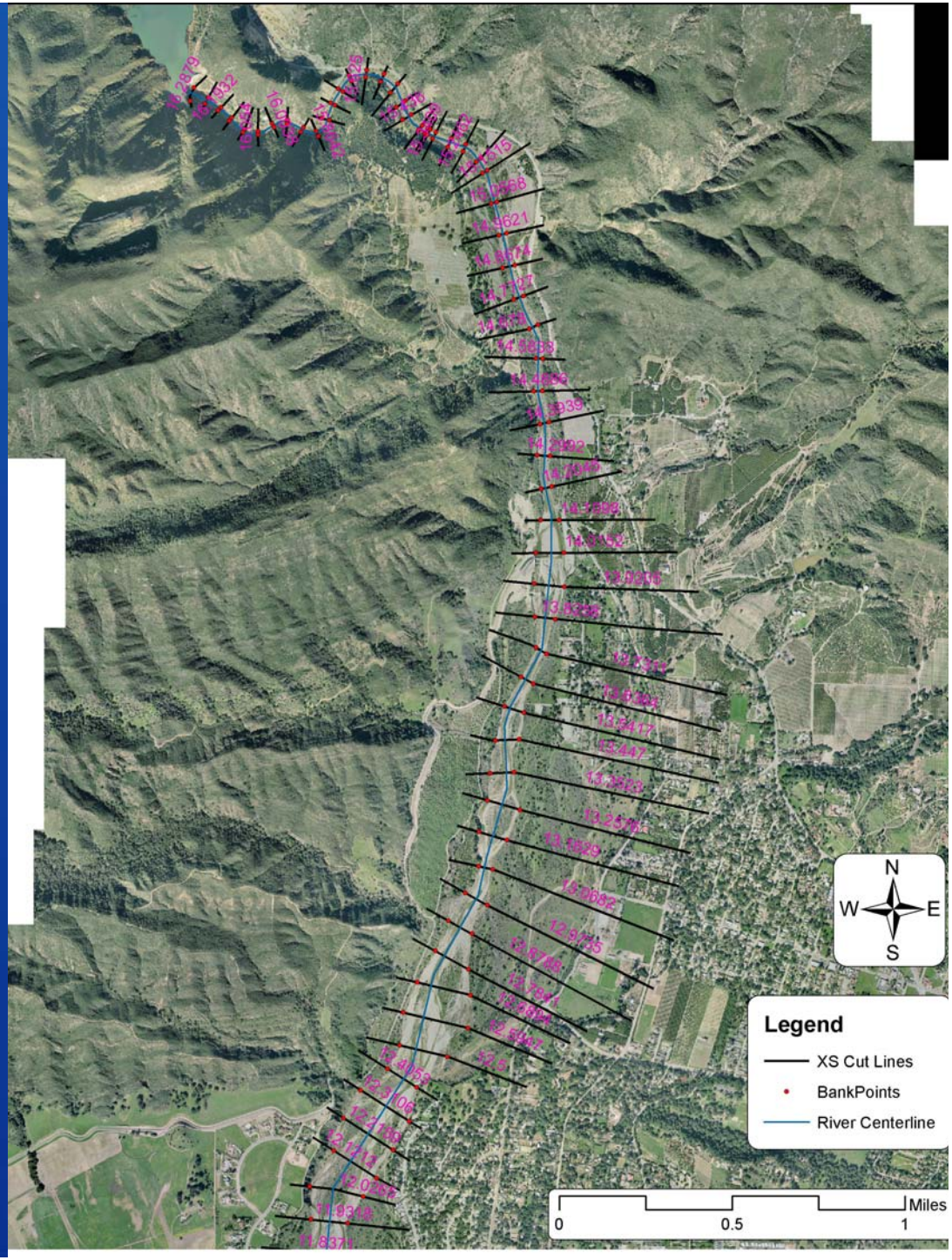
Example: Matilija Dam Removal

Steps:

1. Prepare cross section geometry
2. Calibrate hydraulic model
3. Prepare sediment transport information
4. Calibrate sediment model
5. Make predictions

Cross Section Geometry

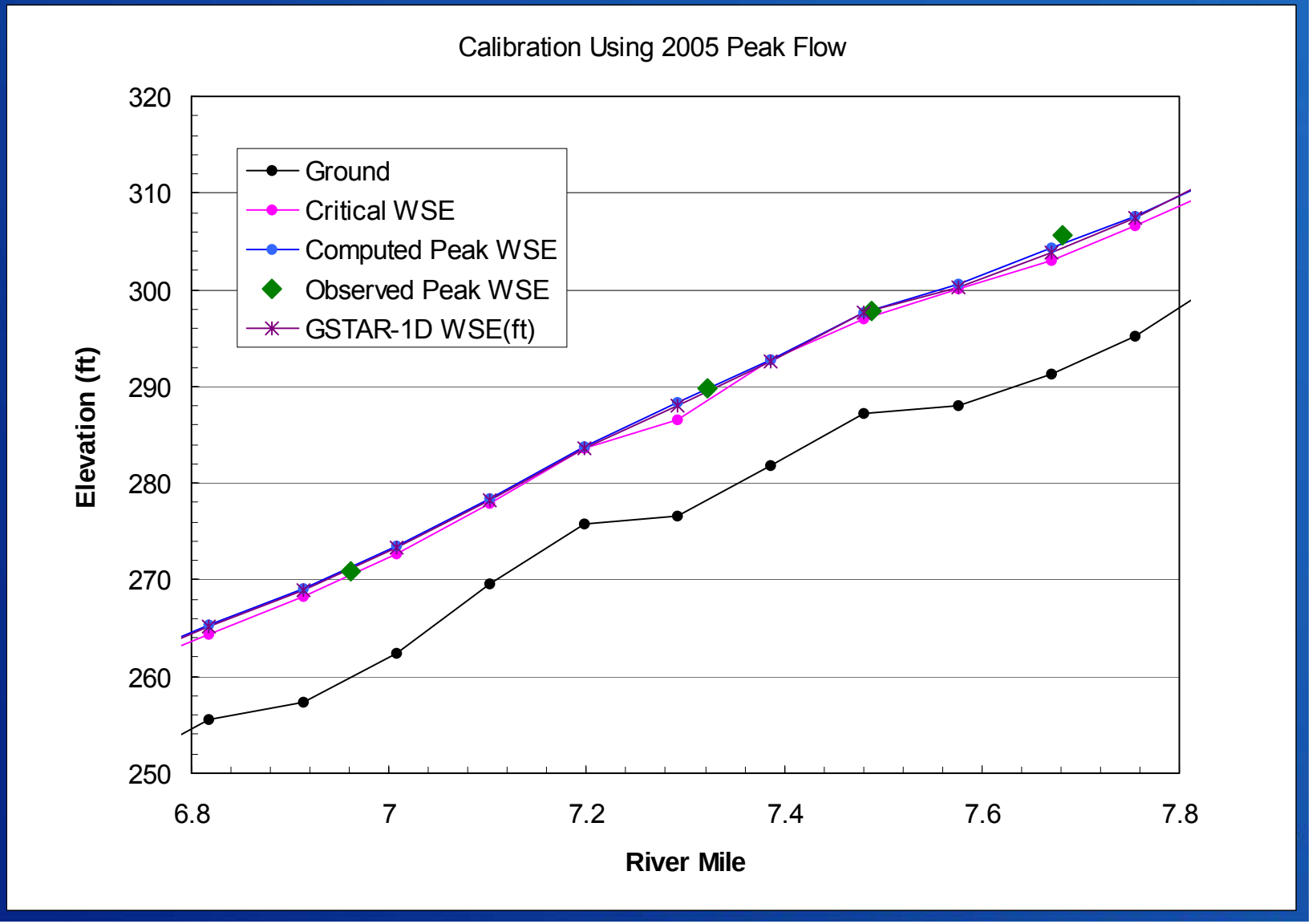
- HEC-GEORAS used to generate XC data from LiDAR data
- XC every 500 feet
- Translated into GSTAR-1D format
- Levees, bridges, weirs, etc…



Hydraulic Calibration

Manning's

n = 0.04



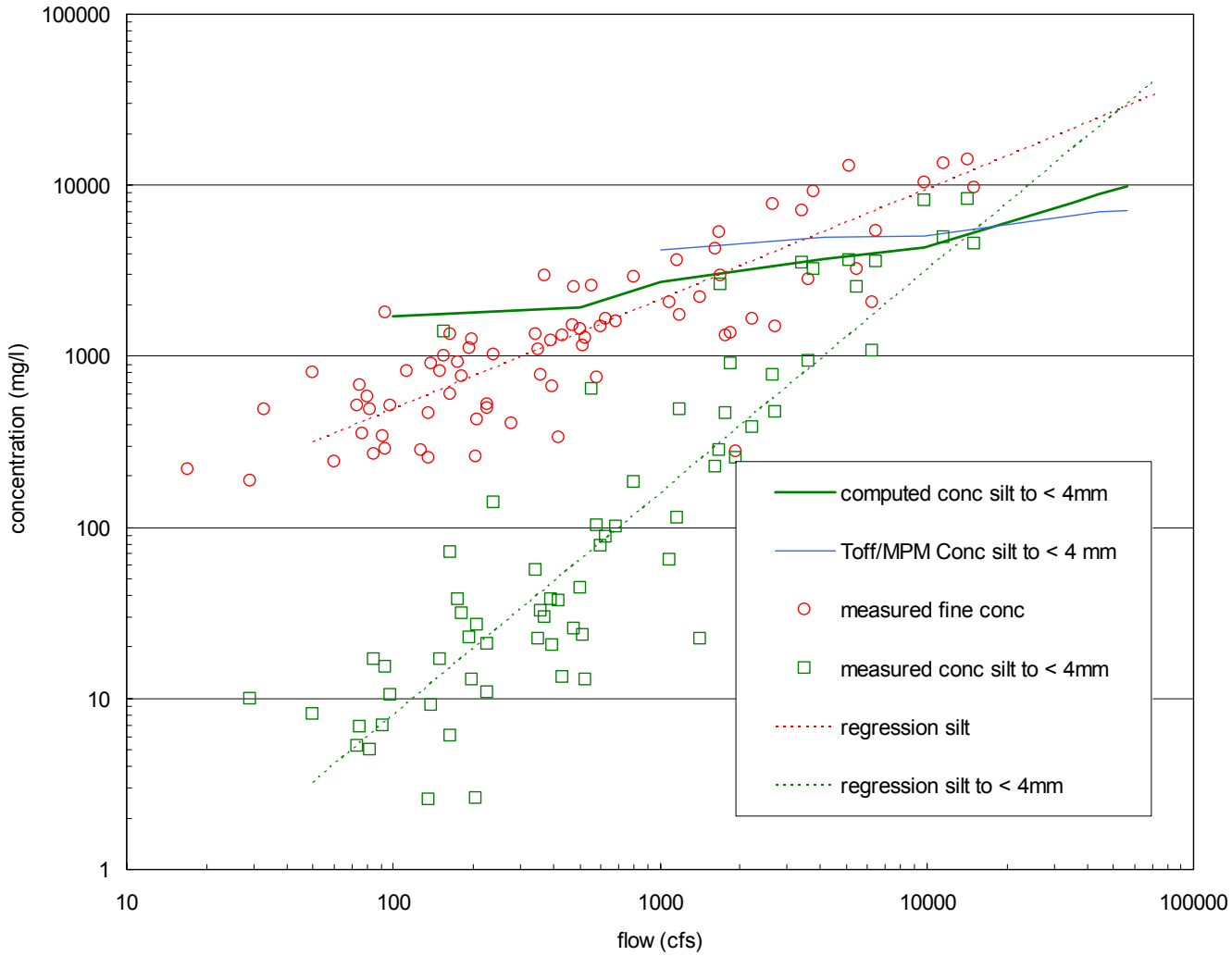
Sediment Transport Information

- Flow boundary conditions (upstream and tributaries)
- Geometry (directly from HEC-RAS)
- Sediment loads by size fraction (upstream and tributaries)
- Bed material
- Transport parameters

Sediment Transport Information

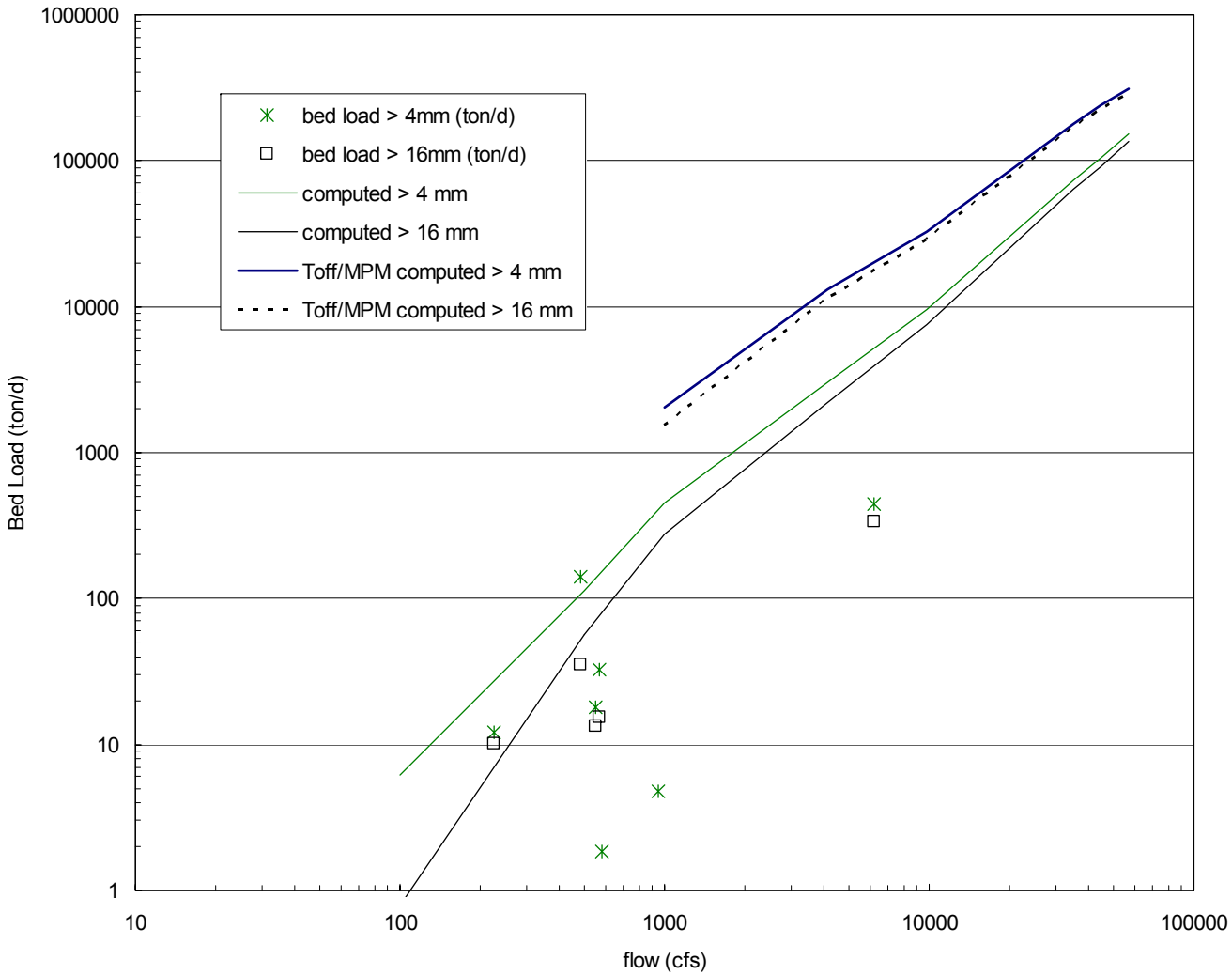
- Transport parameters:
  - Sediment transport equation
  - Cohesive parameters (deposition, erosion, and consolidation)
  - Active layer thickness
  - Non-equilibrium adjustment parameters
  - Angle of repose for banks
  - Active layer to sub-layers exchange parameter

Sediment Calibration



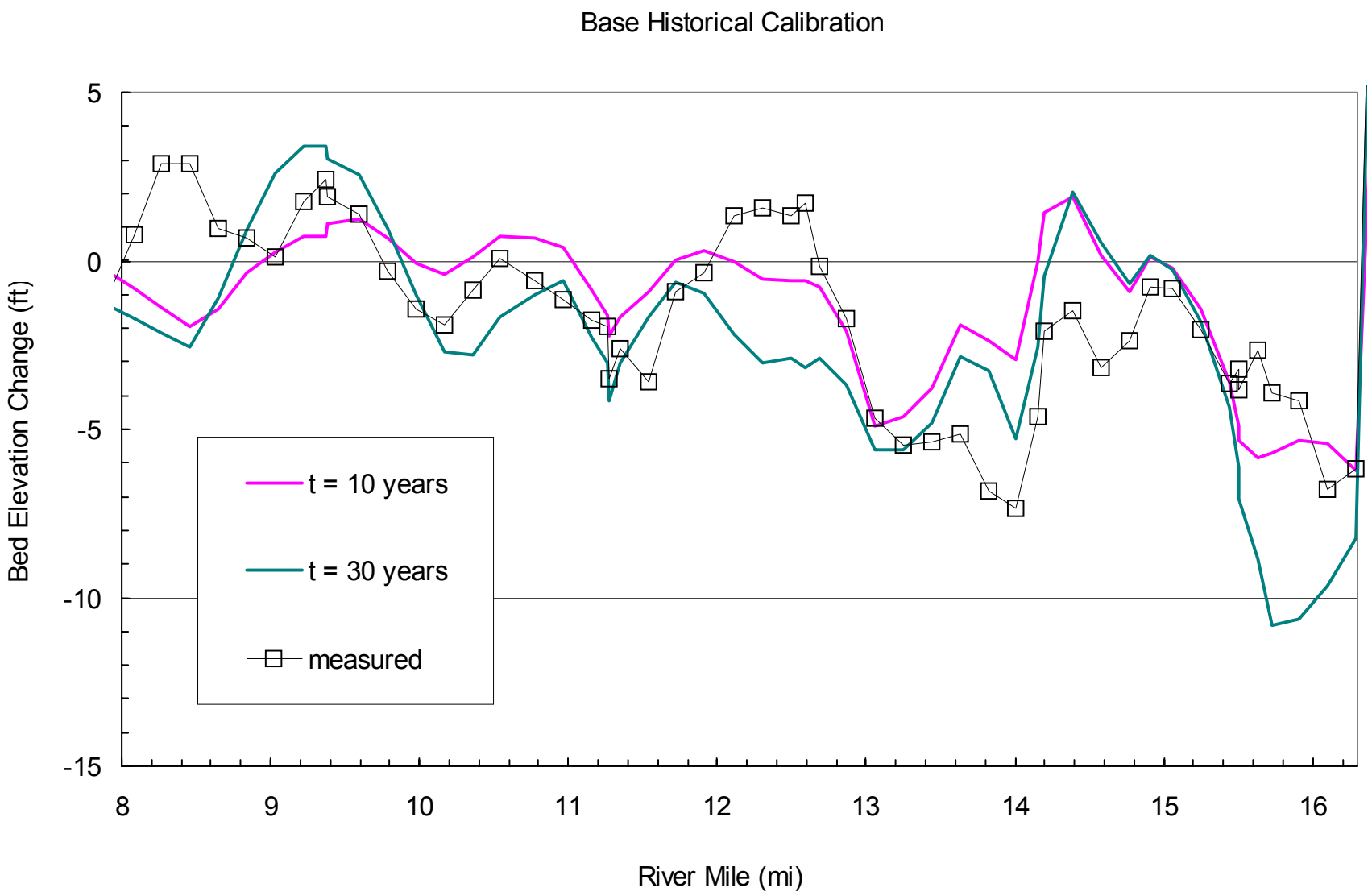
RECLAMATION

Sediment Calibration

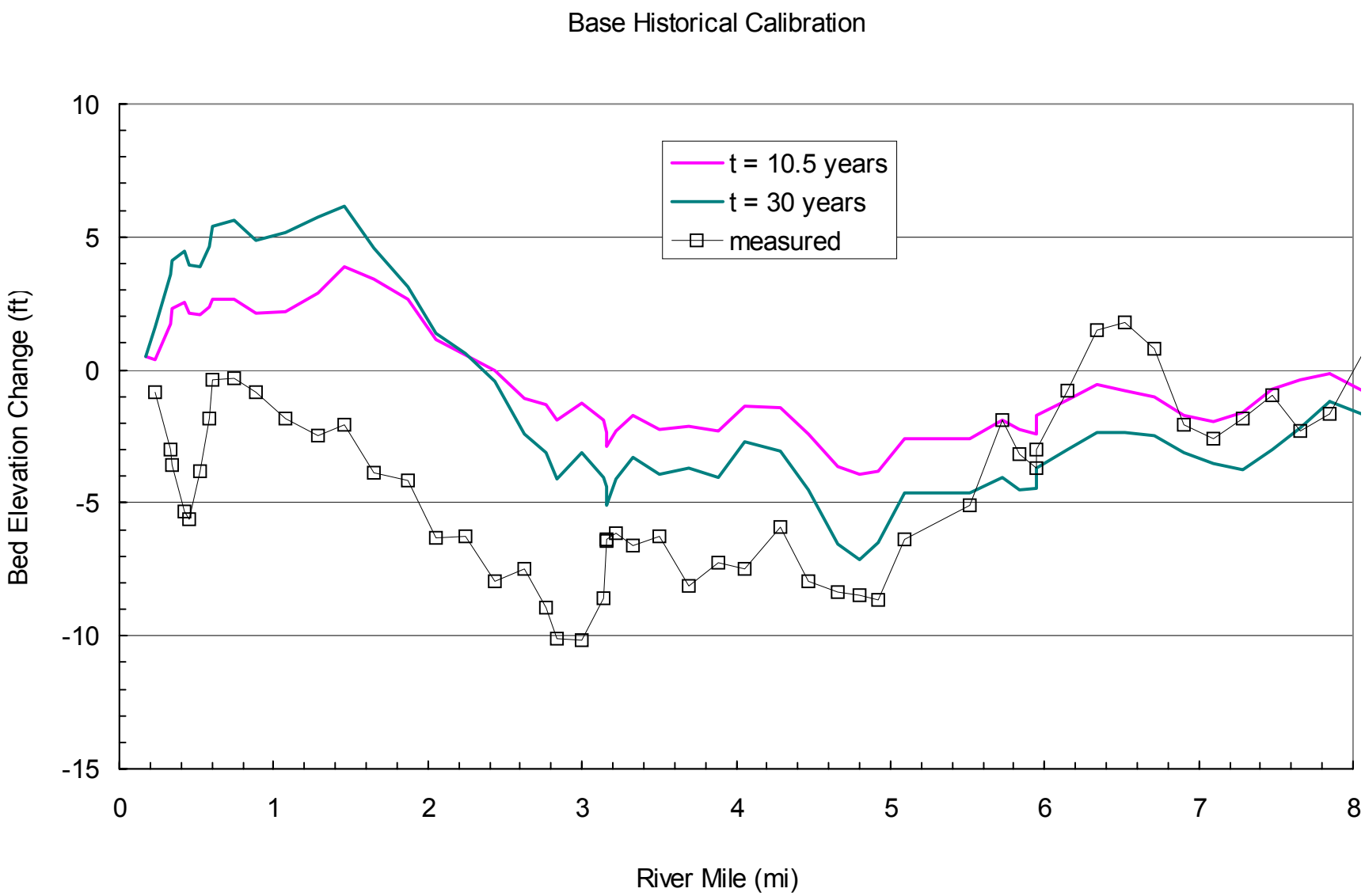


RECLAMATION

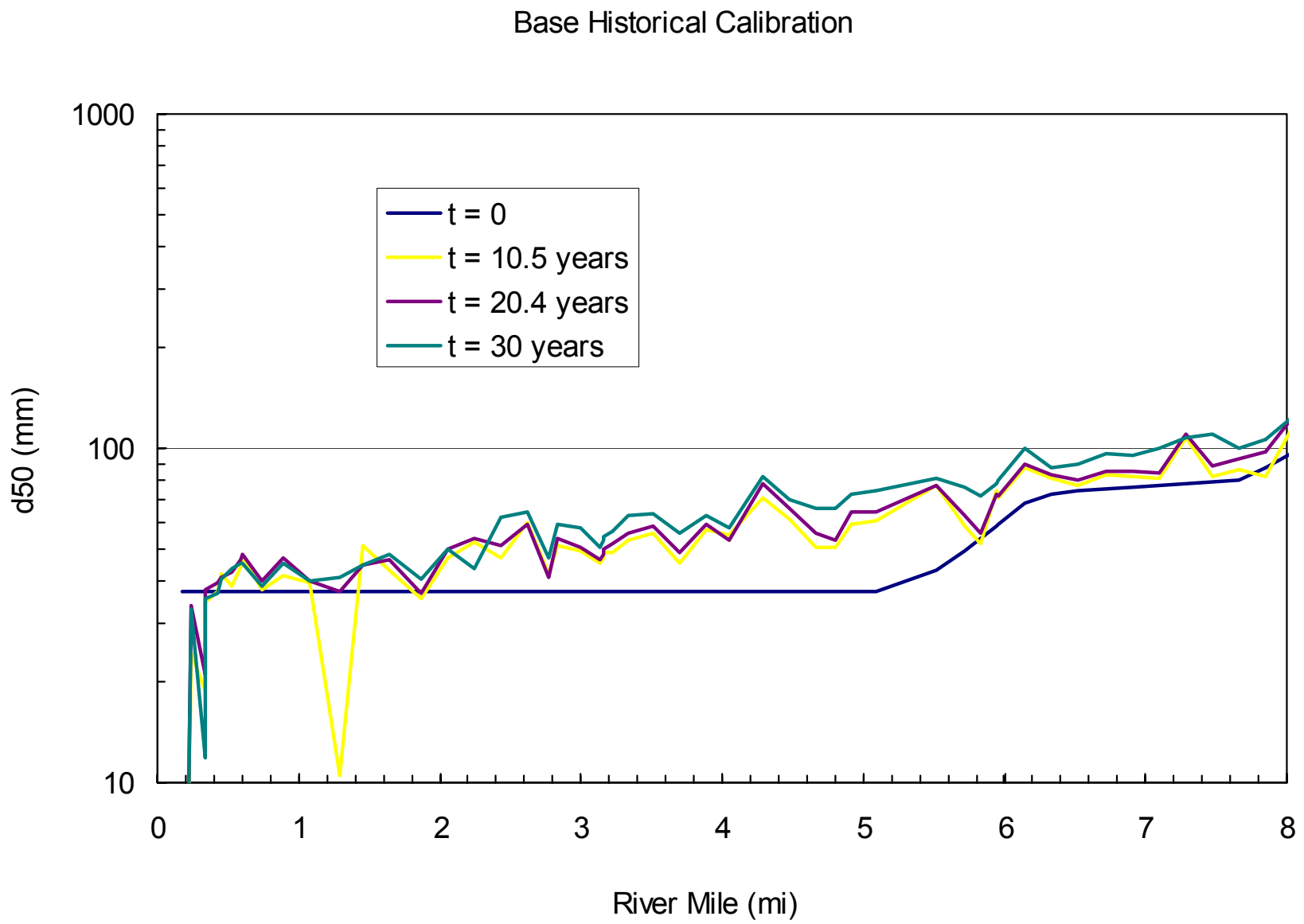
Sediment Calibration



Sediment Calibration



Sediment Calibration



Sediment Calibration

- Parameters modified:
  - Active layer thickness (Δz_a = 2 feet)
  - Critical Shields parameter in Parker's transport formula (θ_c = 0.035)
  - Hiding factor in Parker's transport formula (α = 0.67)

RECLAMATION

Terminology

- **Verification**: Formal proof of model correctness (from IEEE, Jay, 1984).
- **Calibration**: Adjustment of parameters needed to fit observations or experimental data (Roach, 1998).
- **Validation**: Substantiation that a calibrated model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model (Schleinger, 1979).

Validation is a process that requires post project analysis of future predictions

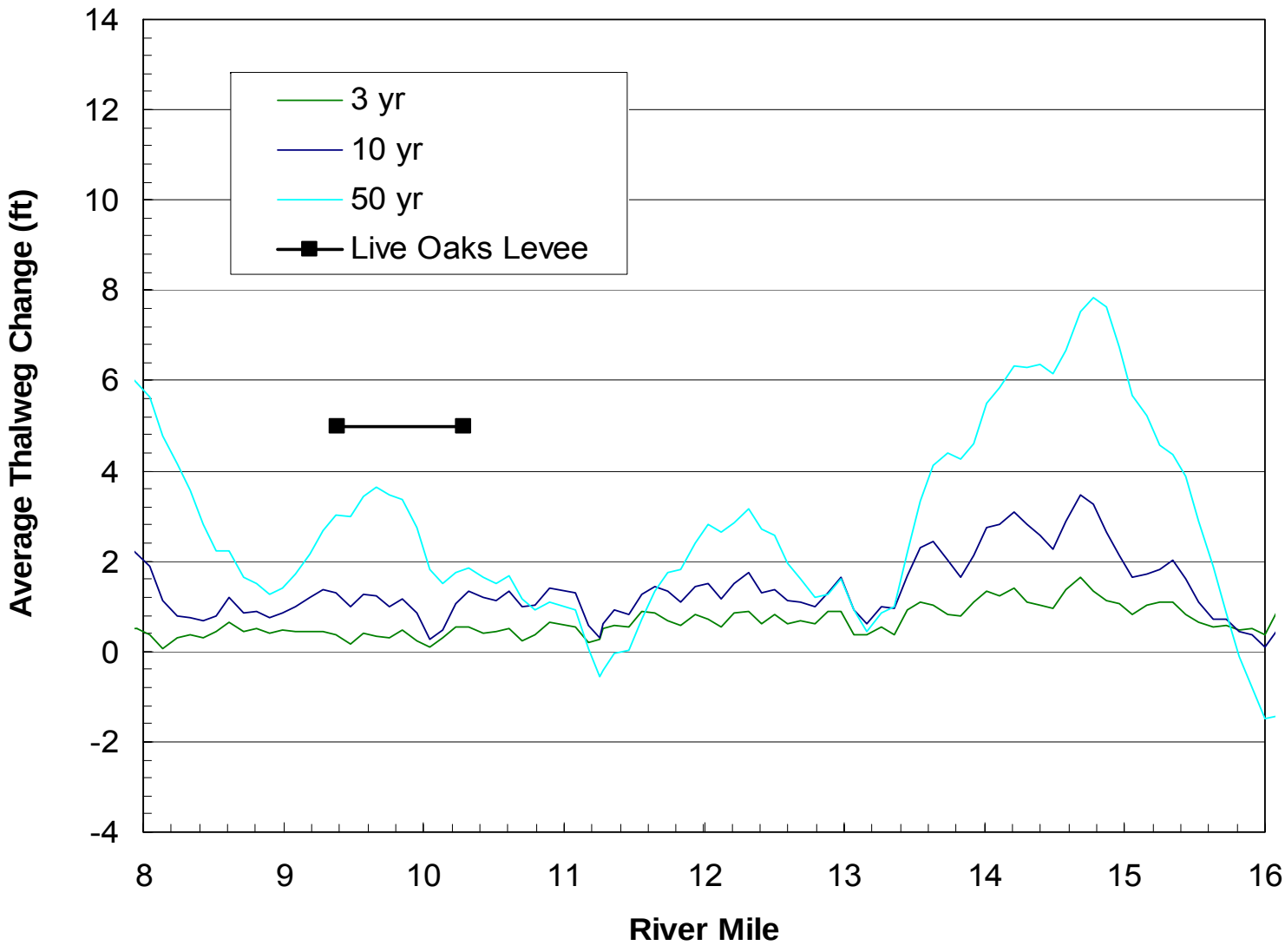
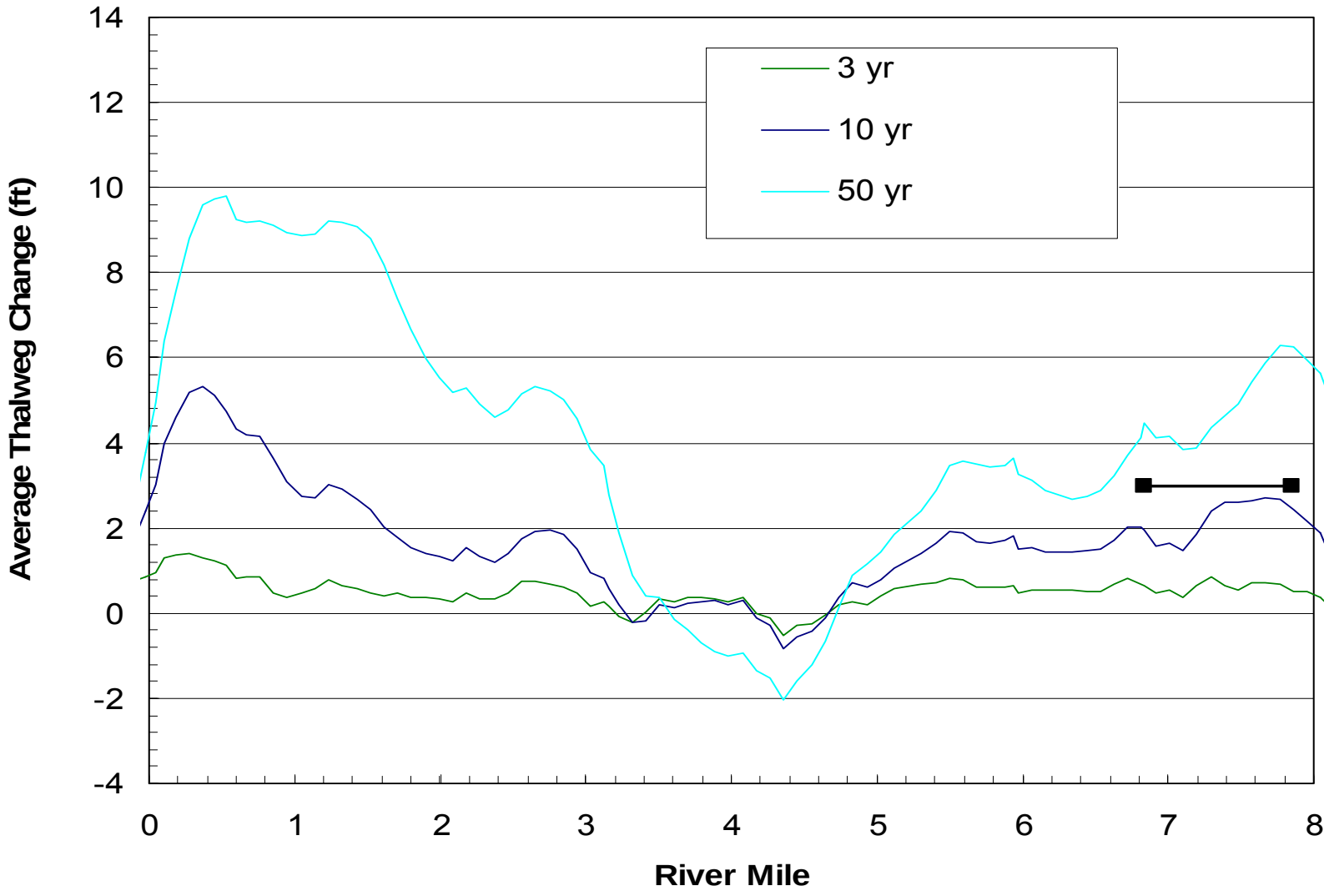
Calibrated ≠ Correct

Don't be fooled: A **calibrated** model may accurately predict the future ***if and only if*** the future is much the same as the past.

In this case, we calibrated to erosion, but we want to predict deposition.

We could be very wrong.

Predictions



Predictions