Chesapeake Sediment Synthesis

Reviewing sediment sources, transport, delivery, and impacts in the Chesapeake Bay watershed to guide management actions v3

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USGS unless otherwise noted

U.S. Department of the Interior
U.S. Geological Survey

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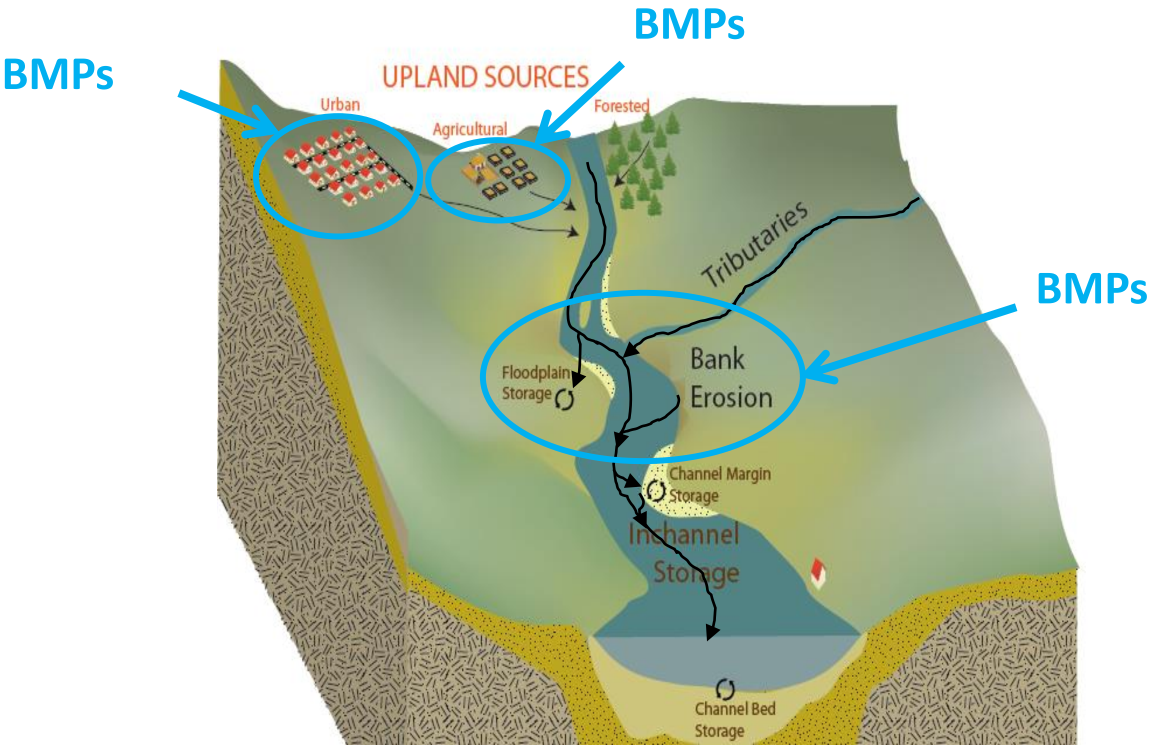
Goal of the synthesis

To summarize the state of knowledge of sediment in the Chesapeake Bay watershed, in order to guide management actions on the landscape for the restoration of the watershed and estuary.



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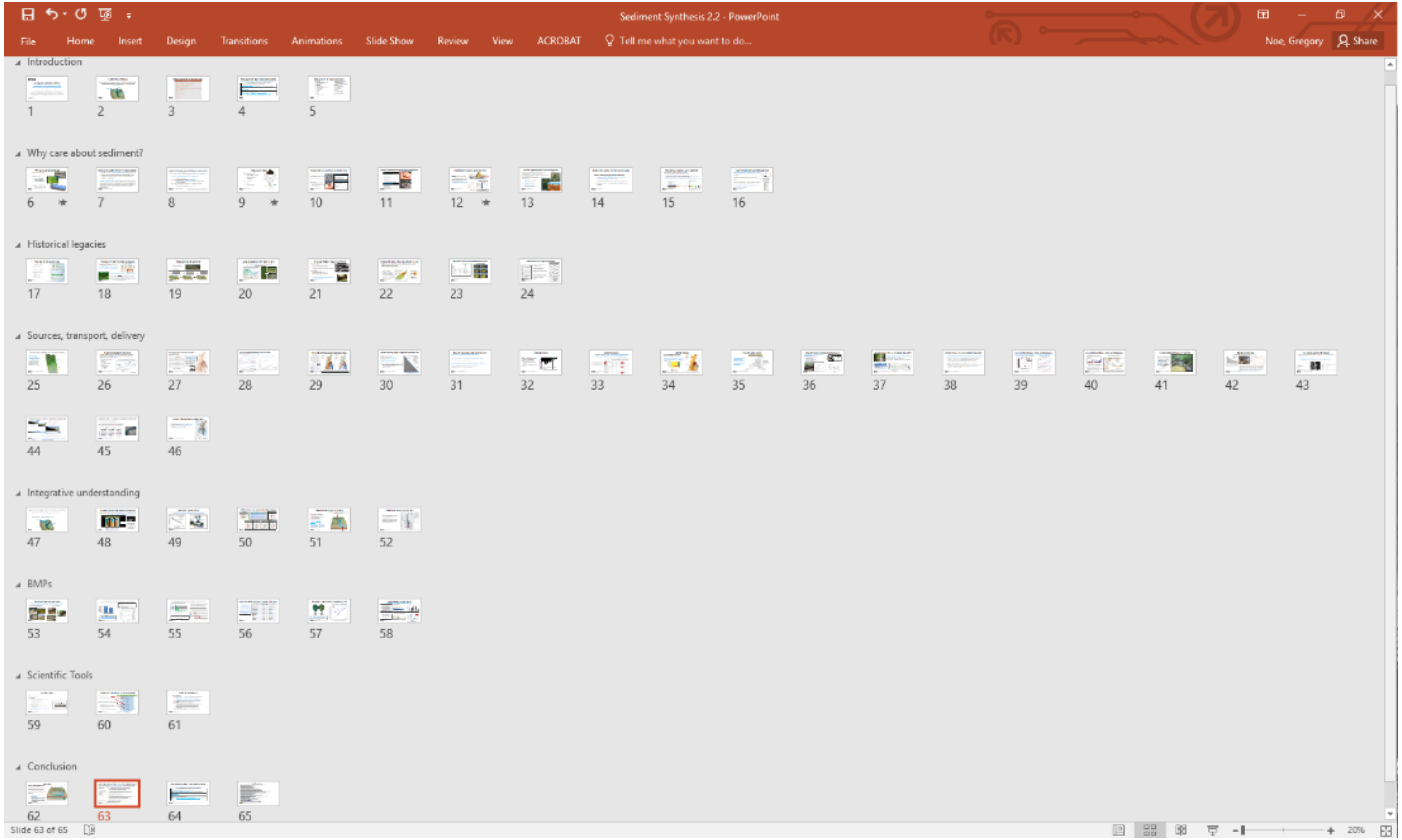
Organization of the presentation

A thorough identification of concepts, data, understanding, and management implications, with frequent summaries, to serve as a resource for the scientific and management communities.



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The Sediment Story: take home points for management

Excessive sediment harms fish and wildlife in the Chesapeake Bay and its watershed

Three important geomorphic principles to guide management:

Scale

Sediment starts in the uplands and moves through stream storage compartments

Sediment processes differ in headwater streams than in larger rivers

Sediment (and attached nutrients) 'hops and rests' downstream, in and out of different storage zones (like floodplains) where it can rest from days to thousands of years, **causing delayed response to management actions**

Time

Historical legacy matters for understanding current sediment issues, and may impact BMP and management effects on loads in the future

Land Use

Nutrients and other pollutants are attached to sediment

Agricultural, developed land, and **stream banks** are all **important sources of sediment**, but locally and temporally variable

Based on models, **BMPs are thought to have reduced the 2014 sediment load to streams by about 23%** in the Chesapeake Bay watershed

New scientific advances continue to improve our ability to understand and guide management of local and regional sediment problems

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Organization of the presentation

1. **Why care about sediment?**
   - Sediment characteristics
   - Impacts on biota, nontidal and tidal
   - Sediment as a vector for nutrients and contaminants
2. **The role of land use history**
   - Before Europeans
   - Historical eras of sediment
   - Land use and river management changes over time
3. **Sediment sources, transport, and delivery**
   - Sediment budget framework
   - Stream loads and yields
   - Stream load trends
   - Upland erosion
   - Upland storage
   - **Stream valley fluxes**
     - Bank erosion
     - Floodplain deposition
     - The balance of erosion and deposition
     - In-channel erosion and deposition
     - Stream valley storage
     - Reservoirs
5. **Integrative understanding of sources and delivery**
   - Fingerprinting to ID sources
   - Residence times and path lengths
   - Holistic pictures from watershed sediment budgets
   - Watershed delivery to the Bay
6. **BMP effects**
   - Tracking BMP implementation
   - Modeled BMP effects
   - Review of BMP efficiencies
   - Newer BMP examples
7. **Scientific tools**
   - Chesapeake Bay Program Phase 6 watershed model
   - New measurement capabilities
8. **State of the Science**
9. **Summary for watershed management**
   - How to guide management actions
   - Specific guidance for WIP and TMDL implementation
10. **References**

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Why care about sediment?

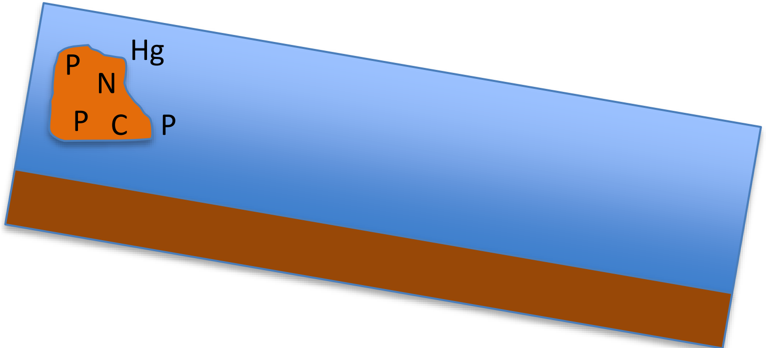
Sediment characteristics

Impacts on biota

- Tidal and nontidal
- Grain size matters
- Multiple mechanisms

Associated contaminants

- Phosphorus and nitrogen
- Other chemicals



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What is the sediment we’re talking about?

- Most focus is on **suspended sediment** (it’s being transported)
- Sediment transported as bedload could be important depending on flow energy and sediment supply, but data are very limited and material is usually coarser than suspended sediment. It’s larger size means it usually carries less nutrients and contaminants but has more important influence on channel form, stability, and habitat.
- **Sediment characteristics matter** (grain size, organic content, mineralogy, and metal chemistry) for impacts on stream organisms, controlling concentrations and transformations of nutrients and contaminants attached to sediment, the likelihood of export from the watershed, and impacting water clarity in the Bay.

What are Chesapeake watershed sediment characteristics?

At 9 major river stations (RIM) before delivery to Bay:

- **90% of suspended sediment load is fine sediment** (clay + silt, <63 microns; Zhang and Blomquist 2018)

- 11% of sediment load is organic, **89% mineral** (Zhang and Blomquist 2018 and Noe in preparation)

- Average concentration of P and N on suspended sediment:

  1.0 mg-P/g, 3.6 mg-N/g (Zhang et al. 2018)

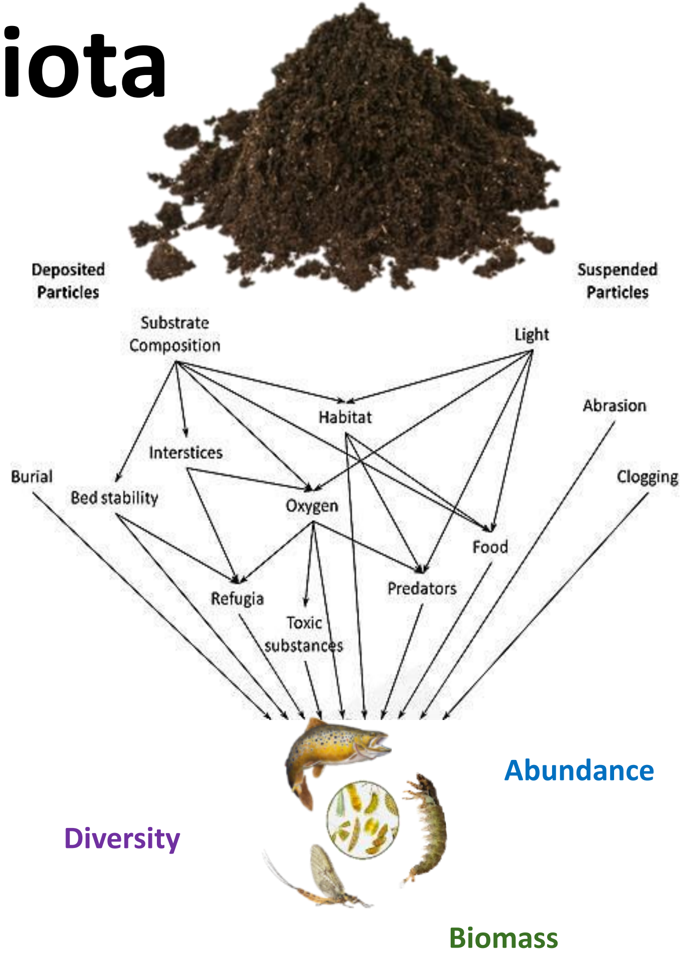
Impacts on biota

Nontidal watershed

- General effects, foodwebs
- Fish and amphibians
- Spawning fish

Chesapeake Bay

- SAV
- Oysters / benthos



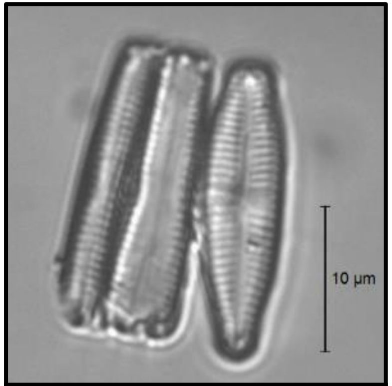
Modified from Jones et al. 2012

Impacts of excess sediment on stream biota

Long history of science on impacts of sediment on stream biota
(Cordone & Kelley 1961, Chutter 1969, Ritchie 1972, Newcombe & MacDonald 1991, Ryan 1991, Waters 1995)

General effects

- Loss of habitat (fills interstitial spaces, anchoring, substrate coating)
- Loss of sensitive species



Primary Producers

Abrasion of periphyton

Covering periphyton and plants

Reduced primary productivity

Benthic Macroinvertebrates

Loss of interstitial habitat

Feeding issues (filter feeders)

Respiration issues

Increased downstream drift

Loss of sensitive species (EPTs) to more tolerant taxa (chironomids and oligochaetes)

Impacts of excess sediment on fish and amphibians

Fish

Reduced adult foraging efficiency

Avoidance of areas

Reduced pool habitat

Loss of spawning habitat

- Interstitial spaces filled

Reproductive success

- Oxygen deprivation in salmonid redds
- Larval salmonid mortality (entrapment)

Potential effects of contaminants

Amphibians and Reptiles

Reduced habitat

Coating of eggs masses

Loss of sensitive species

Potential effects of contaminants

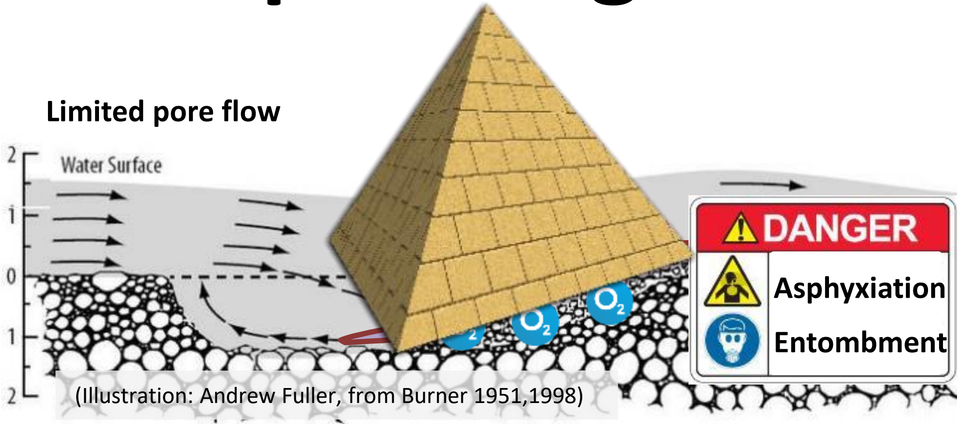
J. Cole


J. Cole

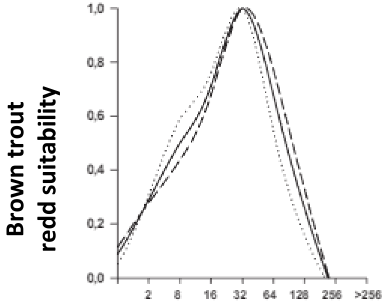
Sediment effects on spawning fish

Spawning and recruitment can limit fish populations

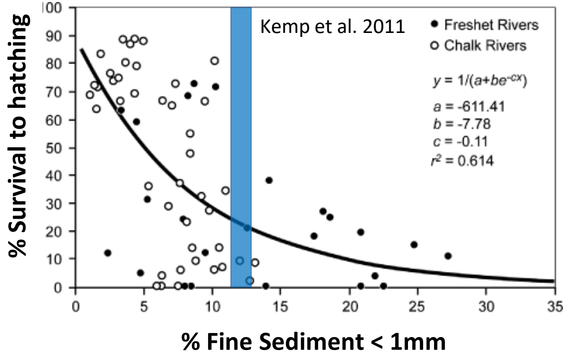
- Gravel-spawning fish need clean gravels
- Adequate pore-flow provides oxygen to embryo and removes waste
- **Spawning redds are vulnerable to excess fine sediment**



(Illustration: Andrew Fuller, from Burner 1951,1998)



Consistent threshold of reduced survivorship with ~10-20% bed fine-sediment by weight



USGS *Impacts on biota*

Sediment negatively affects estuarine organisms

Watershed sediment delivered in floods has a dramatic short-term impact on water clarity (Cerco and Noel 2016, Fabricius et al. 2016)

In some areas, internal resuspension may be more important on average than contemporary inputs (Wang et al. 2013)

Effect of sediment inputs varies regionally (Wang et al. 2013)

Negative effects on biota:

- **Seagrass** (light attenuation, burial)

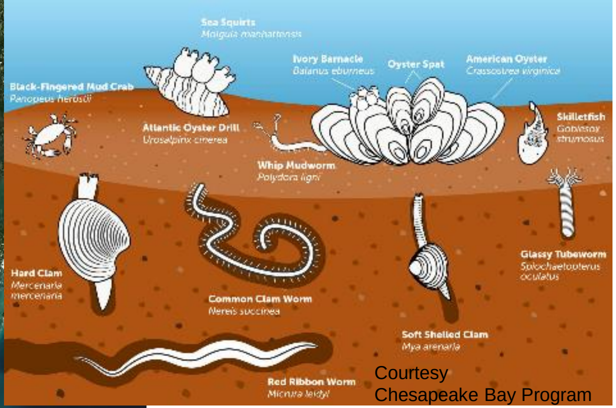
  (Cabaço et al. 2008, Burbisz et al. 2016)

- **Phytoplankton** (light stress)

  (Cloern 1987, Buchanan et al. 2005)

- **Macrobenthic** community biomass and structure (burial, contaminants)

  (Hinchey et al. 2006, Colden et al. 2015, Comeau et al. 2017)



Sediment is a vector for other contaminants

Managing sediment may help with other contaminants

- Phosphorus: **77% of TP load to the Bay is attached to sediment (particulate)** (Zhang et al. 2015)
- Nitrogen: 18% of TN load is attached to sediment (Zhang et al. 2015)
- Metals, pesticides, PCBs, and organic contaminants, for example

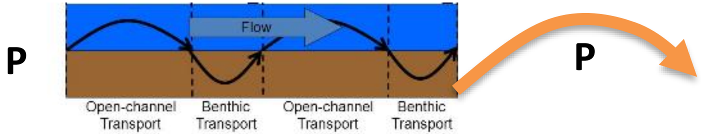
Phosphorus interacts with sediment

Most P is attached to sediment, but not all of it permanently

- Phosphate interacts with sediment in storage and in transport
- Phosphate attaches and detaches from sediment (changing it's availability to biota) depending on waterlogging (redox) and pH
- P spirals downstream, in and out of storage, on and off of sediment
- Typical P concentrations in Chesapeake suspended sediment and streambed sediment around the U.S. are lower than most crop soils but higher than most bank sediments
- **Understanding sediment helps understand most, but not all, of P transport downstream**

P spiraling downstream:

transported as dissolved form, attaching to sediment, and then detaching from sediment or sediment is transported downstream, over and over again.



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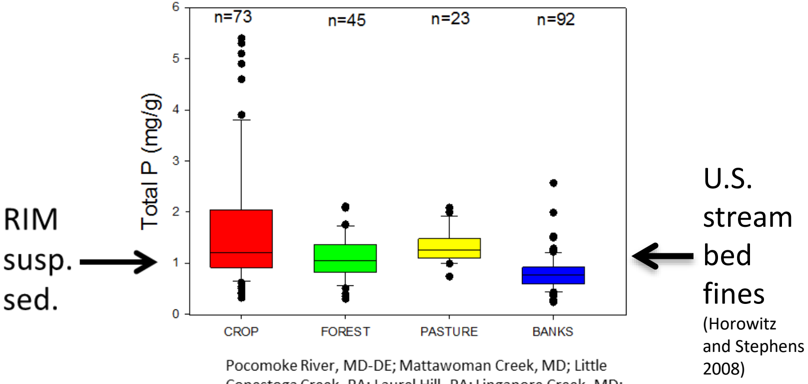
P concentration on sediments



Pocomoke River, MD-DE; Mattawoman Creek, MD; Little Conestoga Creek, PA; Laurel Hill, PA; Linganore Creek, MD; Upper Difficult Run, VA (Gellis et al., 2009; Sloto et al., 2012; Gellis et al., 2015)

Heavy metals interact with sediment

Heavy metals (such as Hg) sorb to sediment and are transported and deposited with sediment, and some can detach from sediment depending on chemical environment (Skalak and Pizzuto 2010, Flanders et al. 2010, Skalak and Pizzuto 2014)

Remobilization of stored contaminants is a result of fluvial processes and can take years to decades (Skalak and Pizzuto 2010, Skalak and Pizzuto 2014)

Contaminant concentration can often be a function of sediment particle size or organic content (Skalak and Pizzuto 2014)

Many heavy metals are enriched in sediment from urban watersheds (Horowitz and Stephens 2008)

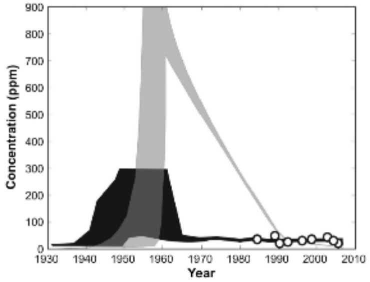
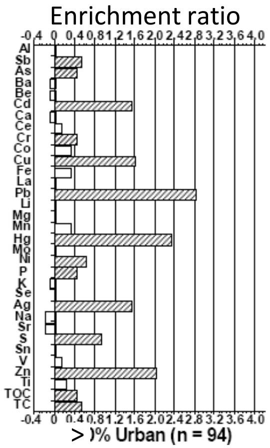


Figure 10. Mercury concentration on suspended particles transported by the South River from 1930 to 2007. The gray region represents model reconstructions based on the age and Hg concentration distributions observed in FGCM deposits in 2007. The black region defines the history documented by the Dooms Dam core (range is defined by the 99% confidence intervals associated with radiometric dating; Skalak and Pizzuto, 2010). Circles are samples from FGCM deposits dated by bomb radiocarbon (data from Skalak and Pizzuto, 2010).

Skalak and Pizzuto 2014



Horowitz and Stephens 2008

USGS *Contaminants*

The role of land use history: eras of sediment

- Before Europeans
- Historical eras
- Land use changes
- Legacy sediment
- Mill dams
- Urbanization

USGS *History*

Brush (2009):

Chesapeake landscape change

Human population

Land cover

Fertilizer sales

Potomac N yield

Crab and oyster harvest

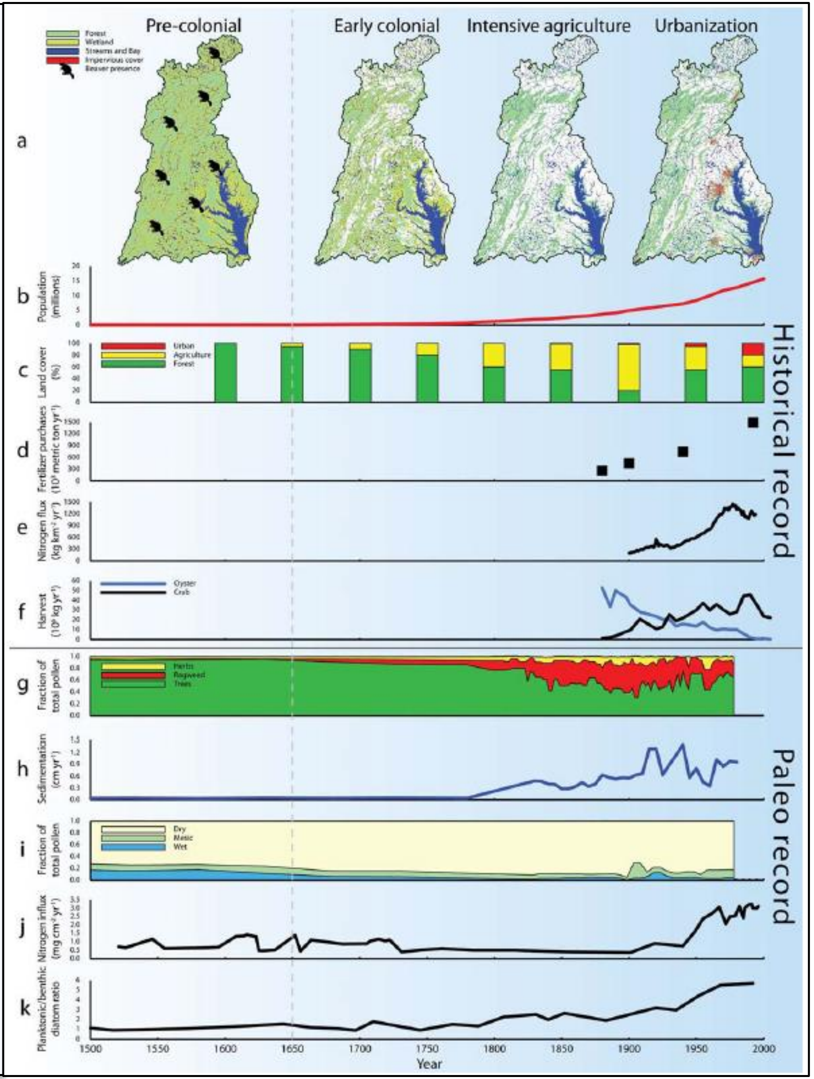
Disturbed vegetation

Estuarine sedimentation

Dewatering landscape

Bay N input

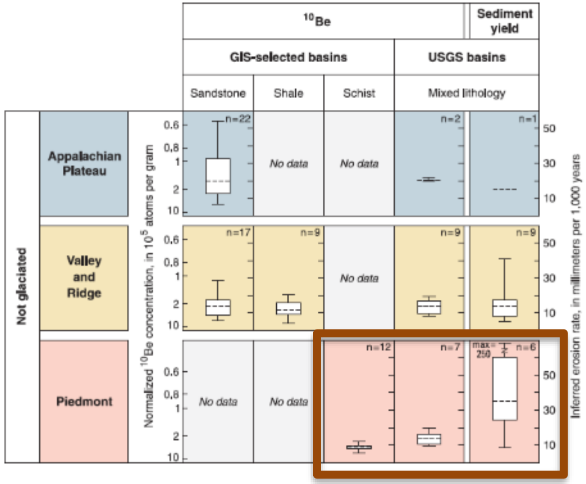
Bay food web



The role of history: before Europeans

Geologic rates of erosion vary across the Chesapeake watershed (Gellis et al. 2009)

The Piedmont had low natural sediment yields, in contrast to its current high yields



Gellis et al. 2009

Elliott et al. 2013

Pre-European Holocene condition: very different than today

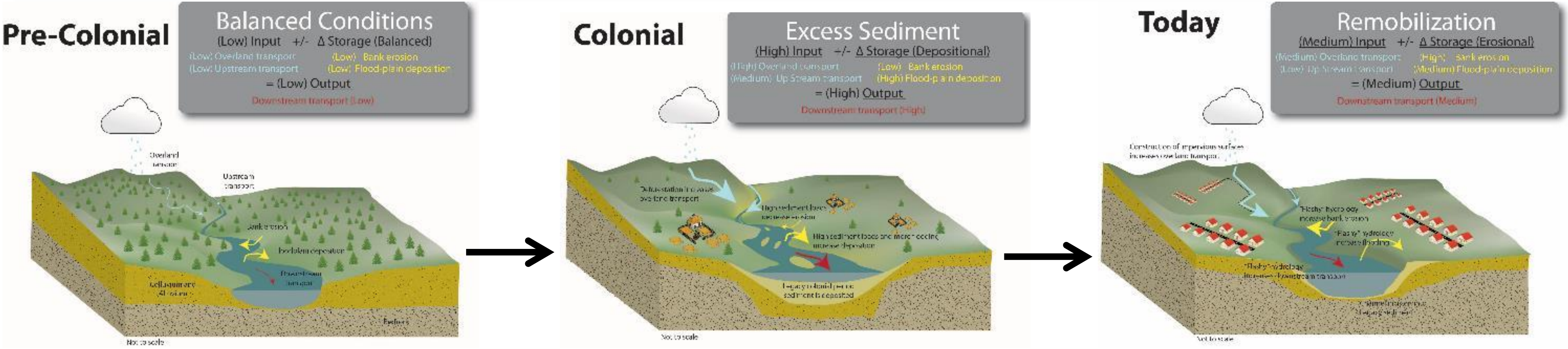
In some locations, <u>headwater</u> streams (likely not the larger streams and rivers) may have had low banks, anastomosing channels, and wetland marsh and swamp floodplains (Elliott et al. 2013), with much beaver influence (Ruedemann and Schoonmaker 1938, Brush 2009), … but more research is needed.

USGS *History*

Historical eras of sediment

Different historical eras changed upland erosion and stream conditions and created the sediment problems we have today

- Demise of beavers
- Deforestation and land clearing
- Upland erosion and agricultural land use
- Wetland drainage and stream channelization
- Build up of legacy sediment
- Industrialization and mill dams
- Soil conservation and BMPs

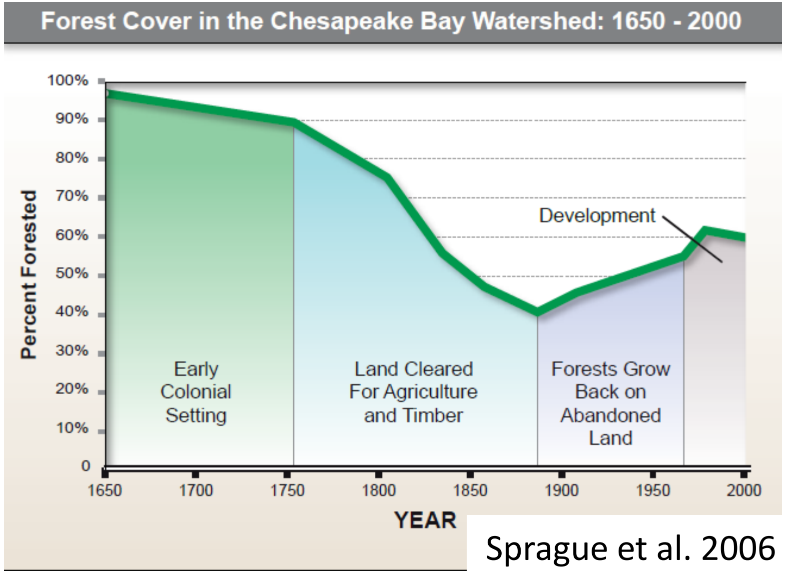


USGS *History*

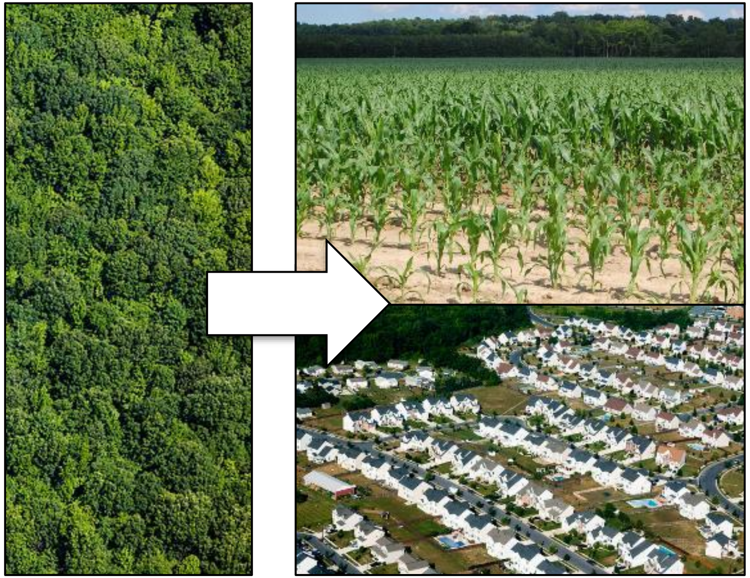
Land use change from 1650 to now

Forest conversion to agriculture and urbanization

increased soil erosion



Sprague et al. 2006



USGS *History*

The role of history: legacy sediment

Definition (2017 STAC workshop)

"For the purposes of the Chesapeake Bay management effort, we would define legacy sediment as sediment stored in the landscape as a byproduct of accelerated erosion caused by landscape disturbance following European settlement."

What it means for landscape processes and restoration

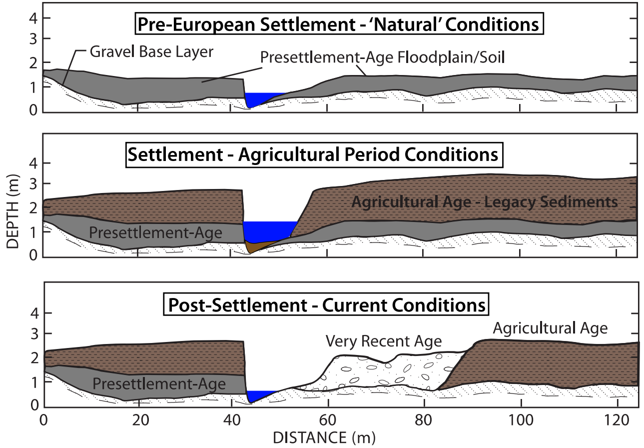
There is a large amount of sediment stored in the fluvial landscape that sets the current impaired conditions and processes that need to be measured and managed to influence stream habitat and downstream loads

How much and where

- Legacy sediment thickness varies
- Some stored sediment is pre-colonial (Pizzuto et al. 2017)
- New remote sensing and GIS tools can estimate local storage

Important because legacy sediment can:

- **Increase sediment loads as it is mobilized**
- **Create long lag times of stream response to upland BMPs** (see later slides)
- **Impair a local waterway even if current landuse may make it seem like it should be a reference "undisturbed" site**



Donovan et al. 2015,
modified from Jacobson and Coleman 1986

Historic plank road buried under floodplain sediment

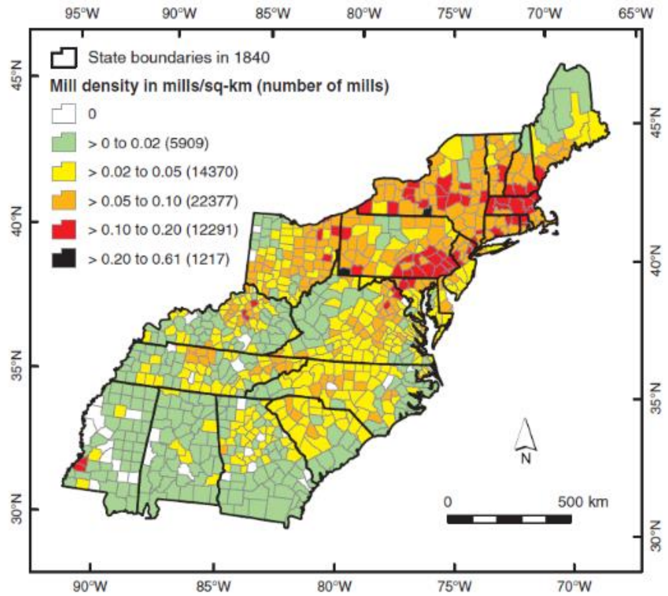
Historic mill dams enhanced sediment storage

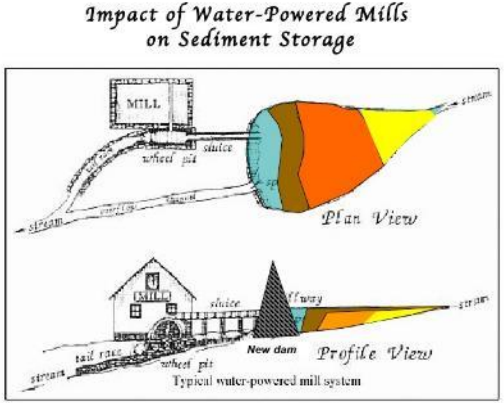
Mill dams were common, and can enhance local sediment storage and current erosion

(Walter and Merritts 2008, Merritts et al. 2011, Hupp et al. 2013, Donovan et al. 2016)

>65,000 water-powered mills in 872 counties in the eastern United States by 1840

(Walter and Merritts 2008)





Courtesy Franklin & Marshall College

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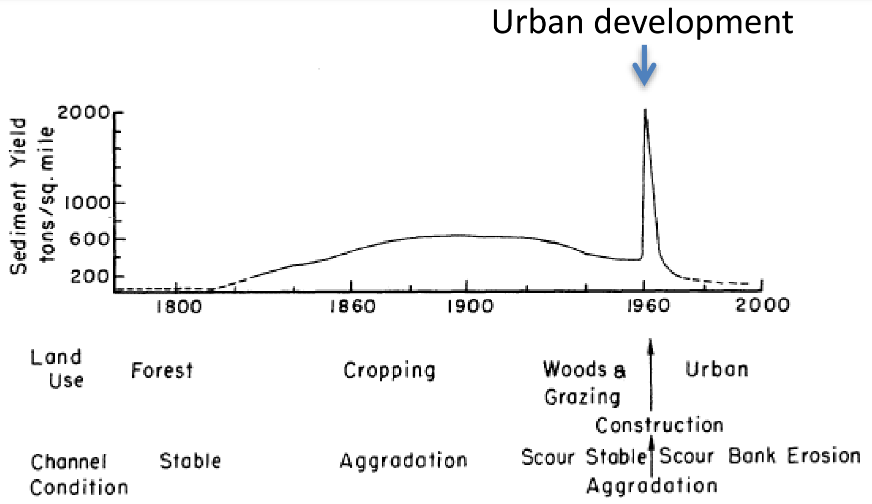
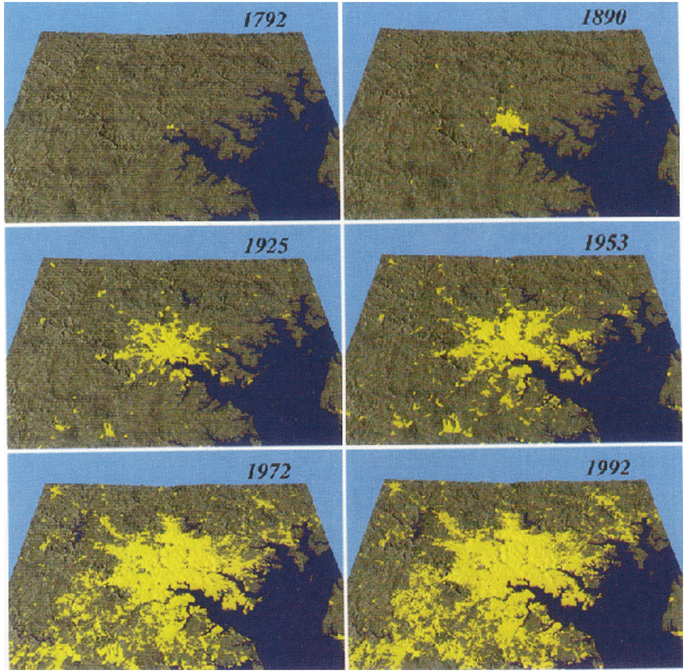
Urbanization leads to increased sediment yields



Wolman 1967

Urban growth in Baltimore



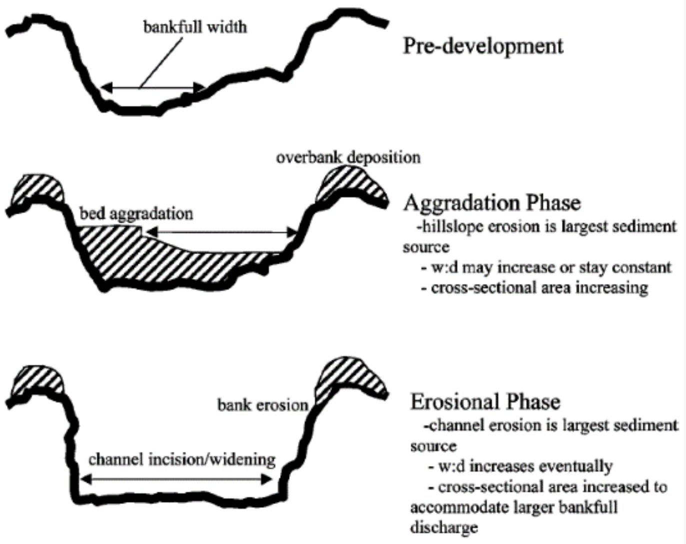
Foresman 1997

But newer findings suggest that sediment export after construction remains high for decades (Gellis et al. 2017)

USGS *History*

Urbanization can change channel form

Channel changes with urbanization



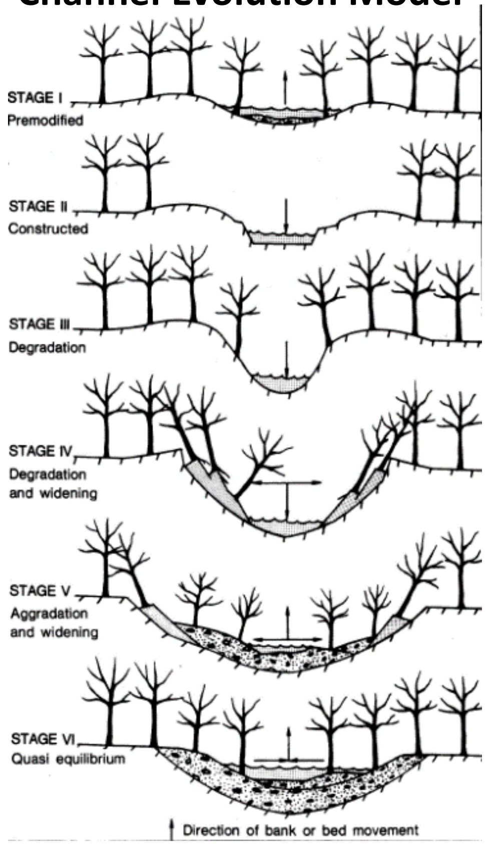
Paul and Meyer 2001

Stream channels are dynamic and can change over time

Understanding the stage of channel evolution can be important for stream and sediment management

Incised channels, which are found throughout the Chesapeake, often go through a progression of changes

Channel Evolution Model



Hupp and Simon 1991

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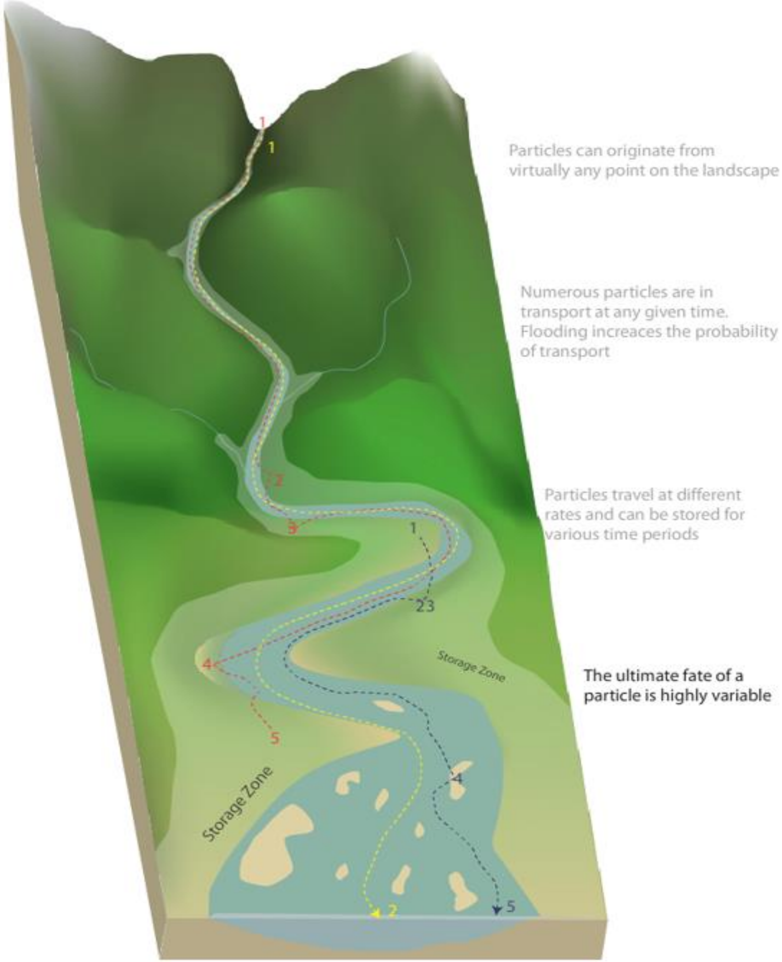
Conceptual model of sediment sources, transport, and delivery

Sediment sources, transport, and storage zones in watersheds vary as a result of land use, management practices, and geology, from headwaters to the Bay



USGS *Source, transport, delivery*

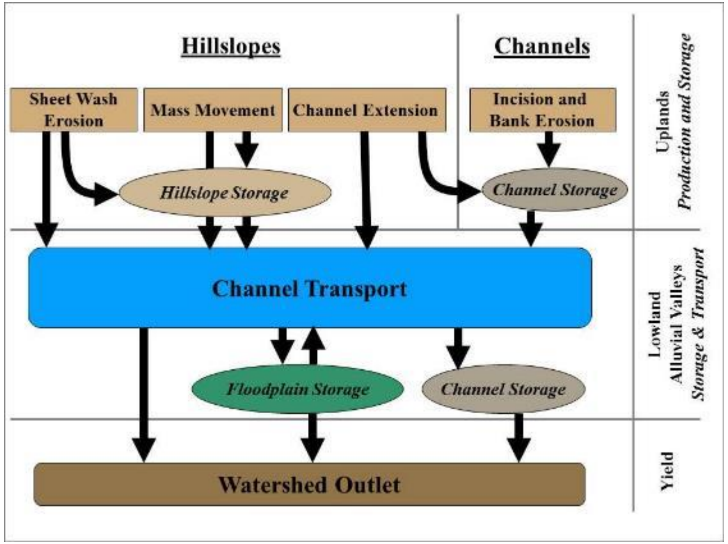
Sediment budget framework

Sediment budgets are useful for describing sediment sources, transport, storage, and export in watersheds. This section is organized around the different parts of a sediment budget:

Typical sediment budget components:

1. Integrated upstream input
2. Downstream output
3. Upland sources
    - Erosion of first order channels
    - Overland rill erosion
4. Tributary input
5. Bank erosion
6. Floodplain storage and surface erosion
7. In-channel storage and erosion
    - Margin deposits
    - Point bars
    - Channel bed

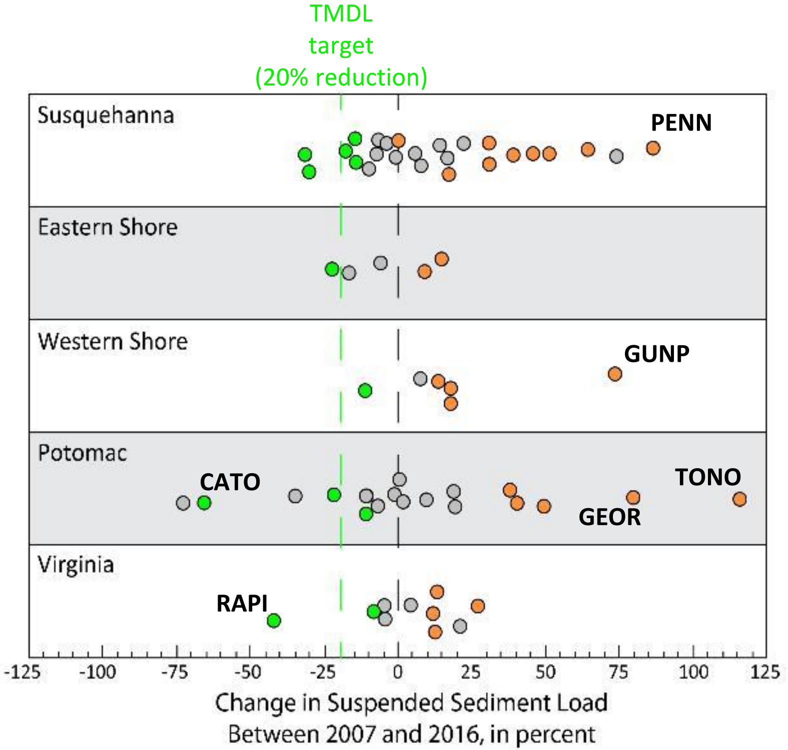
Hypothetical sediment budget for the Chesapeake Bay watershed.
Courtesy of Sean Smith, University of Maine



USGS *Source, transport, delivery*

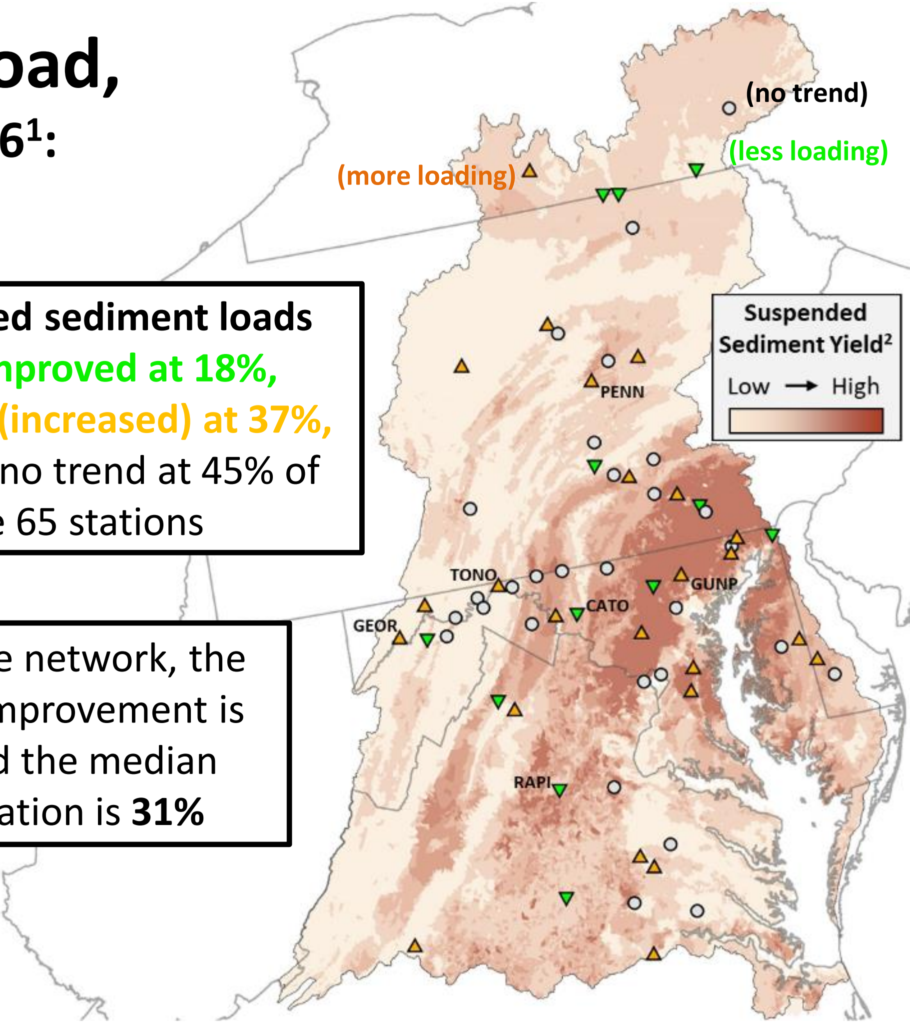
Trends in suspended sediment load,

in the most recent ten year period, 2007-2016[1]:



Suspended sediment loads
have improved at 18%,
degraded (increased) at 37%,
and have no trend at 45% of the 65 stations

Across the network, the median improvement is **20%** and the median degradation is **31%**



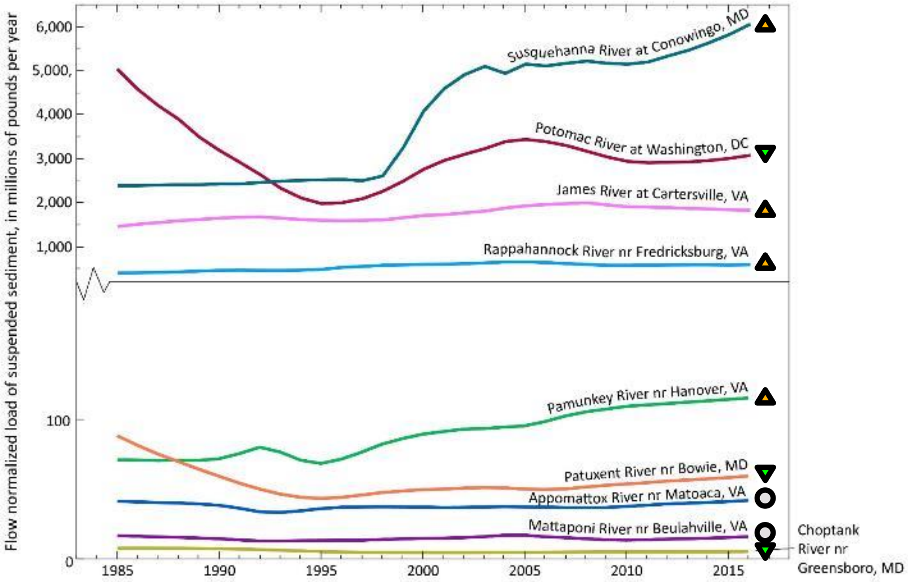
USGS *Source, transport, delivery*

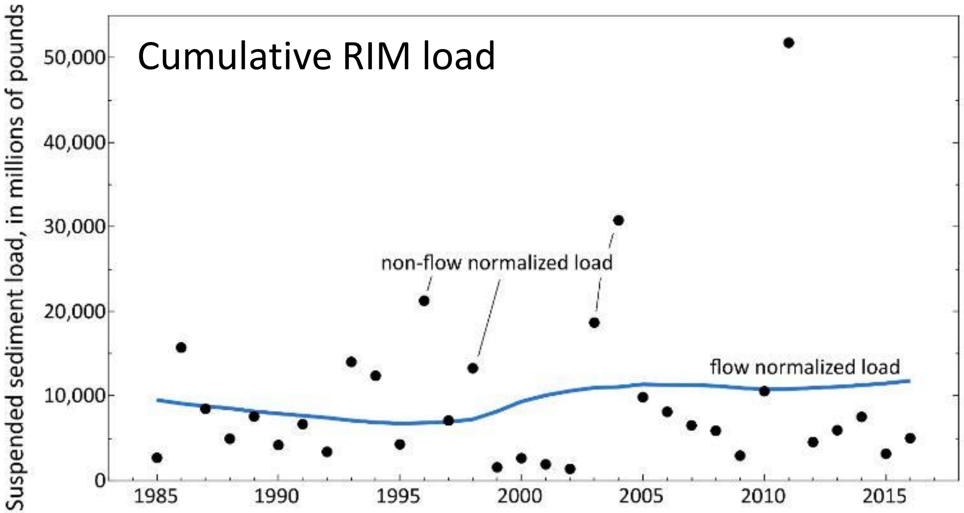
[1]Moyer et al. 2017, [2]Brakebill et al. 2010 http://cbrim.er.usgs.gov/maps.html

Long-term suspended sediment yield to the Bay from RIM stations

Moyer et al. 2017

Most of the rivers with high sediment loads have increasing loads over the past 30 years





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Hot spots of measured sediment yields

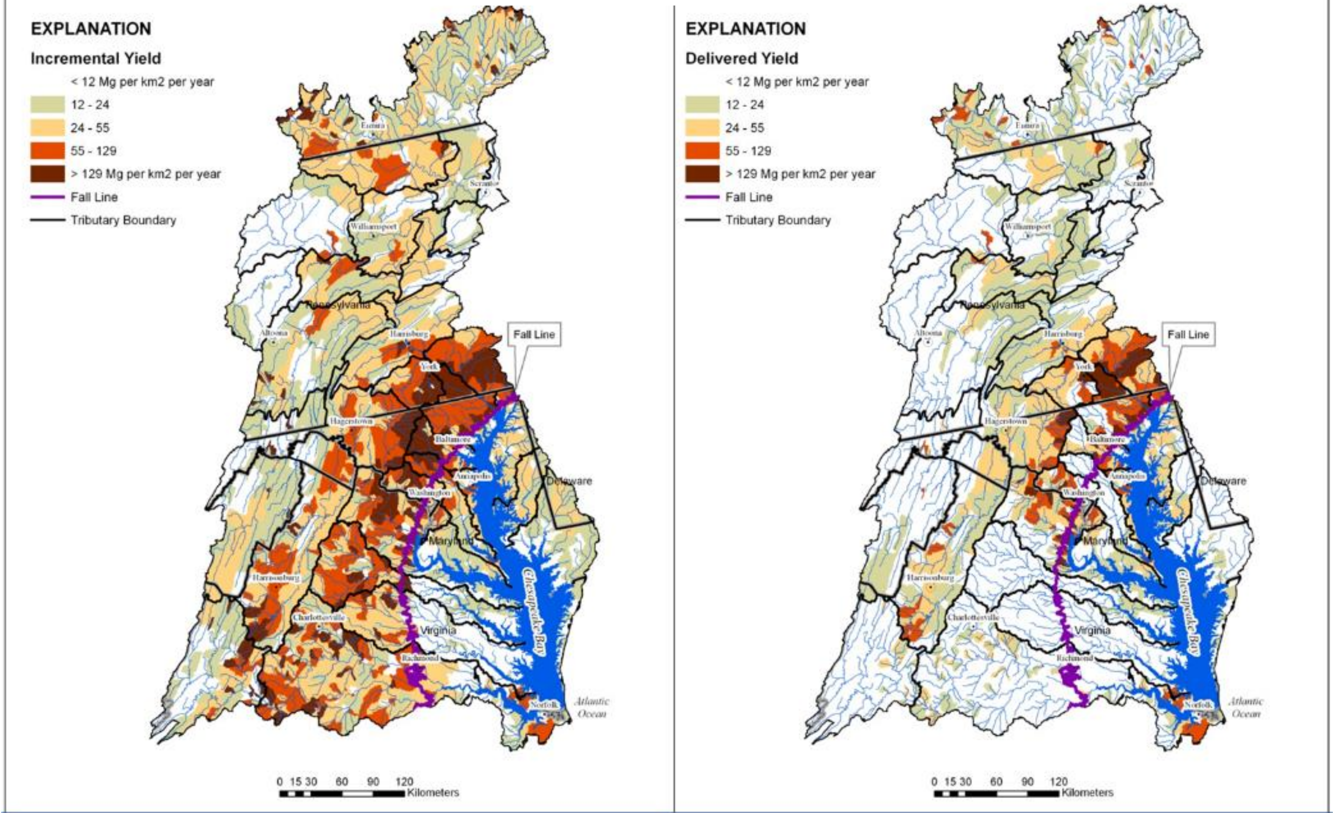
Average annual sediment yields by physiographic province for 65 stations draining the Chesapeake Bay Watershed, 1952–2001

(Gellis et al. 2009)

Physiographic Province	Sediment yield ($Mg/km^2/yr$)
Appalachian Plateau	58.8
Blue Ridge	56.8
Valley and Ridge	66.3
Piedmont	**103.7**
Coastal Plain	11.9

USGS *Source, transport, delivery*

SPARROW modeled sediment yields (Brakebill et al. 2010)



Incremental Yield	Delivered Yield
Input to streams	Delivered to Bay

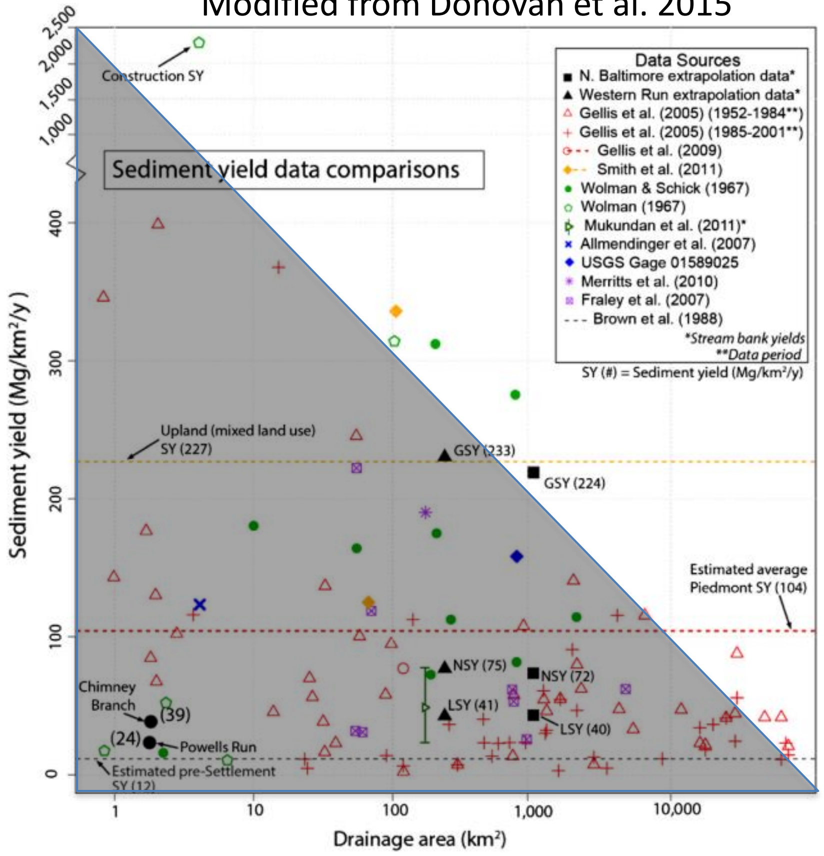
Stream loads and yields change with watershed size

Sediment delivery ratio
(yield vs. drainage area)
indicates that **larger catchments typically have smaller yields**

- due to spatial averaging of erosion rates or fluvial trapping of sediment in larger streams and rivers

(Smith and Wilcock 2015)

Modified from Donovan et al. 2015



USGS *Source, transport, delivery*

Stream load and yield interpretation

18% of rivers have improving sediment loads between 2007 and 2016

- Most improvements represent less than a 25% reduction

Most rivers have degrading or no trend in sediment loads between 2007 and 2016

- Degrading conditions are present in all regions of the bay watershed

There has been little change in total sediment loading to the Bay from the RIM stations

Piedmont has the largest sediment yield, Coastal Plain the smallest

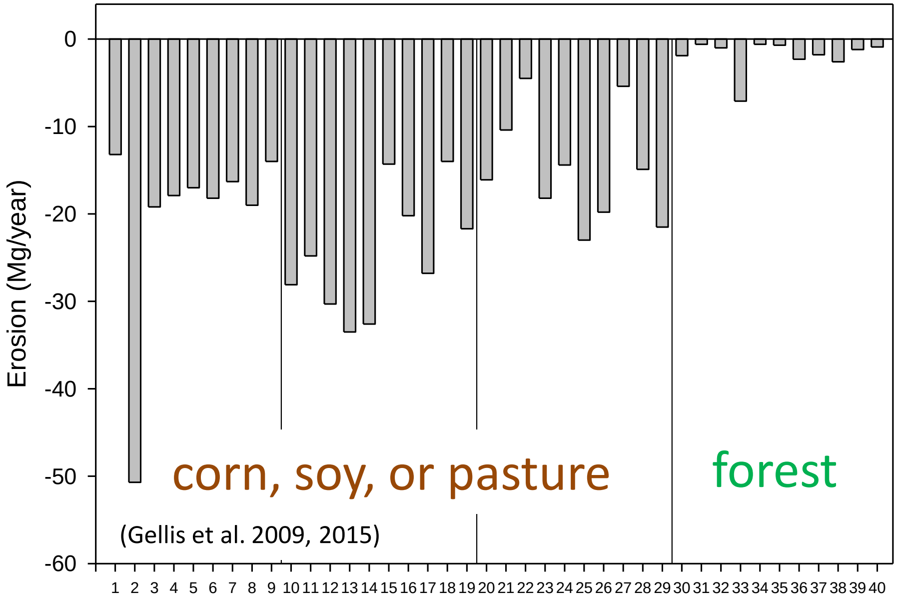
The highest yields are found in the **smallest watersheds**

Upland erosion

What are the important sources of sediment from uplands?

- Agriculture (cropland, pasture)
- Urban, suburban (turfgrass, street residue)
- Disturbance (development, mining)
- Forest

Upland rates of erosion measured using Cesium-137



Upland erosion

On average, where it occurs, **developed land has a much larger effect on suspended sediment loads per unit area than agriculture**

SPARROW model: Brakebill et al. (2010)

Explanatory Variable	Coefficient Units	Mean Coefficient	Standard Error	Probability Level
Sediment sources				
LENGTH1 <0.991 m^3/s above the Fall Line (AFL)	Mg/m/year	0.291	0.132	0.015
LENGTH2 <0.991 m^3/s below the Fall Line (BFL)	Mg/m/year	0		
Agriculture	Mg/km^2/year	56.962	11.988	<0.001
Development	Mg/km^2/year	3928.41	1370.077	0.003
Forest	Mg/km^2/year	0.985	1.442	0.248
Land-to-water delivery				
Basin slope	Dimensionless	0.061	0.035	0.084
Dam density	Dimensionless	−22.966	9.819	0.021
Soil permeability	Dimensionless	−1.195	0.515	0.022
Piedmont uplands	Dimensionless	0.961	0.313	0.002
Aquatic storage AFL				
STORAGE1 > 0.991 < 3.398 m^3/s	day^{-1}	0		
STORAGE3 > 3.398 < 7.709 m^3/s	day^{-1}	0		
STORAGE5 > 7.709 m^3/s	day^{-1}	0		
Aquatic storage BFL				
STORAGE2 > 0.991 < 3.398 m^3/s	day^{-1}	0		
STORAGE4 > 3.398 < 7.709 m^3/s	day^{-1}	2.54	1.02	0.007
STORAGE6 > 7.709 m^3/s	day^{-1}	1.921	0.859	0.014
Aquatic storage from reservoirs				
Reservoir settling velocity	m/year	234.918	127.339	0.034
Model accuracy				
R^2 flux	0.826			
r^2 yield	0.573			
Root mean square error (RMSE)	0.96			
Number of observations	129			
Mean squared error	0.919			

USGS *Source, transport, delivery*

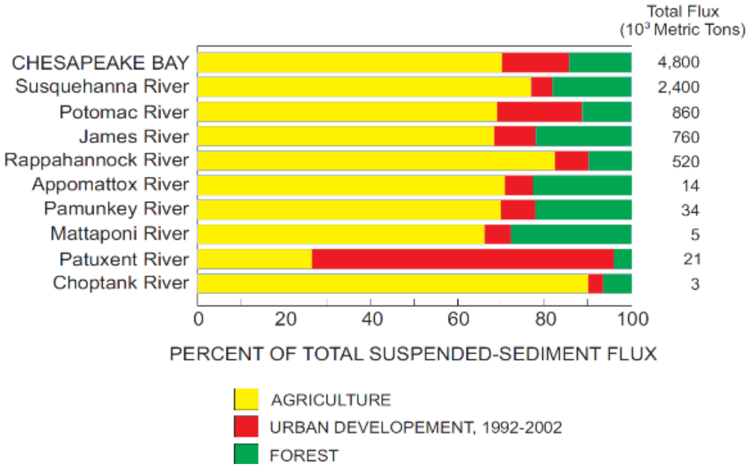
Upland erosion

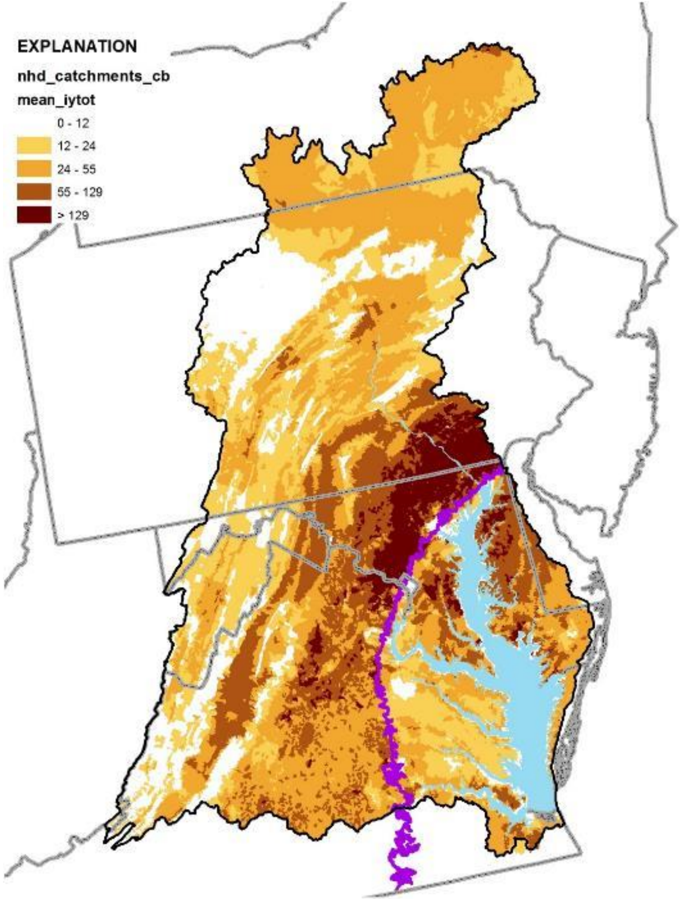
(Brakebill et al. in preparation)

SPARROW suggests that local suspended sediment yields are highest in the developed Piedmont, but that

agriculture is widespread and contributes ~69% of the suspended sediment to Chesapeake Bay

(Brakebill et al. in 2010)

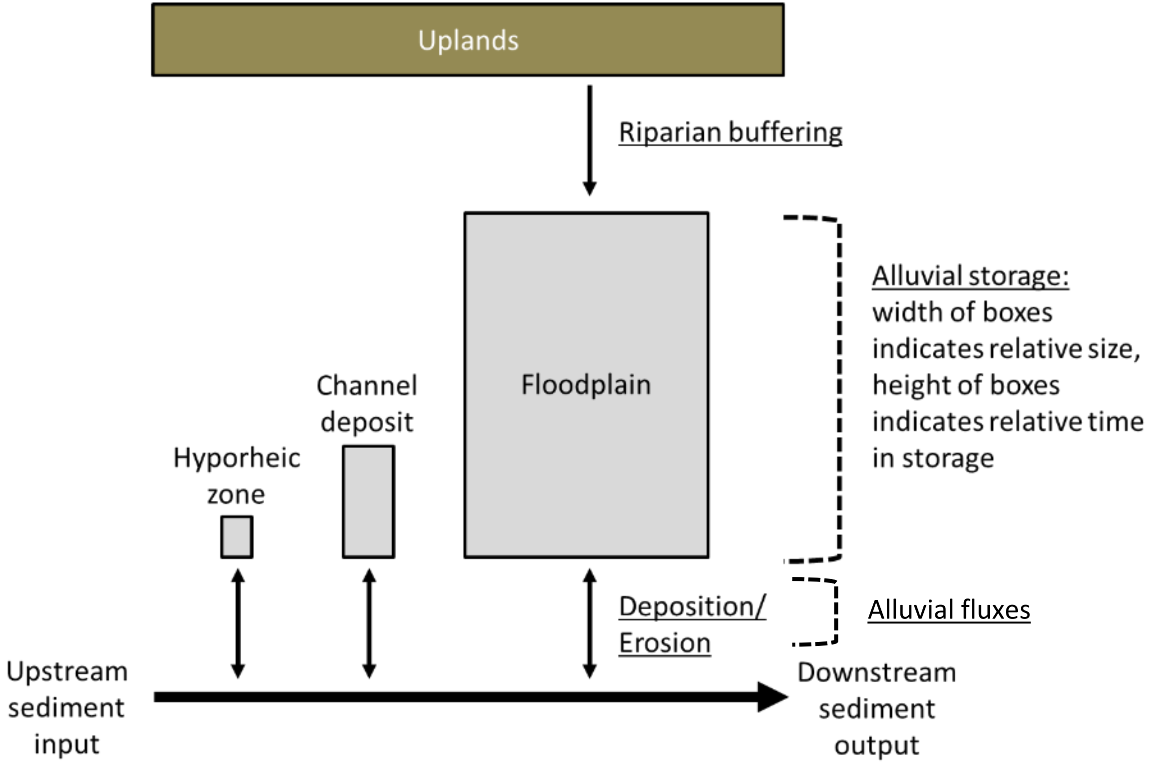




USGS *Source, transport, delivery*

Stream valley fluxes

Geomorphic storage zones of stream valleys can influence sediment transport downstream



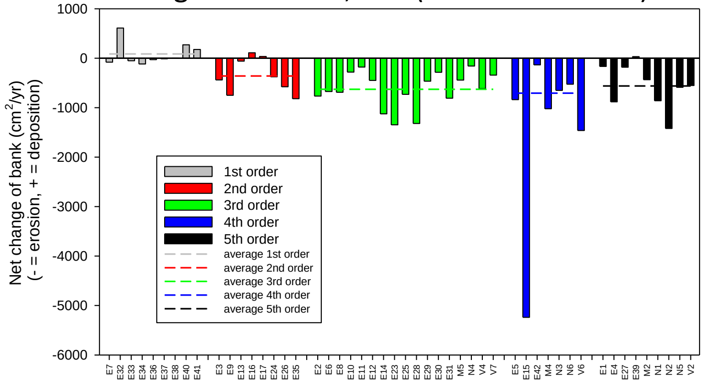
Source, transport, delivery

Stream internal fluxes: Bank erosion

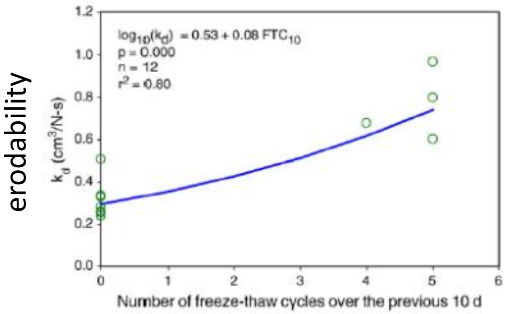
Bank erosion rates are highly variable, and typically increase:

- with stream drainage area (Gellis et al. 2015, Gellis et al. 2017, Hopkins et al. 2018)
- with large floods (Gellis et al. 2017)
- with freeze-thaw cycles (Wynn et al. 2008)
- with warmer water and more acidic and saltier water (Hoomehr et al. 2018)
- with wider channel relative to floodplain (Schenk et al. 2013)
- with less dense soil (Wynn and Mostaghimi 2006)
- with less woody vegetation and less roots (Wynn and Mostaghimi 2006)

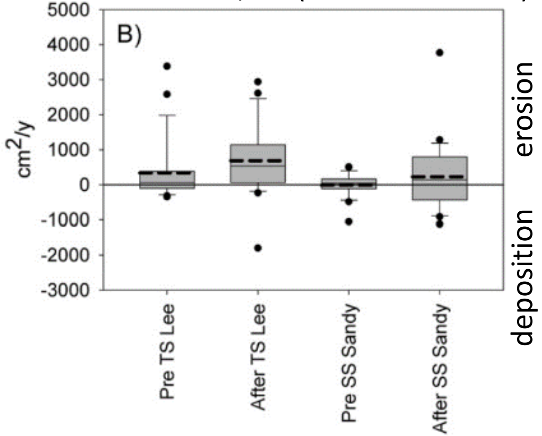
Linganore Creek, MD (Gellis et al. 2015)



Stroubles Creek, VA (Wynn et al. 2008)



Difficult Run, VA (Gellis et al. 2017)



USGS *Source, transport, delivery*

Stream internal fluxes: floodplain deposition

Floodplain trapping is spatially and temporally variable depending on watershed land use, geology, geomorphology, and hydrologic connectivity

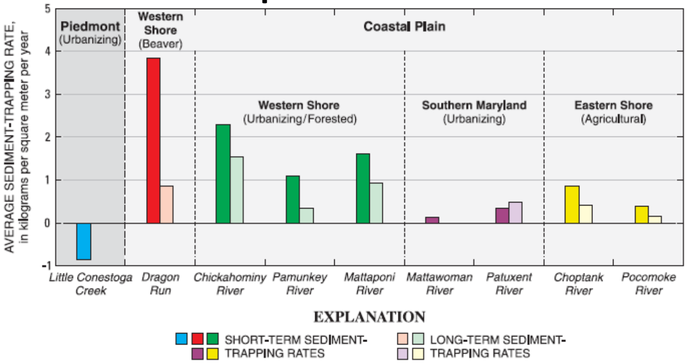
(also see Noe and Hupp 2005, Hupp et al. 2013, Wolf et al. 2013, Gillespie et al. 2018)

Piedmont

Watershed	Floodplain sedimentation (kg m^{-2} yr^{-1})
Difficult Run	6.5
Little Conestoga Creek	4.9
Linganore Creek	9.8

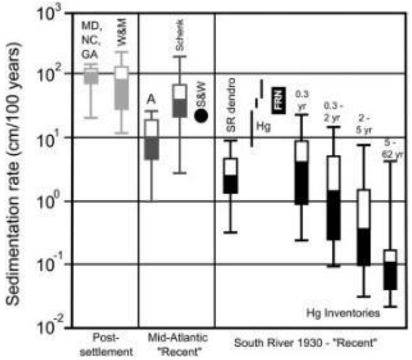
Schenk et al. 2013

Chesapeake watershed



Gellis et al. 2009

Blue Ridge / Valley and Ridge



Pizzuto et al. 2016

USGS *Source, transport, delivery*

Stream internal fluxes: floodplain deposition

Floodplains can trap quantities of sediment similar to annual river loads:

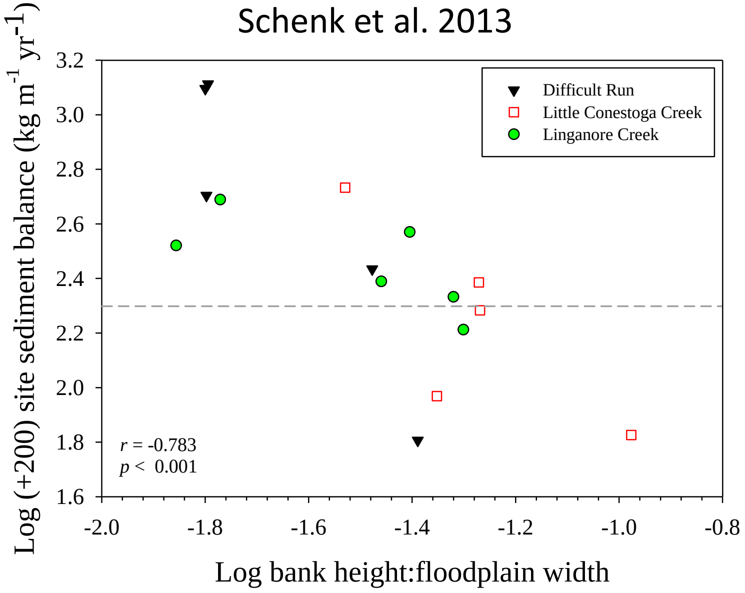
- Sediment accumulating on Coastal Plain floodplains of large rivers typically trapped the equivalent of **119% of annual river loads** (Noe and Hupp 2009)
- **95%** in 147 km^2 Linganore Creek watershed (Maryland; Gellis et al. 2015)
- **19%** in a 7 km^2 and **52%** in a 14 km^2 upper Difficult Run watershed (Virginia; Gellis et al. 2017, Hopkins et al. 2018)
- **413%** in 151 km^2 lower Difficult Run watershed (Virginia; Hopkins et al. 2018)
- SPARROW: 2.2 x 10^6 Mg/yr trapped by floodplains on Coastal Plain rivers, vs. 7.3 x 10^6 Mg/yr generated from uplands of watershed, compared to 3.0 x10^6 Mg/yr delivered to the Chesapeake Bay (Brakebill et al. 2010)

Stream internal fluxes: banks and floodplains

The balance of bank erosion and floodplain deposition is becoming predictable by reach geomorphology

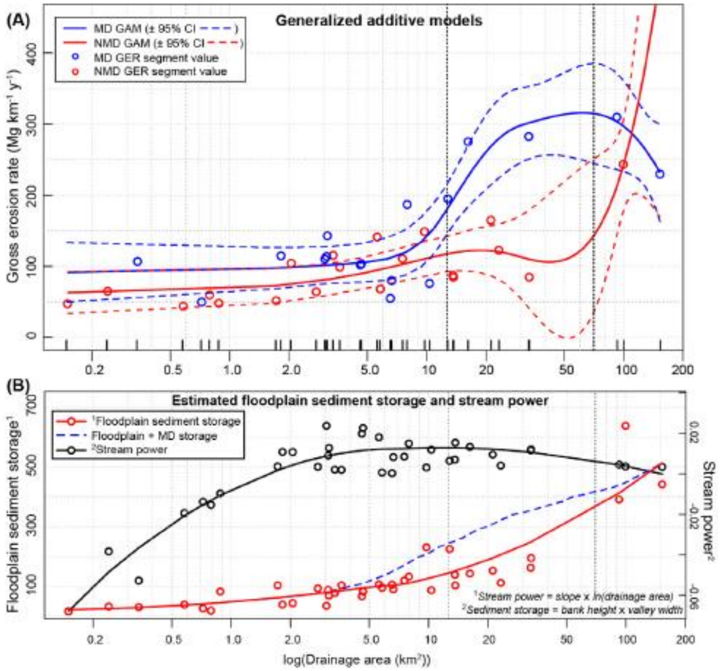
(see also Hopkins et al. 2018)

Schenk et al. 2013



Bank erosion and floodplain trapping fluxes increase with drainage area

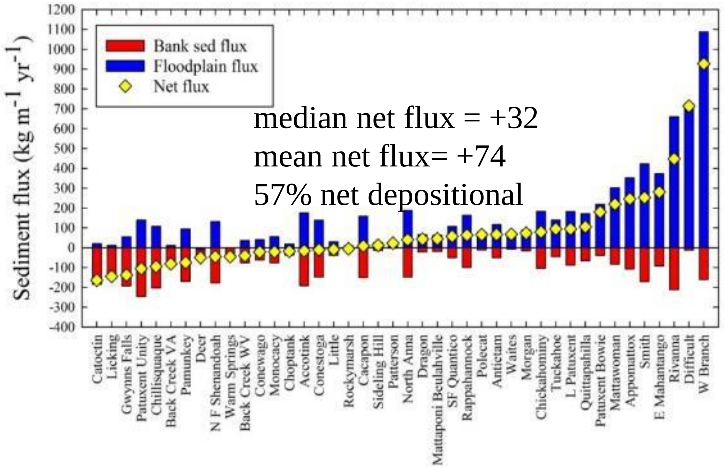
Donovan et al. 2016



USGS *Source, transport, delivery*

Stream internal fluxes: banks and floodplains

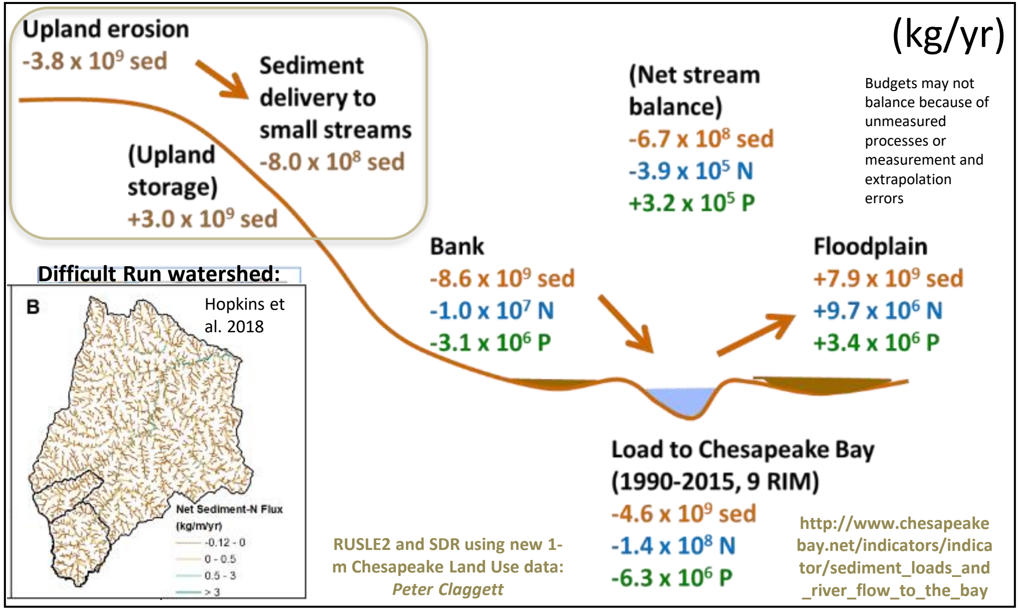
1. The long-term balance of bank erosion and floodplain deposition varies greatly



2. But is potentially predictable from reach geomorphology and watershed hydro, soil and land use characteristics

3. Allowing prediction of fluxes for every NHD+ stream reach in the entire Chesapeake watershed: generating a sediment budget

Mass balance highlighting relative magnitude of sediment sources and sinks



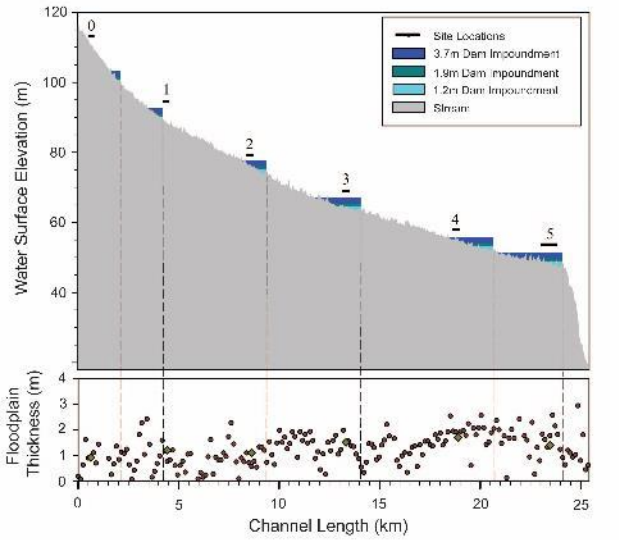
This information is preliminary or provisional and is subject to revision. It is being provided to meet the need for timely best science. The information has not received final approval by the U.S. Geological Survey (USGS) and is provided on the condition that neither the USGS nor the U.S. Government shall be held liable for any damages resulting from the authorized or unauthorized use of the information.

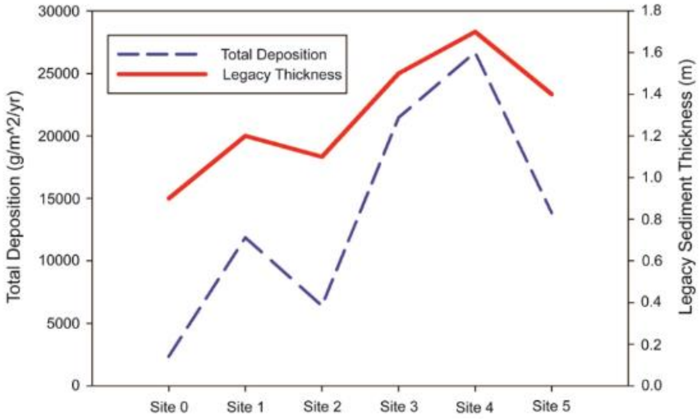
USGS *Source, transport, delivery*

Noe et al. in preparation

Floodplain storage

The example of Difficult Run, VA (Hupp et al. 2013)





The Difficult Run floodplain is composed of fill/legacy sediment. However the (at least six) historic mill ponds were not requisite for substantial deposition on floodplains, they remain active fluvial features not terraces. The similarity between active deposition and legacy thickness suggests there have been no regime changes and that underlying watershed parameters (rather than mill dams) have exercised strong control on fluvial processes in the past and present.

Difficult Run stores on average 132 m^3 per meter of reach, which roughly indicates **2.6 million m^3 of storage between Sites 0 and 5 (approx. 20 km).**

USGS *Source, transport, delivery*

Stream internal fluxes: in-channel

Stream bed and point bar erosion and deposition dynamics are typically **highly variable** and a small proportion of a watershed's **sediment budget**

(Gellis et al. 2015, 2017)

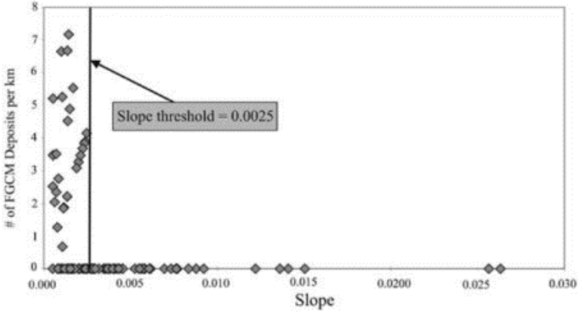
USGS *Source, transport, delivery*

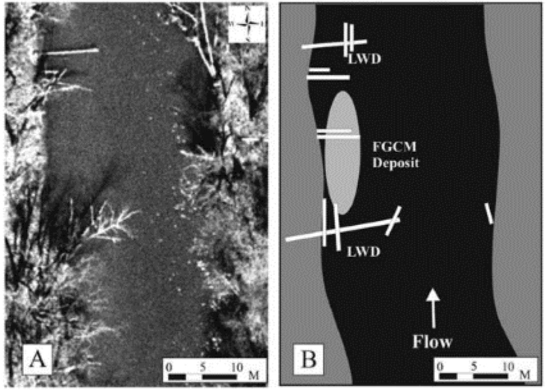
In-channel sediment storage

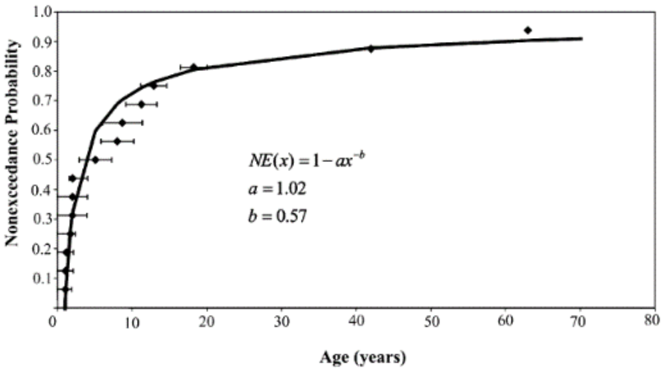
Sediment can be stored within the margins, in point bars, or in the channel bed itself

(Skalak and Pizzuto 2010)

- Significant quantities of sediment (17% of the load by volume) can be stored in the active margins and **usually conditioned by large wood in the channel**
- **Storage can range from years to decades** and is **controlled by channel morphology such as slope**
- Very high in organic content and primarily sand, silt and clay

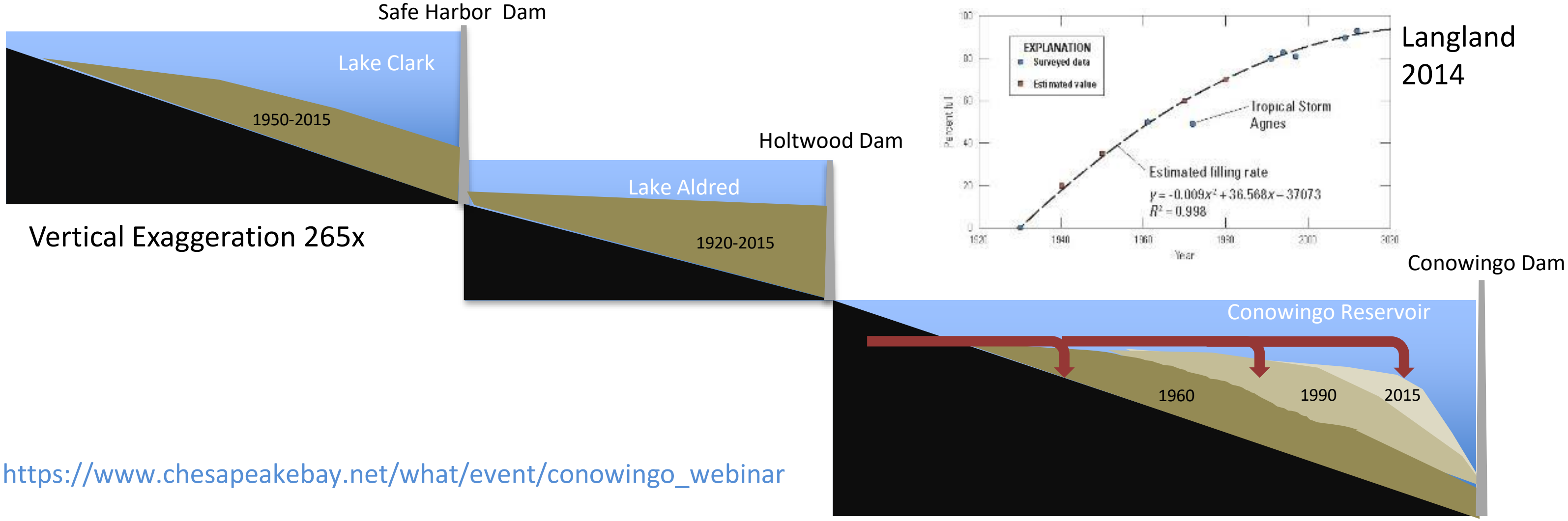






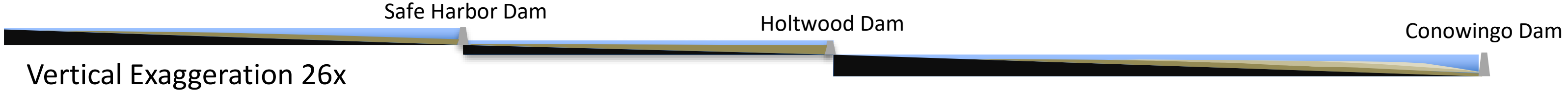
USGS *Source, transport, delivery*

Sediment infill in the lower Susquehanna reservoirs



Langland 2014

https://www.chesapeakebay.net/what/event/conowingo_webinar



Vertical Exaggeration 26x

- **Dams and upstream management practices have reduced sediment loads by ~60 percent in last 100 years.** (Langland 2014)
- LSUS River Reservoir system sediment capacity has been steadily declining and is in a state of **"dynamic equilibrium"** (Hirsch 2012, Langland 2014)
- Averaging over a range of Susquehanna flows, **approximately 30% of sediment transported to Chesapeake Bay is likely from the reservoirs; 70% is likely from the watershed** (roughly 1970-2012 time frame, Langland 2014)

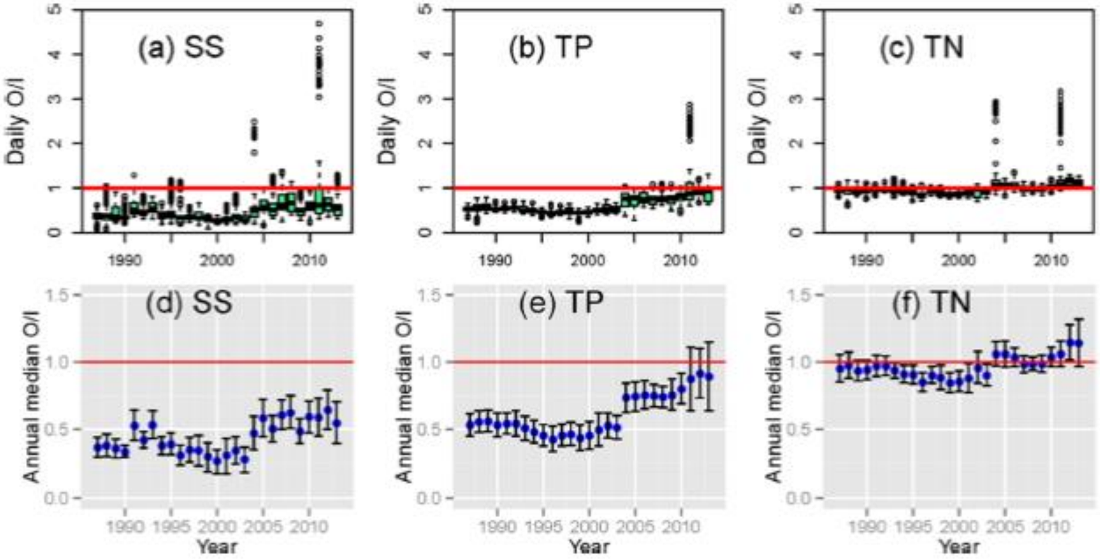
USGS

Source, transport, delivery

Sediment infill in the lower Susquehanna reservoirs

Lower Susquehanna River Reservoir System:

- Decreasing retention of suspended sediment since the 2000s
- More pronounced for finer (and more P-enriched) sediments



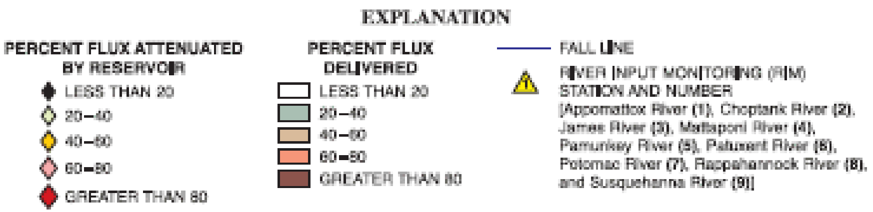
Zhang et al. 2016

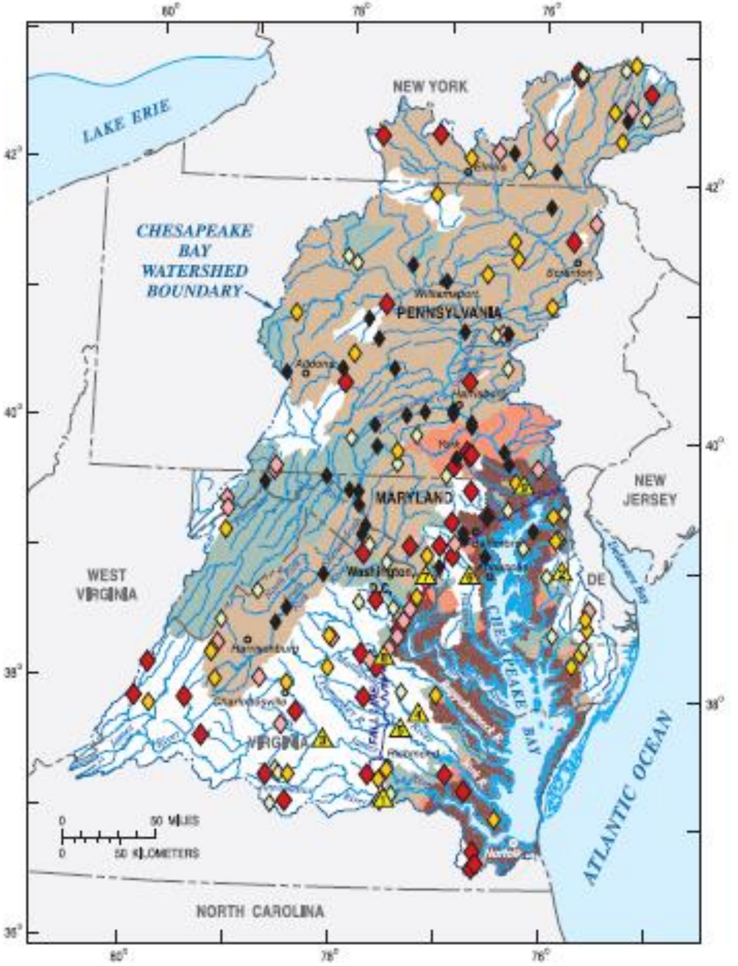
USGS *Source, transport, delivery*

Stream internal fluxes: Reservoirs

SPARROW identifies that **reservoirs trap 29% of sediment** delivered to streams in the Chesapeake watershed

(Brakebill et al. 2010)



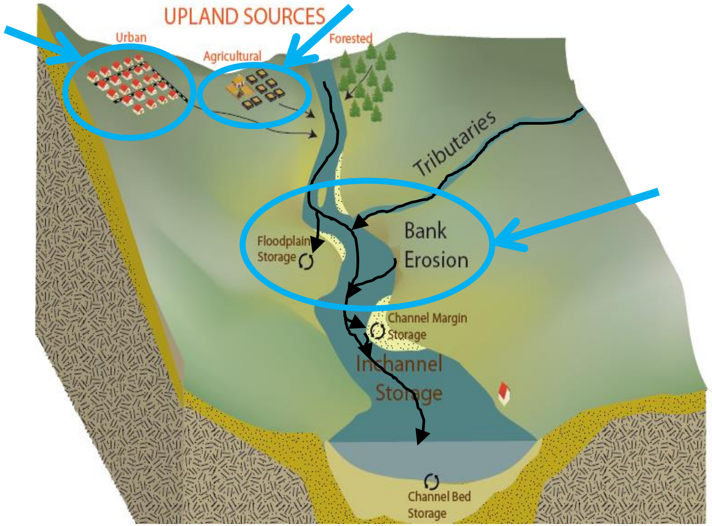


USGS *Source, transport, delivery*

Integrative understanding of sediment sources, transport, and delivery

What are the most important sources of sediment?

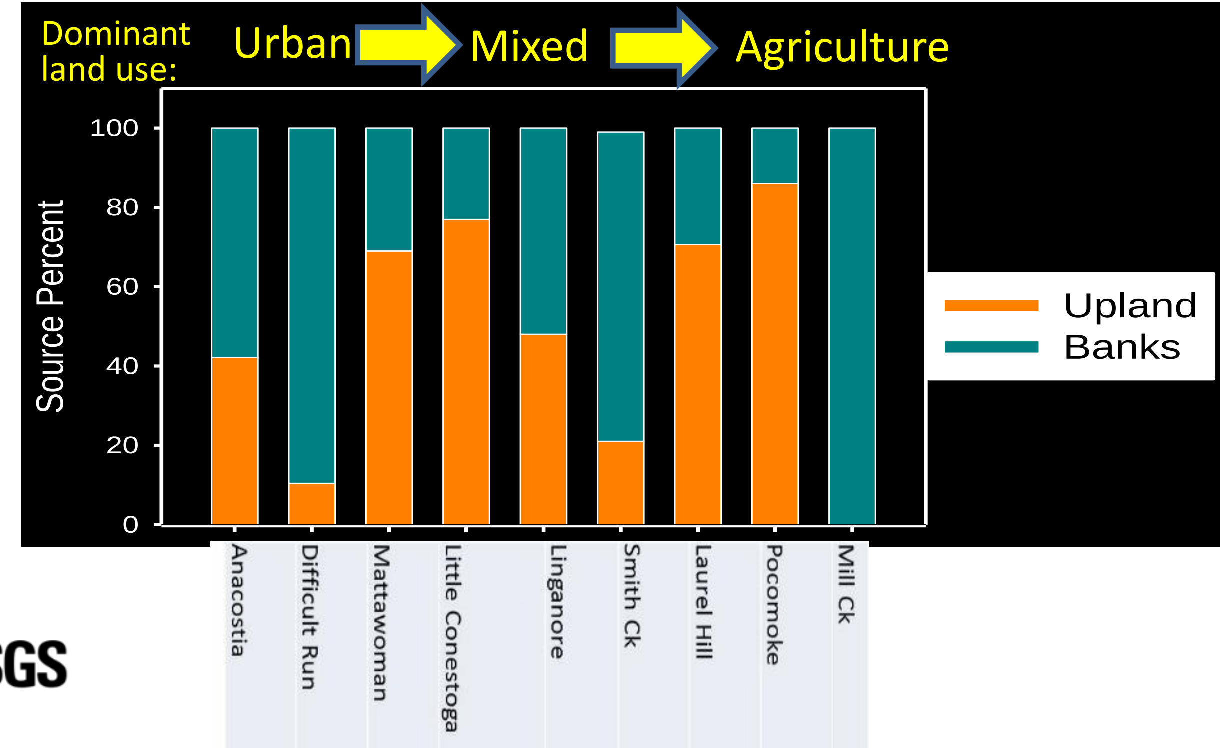
How long does it take to get to the Bay?



USGS

Fingerprinting to ID sediment sources

Sediment fingerprinting studies (n=9) for streams in the Chesapeake Bay Region indicate that **sources of suspended sediment are highly variable both across and within different land use types**



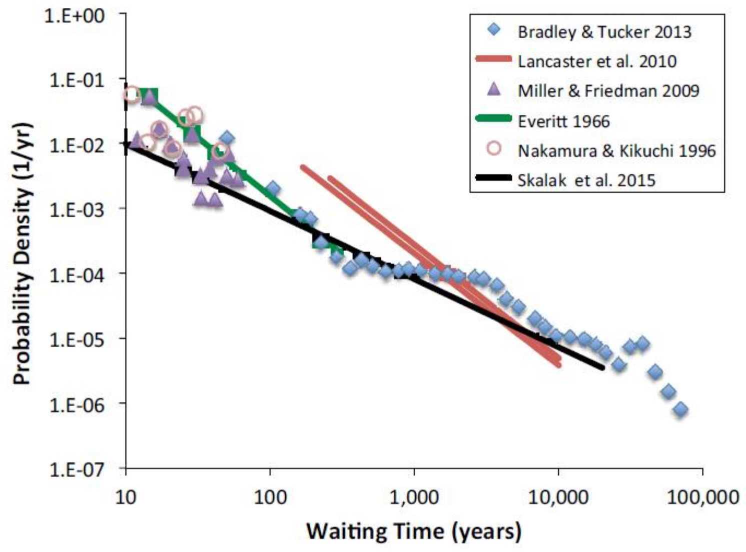
Gellis et al. 2009, Banks et al., 2010, Devereux et al., 2010, Massoudieh et al. 2013, Sloto et al., 2012, Gellis and Noe 2013, Cashman et al. 2018, Gellis and Gorman-Sanisaca 2018

Upland includes all sources outside the channel – (cropland, pasture, forest, streets, construction sites, dirt roads, ditch beds)

USGS

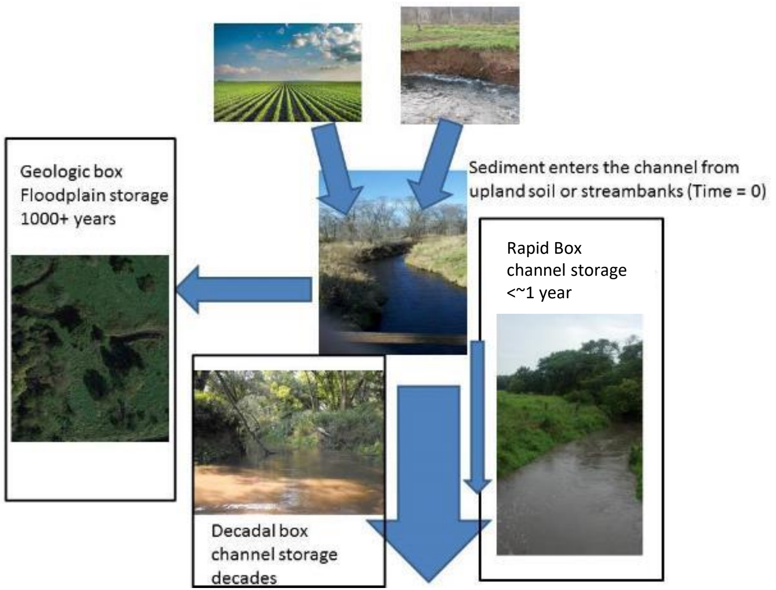
Sediment transit times

Sediment transit times, from erosion to storage zones, can be thought of as a 3-box model:
geologic, decadal, and rapid, each with different management implications



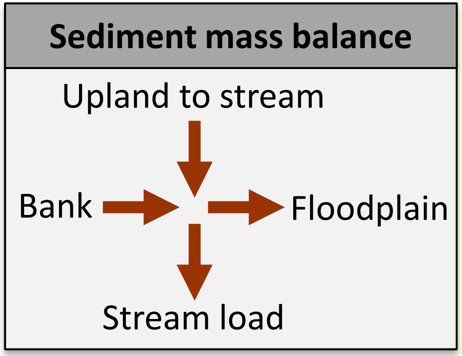
Pizzuto et al. 2017

Gellis et al. 2017

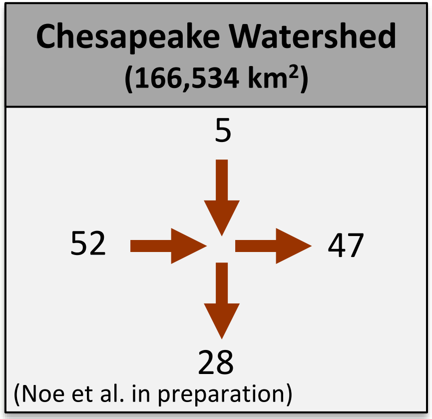


Holistic picture from watershed sediment budgets

Legend

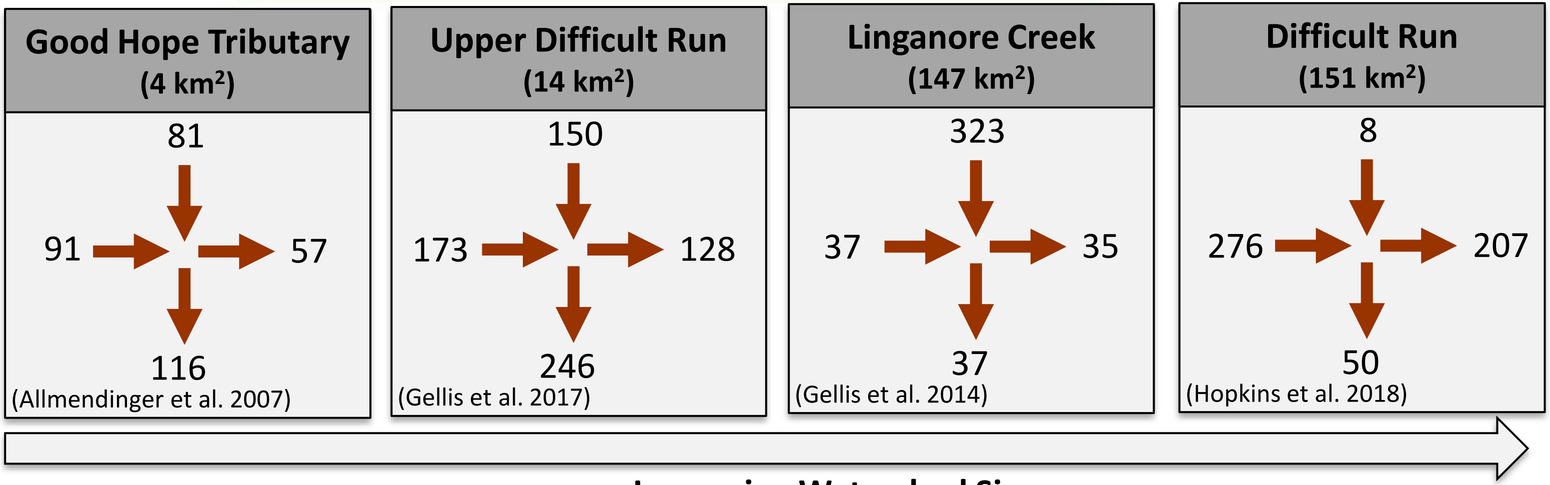


- **Bank erosion slightly greater than floodplain trapping, both are similar or greater than stream load**
- **Upland erosion inputs to streams highly variable**
- **Depends on watershed size and land use**



Fluxes are Mg/km²/yr

Inputs and outputs may not balance because of unmeasured processes or measurement and extrapolation errors



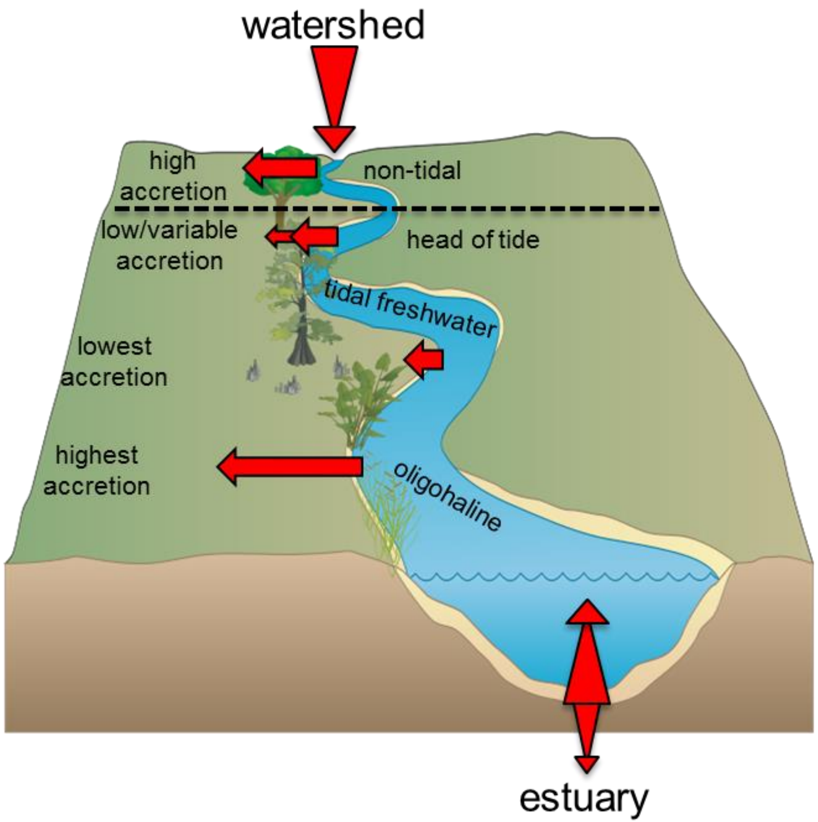
Increasing Watershed Size

USGS

Watershed delivery to the Bay

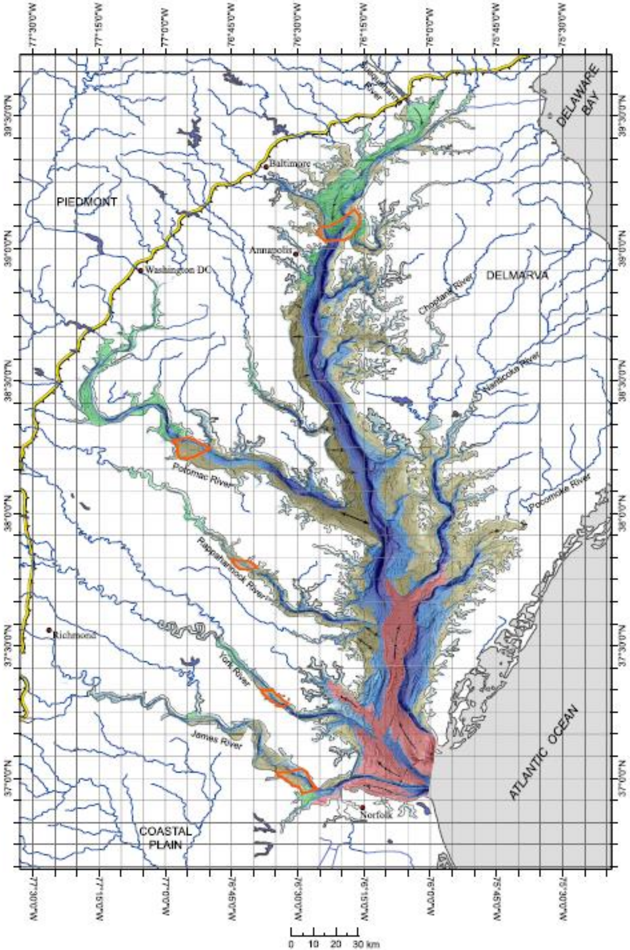
High rates of sediment trapping by Coastal Plain nontidal floodplains and head-of-tide tidal freshwater wetlands creates a **sediment shadow in many tidal rivers, limiting sediment delivery to the main Bay**
(Noe and Hupp 2009, Ensign et al. 2015)

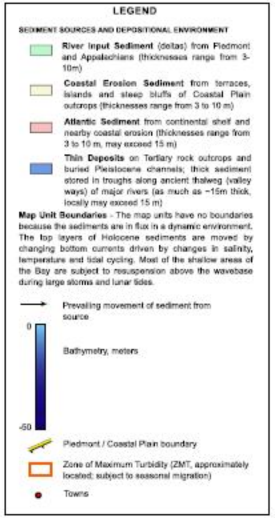
Magnitudes of sediment sources and trapping change along tidal river gradient:



Watershed delivery to the Bay

Sources of sediment within the Chesapeake Bay include river inputs, coastal erosion, and marine inputs, depending on location





Newell et al. 2004

USGS *Delivery to Bay*

Best management practices

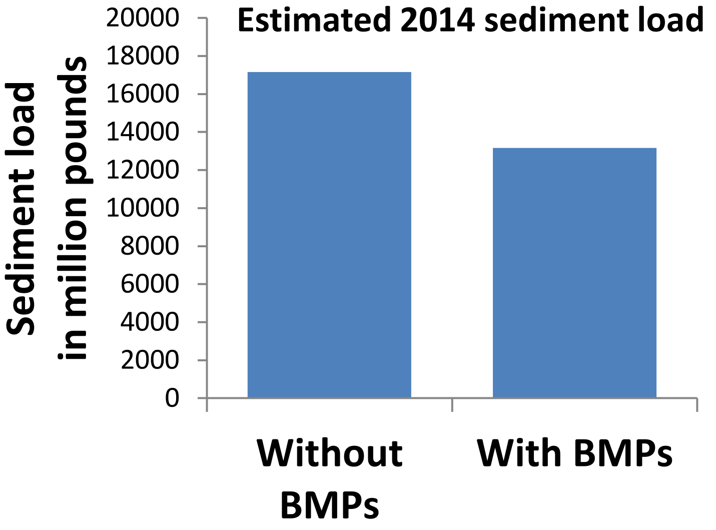
How could watersheds be managed to reduce sediment loads to meet the TMDL?

Soil conservation or stormwater controls in uplands?

Stream restoration?

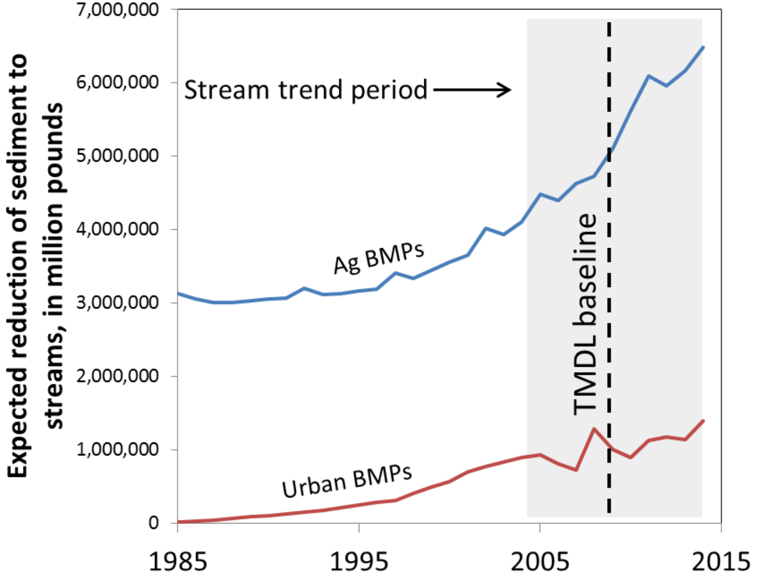
Best management practices in the Chesapeake Bay watershed

Results from the Chesapeake Bay Watershed Model v5.3.2



Ag BMP implementation has accelerated from 1985 to 2014, and is expected to reduce total sediment load to streams by 19%.

Urban BMP implementation is expected to reduce total sediment load to streams by 4%.



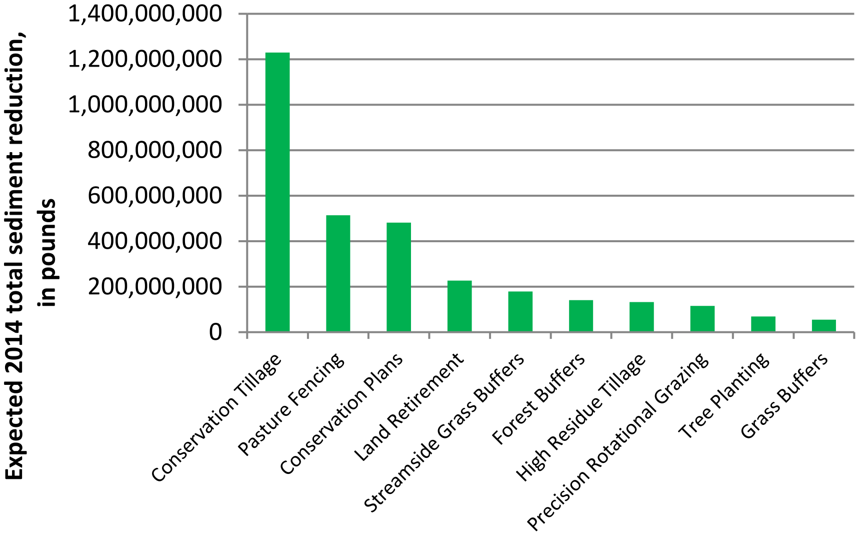
BMPs are estimated to have reduced the sediment load to streams in the Chesapeake Bay watershed by about 23% in 2014.

USGS *BMPs* Sekellick et al. in review

Best management practices in the Chesapeake Bay watershed

Results from the Chesapeake Bay Watershed Model v5.3.2

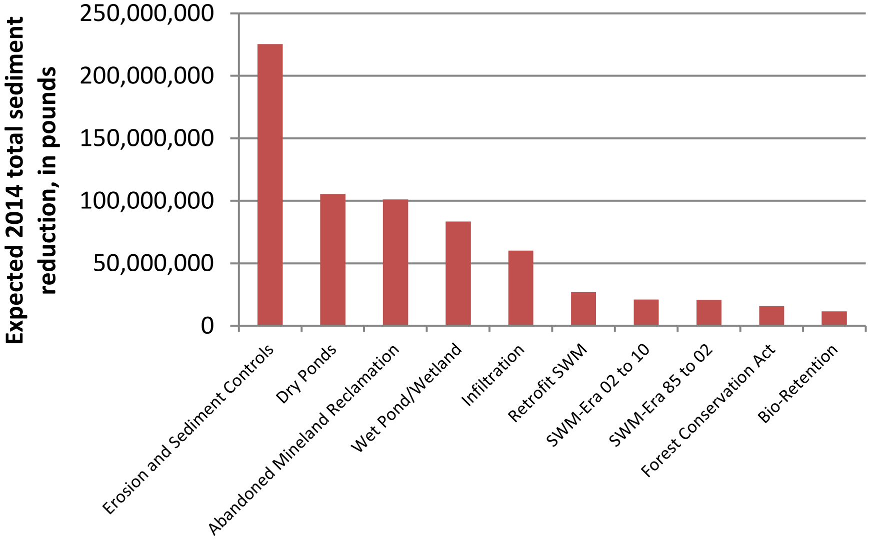
Top 10 Sediment Reducing Agricultural BMPs



The principal BMPs for reducing agricultural sediment loads to streams have a wide variety of modes of action.

The two urban BMPs with the greatest reduction in sediment loadings rely on intercepting sediment and reducing erosion.

Top 10 Sediment Reducing Urban BMPs



USGS *BMPs*

Sekellick et al. in review

Review of BMP sediment removal efficiencies

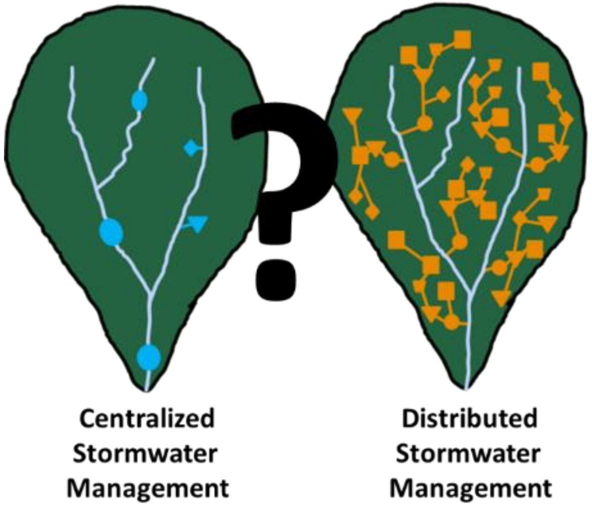
Wide ranges of pollutant removal efficiencies reported for most BMPs, especially urban BMPs.

Limited number of studies specific to Chesapeake Bay states.

modified from Liu et al. 2017

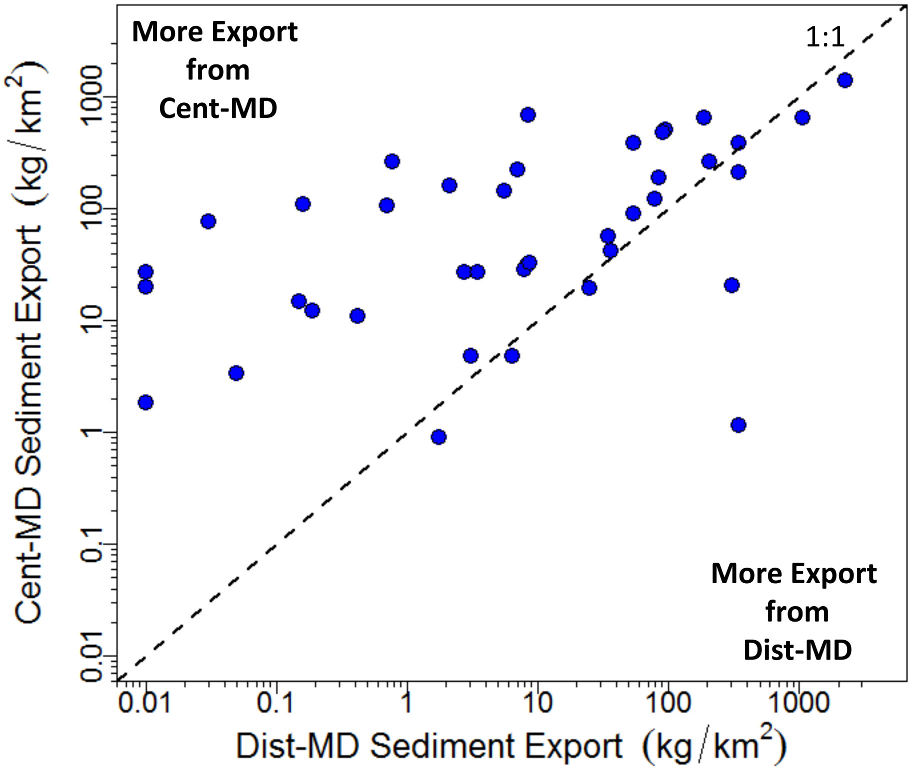
BMPs	TSS Reduction Range	Number of Studies	Citation
Urban BMPs			
Sediment and Erosion Control	46 - 99%	20	Simpson and Weammert 2009
Dry Detention Basins	-52 - 98%	20	Simpson and Weammert 2009
Dry Extended Basins	30 - 85%	5	Simpson and Weammert 2009
Wet Ponds and Wetlands	-78 - 99%	80	Simpson and Weammert 2009
Constructed Wetlands	57 - 99%	8	Cronk 1996
Bioretention/Rain Garden	47 - 99%	17	Ahiablame et al. 2012
Bioretention/Rain Garden	-170 - 96%	4	Dietz 2007
Bioretention/Rain Garden	54 - 99%	12	Davis et al. 2009
Bioretention/Rain Garden	47 - 100%	40	LeFevre et al. 2014
Bioretention/Rain Garden	-170 - 100%	14	Liu et al. 2014
Permeable Pavement	58 - 94%	10	Ahiablame et al. 2012
Swale Systems	30 - 98%	5	Ahiablame et al. 2012
Agricultural BMPs			
Buffer Strip	2 - 100%	54	Arora et al 2010
Buffer Strips	0 - 100%	16	Reichenberger et al 2007
Grass Buffer Strips	53 - 98%	11	Dorioz et al. 2006
Grass Strips	24 - 97%	7	Mekonnen et al. 2015
Grassed waterway	65 - 97%	3	Mekonnen et al. 2015
Shrub and tree buffer	45 - 100%	7	Mekonnen et al. 2015
Vegetated Buffers	45 - 100%	31	Liu et al. 2008
Vegetated Buffers	15 - 100%	20	Yuan et al 2009
Streamside forest buffer	21 - 97%	37	Sweeney and Newbold 2014
Riparian Buffer Strip	75 to 94%	16	Simpson and Weammert 2009

Case Study: Urban BMPs in Clarksburg, MD



Hopkins et al. 2017

Storm Events in Summer 2011-2012

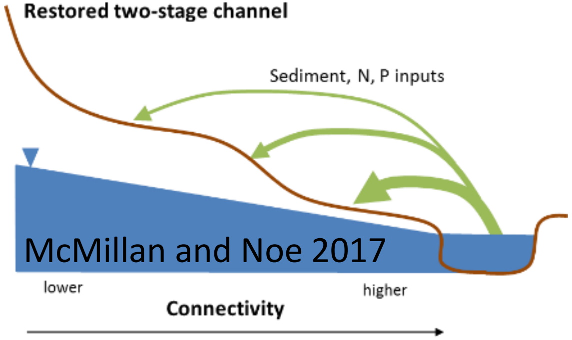


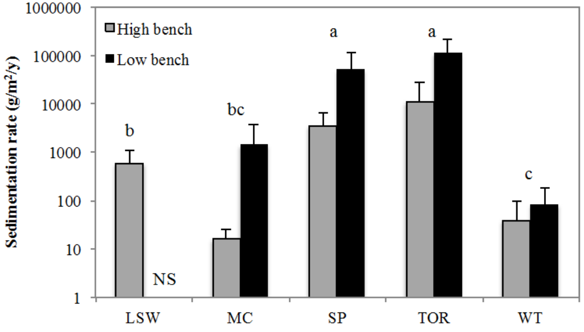
Storm event sampling indicated **less sediment export from watershed with distributed stormwater BMPs** compared to watershed with centralized stormwater BMPs, especially for small rain events.

Case study: stream BMPs

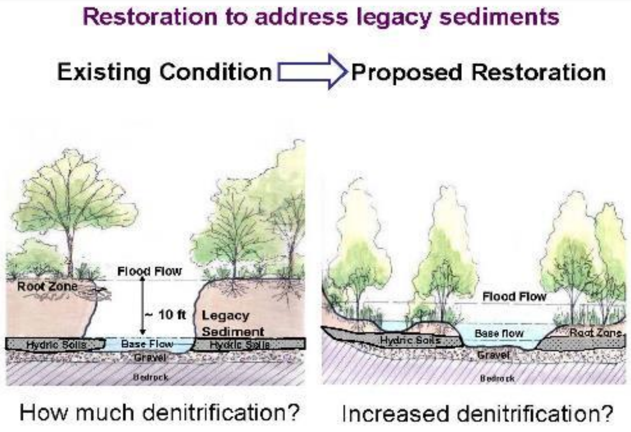
Preventing bank erosion and reconnecting floodplains works

Stream geomorphic 'restoration' (e.g. Natural Channel Design) can be effective at increasing sediment trapping through floodplain creation (Charlotte, NC example)

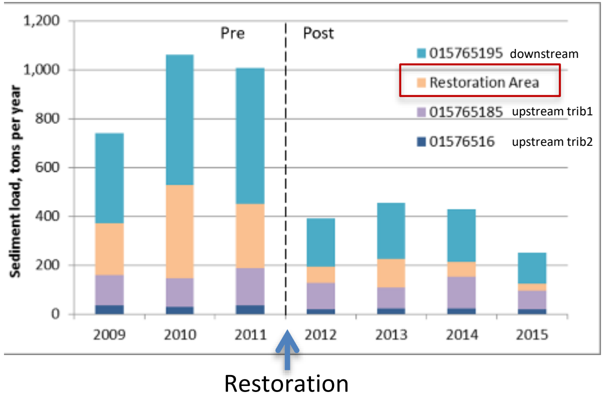




Removal of legacy sediment reduces downstream sediment load (Big Spring Run, PA example)



Langland et al. in review



USGS *BMPs*

Scientific tools

Data

- Suspended sediment, bedload, rates of sediment erosion and trapping

Sediment fingerprinting

- SED_SAT

Sediment budgets

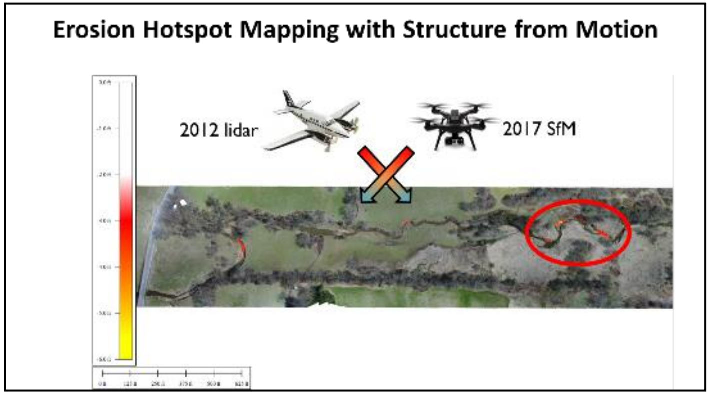
- Individual studies of erosion and deposition rates across watersheds
- Combined inference with fingerprinting

Models

- CB Watershed Model (now Phase 6)
- SPARROW
- SWAT
- 1-D Transport and storage
- Chesapeake Floodplain (and Bank) Network

Geomorphic characterization

- LIDAR and LIDAR change, SFM, FACET, surveying, bathymetry, photogrammetry, visual assessments, etc.



A robust toolkit is growing and refining … applying it to observe and model your watershed will help you to implement management actions to reduce sediment loading and impacts!

Sediment simulation in Phase 6 WSM

RUSLE = Edge-of-Field Loads

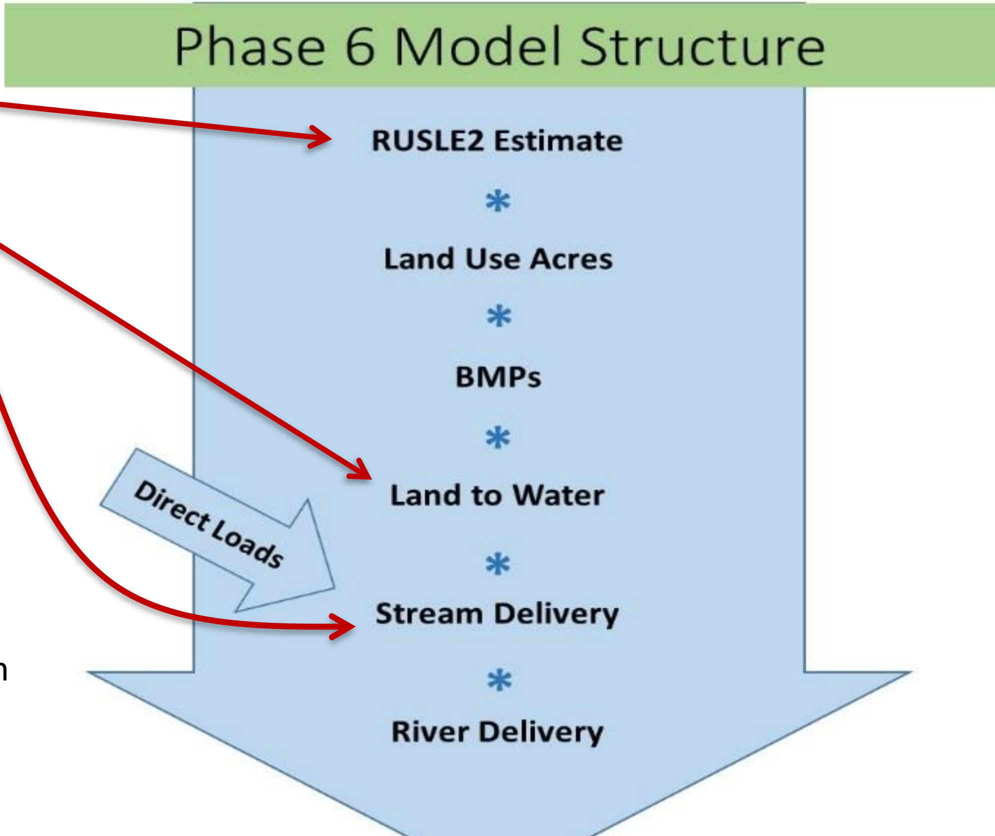
- 10 m pixel of land use

Interconnectivity Metric for Land-to-Water

- Calculation related to Slope, Area, Flowpath Length, and Roughness

Stream Delivery – based on USGS Chesapeake Floodplain Network

- Apply average bank erosion per meter to NHD streamlines
- Assume that equal floodplain deposition takes place in the streams
- Deposition affects bank erosion loads and terrestrial loads proportionally, creating a stream sediment delivery ratio for each watershed.



Chesapeake Bay Program 2017

USGS *Scientific tools*

State of the science

Measurement techniques

- Different techniques (e.g. sediment budget methods) can yield different results in space and time
- **Can target hot spots of erosion, erosion sources, and trapping zones**
- **Quantifying suspended sediment loads in response to management actions**
- Scientific expertise for addressing management questions is growing and available

What are the least certain elements of our conceptual model?

- How long sediment rests in different storage zones (e.g. floodplains, in-channel) in differing watersheds, and how that can lead to lag times in the …
- Predicted vs. observed changes in river loads associated with BMPs
- Interactions of sediment transport and storage with phosphorus
- Balance of alluvial storage and erosion and magnitudes compared to downstream loads
- How does an individual BMP affect downstream sediment processes?

Summary

How to guide management actions:

Scale, Time, and Land Use

Lane et al. 2007

Geology and historical land use generated a physical template that current land use, and climate, in addition to management, are acting upon to control the sediment delivery to the Chesapeake Bay.

Variations in the temporal and spatial scale of these factors and landscape processes interact in complex ways and require further study to improve predictability of sediment sources, transport, fate and BMP effectiveness.

Scale-dependent factors influencing management action choices:

Sediment sources

- **Piedmont, urban and agriculture land use, headwater streams are all important**

Transport times and lags

- **Active sediment storage can delay detection of effects of BMPs on sediment loads**

BMPs

- **Wide range in efficiencies, but many are effective, although trends in stream loads are not consistent**
- **Improving knowledge of sources and lags can help target BMP type and locations**

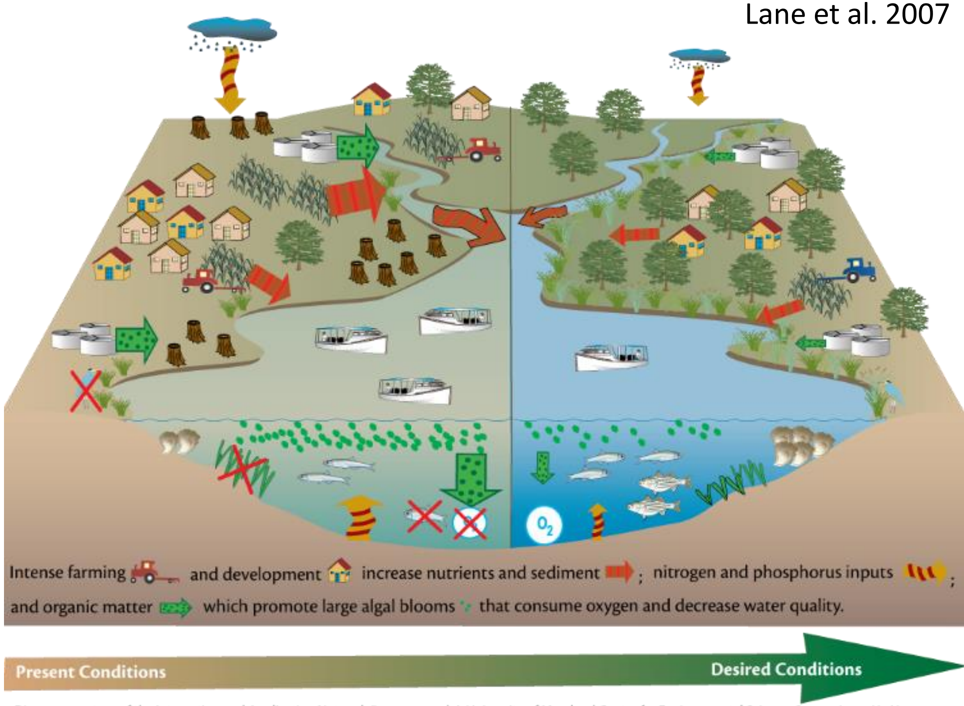


Diagram courtesy of the Integration and Application Network (ian.umces.edu), University of Maryland Center for Environmental Science. Source: Lane, H., J.L. Woerner, W.C. Dennison, C. Neill, C. Wilson, M. Elliott, M. Shively, J. Graine, and R. Jeavons. 2007. Defending our National Treasure: Department of Defense Chesapeake Bay Restoration Partnership 1998-2004. Integration and Application Network, University of Maryland Center for Environmental Science, Cambridge: MD.

Specific guidance for WIP and TMDL implementation

The state of the science points to urban, Piedmont, and headwater streams as having the greatest rates of sediment yield in the Chesapeake watershed, whereas agricultural streams generally have lower rates but are more widespread

Headwater streams: *1st and 2nd order channels erode their streambanks but typically have minimal active floodplains*

TMDL implications: consider practices associated with stream restoration to prevent bank erosion

Co-benefit considerations: improve stream health and fish habitat and increase fish passage

Larger streams and rivers: *If well connected to channels, floodplains can trap much of the sediment eroded upstream*

TMDL implications: conserve and restore hydrologic connectivity to floodplains

Co-benefit considerations: improve wildlife and fish habitat and biodiversity, and mitigate flooding

Urban areas: *Bank erosion is the dominant source of sediment export*

TMDL implications: consider stormwater control in the uplands with stream restoration to prevent bank erosion

Co-benefit considerations: improve stream health, fish habitat, and recreation

Agricultural areas: *Both bank erosion and upland soil erosion are important sediment sources in agricultural areas; the two can often be visually assessed*

TMDL implications: consider practices to reduce soil erosion and implement stream buffers

Co-benefit considerations: improve stream health and fish habitat and forest buffer

TMDL implications: legacy sediment removal can prevent bank erosion and restore floodplain connectivity

Co-benefit considerations: improve wetland and fish and wildlife habitat

Not all sediment is equal: *Contaminated sediment can be targeted for management*

Coarse sediment is needed for stream habitat, whereas fine sediment has the largest impact on stream biota

The Sediment Story: take home points

Excessive sediment harms fish and wildlife in the Chesapeake Bay and its watershed

Three important geomorphic principles to guide management:

Scale	Sediment starts in the uplands and moves through stream storage compartments Sediment processes differ in headwater streams than in larger rivers Sediment 'hops and rests' downstream, in and out of different storage zones (like floodplains), trapping large amounts of sediment (and nutrients), and causing lag times (sometimes fast, often slow) of response to management actions
Time	Historical legacy matters for understanding current sediment issues, and may impact BMP and management effects on loads in the future
Land Use	Nutrients and other pollutants are attached to sediment Agricultural, developed land, and stream banks are all important sources of sediment, but locally and temporally variable Based on models, BMPs are expected to have reduced the 2014 sediment load to streams by about 23% in the Chesapeake Bay watershed

New scientific advances continue to improve our ability to understand and guide management of local and regional sediment problems

USGS *Summary for watershed management*

References

- Allmendinger, N.E., J.E. Pizzuto, G.E. Moglen, and M. Lewicki. 2007. A Sediment Budget for an Urbanizing Watershed, 1951-1996, Montgomery County, Maryland, USA. JAWRA Journal of the American Water Resources Association 43:1483-1498.
- Banks, W.S.L., A.C. Gellis, and G. Noe. 2010. Sources of fine-grained suspended sediment in Mill Stream Branch watershed, Corsica River Basin, a tributary to the Chesapeake Bay, Maryland. In: Proceedings, 2nd Joint Federal Interagency, Las Vegas, NV, June 27 - July 1, 2010.
- Brakebill, J.W., S.W. Ator, and G.E. Schwarz. 2010. Sources of suspended-sediment flux in streams of the Chesapeake Bay watershed: a regional application of the SPARROW model. JAWRA Journal of the American Water Resources Association 46:757-776.
- Brush, G.S. 2009. Historical land use, nitrogen, and coastal eutrophication: A paleoecological perspective. Estuaries and Coasts 32:18-28.
- Buchanan, C., R.V. Lacouture, H.G. Marshall, M. Olson, and J.M. Johnson. 2005. Phytoplankton reference communities for Chesapeake Bay and its tidal tributaries. Estuaries 28:138-159.
- Burner, C.J. 1951. Characteristics of spawning nests of Columbia River salmon. U.S. Fish Wildlife Serv. Bull. 61: 97-110.
- Cabaço, S., R. Santos, and C.M. Duarte. 2008. The impact of sediment burial and erosion on seagrasses: a review. Estuarine, Coastal and Shelf Science 79:354-366.
- Cashman, M.J., A. Gellis, L.G. Sanisaca, G.B. Noe, V. Cogliandro, and A. Baker. 2018. Bank-derived material dominates fluvial sediment in a suburban Chesapeake Bay watershed. River Research and Applications 43:1032-1044.
- Cerco, C.F., and M.R. Noel. 2016. Impact of reservoir sediment scour on water quality in a downstream estuary. Journal of Environmental Quality 45:894-905.
- Chesapeake Bay Program. 2017. Chesapeake Assessment and Scenario Tool (CAST) Version 2017. Chesapeake Bay Program Office, Annapolis, Maryland.
- Chutter, F.M. 1969. The effects of silt and sand on the invertebrate fauna of streams and rivers. Hydrobiologia 34:57-76.
- Cloern, J.E. 1987. Turbidity as a control on phytoplankton biomass and productivity in estuaries. Continental Shelf Research 7:1367-1381.
- Colden, A.M., and R.N. Lipcius. 2015. Lethal and sublethal effects of sediment burial on the eastern oyster Crassostrea virginica. Marine Ecology Progress Series 527:105-117.
- Comeau, L.A., A. Mallet, C. Carver, J.-B. Nadalini, and R. Tremblay. 2017. Behavioural and lethal effects of sediment burial on quiescent Eastern oysters Crassostrea virginica. Aquaculture 469:9-15.
- Cordone, A.J., and D.W. Kelley. 1961. The influences of inorganic sediment on the aquatic life of streams California Department of Fish and Game.
- Devereux, O.H., K.L. Prestegaard, B.A. Needelman, and A.C. Gellis. 2010. Suspended-sediment sources in an urban watershed, Northeast Branch Anacostia River, Maryland. Hydrological Processes 24:1391-1403.
- Donovan, M., A. Miller, M. Baker, and A. Gellis. 2015. Sediment contributions from floodplains and legacy sediments to Piedmont streams of Baltimore County, Maryland. Geomorphology 235:88-105.
- Donovan, M., A. Miller, and M. Baker. 2016. Reassessing the role of milldams in Piedmont floodplain development and remobilization. Geomorphology 268:133-145.
- Elliott, S.J., P. Wilf, R.C. Walter, and D.J. Merritts. 2013. Subfossil leaves reveal a new upland hardwood component of the pre-European Piedmont landscape, Lancaster County, Pennsylvania. PLoS ONE 8:e79317.
- Ensign, S.H., G.B. Noe, C.R. Hupp, and K.J. Skalak. 2015. Head-of-tide bottleneck of particulate material transport from watersheds to estuaries. Geophysical Research Letters 42:10,671–10,679.
- Fabricius, K.E., M. Logan, S.J. Weeks, S.E. Lewis, and J. Brodie. 2016. Changes in water clarity in response to river discharges on the Great Barrier Reef continental shelf: 2002-2013. Estuarine, Coastal and Shelf Science 173:A1-A15.
- Flanders, J.R., R.R. Turner, T. Morrison, R. Jensen, J. Pizzuto, K. Skalak, and R. Stahl. 2010. Distribution, behavior, and transport of inorganic and methylmercury in a high gradient stream. Applied Geochemistry 25:1756-1769.
- Foresman, T.W., S.T.A. Pickett, and W.C. Zipperer. 1997. Methods for spatial and temporal land use and land cover assessment for urban ecosystems and application in the greater Baltimore-Chesapeake region. Urban Ecosystems 1:201-216.
- Gellis, A.C., C.R. Hupp, M.J. Pavich, J.M. Landwehr, W.S.L. Banks, B.E. Hubbard, M.J. Langland, J.C. Ritchie, and J.M. Reuter. 2009. Sources, transport, and storage of sediment at selected sites in the Chesapeake Bay Watershed. U. S. Geological Survey.
- Gellis, A.C., and G.B. Noe. 2013. Sediment source analysis in the Linganore Creek watershed, Maryland, USA, using the sediment fingerprinting approach: 2008 to 2010. Journal of soils and sediments 13:1735-1753.
- Gellis, A.C., G.B. Noe, J.W. Clune, M.K. Myers, C.R. Hupp, E.R. Schenk, and G.E. Schwarz. 2015. Sources of fine-grained sediment in the Linganore Creek watershed, Frederick and Carroll Counties, Maryland, 2008-10 2328-0328. US Geological Survey.
- Gellis, A.C., M.K. Myers, G.B. Noe, C.R. Hupp, E.R. Schenk, and L. Myers. 2017. Storms, channel changes, and a sediment budget for an urban-suburban stream, Difficult Run, Virginia, USA. Geomorphology 278:128-148.
- Gellis, A.C., C.C. Fuller, P.C. Van Metre, C. Filstrup, M.D. Tomer, and K. Cole. 2017. The sources and ages of fine-grained sediment using elemental analysis and fallout radionuclides for an agricultural stream, Walnut Creek, Iowa. Geological Society of America Abstracts with Programs 49(6), doi: 10.1130/abs/2017AM-305664; available at https://gsa.confex.com/gsa/2017AM/webprogram/Paper305664.html; accessed March 9, 2018
- Gellis, A.C., and L. Gorman Sanisaca. 2018. Sediment fingerprinting to delineate sources of sediment in the agricultural and forested Smith Creek watershed, Virginia, USA. JAWRA Journal of the American Water Resources Association 2018: 1-25.
- Gillespie, J.L., G.B. Noe, C.R. Hupp, A.C. Gellis, and E.R. Schenk. 2018. Floodplain trapping and cycling compared to streambank erosion of sediment and nutrients in an agricultural watershed. JAWRA Journal of the American Water Resources Association.
- Gurbisz, C., W.M. Kemp, L.P. Sanford, and R.J. Orth. 2016. Mechanisms of storm-related loss and resilience in a large submersed plant bed. Estuaries and Coasts 39:951-966.
- Hirsch, R.M. 2012. Flux of nitrogen, phosphorus, and suspended sediment from the Susquehanna River Basin to the Chesapeake Bay during Tropical Storm Lee, September 2011, as an indicator of the effects of reservoir sedimentation on water quality 2328-0328. US Geological Survey.
- Hinchey, E.K., L.C. Schaffner, C.C. Hoar, B.W. Vogt, and L.P. Batte. 2006. Responses of estuarine benthic invertebrates to sediment burial: the importance of mobility and adaptation. Hydrobiologia 556:85-98.
- Hoomehr, S., A.I. Akinola, T. Wynn-Thompson, W. Garnand, and M.J. Eick. 2018. Water temperature, pH, and road salt impacts on the fluvial erosion of cohesive streambanks. Water 10:302.
- Hopkins, K.G., J.V. Loperfido, L.S. Craig, G.B. Noe, and D.M. Hogan. 2017. Comparison of sediment and nutrient export and runoff characteristics from watersheds with centralized versus distributed stormwater management. Journal of Environmental Management 203:286-298.
- Hopkins, K.G., G.B. Noe, F. Franco, E.J. Pindilli, S. Gordon, M.J. Metes, P.R. Claggett, A.C. Gellis, C.R. Hupp, and D.M. Hogan. 2018. A method to quantify and value floodplain sediment and nutrient retention ecosystem services. Journal of Environmental Management 220:65-76.
- Horowitz, A.J., and V.C. Stephens. 2008. The effects of land use on fluvial sediment chemistry for the conterminous US: Results from the first cycle of the NAWQA Program: Trace and major elements, phosphorus, carbon, and sulfur. Science of The Total Environment 400:290-314.
- Hupp, C.R., and A. Simon. 1991. Bank accretion and the development of vegetated depositional surfaces along modified alluvial channels. Geomorphology 4:111-124.
- Hupp, C.R., G.B. Noe, E.R. Schenk, and A.J. Benthem. 2013. Recent and historic sediment dynamics along Difficult Run, a suburban Virginia Piedmont stream. Geomorphology 180:156-169.
- Jacobson, R.B., and D.J. Coleman. 1986. Stratigraphy and recent evolution of Maryland Piedmont flood plains. American Journal of Science 286:617-637.
- Jones, J.I., J.F. Murphy, A.L. Collins, D.A. Sear, P.S. Naden, and P.D. Armitage. 2012. The impact of fine sediment on macro-invertebrates. River Research and Applications 28:1055-1071.
- Kemp, P., D. Sear, A. Collins, P. Naden, and I. Jones. 2011. The impacts of fine sediment on riverine fish. Hydrological Processes 25:1800-1821.
- Lane, H., J.L. Woerner, W.C. Dennison, C. Neill, C. Wilson, M. Elliott, M. Shively, J. Graine, and R. Jeavons. 2007. Defending Our National Treasure: Department of Defense Chesapeake Bay Restoration Partnership 1998-2004. Integration and Application Network, University of Maryland Center for Environmental Science, Cambridge, Maryland.
- Langland, M., and T. Cronin. 2003. A summary report of sediment processes in Chesapeake Bay and watershed. US Geological Survey.
- Langland, M.J. 2015. Sediment transport and capacity change in three reservoirs, Lower Susquehanna River Basin, Pennsylvania and Maryland, 1900-2012 2331-1258. US Geological Survey.
- Liu, Y., B.A. Engel, D.C. Flanagan, M.W. Gitau, S.K. McMillan, and I. Chaubey. 2017. A review on effectiveness of best management practices in improving hydrology and water quality: needs and opportunities. Science of The Total Environment 601:580-593.
- Louhi, P., A. Mäki-Petäys, and J. Erkinaro. 2008. Spawning habitat of Atlantic salmon and brown trout: general criteria and intragravel factors. River Research and Applications 24:330-339.
- Massoudieh, A., A. Gellis, W.S. Banks, and M.E. Wieczorek. 2013. Suspended sediment source apportionment in Chesapeake Bay watershed using Bayesian chemical mass balance receptor modeling. Hydrological Processes 27:3363-3374.
- McMillan, S.K., and G.B. Noe. 2017. Increasing floodplain connectivity through urban stream restoration increases nutrient and sediment retention. Ecological Engineering 108:284-295.
- Merritts, D., R. Walter, M. Rahnis, J. Hartranft, S. Cox, A. Gellis, N. Potter, W. Hilgartner, M. Langland, and L. Manion. 2011. Anthropocene streams and base-level controls from historic dams in the unglaciated mid-Atlantic region, USA. Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences 369:976-1009.
- Moyer, D.L., J.G. Chanat, G. Yang, J.D. Blomquist, and M.J. Langland. 2017. Nitrogen, phosphorus, and suspended-sediment loads and trends measured at the Chesapeake Bay Nontidal Network stations: Water years 1985-2014. U.S. Geological Survey data release, https://doi.org/10.5066/F7XK8D2R.
- Newcombe, C.P., and D.D. MacDonald. 1991. Effects of suspended sediments on aquatic ecosystems. North American journal of fisheries management 11:72-82.
- Newell, W.L., I. Clark, and O. Bricker. 2004. Distribution of Holocene sediment in Chesapeake Bay as interpreted from submarine geomorphology of the submerged landforms, selected core holes, bridge borings and seismic profiles. U.S. Geological Survey, Reston, Virginia, USA.
- Noe, G.B., and C.R. Hupp. 2005. Carbon, nitrogen, and phosphorus accumulation in floodplains of Atlantic Coastal Plain rivers, USA. Ecological Applications 15:1178-1190.
- Noe, G.B., and C.R. Hupp. 2009. Retention of riverine sediment and nutrient loads by Coastal Plain floodplains. Ecosystems 12:728-746.
- Paul, M.J., and J.L. Meyer. 2001. Streams in the urban landscape. Annual Review of Ecology and Systematics 32:333-365.
- Pizzuto, J., K. Skalak, A. Pearson, and A. Benthem. 2016. Active overbank deposition during the last century, South River, Virginia. Geomorphology 257:164-178.
- Pizzuto, J., J. Keeler, K. Skalak, and D. Karwan. 2017. Storage filters upland suspended sediment signals delivered from watersheds. Geology 45:151-154.
- Ritchie, J.C. 1972. Sediment, fish, and fish habitat. Journal of Soil and Water Conservation 27:124-125.
- Ruedemann, R., and W.J. Schoonmaker. 1938. Beaver-dams as geologic agents. Science 88:523-525.
- Ryan, P.A. 1991. Environmental effects of sediment on New Zealand streams: a review. New Zealand journal of marine and freshwater research 25:207-221.
- Schenk, E.R., C.R. Hupp, A. Gellis, and G. Noe. 2013. Developing a new stream metric for comparing stream function using a bank–floodplain sediment budget: a case study of three Piedmont streams. Earth Surface Processes and Landforms 38:771–784.
- Skalak, K., and J. Pizzuto. 2010. The distribution and residence time of suspended sediment stored within the channel margins of a gravel-bed bedrock river. Earth Surface Processes and Landforms 35:435-446.
- Skalak, K.J., and J. Pizzuto. 2014. Reconstructing suspended sediment mercury contamination of a steep, gravel-bed river using reservoir theory. Environmental Geosciences 21:17-35.
- Sloto, R.A., A.C. Gellis, and D.G. Galeone. 2012. Total nitrogen and suspended-sediment loads and identification of suspended-sediment sources in the Laurel Hill Creek watershed, Somerset County, Pennsylvania, water years 2010–11. U.S. Geological Survey Scientific Investigations Report 2012–5250.
- Smith, S.M.C., and P.R. Wilcock. 2015. Upland sediment supply and its relation to watershed sediment delivery in the contemporary mid-Atlantic Piedmont (USA). Geomorphology 232:33-46.
- Sprague, E., D. Burke, S. Claggett, and A. Todd, ed. 2006. The state of Chesapeake Forests. The Conservation Fund, Arlington, Virginia.
- Trimble, S.W. 1981. Changes in sediment storage in the Coon Creek basin, Driftless Area, Wisconsin, 1853 to 1975. Science 214:181-183.
- Visualizing Early Baltimore. 2018. University of Maryland Baltimore Campus. http://earlybaltimore.org/, accessed 3/9/2018.
- Walter, R.C., and D.J. Merritts. 2008. Natural streams and the legacy of water-powered mills. Science 319:299-304.
- Wang, P., L.C. Linker, and R.A. Batiuk. 2013. Monitored and modeled correlations of sediment and nutrients with Chesapeake Bay water clarity. JAWRA Journal of the American Water Resources Association 49:1103-1118.
- Waters, T.F. 1995. Sediment in streams. American Fisheries Society, Monograph 7.
- Wolf, K.L., G.B. Noe, and C. Ahn. 2013. Hydrologic connectivity to streams increases nitrogen and phosphorus inputs and cycling in soils of created and natural floodplain wetlands. Journal of Environmental Quality 42:1245-1255.
- Wolman, M.G. 1967. A cycle of sedimentation and erosion in urban river channels. Geografiska Annaler: Series A, Physical Geography 49:385-395.
- Wynn, T., and S. Mostaghimi. 2006. The effects of vegetation and soil type on streambank erosion, southwestern Virginia, USA. JAWRA Journal of the American Water Resources Association 42:69-82.
- Wynn, T.M., M.B. Henderson, and D.H. Vaughan. 2008. Changes in streambank erodibility and critical shear stress due to subaerial processes along a headwater stream, southwestern Virginia, USA. Geomorphology 97:260-273.
- Zhang, Q., D.C. Brady, W.R. Boynton, and W.P. Ball. 2015. Long-term trends of nutrients and sediment from the nontidal Chesapeake watershed: an assessment of progress by river and season. JAWRA Journal of the American Water Resources Association 51:1534-1555.
- Zhang, Q., R.M. Hirsch, and W.P. Ball. 2016. Long-term changes in sediment and nutrient delivery from Conowingo dam to Chesapeake Bay: effects of reservoir sedimentation. Environmental Science & Technology 50:1877-1886.
- Zhang, Q., and J.D. Blomquist. 2018. Watershed export of fine sediment, organic carbon, and chlorophyll-a to Chesapeake Bay: Spatial and temporal patterns in 1984-2016. Science of The Total Environment 619:1066-1078.
- Zhang, Q., D. Ha, H. Wei, and W. Bal. 2018. Retrospective analysis of sediment-associated phosphorus concentration in the major tributaries to Chesapeake Bay, Chesapeake Research and Modeling Symposium, Annapolis, MD.