

Lag Times Associated With The
Storage of Sediment:
Progress Towards Developing
Conceptual and Quantitative Models

Jim Pizzuto

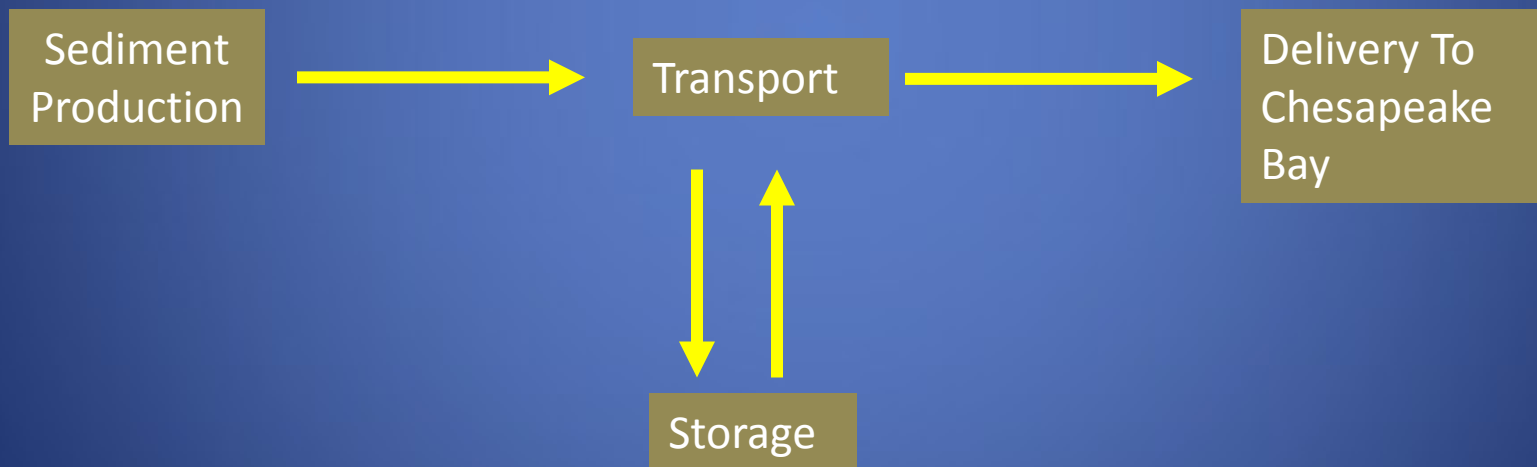
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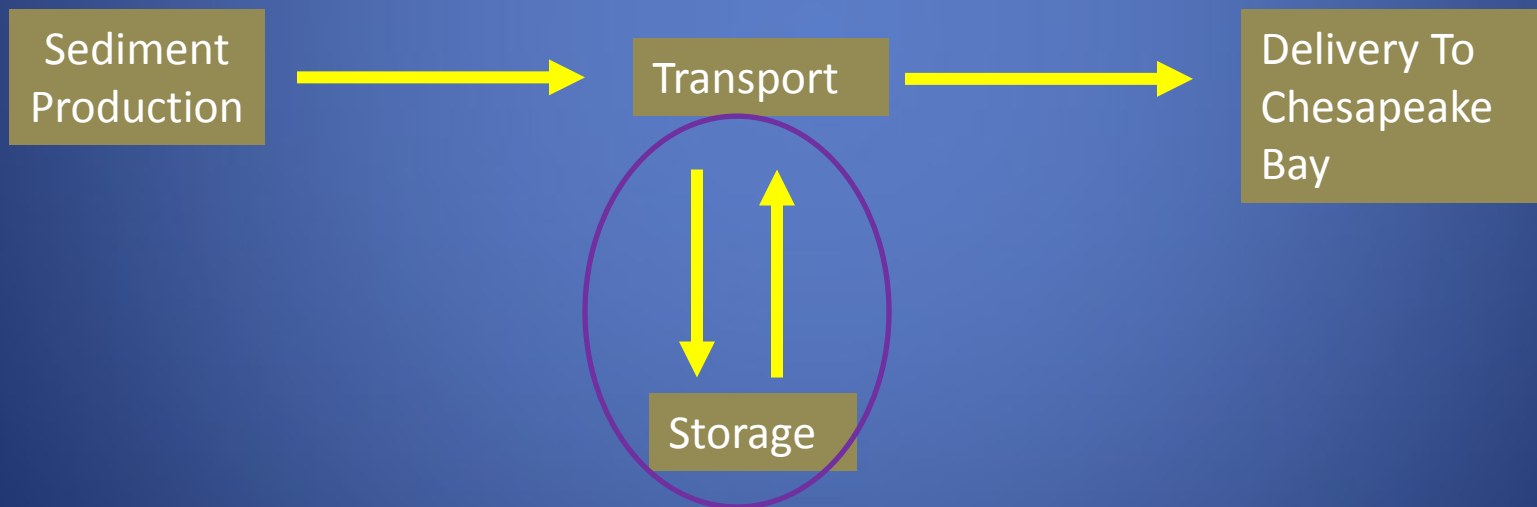
Outline

- Working hypothesis:
 - storage (not transport) controls particle delivery timescales
- Conceptual models for TIMESCALES of sediment delivery in the Chesapeake Bay need development
- Illustrative case study of sediment storage timescales in the Chesapeake Bay Watershed
- Towards useful predictive models to quantify sediment storage timescales

Sediment and (Adsorbed Contaminants) Do Not Travel Directly From Watershed Sources to the Chesapeake Bay

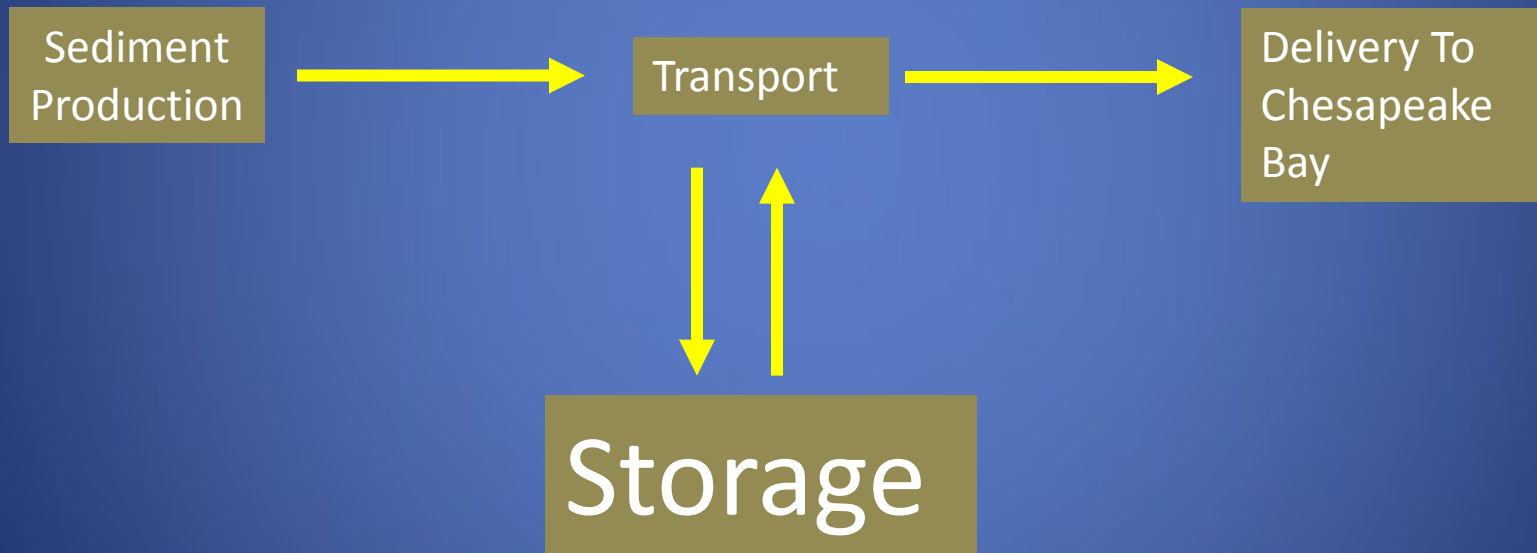


Sediment and Adsorbed Contaminants) Do Not Travel Directly From Watershed Source to the Chesapeake Bay

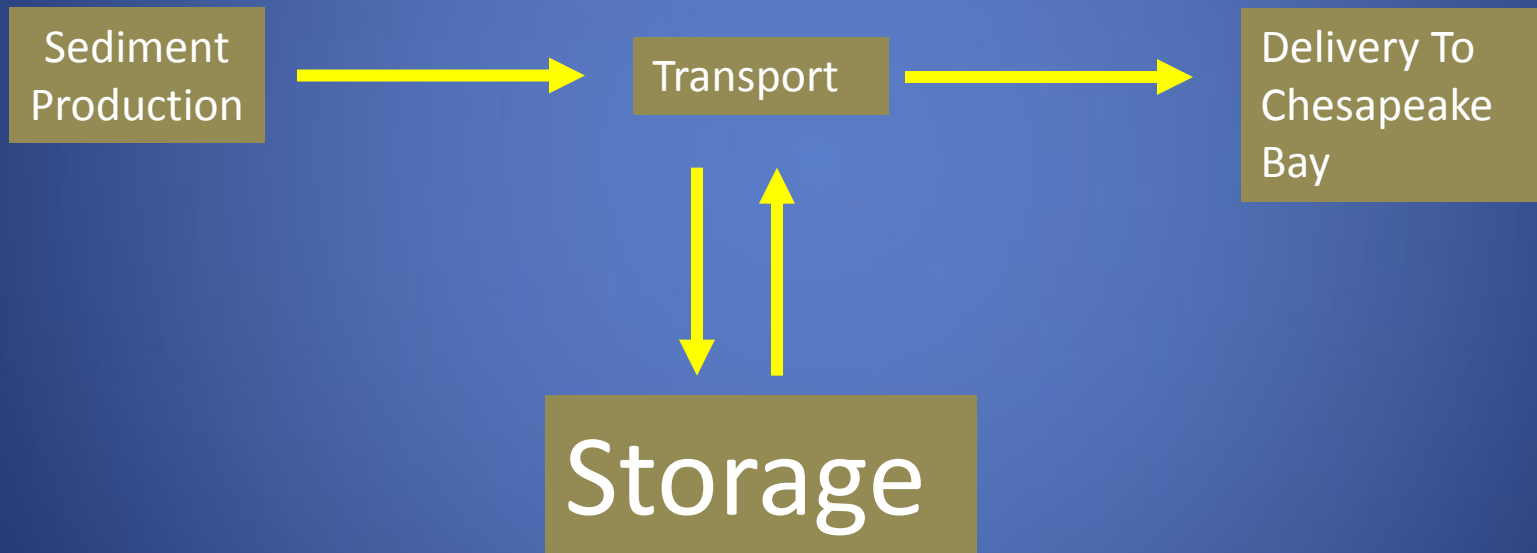


Transport is interrupted by STORAGE

Current Geological Understanding of Watershed Scale Sediment Transport: Storage Timescales >>>> Transport Timescales



Current Geological Understanding of Watershed Scale Sediment Transport: Storage Timescales >>> Transport Timescales



Storage (not transport) controls rates of delivery

Current Watershed Modeling Framework Using Hydrologic Models

$$\begin{aligned} \text{Net Delivery} = & \text{Hydrodynamic Transport Out} \\ & - \text{Hydrodynamic Transport In} \\ & + \\ & \text{Erosion - Deposition} \end{aligned}$$

Current Watershed Modeling Focuses

on

Net Delivery =

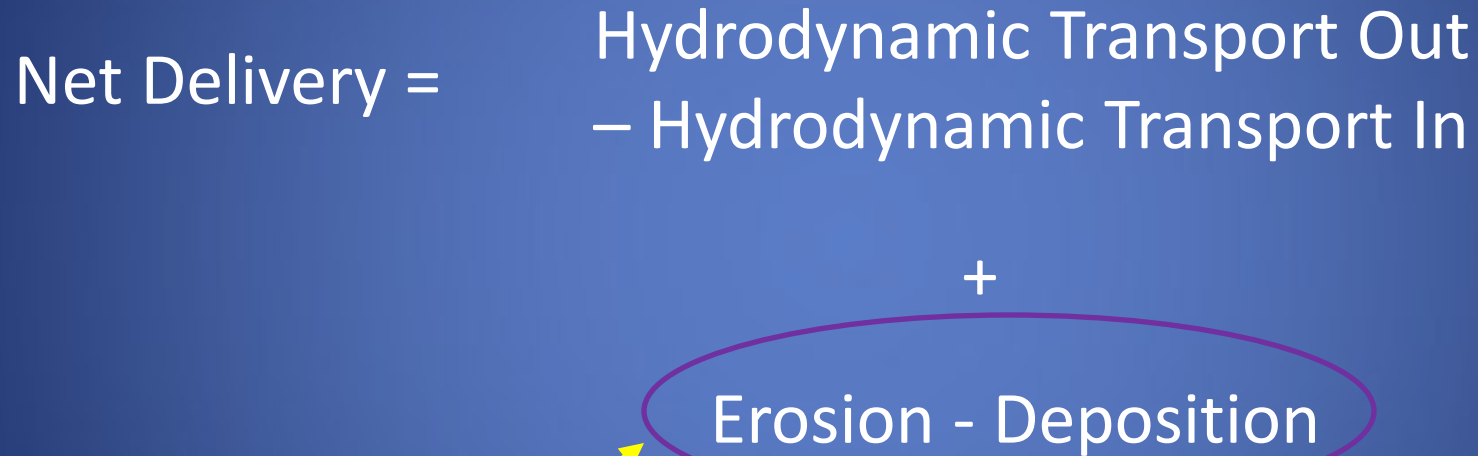
Hydrodynamic Transport Out
– Hydrodynamic Transport In

+

Erosion - Deposition

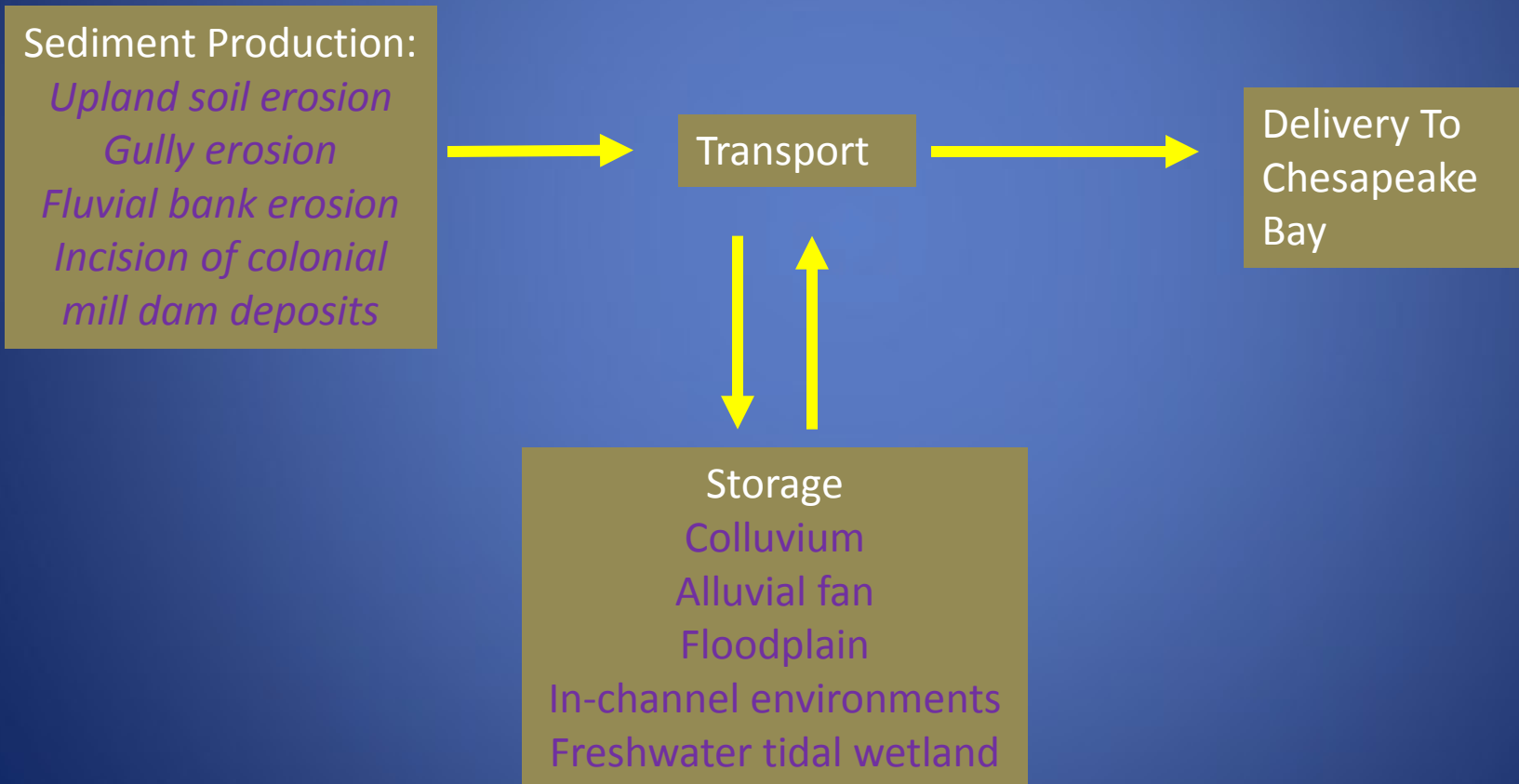
Well-understood short-term processes that move particles rapidly from one storage site to another

But DELIVERY is CONTROLLED by:

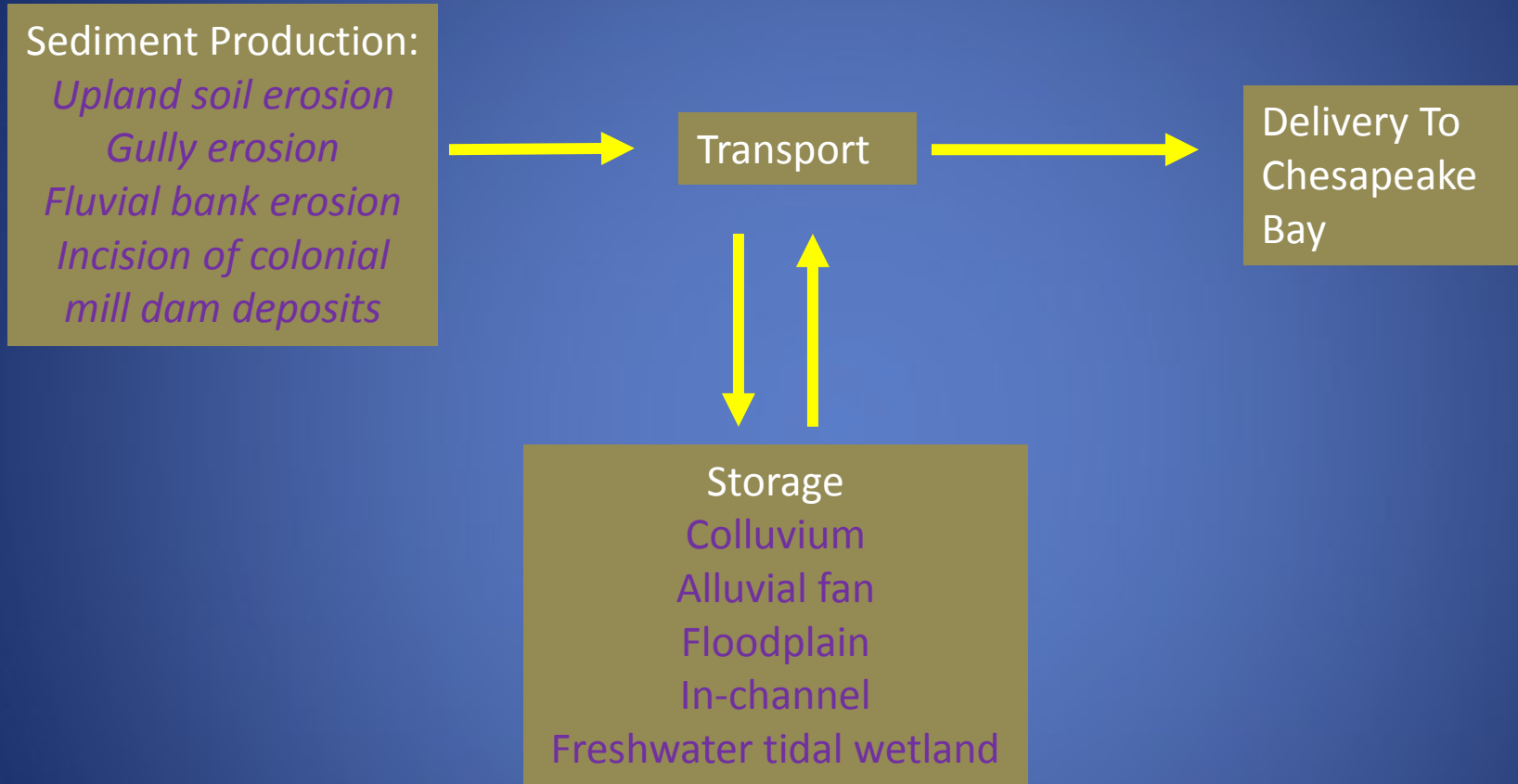
$$\text{Net Delivery} = \text{Hydrodynamic Transport Out} - \text{Hydrodynamic Transport In} + \text{Erosion - Deposition}$$


Long-time scales of storage, governed by poorly understood processes of erosion and deposition represented by “calibration knobs” in most watershed hydrologic transport models

Conceptual Models of Chesapeake Bay Sediment Budgets

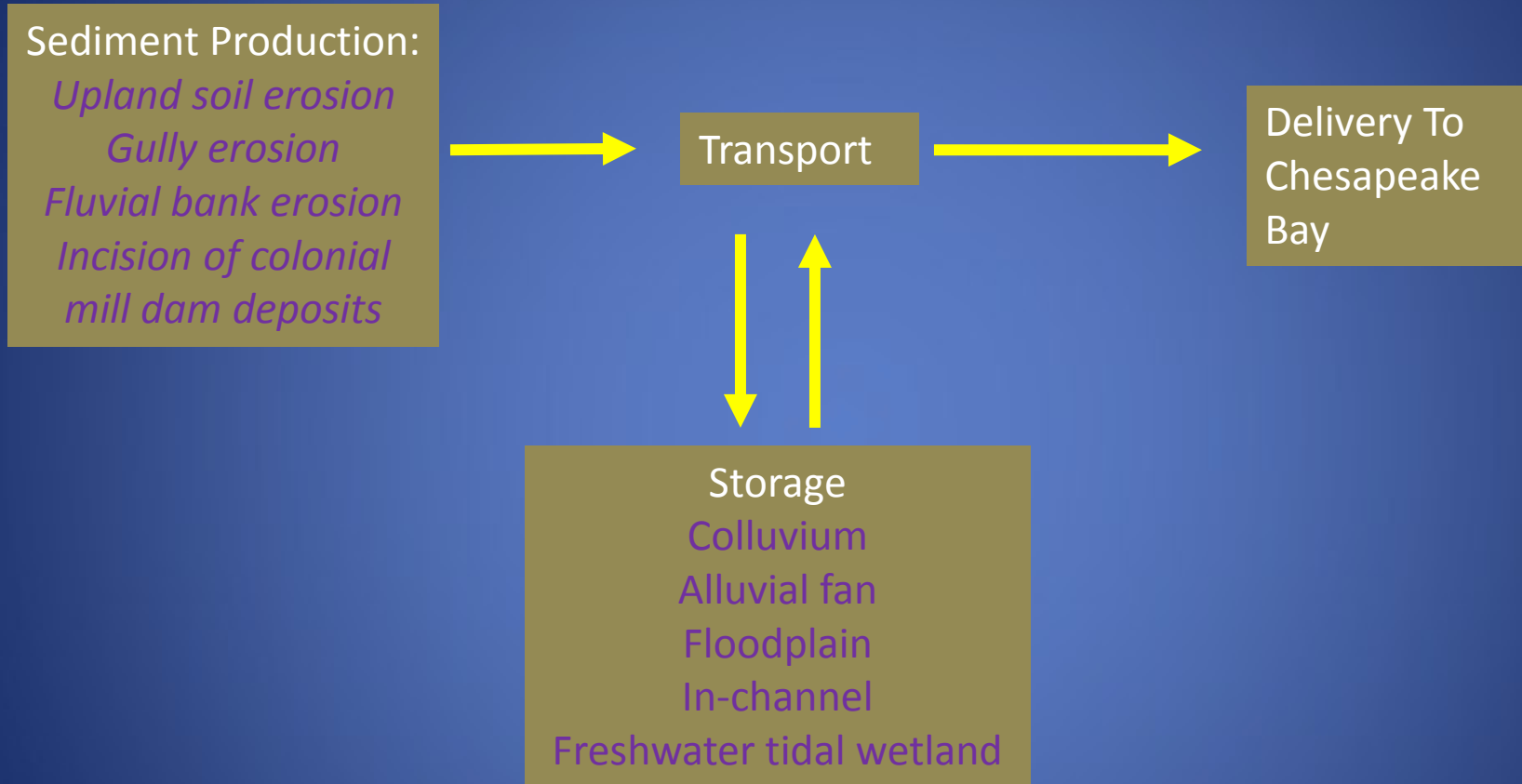


Relative Rates of Production and Storage.....



are poorly documented for Chesapeake Bay Watershed (useful methods are available)

Contemporary TIMESCALES of Storage.....



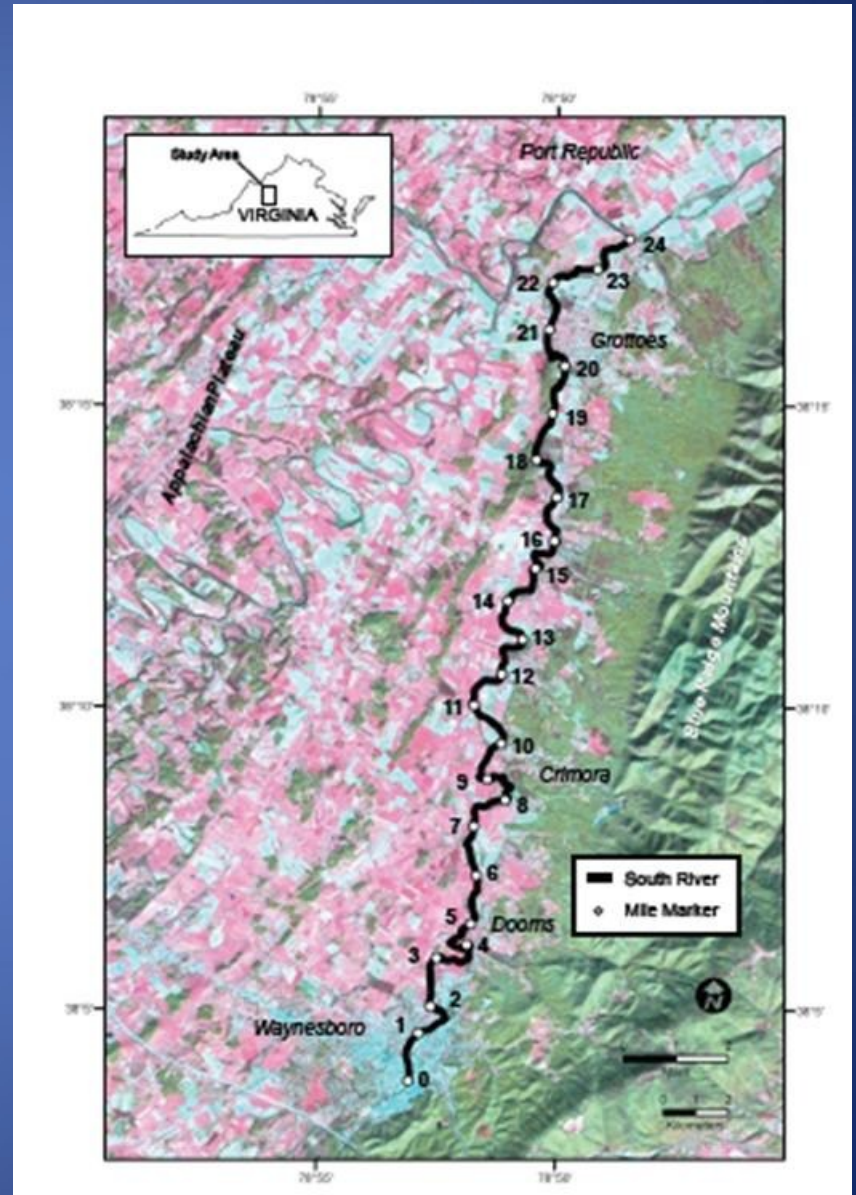
remain virtually unknown
(but we have the tools...)

Mercury Storage: South River, Virginia

- An example that documents
 - Timescales of particle storage along a 4th order river valley

Location

- *The South River flows north in the Shenandoah Valley, VA*
- *Just west of Shenandoah National Park*



A Steep, Gravel-Bed, Bedrock-controlled River



The Mercury.....

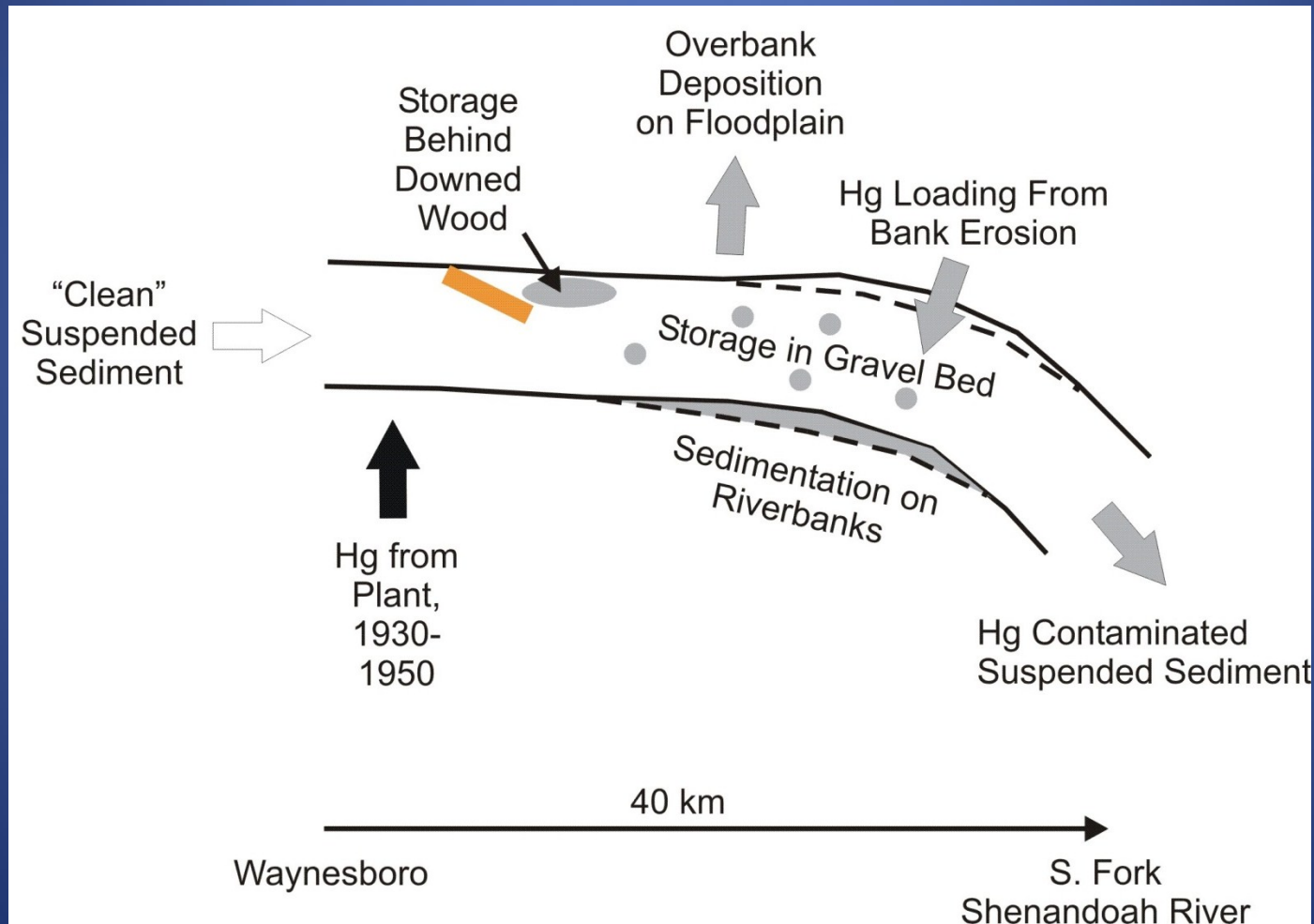
- The former DuPont plant (now Invista) is located on the South River in Waynesboro, VA.
- Mercury used as a catalyst in the production of rayon acetate fiber between 1929 and 1950
 - At former DuPont (now Invista) plant in Waynesboro, VA
- Approximately 1% of Hg used was discharged into the river.

Particle Storage?

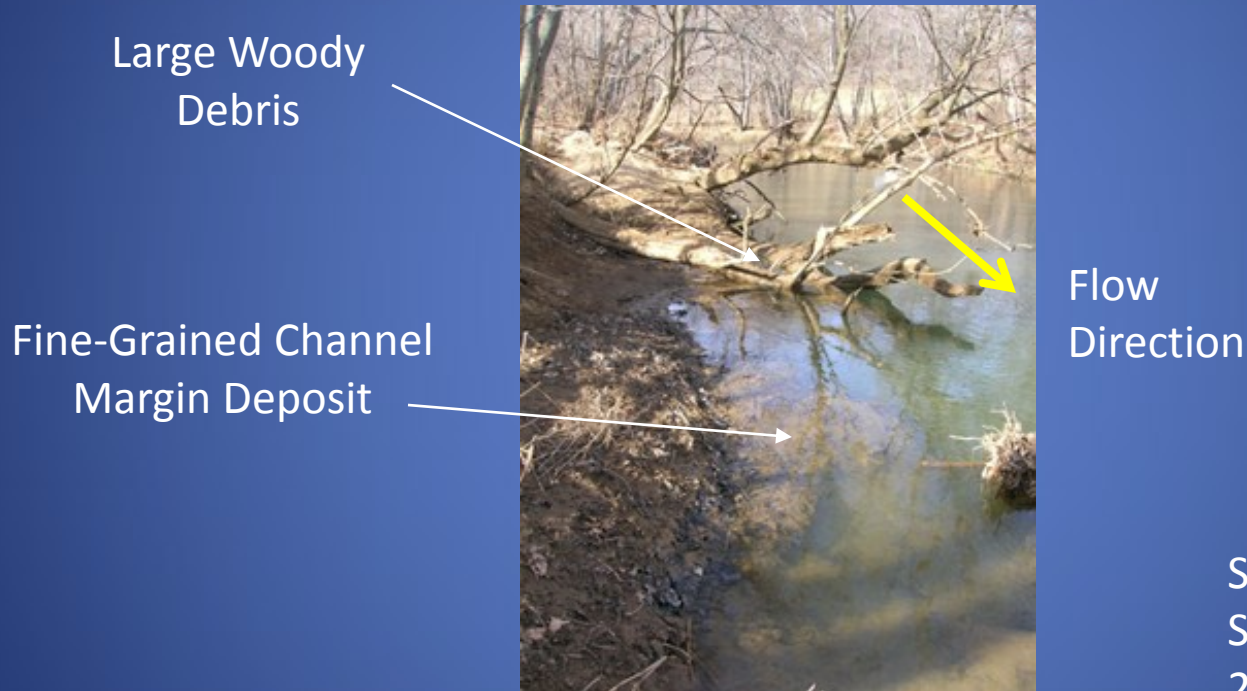
- Hg strongly adsorbs to particles
- > 100,000 # of Hg are stored in the South River valley downstream of Waynesboro
 - Unambiguous evidence of multidecadal/centennial particle storage!

Use Sediment Budget Analysis to Quantify Storage Processes and Timescales

Sediment Budget Components (and Hg cycling)



FGCM Deposits



Large Woody
Debris

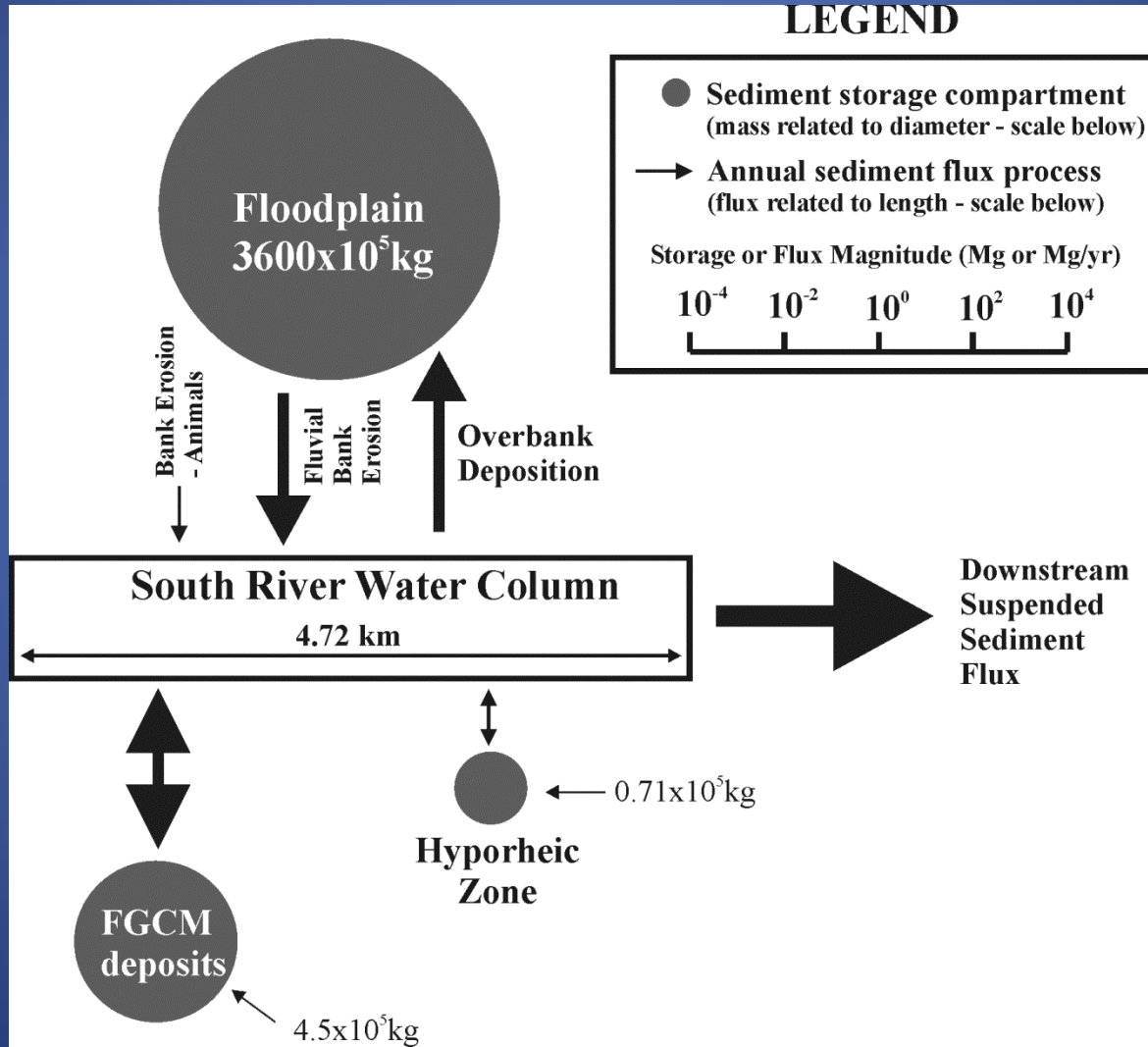
Fine-Grained Channel
Margin Deposit

Flow
Direction

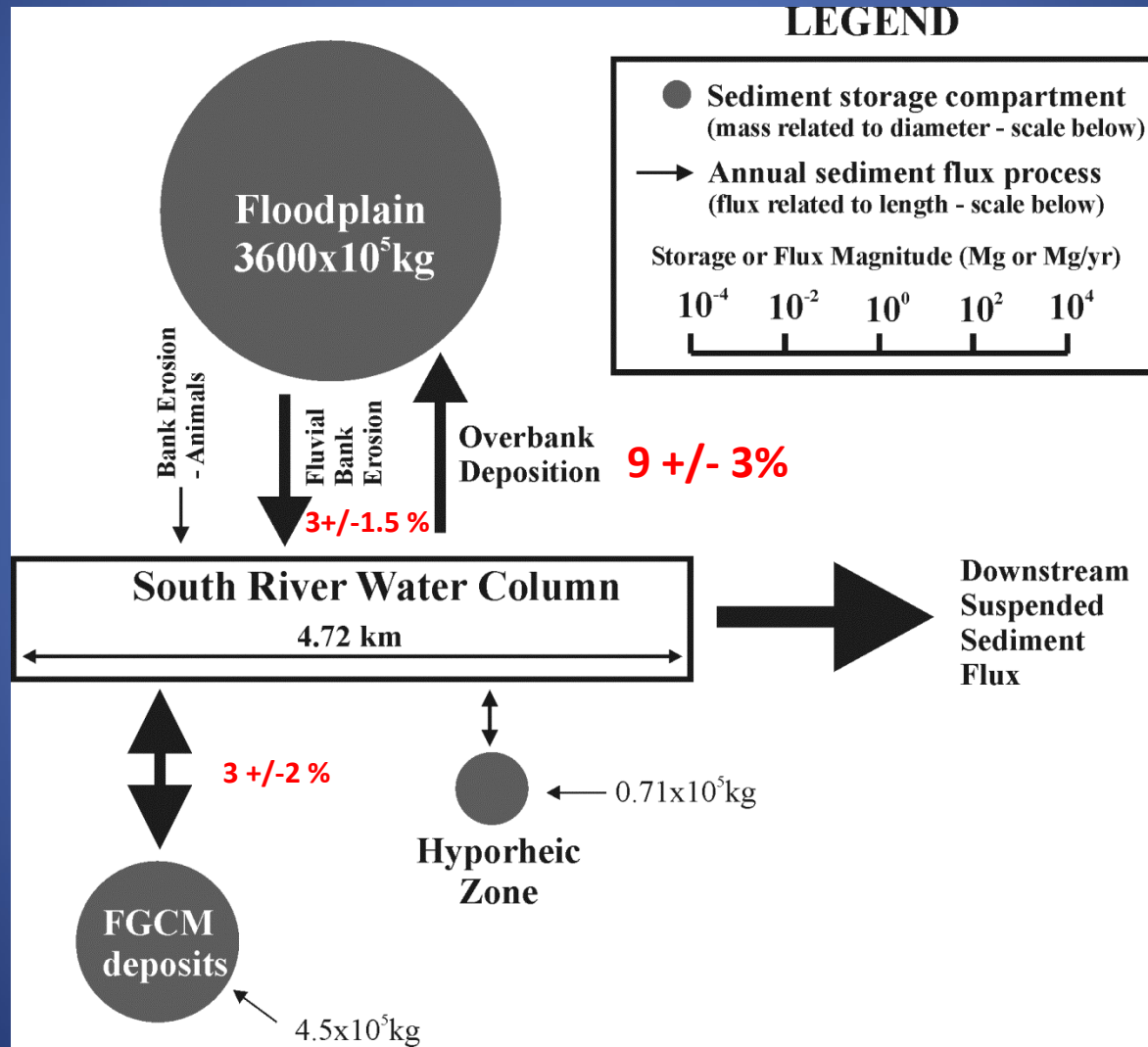
Skalak, 2009, thesis
Skalak and Pizzuto,
2009, ESPL

- Store 17-43% of annual suspended sediment load
- Sediment residence time 1.4 years

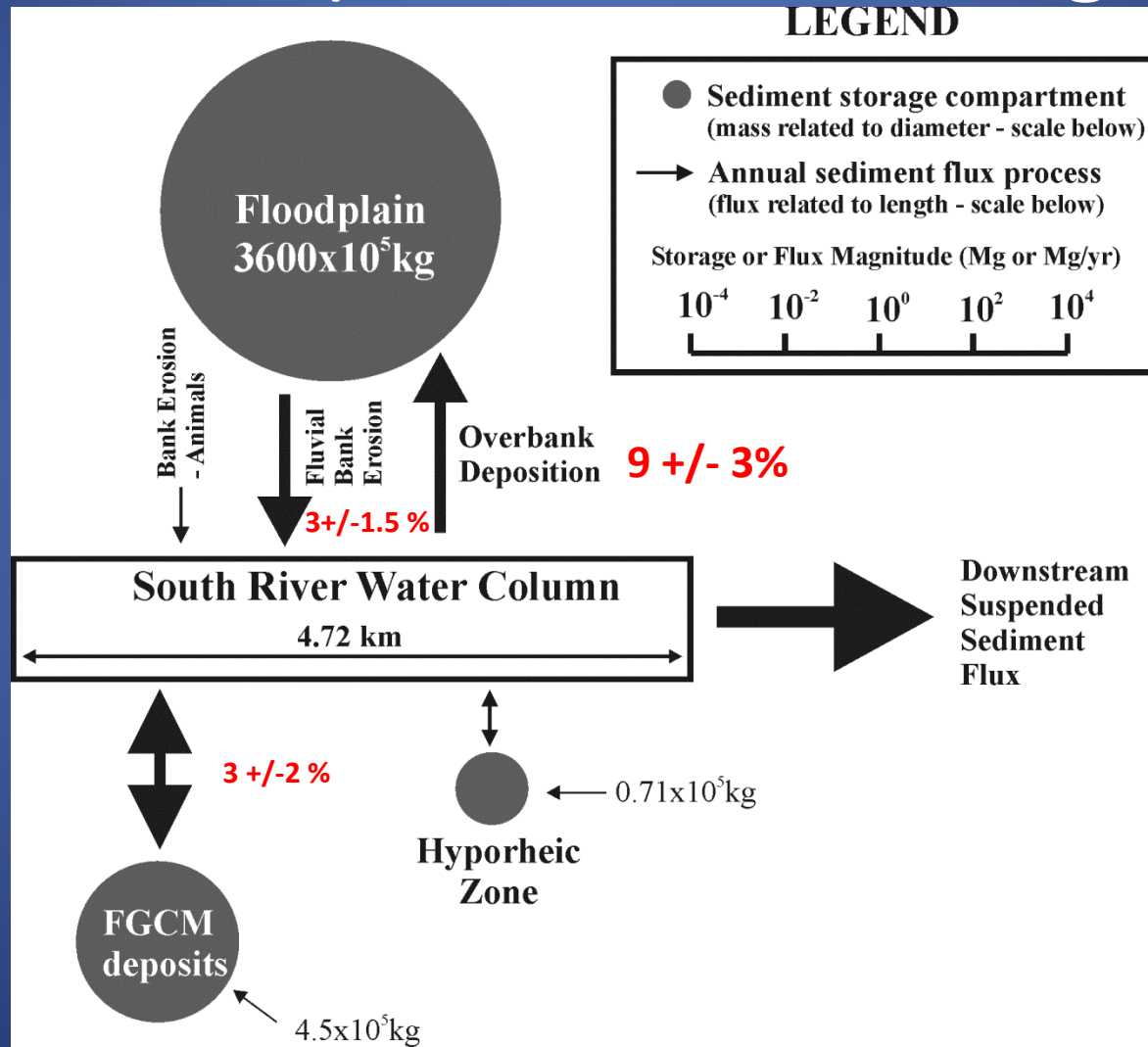
The Sediment Budget



By % of Annual Suspended Sediment Load...



Overbank Deposition is ~ 3x Bank Erosion (but errors are large)



FGCM exchange = bank erosion!

Analysis of the Sediment Budget

Approach

- ASSUME that the budget components balance
- Determine the TOTAL exchange between all storage components
 - Floodplain, FGCM deposits, hyporheic zone
- Apply to an idealized length of the South River
 - Without tributaries
 - Uniform, so that the exchange with storage is spatially and temporally constant
- Compute time and spatially averaged downstream suspended sediment velocity that accounts for storage

Approach

- ASSUME that the budget components balance
- Determine the TOTAL exchange between all storage components and the water column
 - Floodplain, FGCM deposits, hyporheic zone
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The Exchange Rate of Suspended Sediment

- Fraction of suspended sediment load exchanged with sediment in storage = 0.022
+/- 0.10 per km

Distance Required To Exchange 100% of the Load with Stored Sediment

- Fraction of suspended sediment load exchanged with sediment in storage = 0.022 ± 0.10 per km
- *This is the inverse of the exchange rate = $(1/0.022) = 46 \pm 22$ km*

Average Time Spent In Storage

- Average “storage time” = stored volume/exchange rate*4800+/- 2600 yrs*
- A long time, BUT
 - Consistent with many C¹⁴ dates from floodplains in the region (none available at South River)
 - Previous sediment budgets (Jackson et al., 2005)
- Unstated assumptions and caveats
 - Explored below

Time and Spatially Averaged Transport Velocity

- = Exchange Length/Storage Time = 46
km/4800 yrs =

Time and Spatially Averaged Transport Velocity

- = Exchange Length/Storage Time = 46
km/4800 yrs =

9 +/- 7 m/yr

Caveats....

- Applies to an “average particle” in storage and transport
- All particles may not be stored
 - Perhaps the smallest, most reactive particles are NOT stored
- Particles with different sizes and densities may behave differently
 - Need to analyze storage timescales by sediment size, character
- Location matters
 - Storage reservoirs are not “well-mixed”

To Develop Quantitative, Predictive Models of Storage....

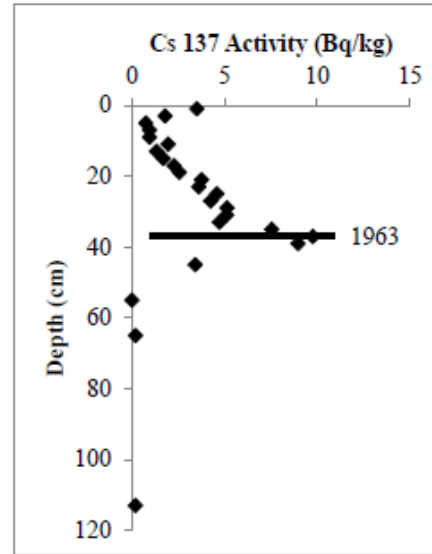
- DEVELOP simple models that
 - Include important variables
 - Vegetation
 - Particle character
 - Regional geomorphic controls (valley slope, etc.)
 - Local hydraulic setting
 - Simple enough to be incorporated into larger modeling framework
 - Can be calibrated (see below)
- CALIBRATE using field measurements of decadal particle accumulation
 - Settings must reflect range of watershed conditions
 - Decadal timescales needed to resolve rates

Deposition Rates

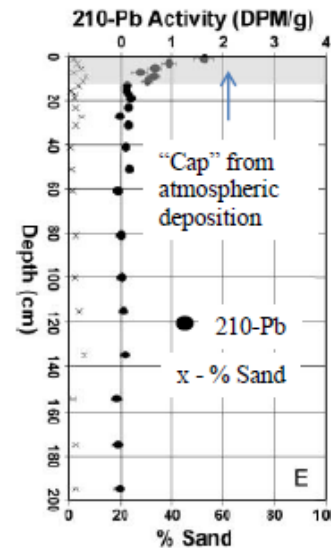
- Analytical Models of Hydraulic Processes
 - that can be integrated over multidecadal (not event scale) timescales
 - We can only readily measure MULTIDECADAL accumulation
- Calibrate to DEPOSITION RATES determined using:
 - New high resolution radiometric dating methods
 - Accumulation of contaminants (i.e., mercury) with known concentration history
 - Dendrochronology
 - Field monitoring through time where feasible

New methods for analyzing fallout radionuclides provide improved resolution in dating sediment accumulation

A (Pizzuto, unpublished)



B (Singer and Aalto, 2009).



C (Aalto and Nittrouer, 2012)

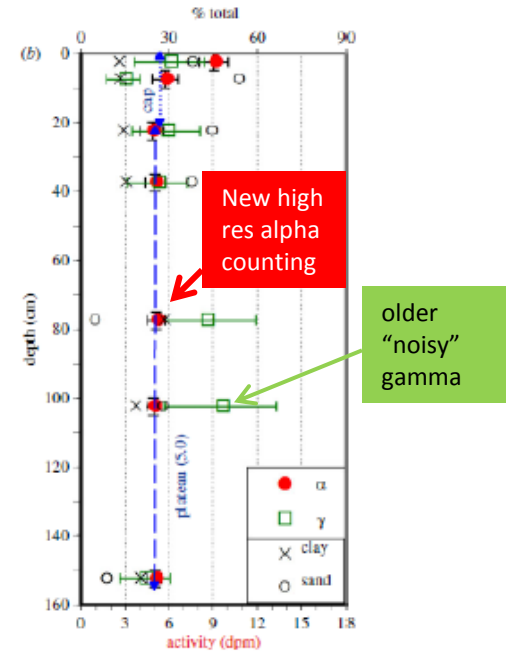


Figure 6. A. Cs-137 profile obtained from the White Clay Cr. floodplain in Delaware. B. Clay-normalized adsorbed excess Pb-210 activity and sand content for a core from the Sacramento R. floodplain. Profile indicates an erosion event that occurred in 1986 (dated using the excess activity of the meteoric cap). C. % clay and sand and Pb-210 activity from a floodplain core of the Beni River floodplain, Bolivia. Alpha-counted Pb-210 indicates a single pulse of deposition of 160 cm (dated from the "plateau" of excess activity indicated by the dashed line) in 1987 (+/-). Increase in activity near the surface is due to atmospheric deposition. Note greater precision of alpha counting as compared to gamma counting.

Calibrated Process-based Models To Predict Storage (Sediment OR Mercury)

$$M_{Hg} = \Phi \sigma k_w (1 - e^{-\lambda h}) \left[(t_f - t_1) e^{-\lambda z_{cf}} + \frac{(1 - e^{-\lambda m t_1}) (e^{-\lambda z_{c0}})}{\lambda m} \right] \quad (17)$$

Pizzuto, Water Resources Research, 2012

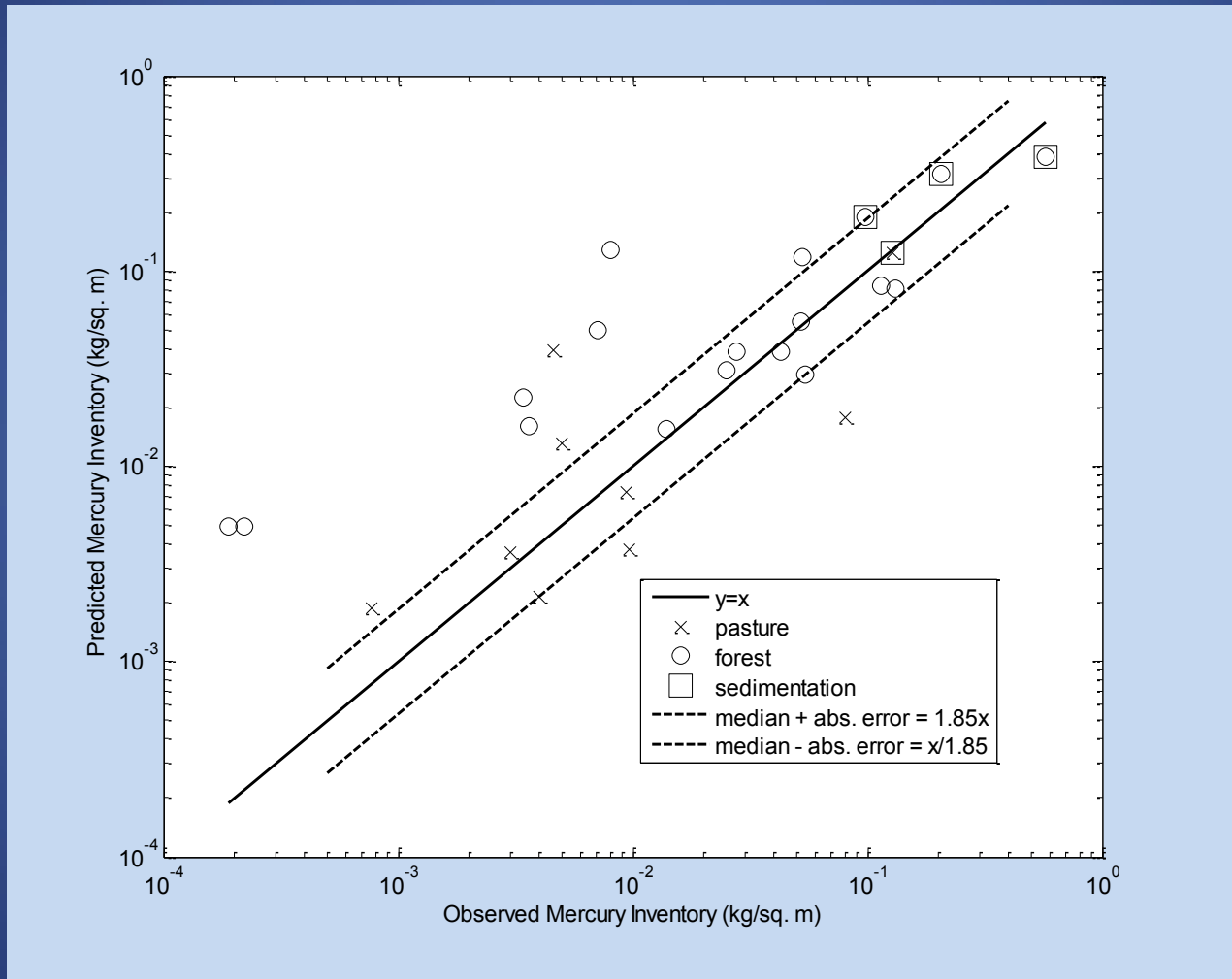
Analytical model for mercury accumulation on near-bank areas that accounts for:

- Frequency of flooding
- Mercury (or sediment) deposition rates during flood events
- Increased accumulation due to riparian vegetation
- Minimum threshold depth (stress) for accumulation

4 unknown parameters determined by calibration using Hg data from cores!!

Parameter	Value	95% Confidence Interval
Φ (kg/m ² /yr)	0.040	0.032-0.048
σ	3.05	2.43-3.67
h (m)	0.98	0.45-1.53
t_1 (yr)	39	22-56

Calibrated Equation Explains 2/3 of Variation in Observed Hg Inventories



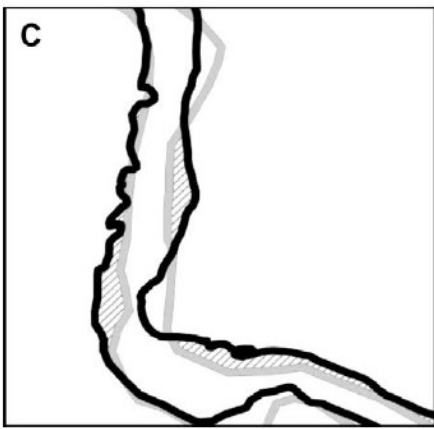
The same equation can predict sediment accumulation by a simple change of units!!

Bank Erosion Rates

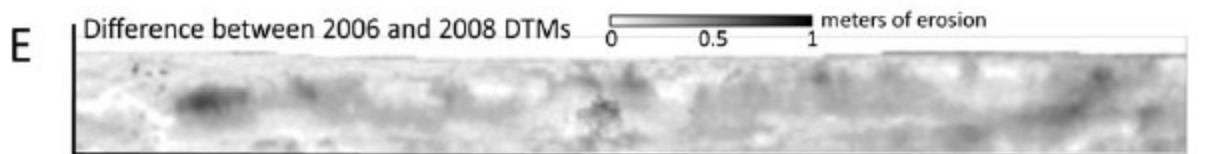
- Controls are still being debated, but....
 - Simple hydraulic models can be developed
 - and fit to field measurements

Decadal Bank Erosion Rates - Methods

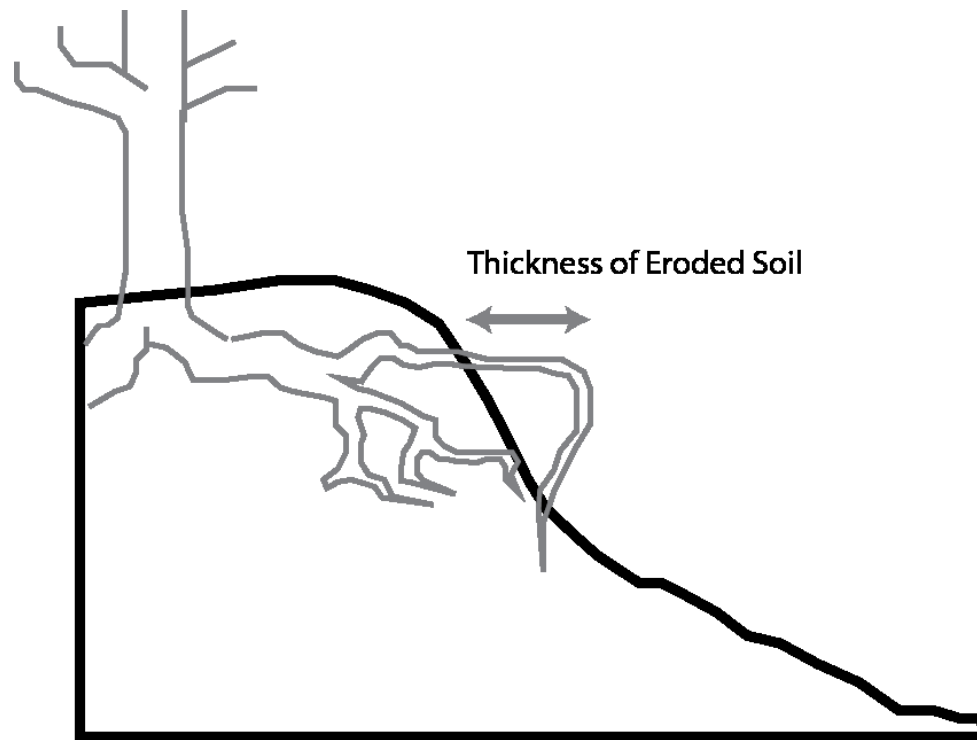
Historical aerial
photos (Rhoades et al.,
Applied Geog. 2009)



Tripod-mounted LiDAR (O'Neal and Pizzuto, ESPL, 2010)



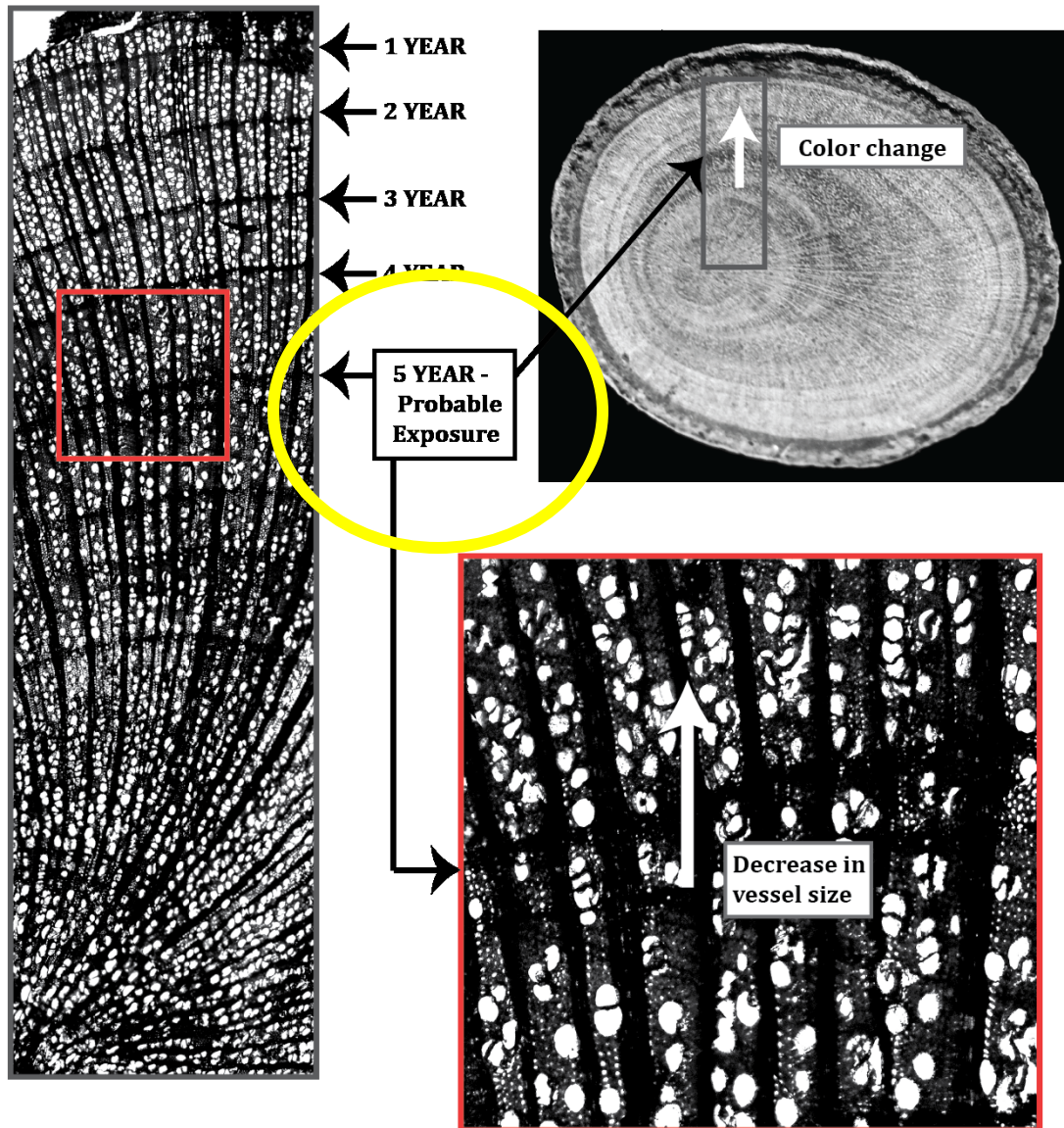
Bank erosion rates from dating tree root exposure



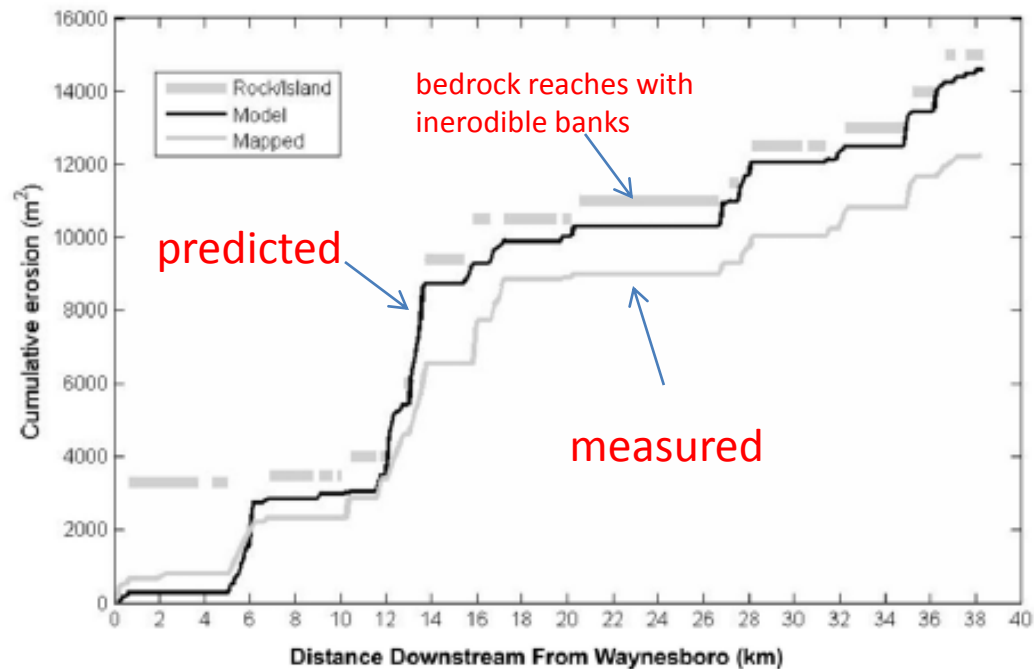
TULIP POPLAR

Thickness of
Eroded Soil: 22.9 cm

Erosion Rate: 4.6 cm/year



Cumulative Bank Erosion From a Calibrated 1-d, Curvature-Based Hydrodynamic Model (Narinesingh, 2009) (South River, 1937-2005)



Conclusions

- Our working hypothesis:
 - Storage, not transport, controls particle delivery to the Chesapeake Bay
 - Event scale hydrologic models focus on variables and processes that are unimportant
- The few useful data available suggest that **AVERAGE** suspended sediment particles may have **VERY LOW** downstream transport rates due to long storage timescales

Needed Research

- *Develop* improved conceptual models to document controls on particle storage and reworking
 - *Resolve controversies involving colonial mill dam sediments, upland vs riverbank sources of sediment production, etc.*
- Use new methods for MEASURING decadal averaged deposition and erosion rates to
 - *Calibrate* models to predict storage timescales
 - Models must be simple enough to facilitate calibration AND to be incorporated at the scale of the CHESAPEAKE BAY WATERSHED
- Improve stream gaging and observational methods to determine storage timescales by particle class
 - Size, composition, density
 - In progress as part of the Christina River Basin Critical Zone Observatory
- Account for factors that bias storage timescales
 - LOCATION
 - AGE
- Incorporate into watershed scale hydrologic models
 - *Couple* relevant short and long-term timescale processes for the particles that really count!

The Christina River Basin Critical Zone Observatory (www.udel.edu/czo)

- Where some of these programs are getting a “trial run”
- Hopefully expand to Chesapeake Bay Watershed though additional NSF support (pending)

