Making Stream Restoration More Sustainable

Bob Hawley, PhD, PE

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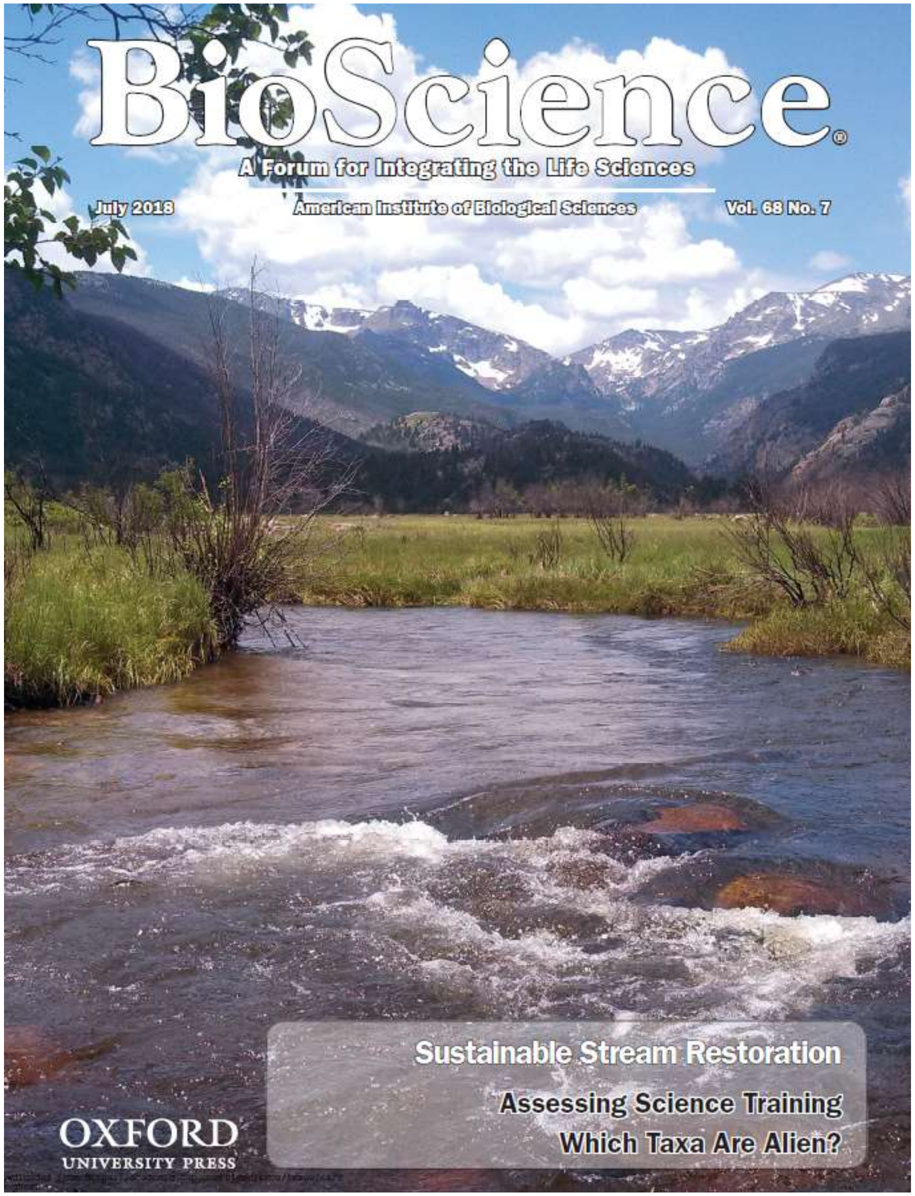

Making Stream Restoration More Sustainable: A Geomorphically, Ecologically, and Socioeconomically Principled Approach to Bridge the Practice with the Science

ROBERT J. HAWLEY

Despite large advances in the state of the science of stream ecology and river mechanics, the practitioner-driven field of stream restoration remains plagued by narrowly focused projects that sometimes even fail to improve aquatic habitat or geomorphic stability—two nearly universal project goals. The intent of this article is to provide an accessible framework that bridges that gap between the current state of practice and a more geomorphically robust and ecologically holistic foundation that also provides better accounting of socioeconomic factors in support of more sustainable stream restoration outcomes. It points to several more comprehensive design references and presents some simple strategies that could be used to protect against common failure mechanisms of ubiquitous design approaches (i.e., regional curves, Rosgen planform, and grade control). From the simple structure design to the watershed-scale restoration program, this may be a first step toward a more geomorphically principled, ecologically holistic, and socioeconomically sustainable field.

Keywords: stream restoration, sustainability, ecological engineering, freshwater biology, geomorphology

The state of the practice of stream restoration includes sweeping variability across ecoregions, political jurisdictions, and practitioner groups (Bernhardt et al. 2005). Design philosophies range from "cookie-cutter" form-based methods to highly tailored process-based approaches that incorporate ecological and hydrogeomorphic drivers. Project stakeholders can encompass assortments of regulators, developers, environmentalists, recreationalists, city or infrastructure managers, property owners, and others. Spatial scales span from the single structure (e.g., less than a 10-meter reach) to the entire watershed, with goals extending from improved channel stability to the restoration of ecosystem processes. Project outcomes can fluctuate from actually *degrading* stream habitat (Smith SM and Prestegaard 2005) and biotic integrity (Palmer et al. 2010) to restoring a more natural flow regime and facilitating ecological improvement, such as expanded availability of habitat (Hawley et al. 2017) or improved water quality (Roley et al. 2012). Costs can range from less than $1000 to more than $1 billion (Jamison 2015) and are a poor predictor of project outcomes in many cases.

The most prevalent types of United States–based stream restoration activities typically focus on manipulating in-stream habitat via heavy construction (e.g., installing boulder structures, remeandering a channel via large-scale earth moving, and engaging in other activities requiring large equipment). Although the industry has experienced incremental shifts toward more geomorphically robust and ecologically viable approaches—for example, "River Styles" in Australia and New Zealand (Brierley and Fryirs 2005) and United Kingdom–based guidance centered on reducing runoff at the source (Environment Agency 2010)—a plurality of United States–based stream channel designers (perhaps even a majority?) organize their designs around three well-intended but fallible practices: regional curve dimensions, Rosgen (1994) planform pattern, and grade control structures to constrain the profile (i.e., "dimension, pattern, and profile"; see box 1). The popular form-based approach

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Stream Restoration Industry

“Restored”

Preserved

Adapted from Hawley (2018)
BioScience

Floodplain Erosion

Adapted from Hawley (2018)
BioScience

Chute Cutoffs

Adapted from Hawley (2018)
BioScience

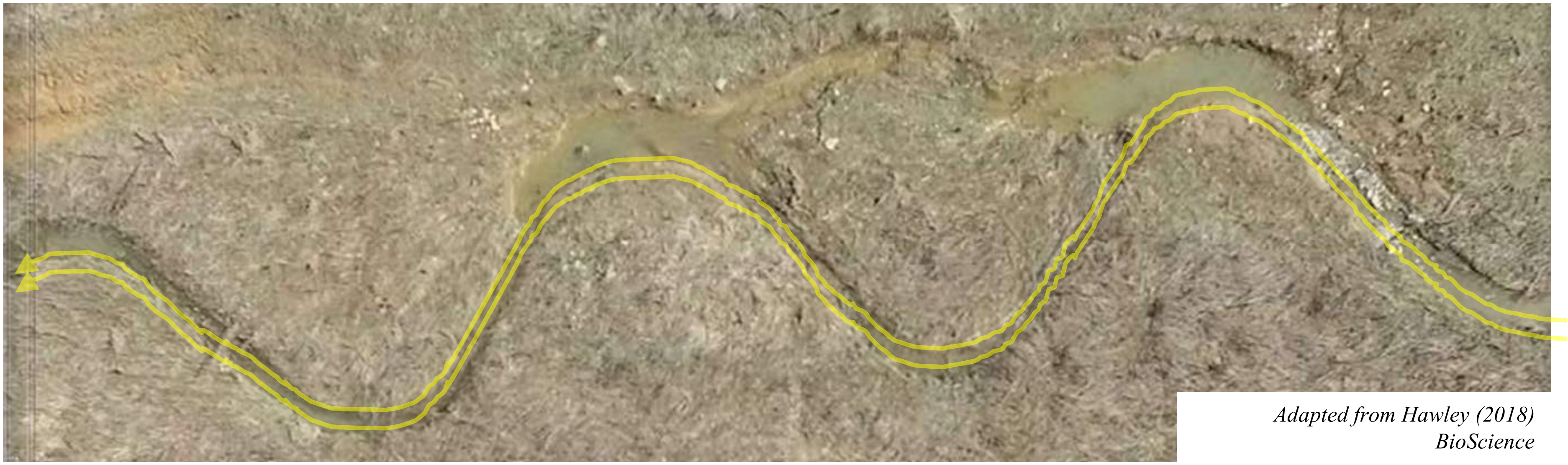
Grade Control Flanking

Adapted from Hawley (2018)
BioScience

Inadequate Armor

Adapted from Hawley (2018)
BioScience

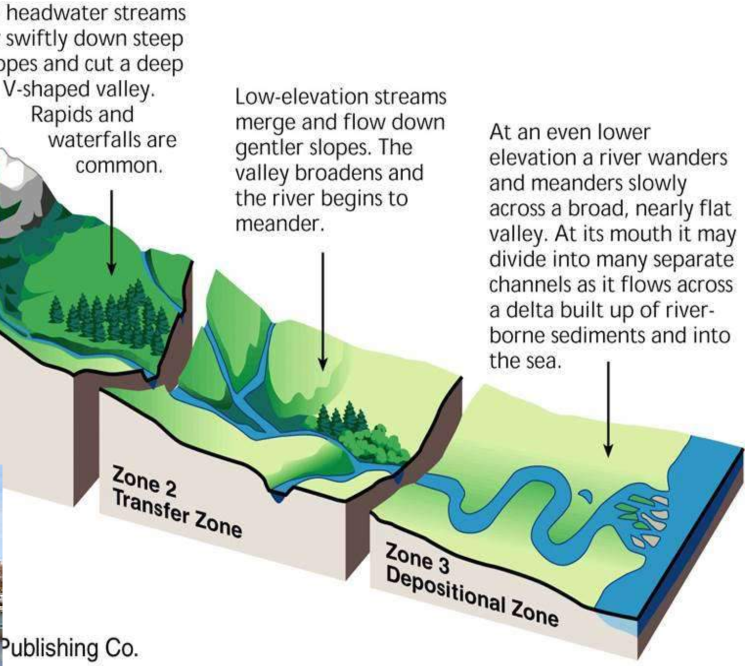
Even "Easy" Settings Can Be Prone to Failures



Adapted from Hawley (2018)
BioScience


HELP!

Let’s Get It Right



Mountain headwater streams flow swiftly down steep slopes and cut a deep V-shaped valley. Rapids and waterfalls are common.

Low-elevation streams merge and flow down gentler slopes. The valley broadens and the river begins to meander.

At an even lower elevation a river wanders and meanders slowly across a broad, nearly flat valley. At its mouth it may divide into many separate channels as it flows across a delta built up of river-borne sediments and into the sea.

Publishing Co.

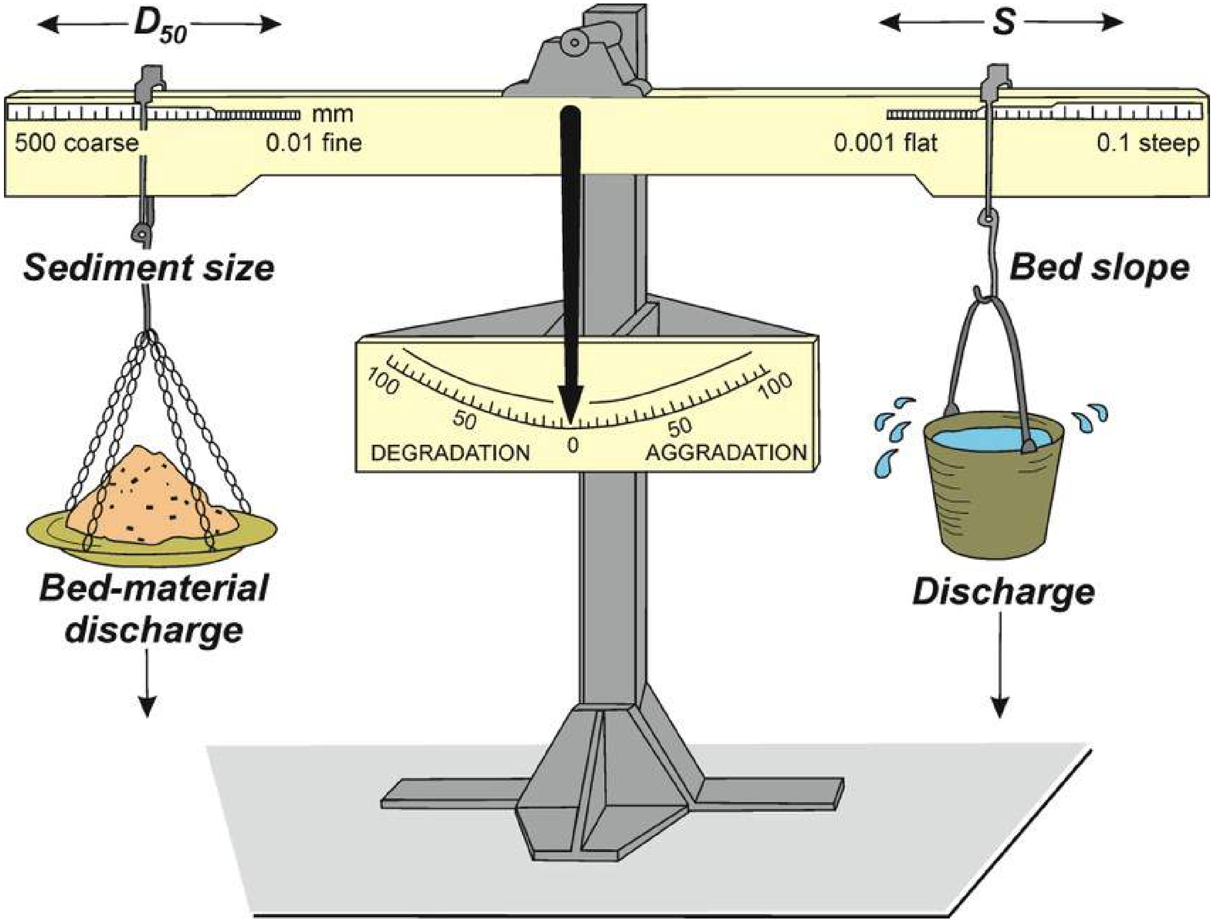
– Three longitudinal profile zones.
Corridor Restoration: Principles, Processes, and Practices, 10/98.
Stream Restoration Working Group (15 Federal Agencies of the US).

Stream Geomorphology 101: Tendency Toward Equilibrium

Resistance α Erosion

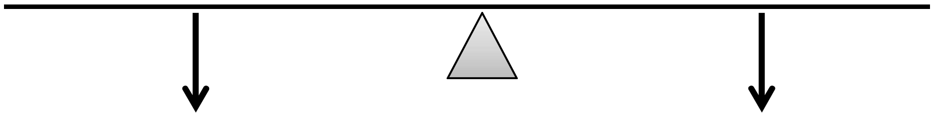
Sediment Supply in Balance with Water Supply and Slope

Lane's (1955) Balance



Lane's (1955) Balance

Resistance α **Erosion**



sediment supply (Qs)

sediment size (d_{50})

bankfull width (W)

floodplain width

grade control

bank strength

vegetation …

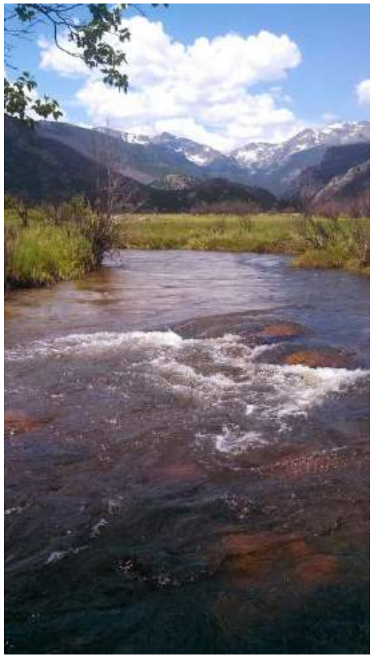
discharge (Q)

slope (S)

bankfull depth (y)

floodplain depth

valley slope …



Adapted from Hawley (2018)
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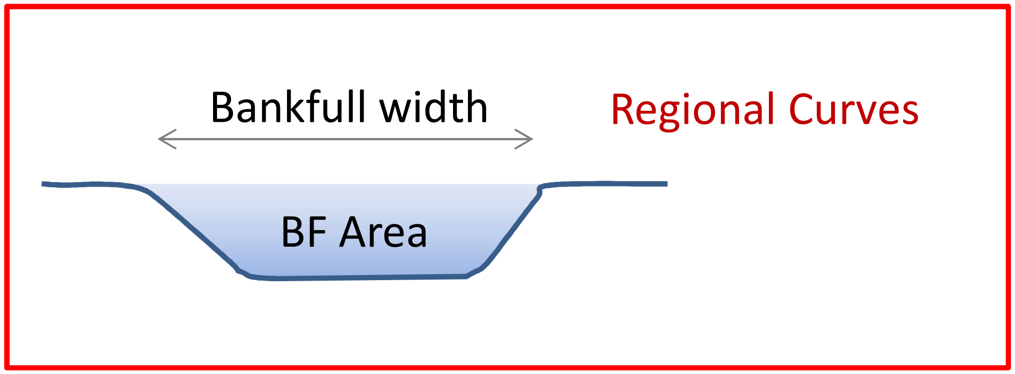
Common Practice

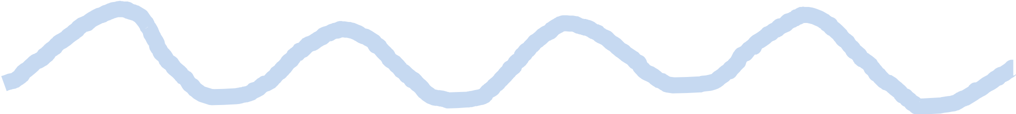
- **Dimension**



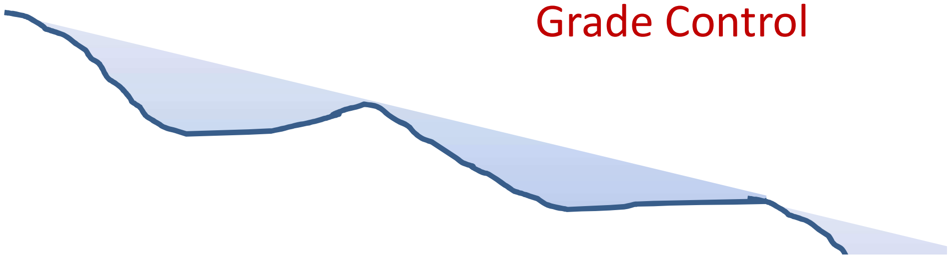
Regional Curves

- **Pattern**

Rosgen Stream Type

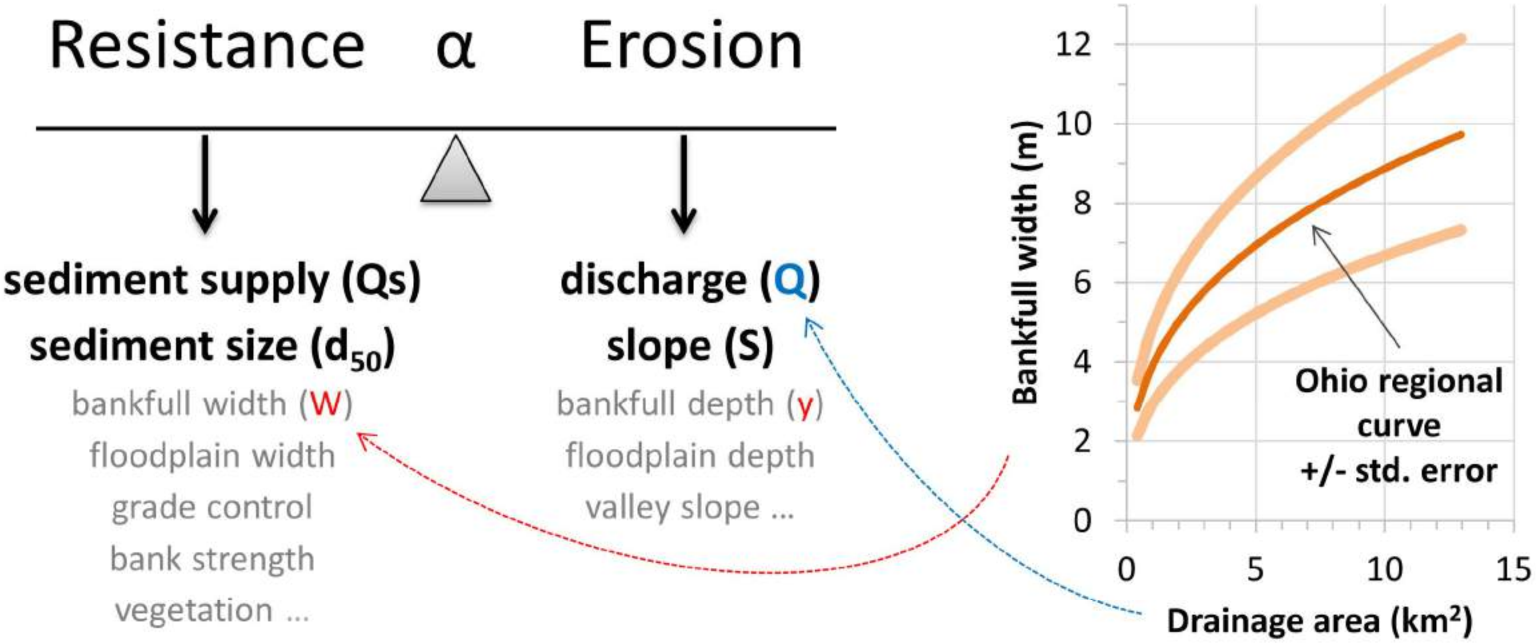


- **Profile**



Grade Control

Regional Curve Approaches typically Do Not Fully Account for Lane's Balance



Resistance α Erosion

sediment supply (Qs)
sediment size (d_{50})
bankfull width (W)
floodplain width
grade control
bank strength
vegetation …

discharge (Q)
slope (S)
bankfull depth (y)
floodplain depth
valley slope …

Adapted from Hawley (2018) BioScience

Regional Curve Approaches typically <u>Do Not</u> Fully Account for Lane's Balance

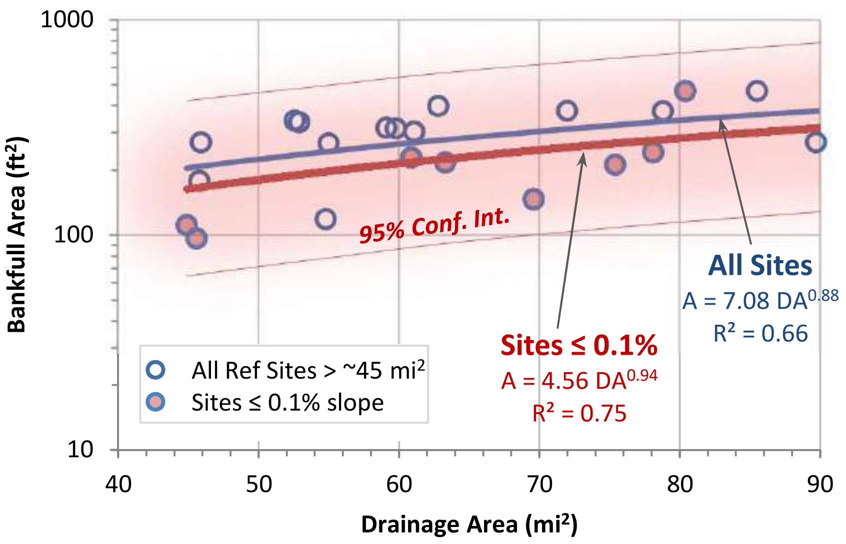
Constructed Reach

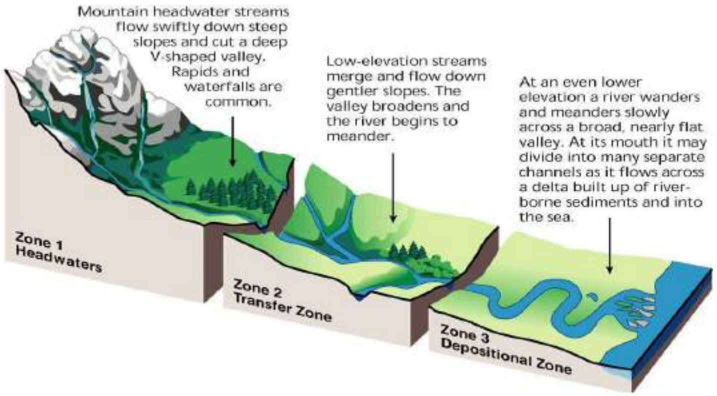
Fine bed material, high mobility

Sediment Supply Reach

Coarse bed material, low mobility

Regional Curves often Mask Considerable Scatter across Reference Sites





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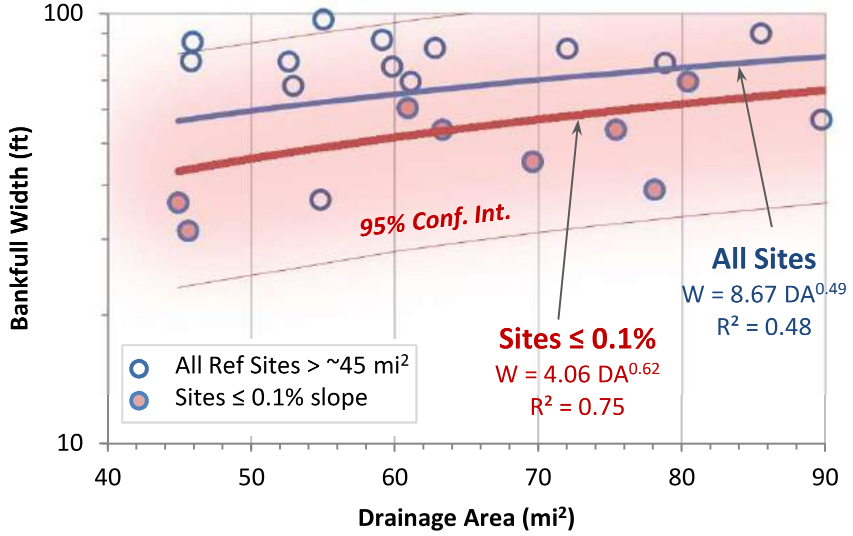
Steeper Settings

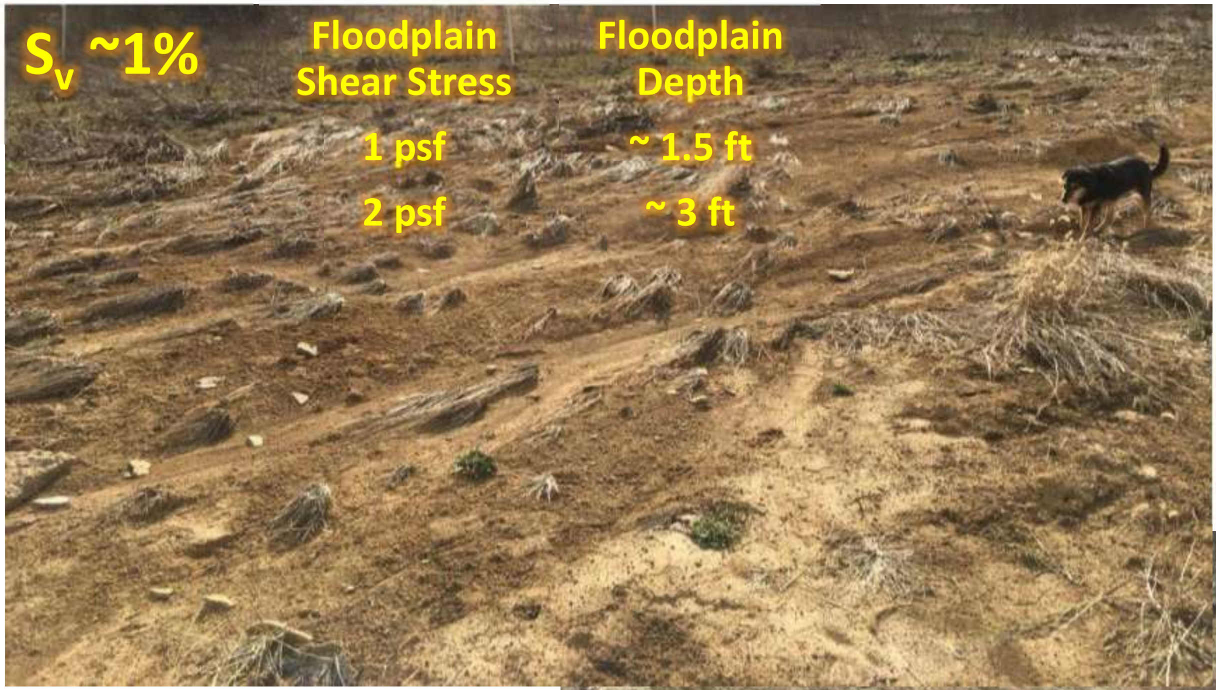
→ Higher Energy

→ Larger Channels



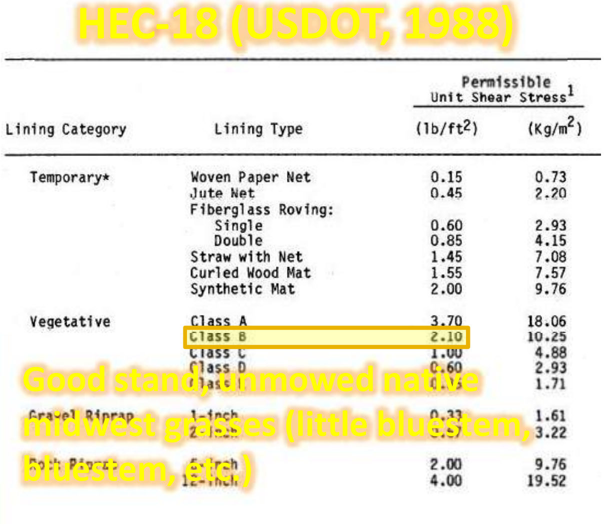
Piedmont and Coastal Plain reference stream data draining large watersheds (> ~45 mi²)

Too Small of a Channel in a Moderately Steep Valley → Floodplain Erosion



S_v ~1%

Floodplain Shear Stress	Floodplain Depth
1 psf	~ 1.5 ft
2 psf	~ 3 ft



HEC-18 (USDOT, 1988)

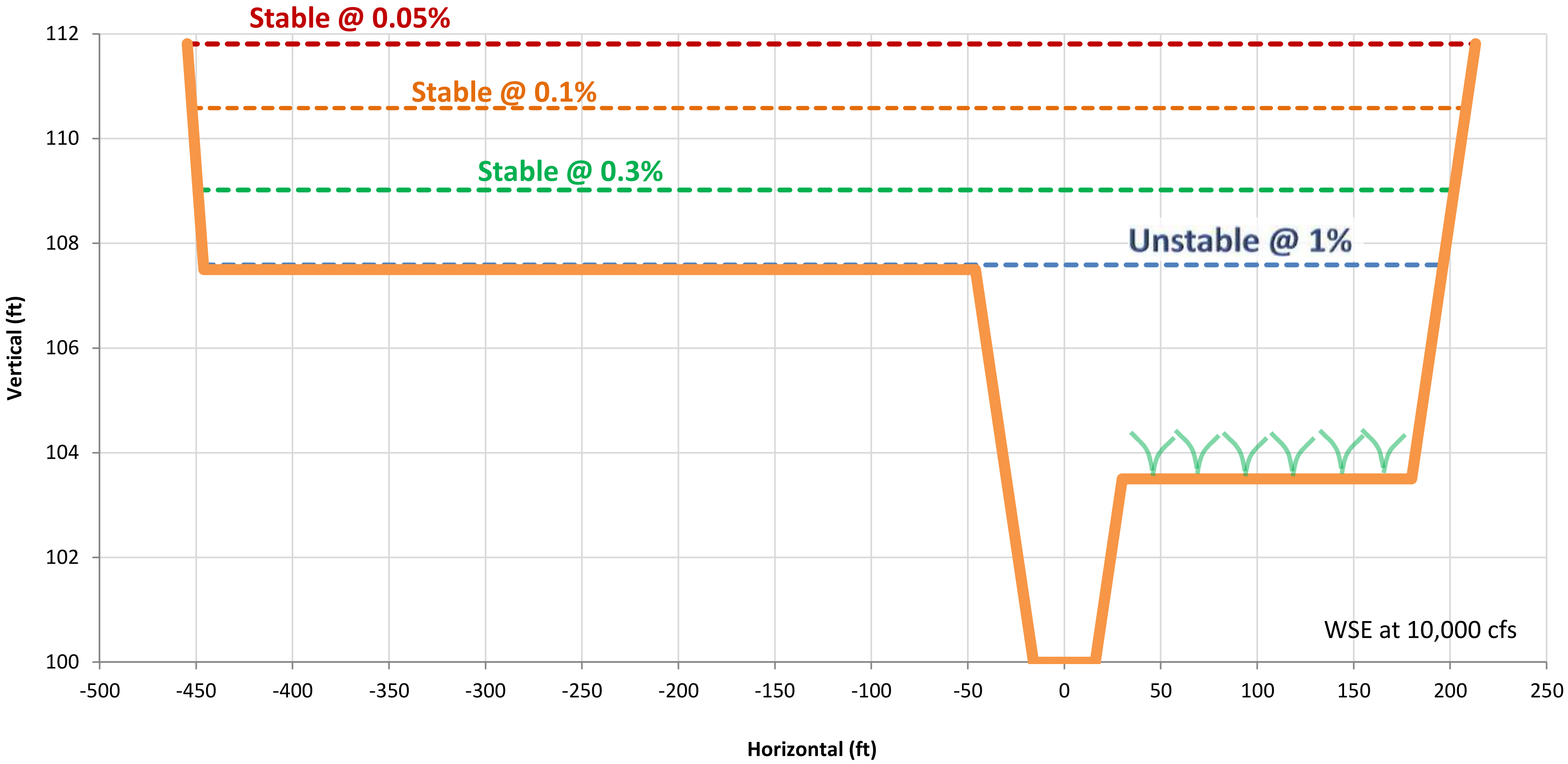
Lining Category	Lining Type	Permissible Unit Shear Stress[1] (lb/ft²)	Permissible Unit Shear Stress[1] (Kg/m²)
Temporary*	Woven Paper Net	0.15	0.73
	Jute Net	0.45	2.20
	Fiberglass Roving:		
	Single	0.60	2.93
	Double	0.85	4.15
	Straw with Net	1.45	7.08
	Curled Wood Mat	1.55	7.57
	Synthetic Mat	2.00	9.76
Vegetative	Class A	3.70	18.06
	Class B	2.10	10.25
	Class C	1.00	4.88
	Class D	0.60	2.93
	Class [illegible]	[illegible]	1.71
Gravel Riprap	1-inch	0.33	1.61
	2-inch	[illegible]	3.22
Rock Riprap	6-inch	2.00	9.76
	12-inch	4.00	19.52

Good stand, unmowed native midwest grasses (little bluestem, bluestem, etc.)

S_v ~0.5%

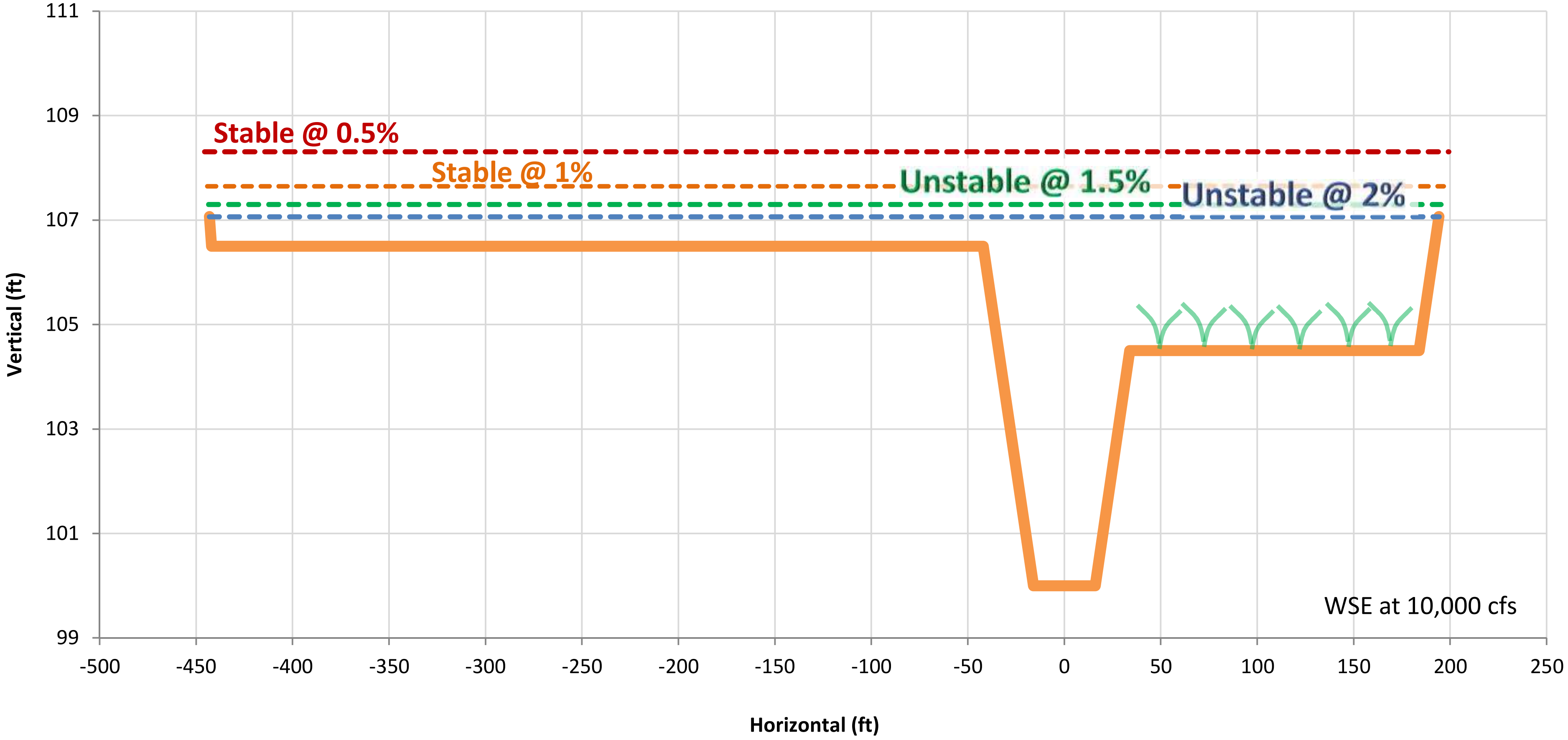
Floodplain Shear Stress	Floodplain Depth
1 psf	~ 3 ft
2 psf	~ 6 ft

Bench/Floodplain Shear Stress Increases with Slope



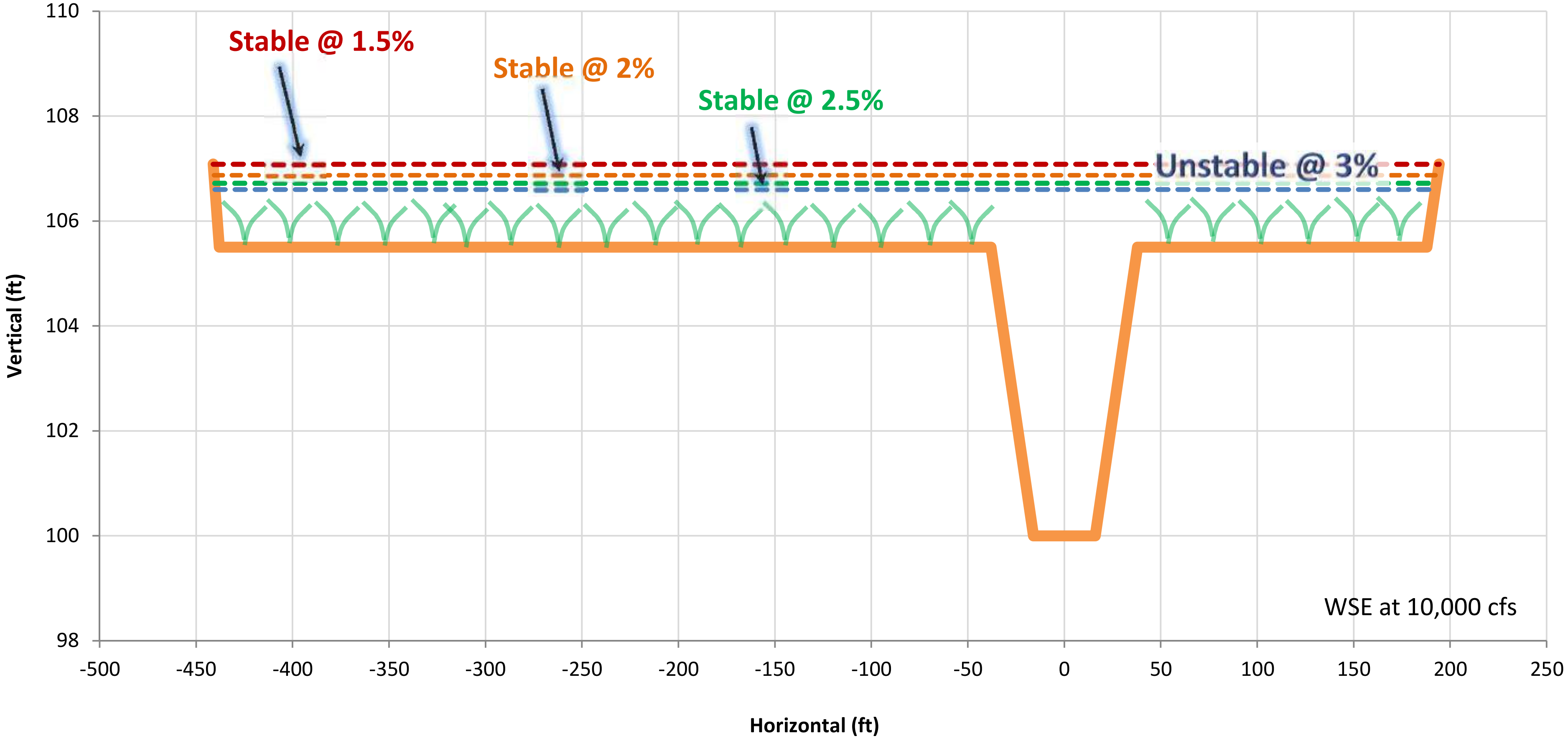
Flatter Slopes, Smaller Channel, Lower Bench

Bench/Floodplain Shear Stress Increases with Slope



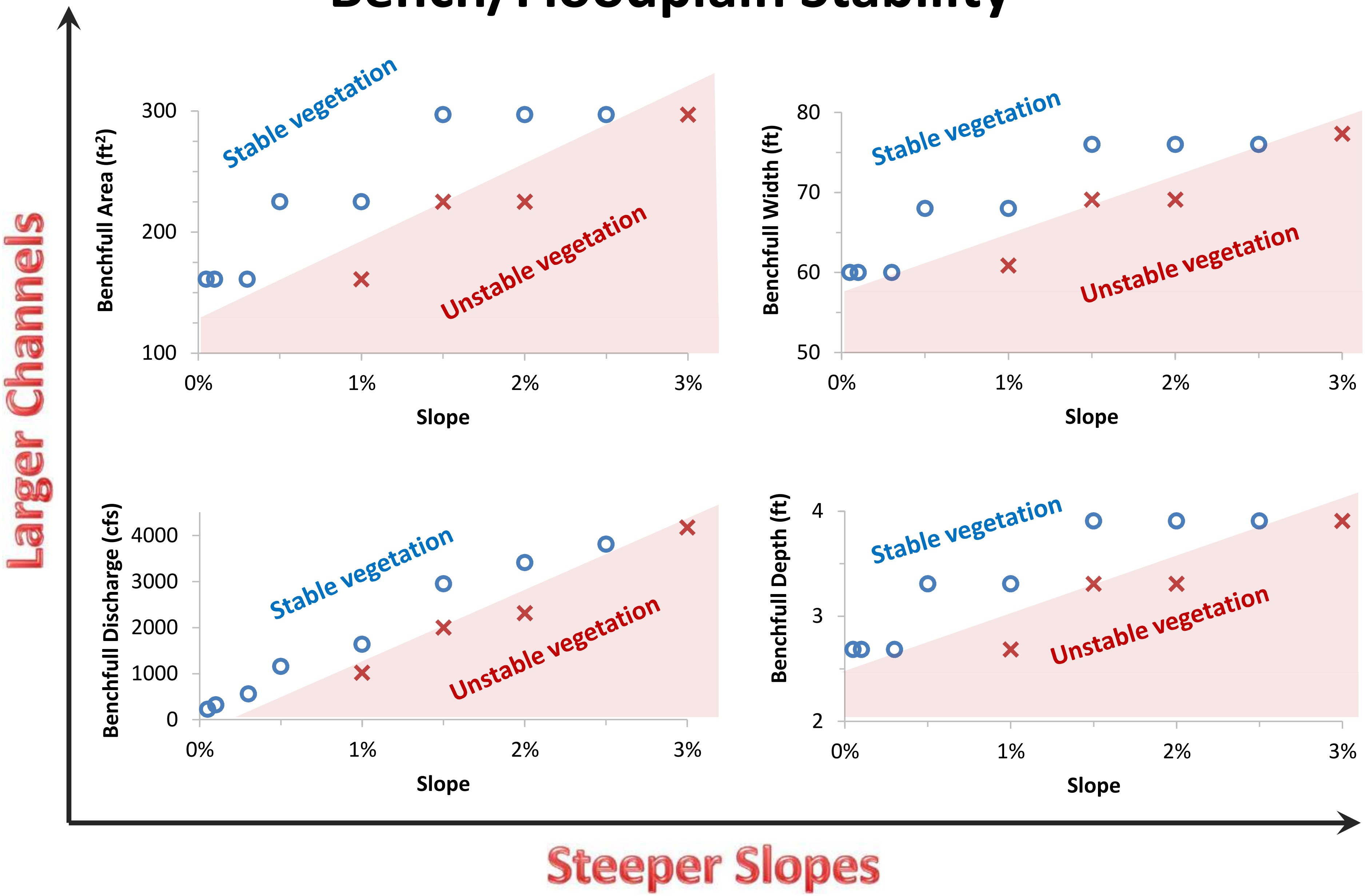
Moderate Slopes, Medium Channel, Taller Bench

Bench/Floodplain Shear Stress Increases with Slope



Steeper Slopes, Larger Channel, No Bench

Steeper Slopes Require Larger Channels for Bench/Floodplain Stability



Common Practice

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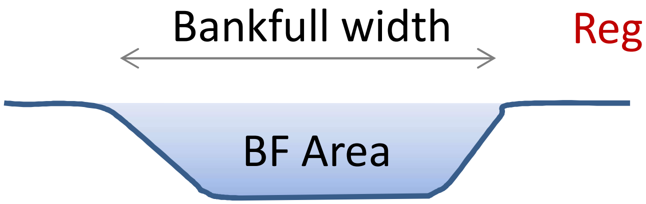
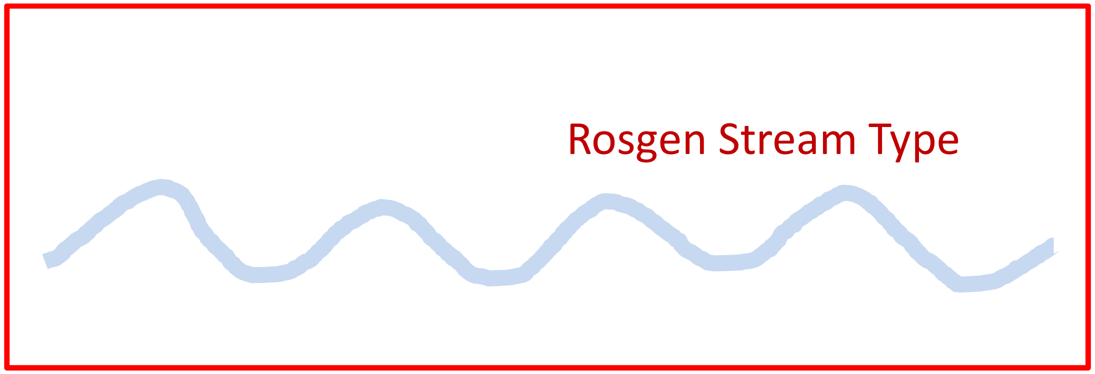


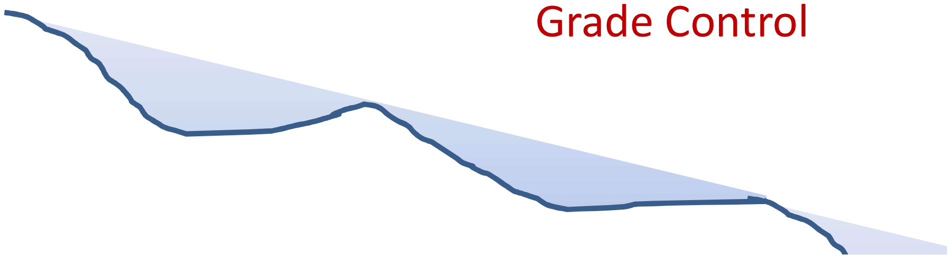
Regional Curves

- **Pattern**



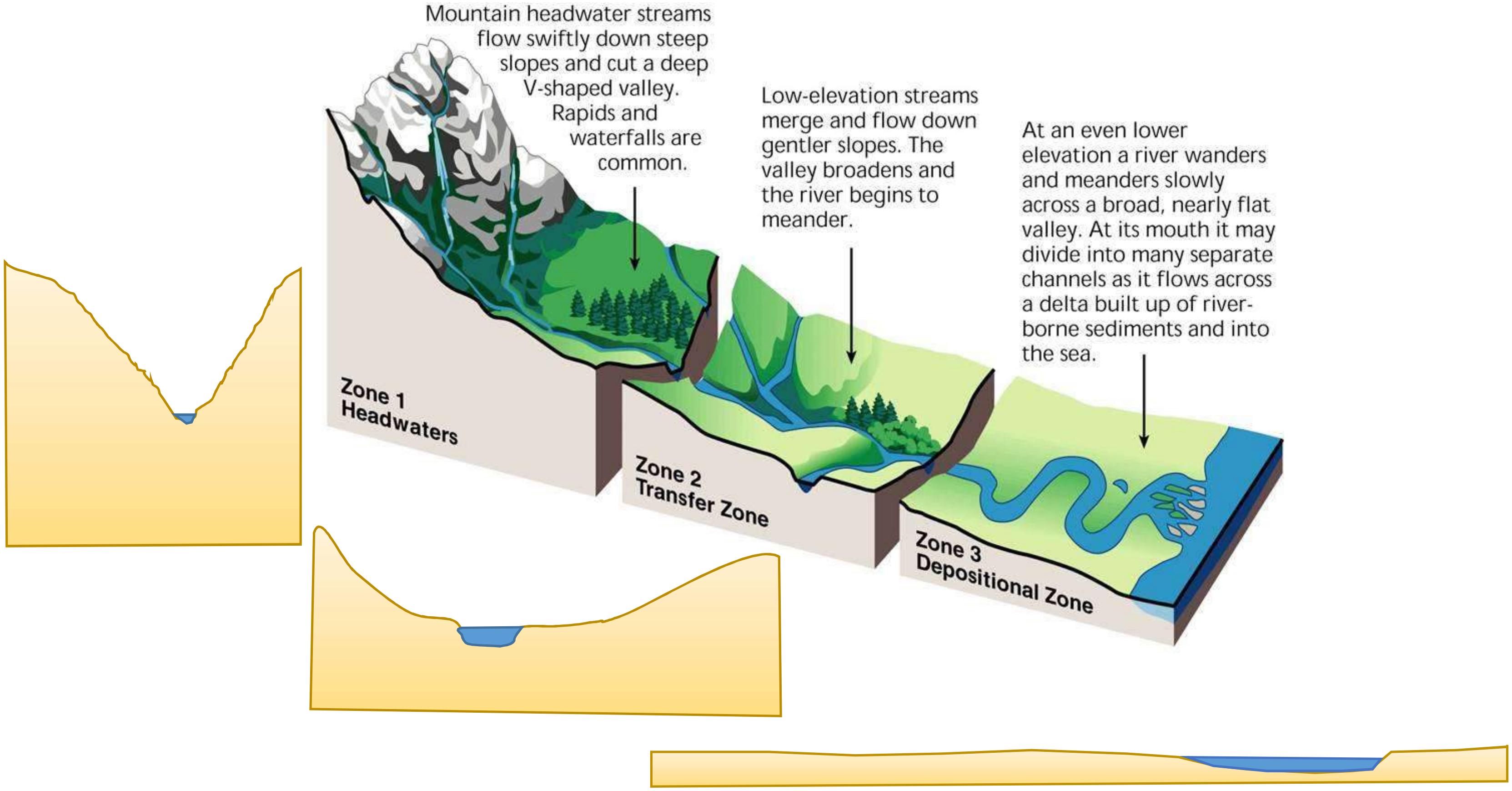
Rosgen Stream Type

- **Profile**



Grade Control

“In every respect, the valley rules the stream” (Hynes 1975)



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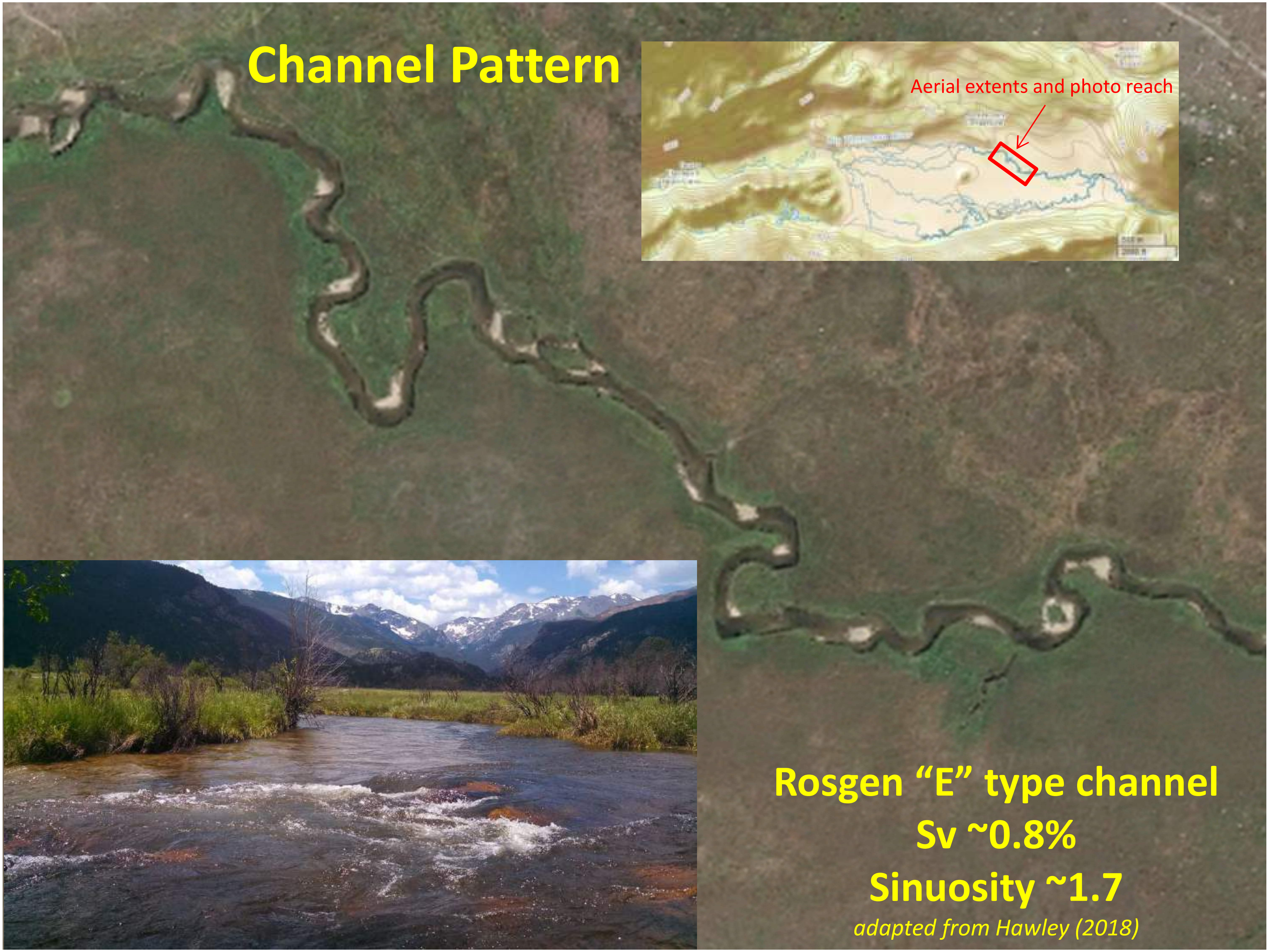
Channel Pattern



Rosgen "E" type channel

Sv ~0.8%

Sinuosity ~1.7

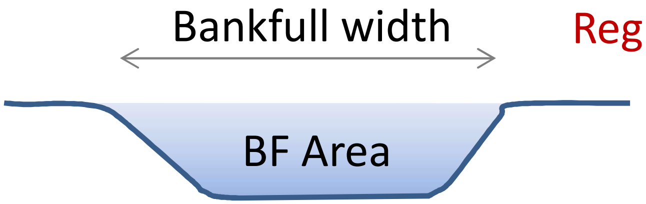
adapted from Hawley (2018)

Stable Channel Patterns Require Proportional Energy and Resistance

Adapted from Hawley (2018) BioScience

Common Practice

- **Dimension**



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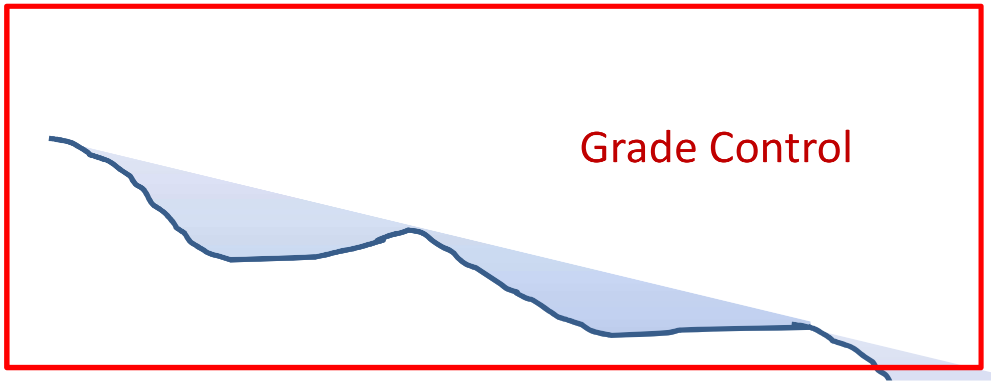
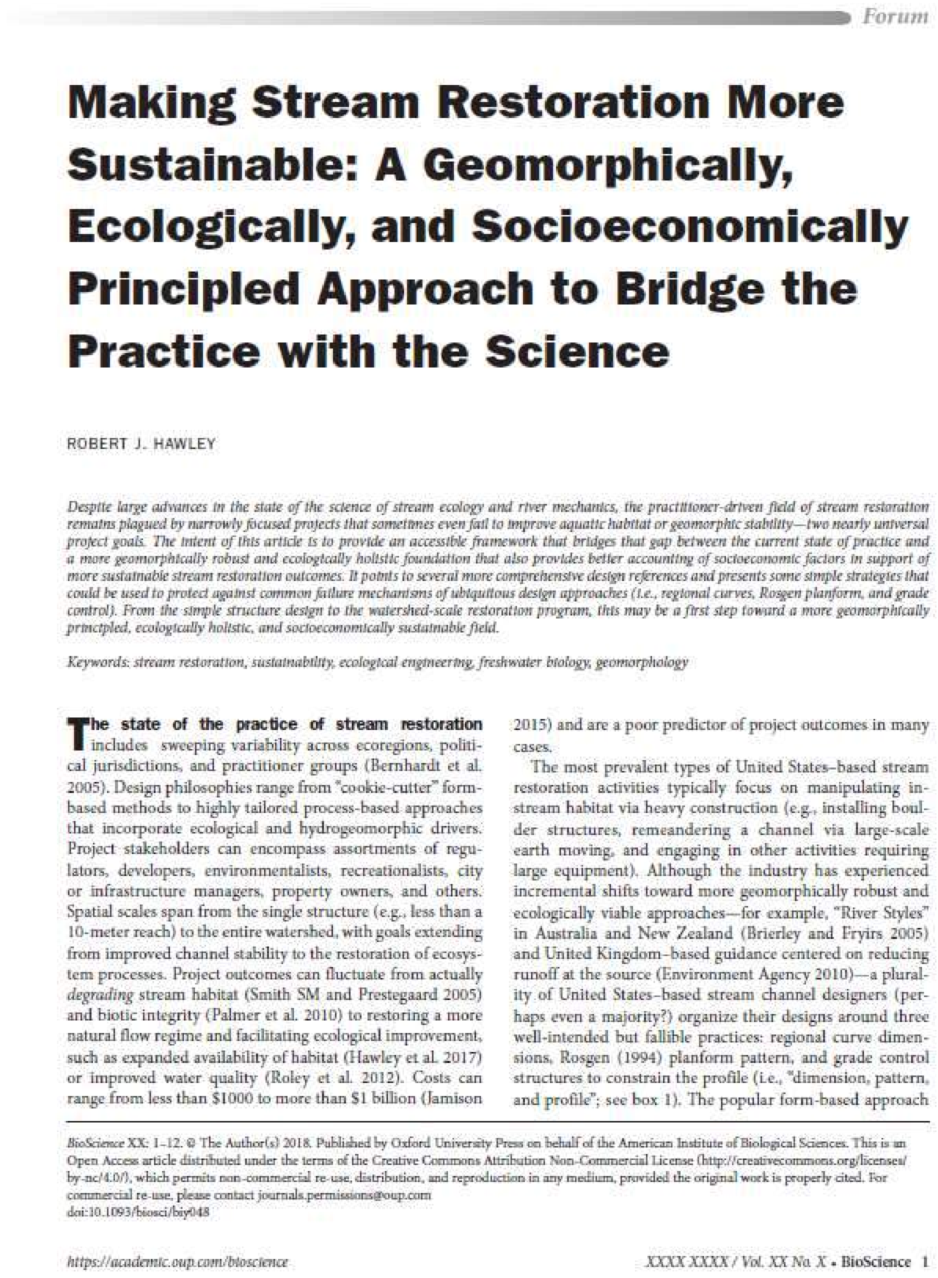


Grade Control

Grade Control Must Actually Control the Grade

Adapted from Hawley (2018) BioScience



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BioScience XX: 1–12.
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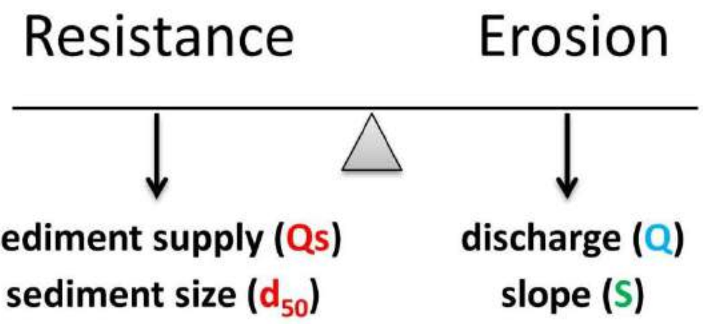
Geomorphic Principles

- Floodplain shear stress
  - less than ~1-2 psf
- Equilibrium pattern
  - balanced energy & resistance through bends
- Account for 'reference' stream resistance
- Adequate rock sizing/ grade control
  - e.g. Q100 + FS
- Sediment continuity
  - i.e. Bledsoe et al. 2017

Sediment Continuity Approaches (such as "CSR" Tool) Can Fully Account for Lane's Balance

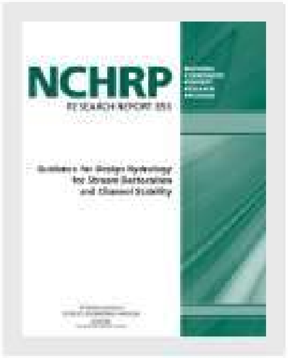


Resistance

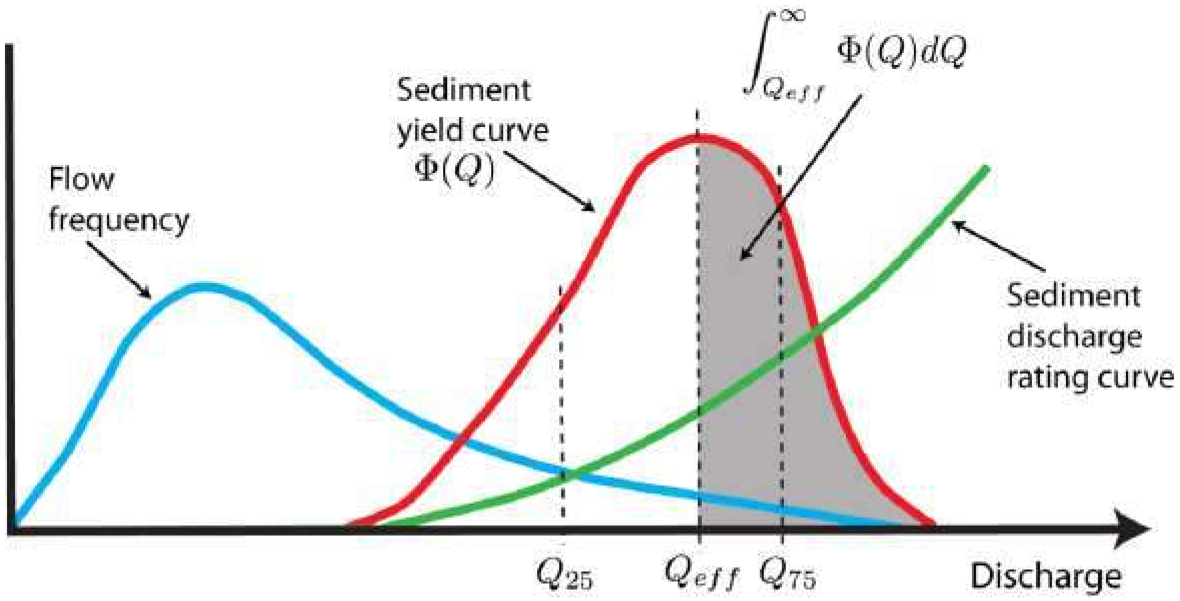
Erosion

sediment supply (Qs)
sediment size (d_{50})

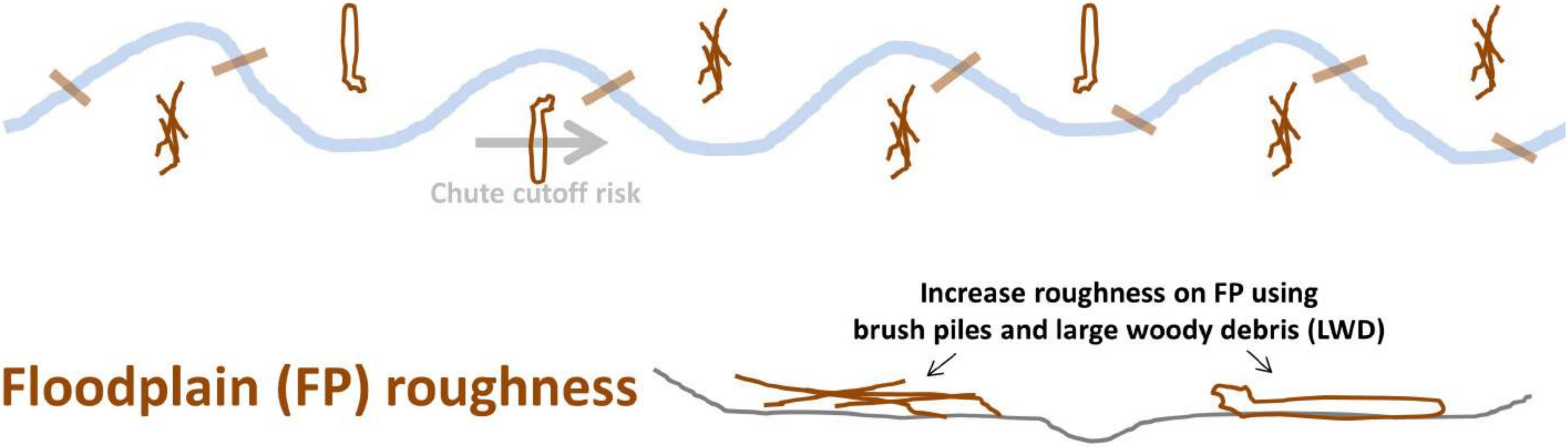
discharge (Q)
slope (S)



(Bledsoe et al., 2017)



Simple Strategies to Help Balance Resistance & Erosion



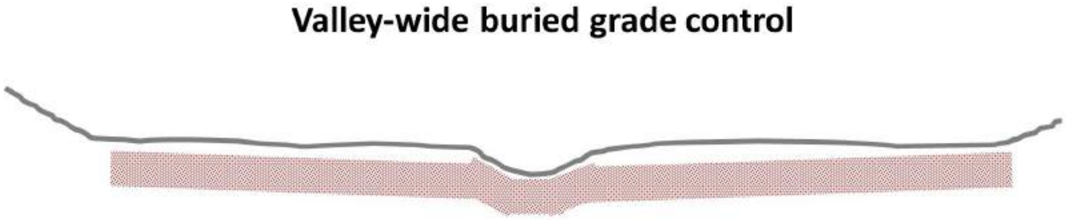
Floodplain (FP) roughness

Increase roughness on FP using brush piles and large woody debris (LWD)

Adapted from Hawley (2018) BioScience

Simple Strategies to Help Balance Resistance & Erosion

Valley grade control



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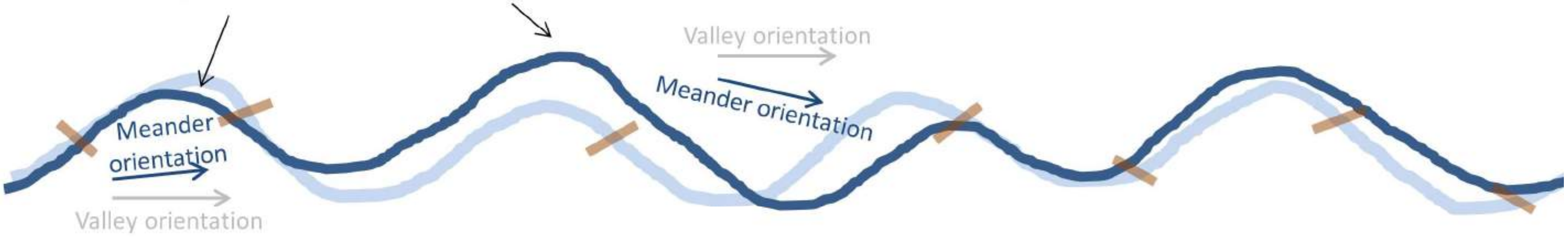
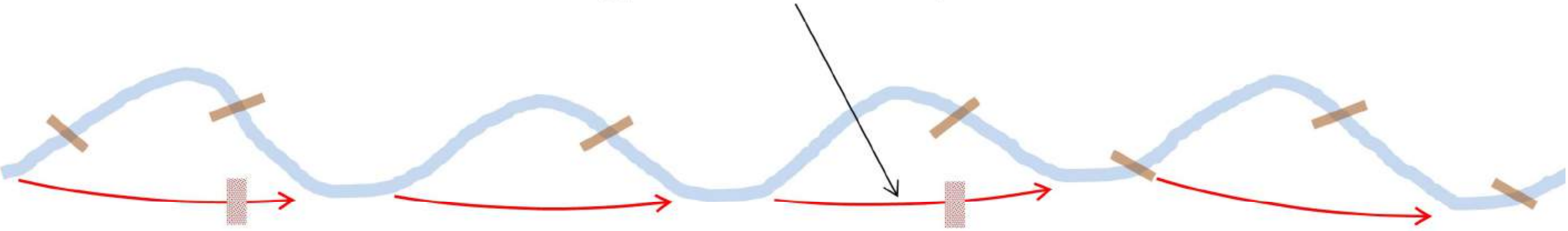

Meander bends between consecutive wavelengths misaligned from down-valley direction

Irregular planform

Adapted from Hawley (2018) BioScience

Simple Strategies to Help
Balance Resistance & Erosion



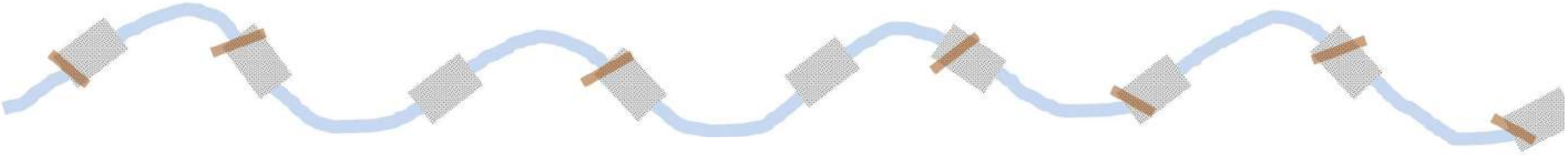
Intentional secondary channels to reduce the energy on the rest of the floodplain

Secondary channel
armored with coir fabric and/or buried grade control

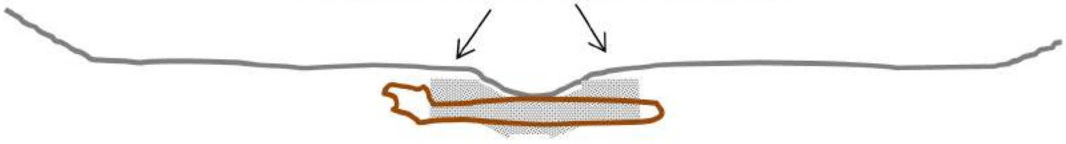
Secondary channels

Adapted from Hawley
(2018) BioScience

Simple Strategies to Help Balance Resistance & Erosion



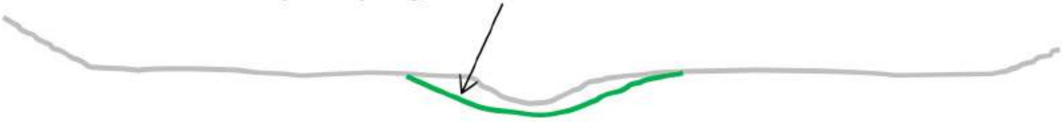
More stone/LWD


Bury riffle armor well into banks

Adapted from Hawley (2018) BioScience

Simple Strategies to Help Balance Resistance & Erosion

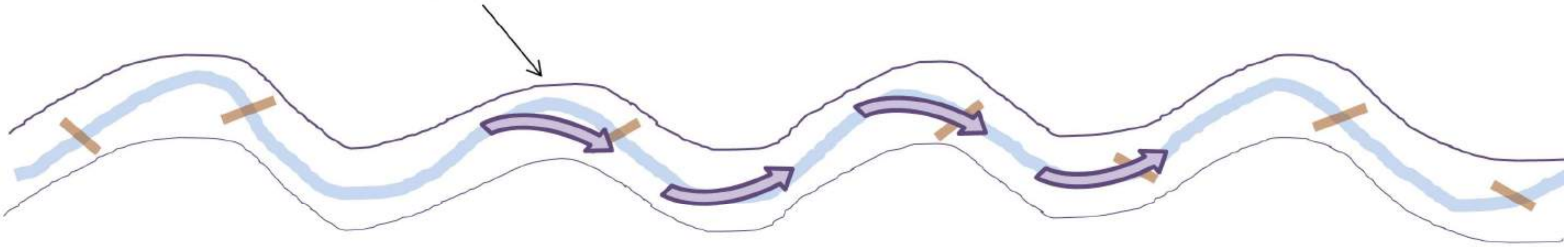
Larger cross section



Design FP for stable vegetation (max ~1-2 psf at Q_{100}) by keeping more water in the channel

Adapted from Hawley (2018) BioScience

Simple Strategies to Help Balance Resistance & Erosion



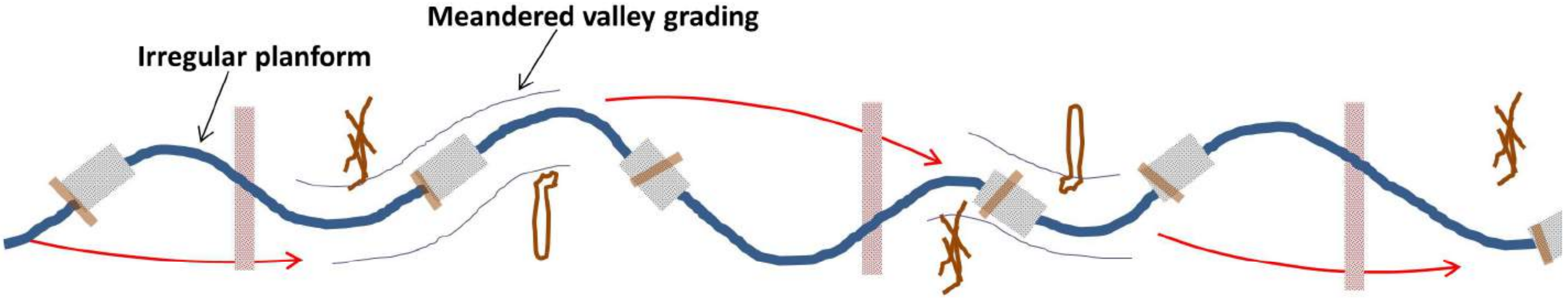
Meander the dominant flow path during flood flows using valley grading

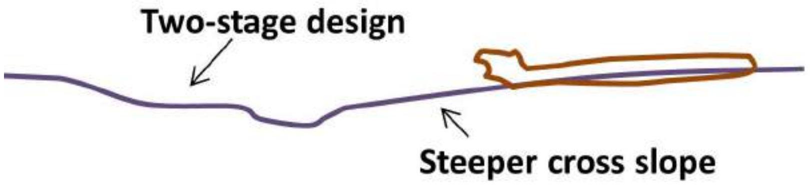
Irregular cross section

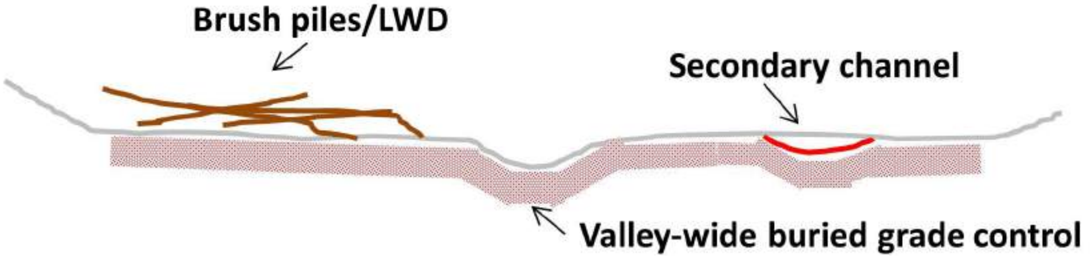
Keep the dominant flow path closer to the main channel using two-stage design and/or steeper cross slopes

Adapted from Hawley (2018) BioScience

Simple Strategies to Help Balance Resistance & Erosion

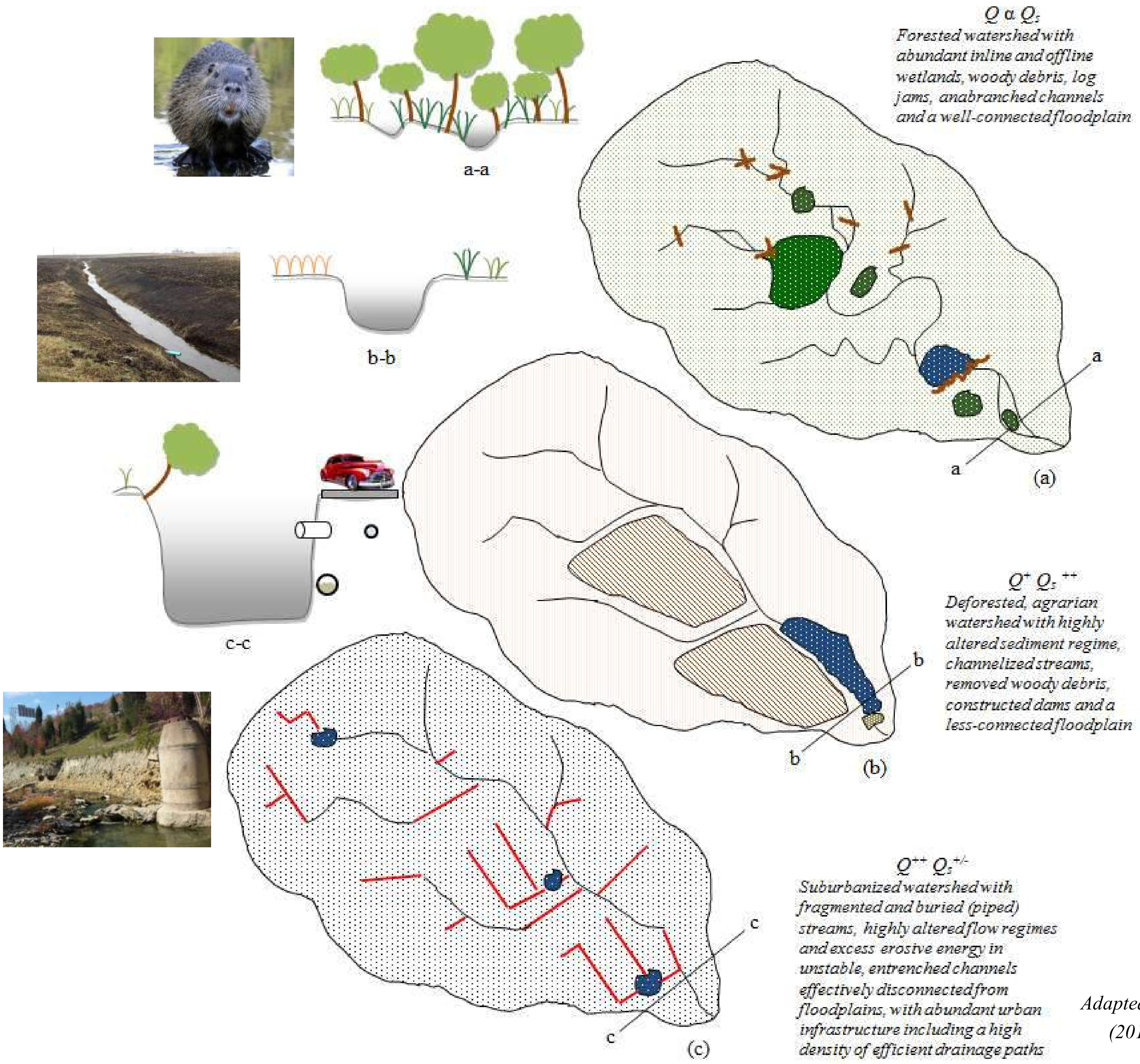






Adapted from Hawley (2018) BioScience

“Streams not just as things in space but processes through time”
(Bledsoe et al., 2008)



$Q \propto Q_s$
Forested watershed with abundant inline and offline wetlands, woody debris, log jams, anabranched channels and a well-connected floodplain

$Q^{+}\ Q_s^{\ ++}$
Deforested, agrarian watershed with highly altered sediment regime, channelized streams, removed woody debris, constructed dams and a less-connected floodplain

$Q^{++}\ Q_s^{\ +/-}$
Suburbanized watershed with fragmented and buried (piped) streams, highly altered flow regimes and excess erosive energy in unstable, entrenched channels effectively disconnected from floodplains, with abundant urban infrastructure including a high density of efficient drainage paths

Adapted from Hawley (2018) BioScience

Bankfull Wetlands

Reduce in-stream erosion by creating storage in a disconnected floodplain

Bankfull Wetlands

Bankfull Wetlands

Bankfull Wetlands

Hand-placed Wood Structures

Restore geomorphic/WQ processes without destroying canopy

BEFORE

Hand-placed Wood Structures

Hand-placed Wood Structures

Hand-placed Wood Structures

Ecological Rejuvenation along Highways

Reduce in-stream erosion and restore baseflows by creating habitat in highway right-of-ways

CONVENTIONAL DITCH

Ecological Rejuvenation along Highways

Ecological Rejuvenation along Highways

STREAM/WETLAND COMPLEX

Ecological Rejuvenation along Highways

STREAM/WETLAND COMPLEX

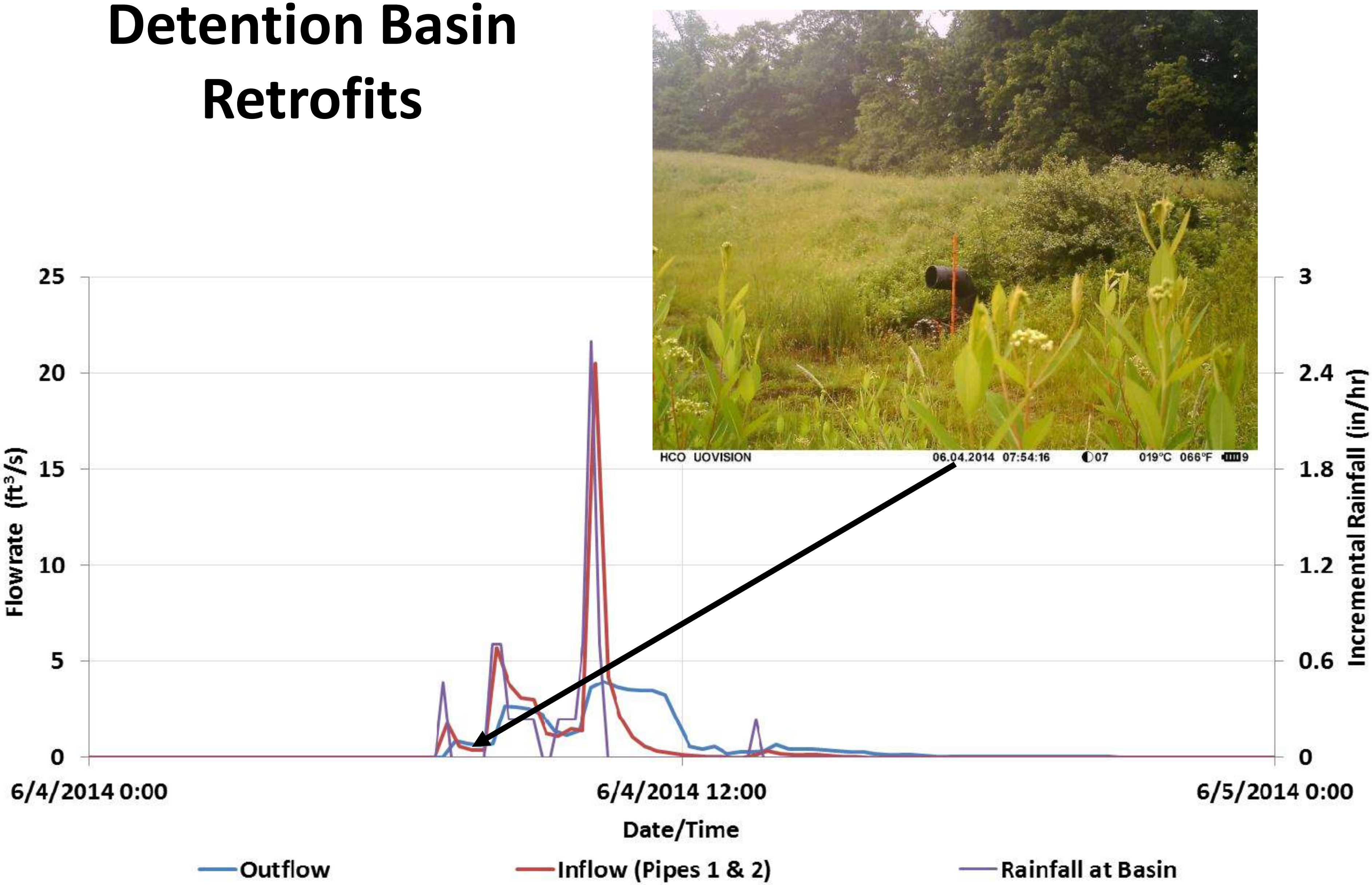
Detention Basin Retrofits

Reduce in-stream erosion and restore baseflows by restricting outlets

CONVENTIONAL OUTLET

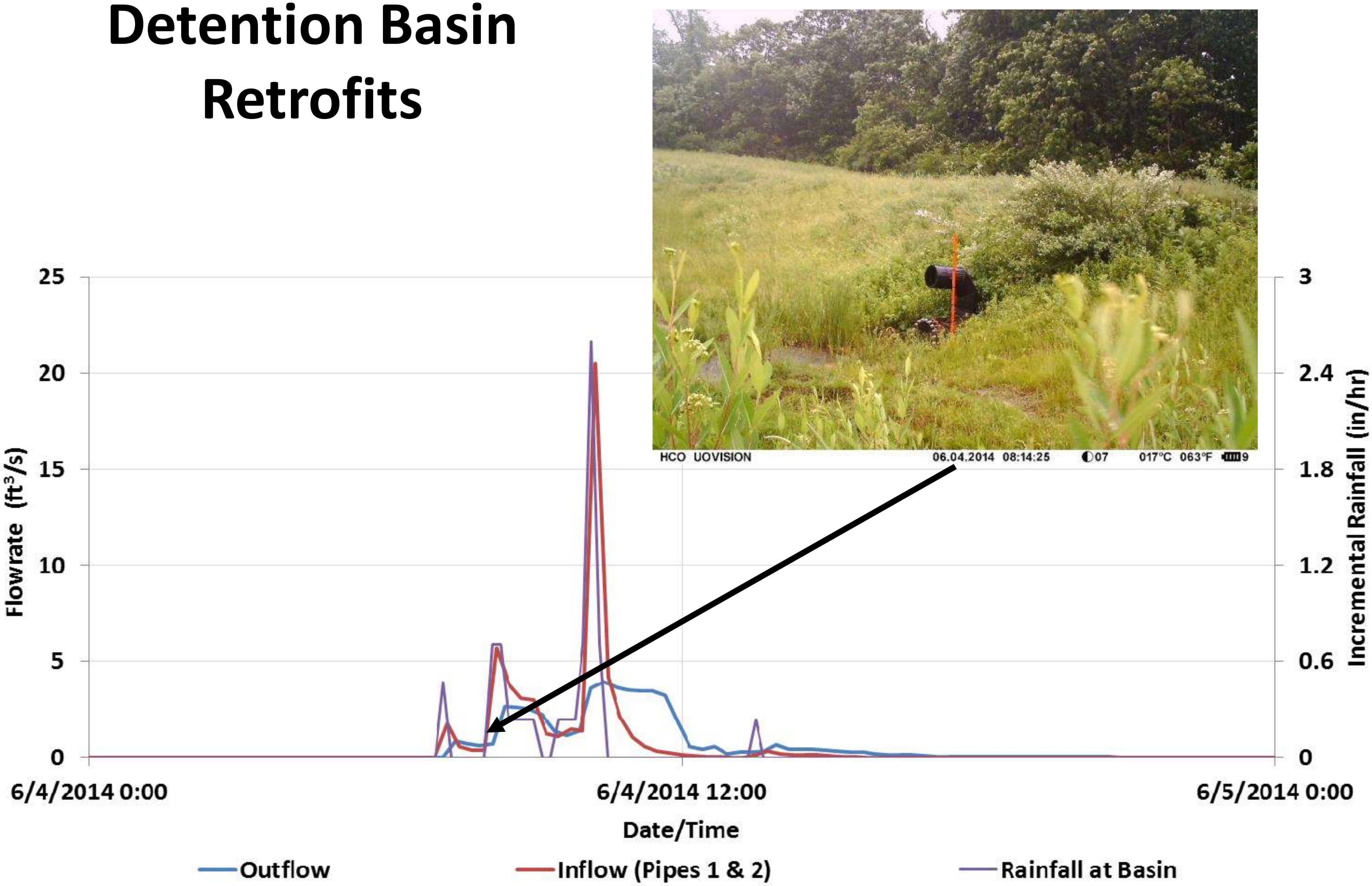
RESTRICTED OUTLET WITH BYPASS

Detention Basin Retrofits



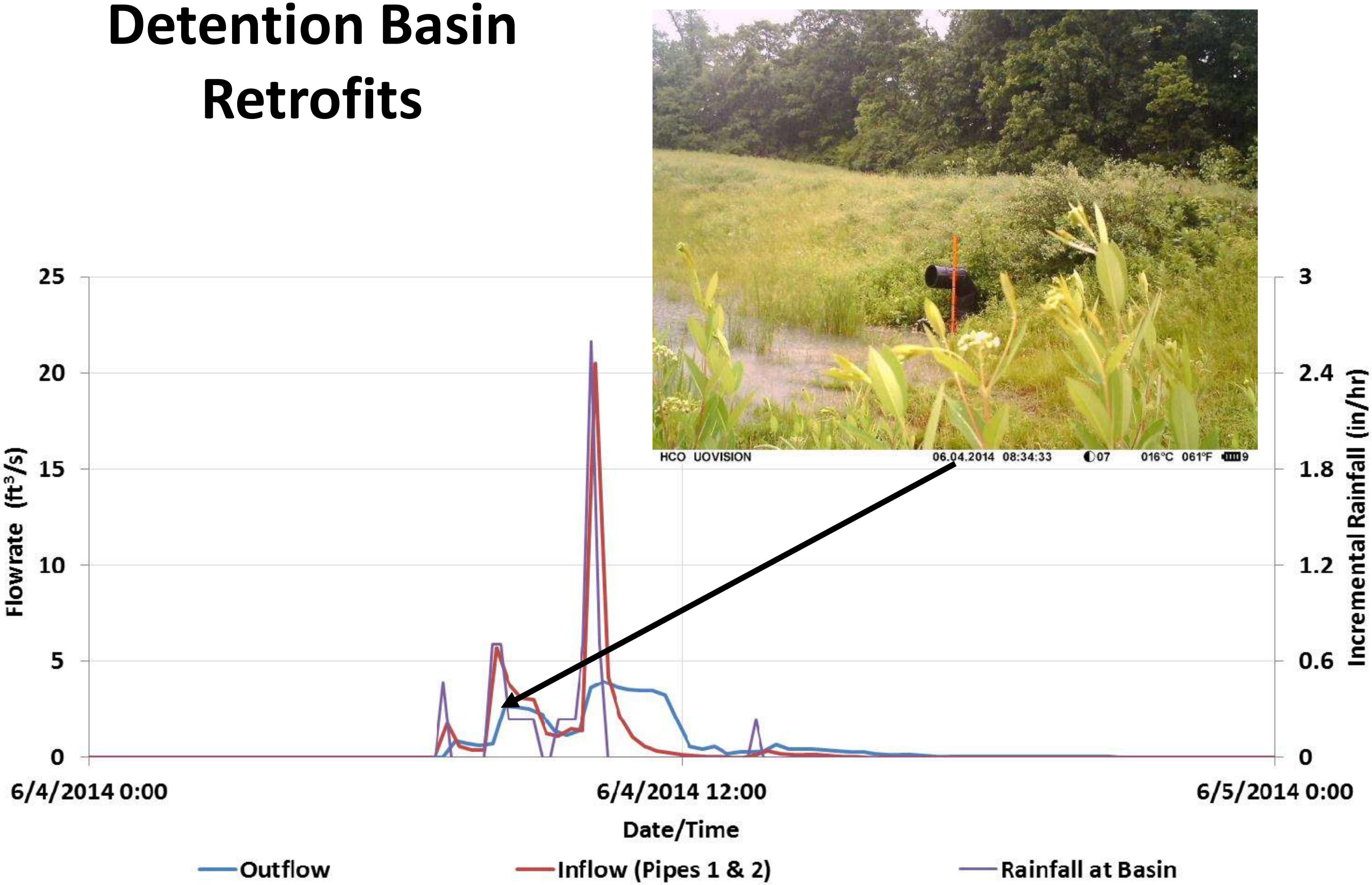
Adapted from Hawley et al. (2017)

Detention Basin Retrofits



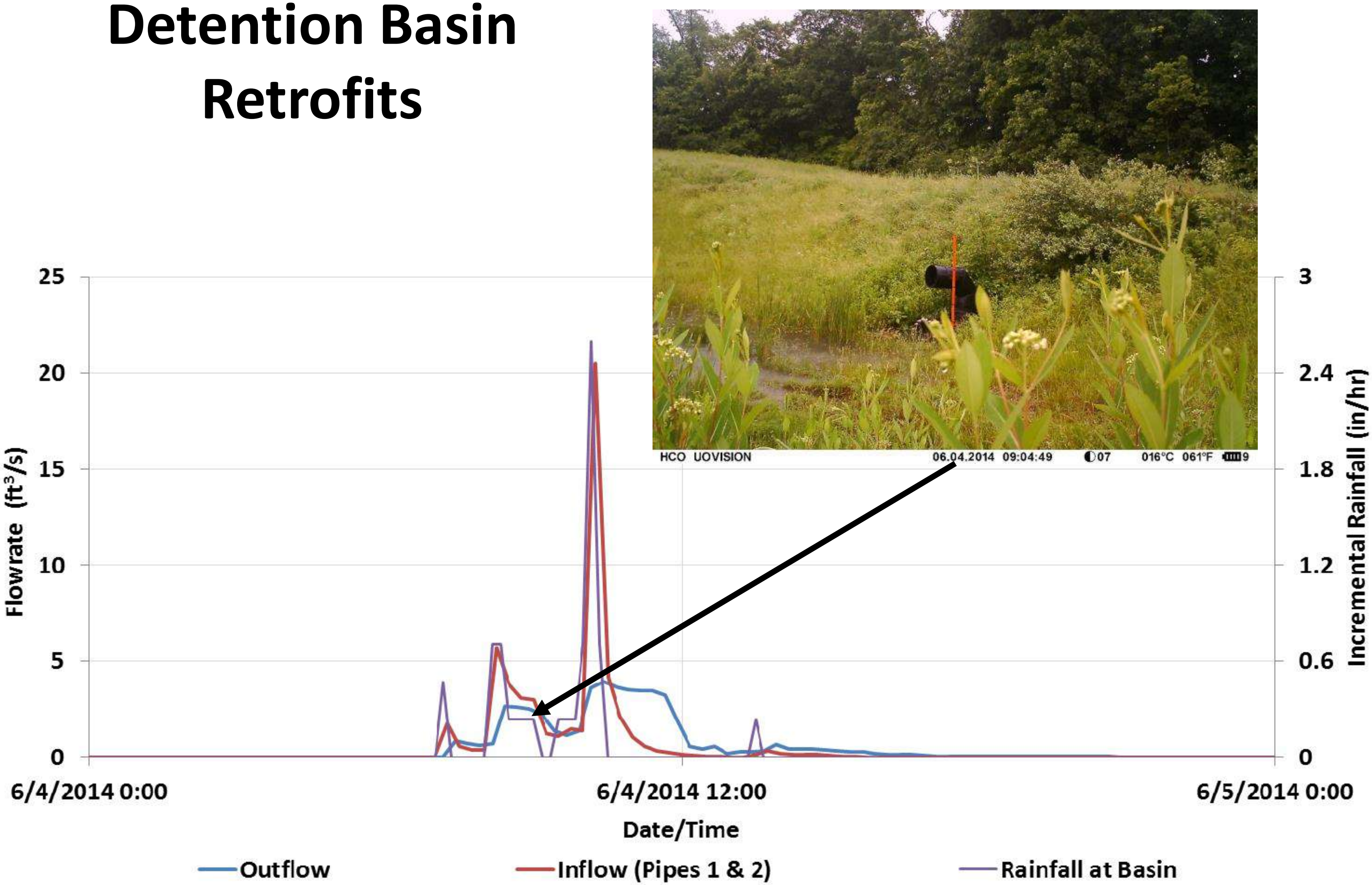
Adapted from Hawley et al. (2017)

Detention Basin Retrofits



Adapted from Hawley et al. (2017)

Detention Basin Retrofits



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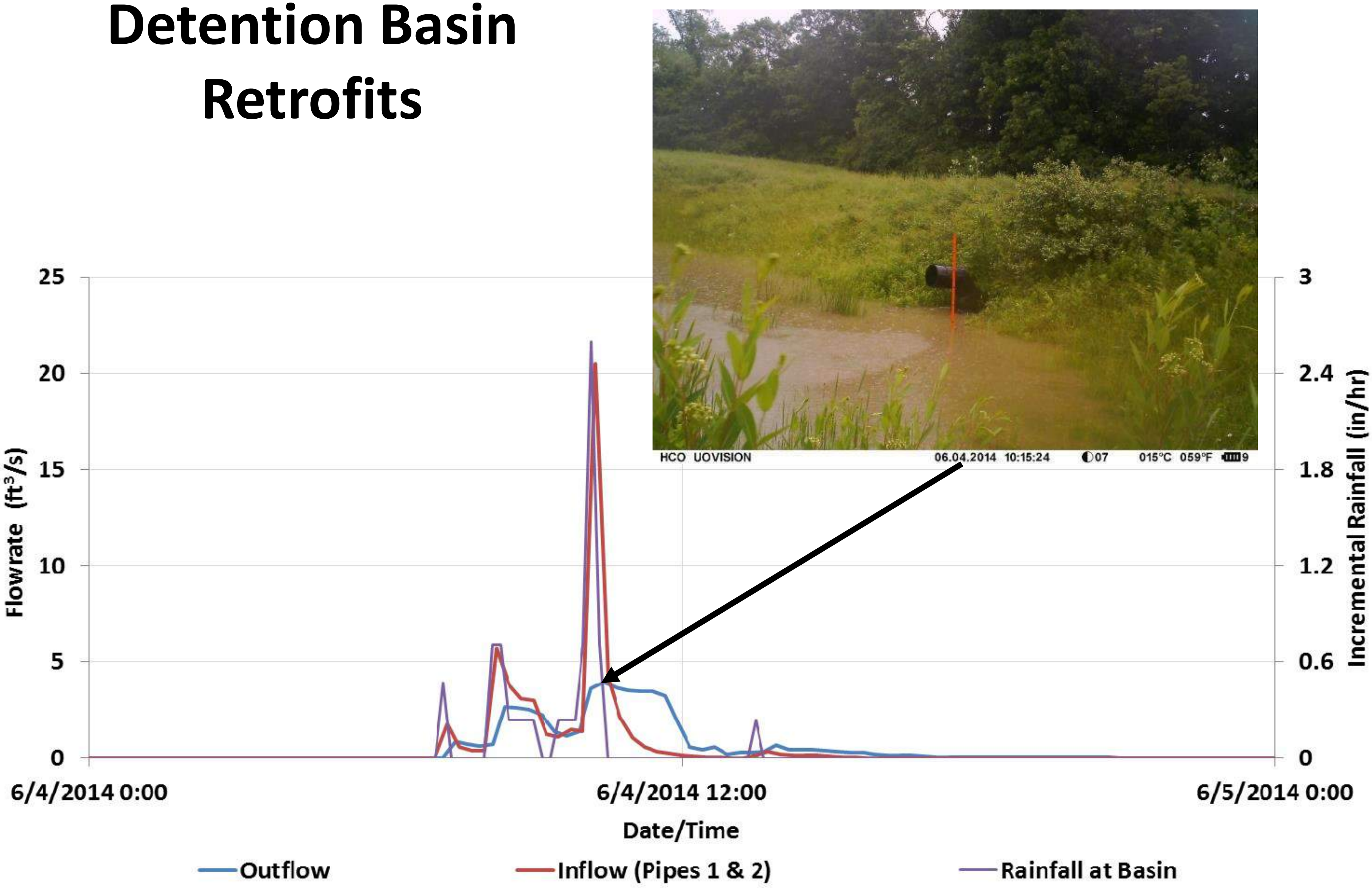
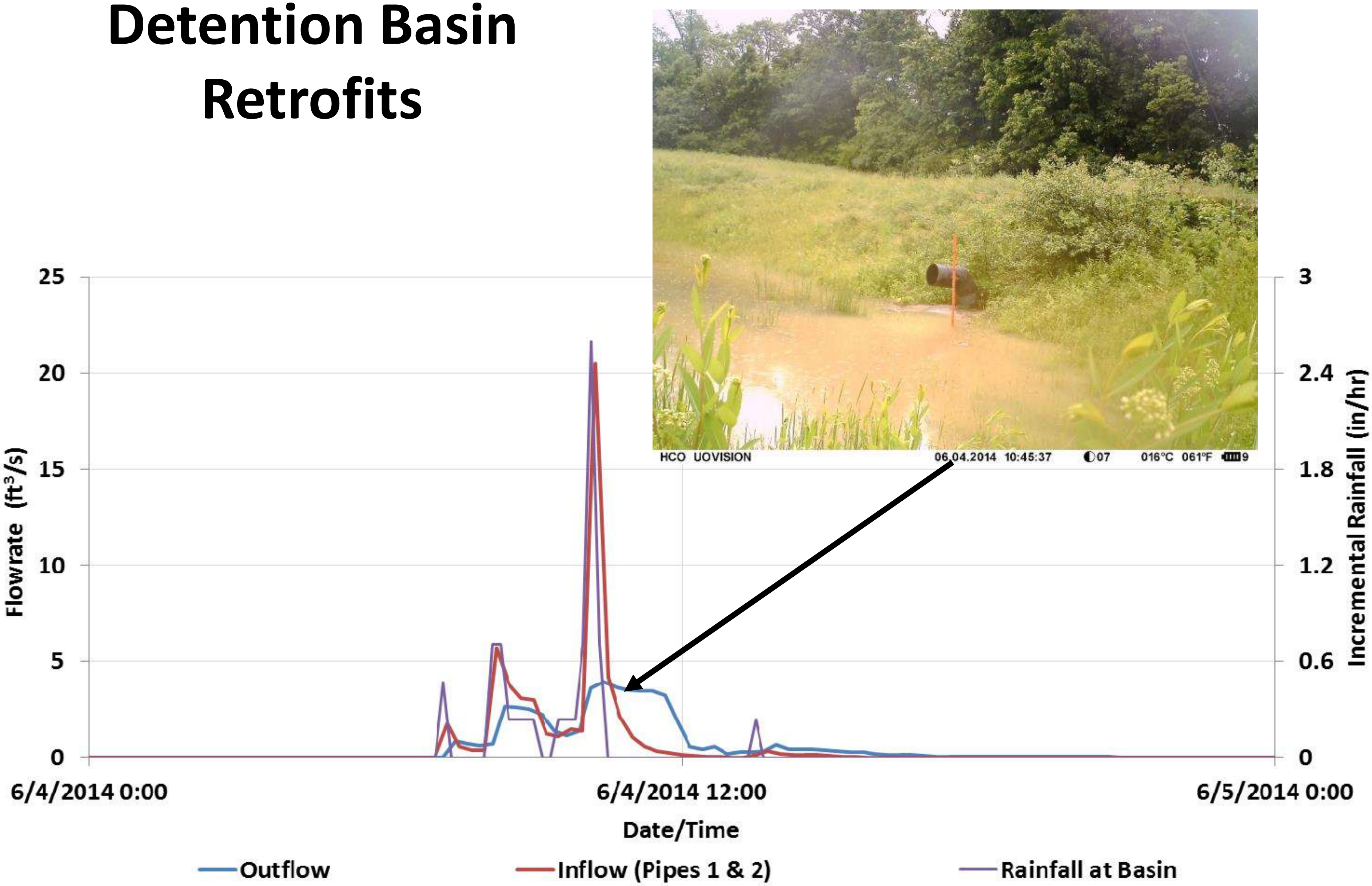
Detention Basin Retrofits



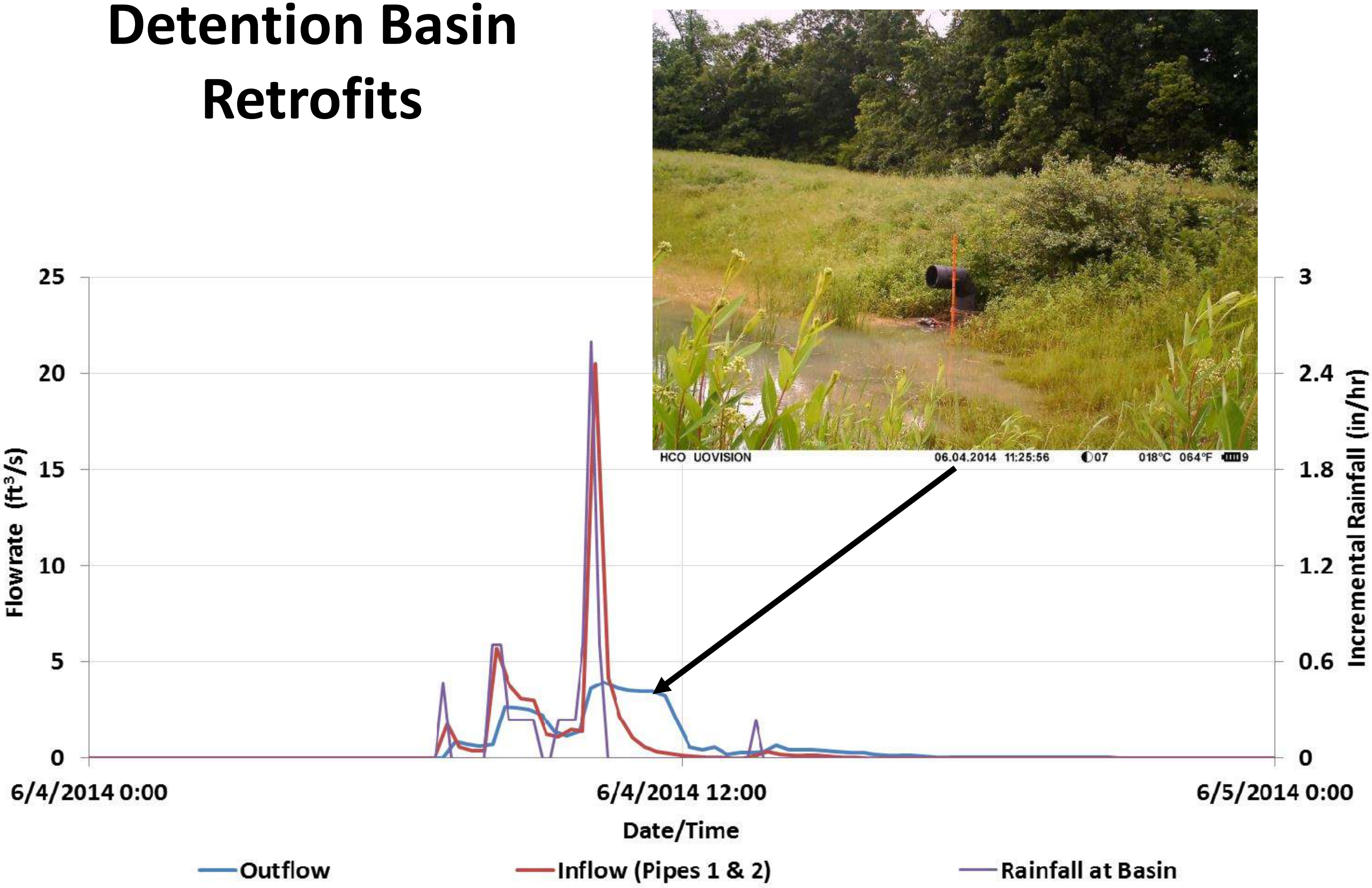
Adapted from Hawley et al. (2017)

Detention Basin Retrofits



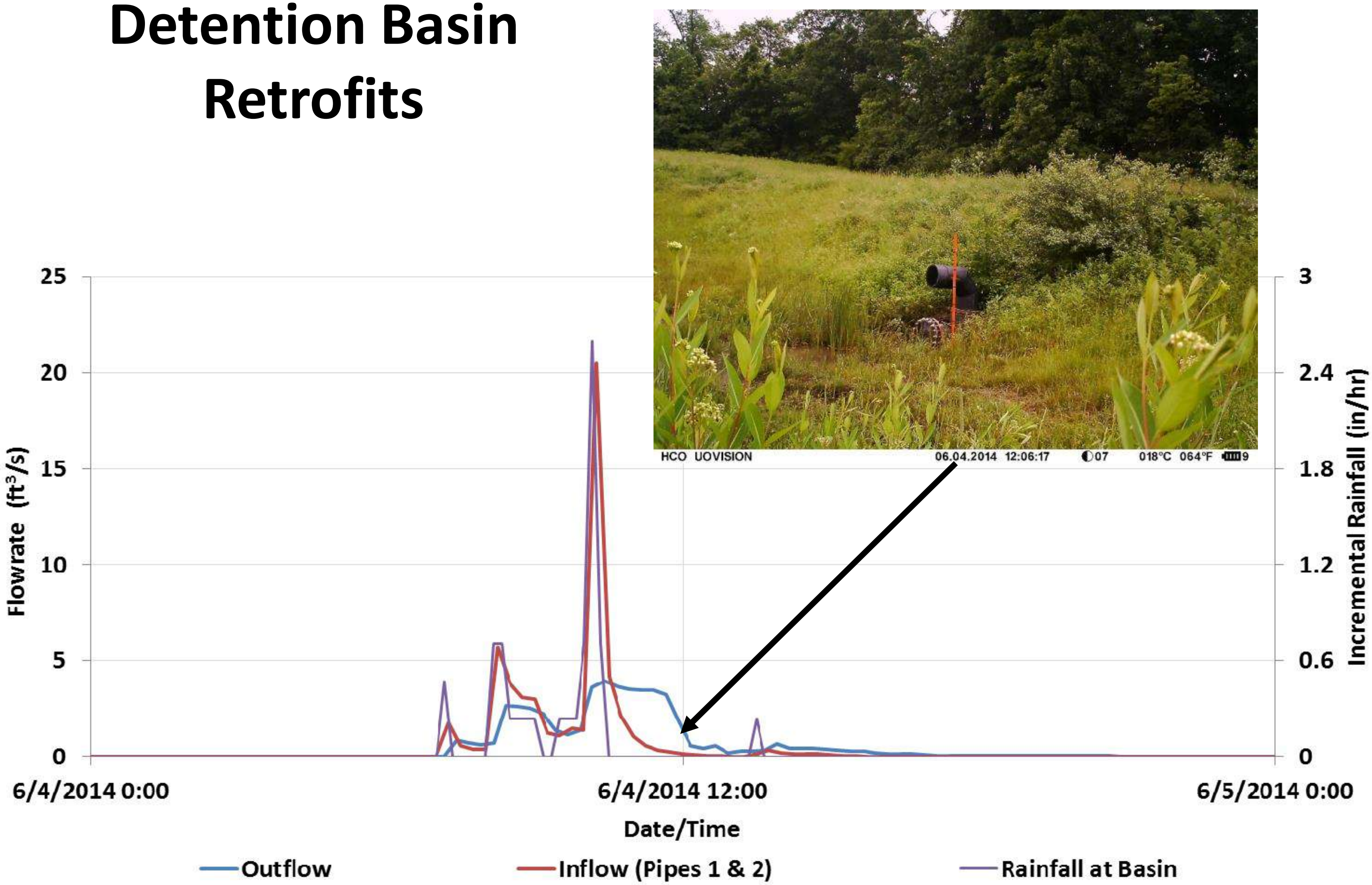
Adapted from Hawley et al. (2017)

Detention Basin Retrofits



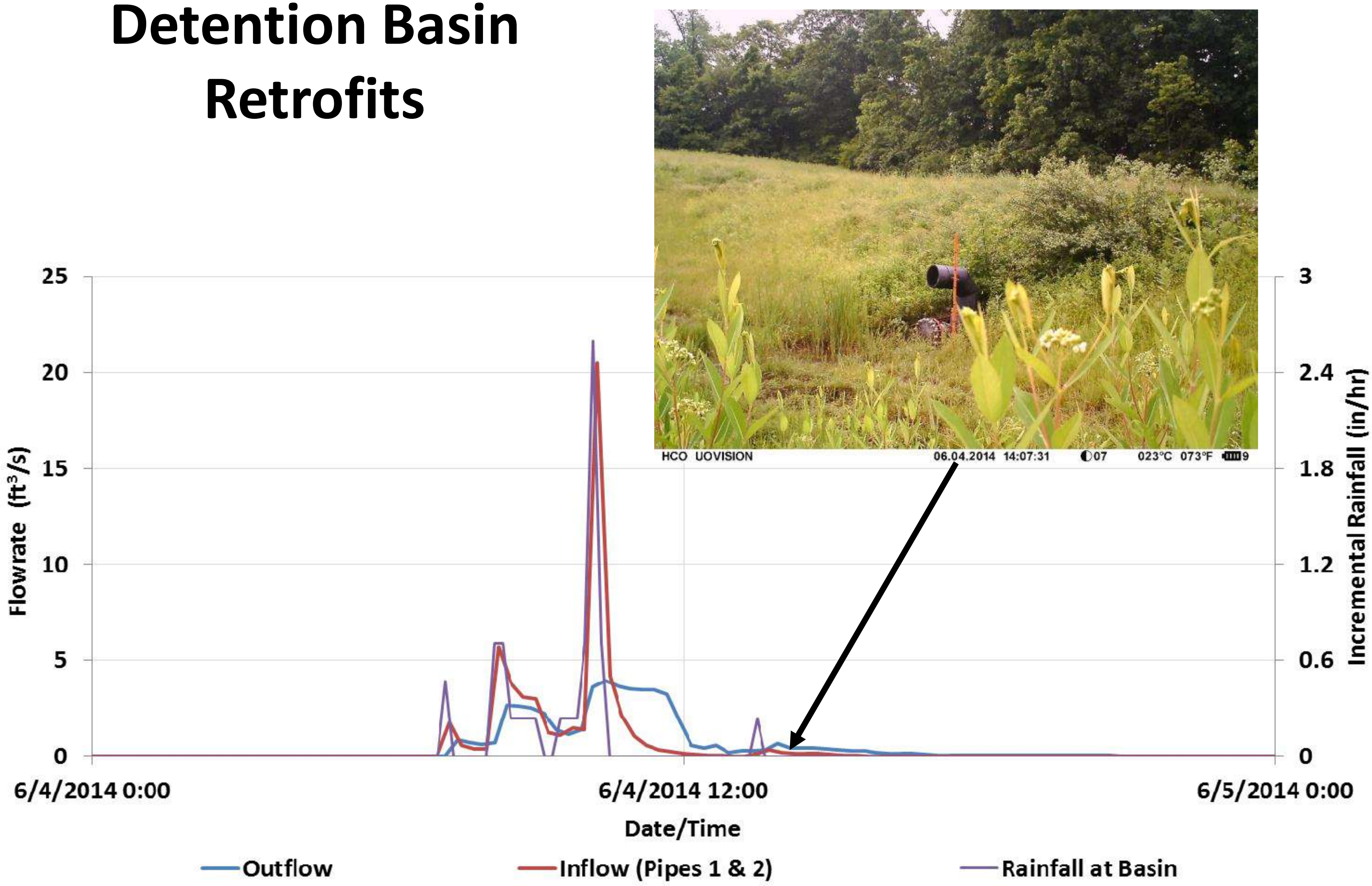
Adapted from Hawley et al. (2017)

Detention Basin Retrofits



Adapted from Hawley et al. (2017)

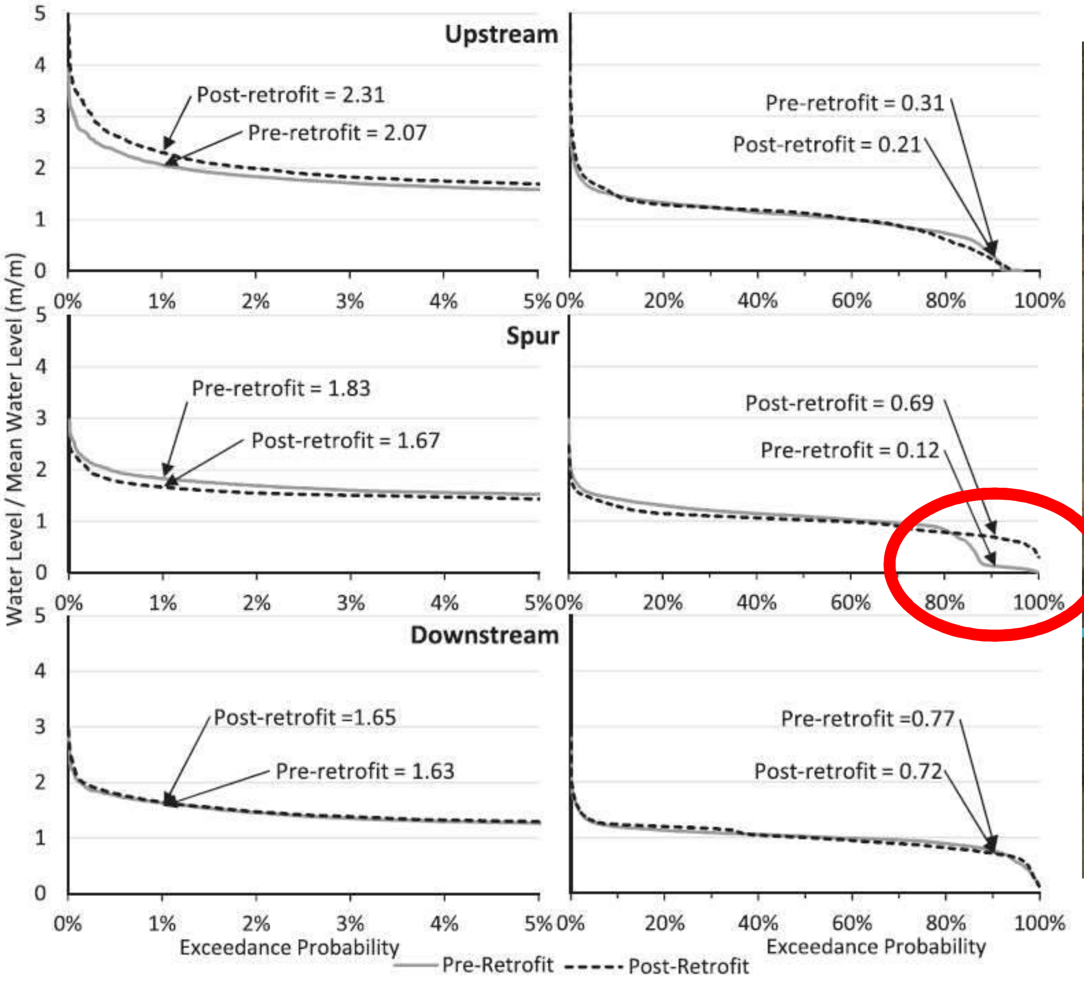
Detention Basin Retrofits



Adapted from Hawley et al. (2017)

Detention Basin Retrofits

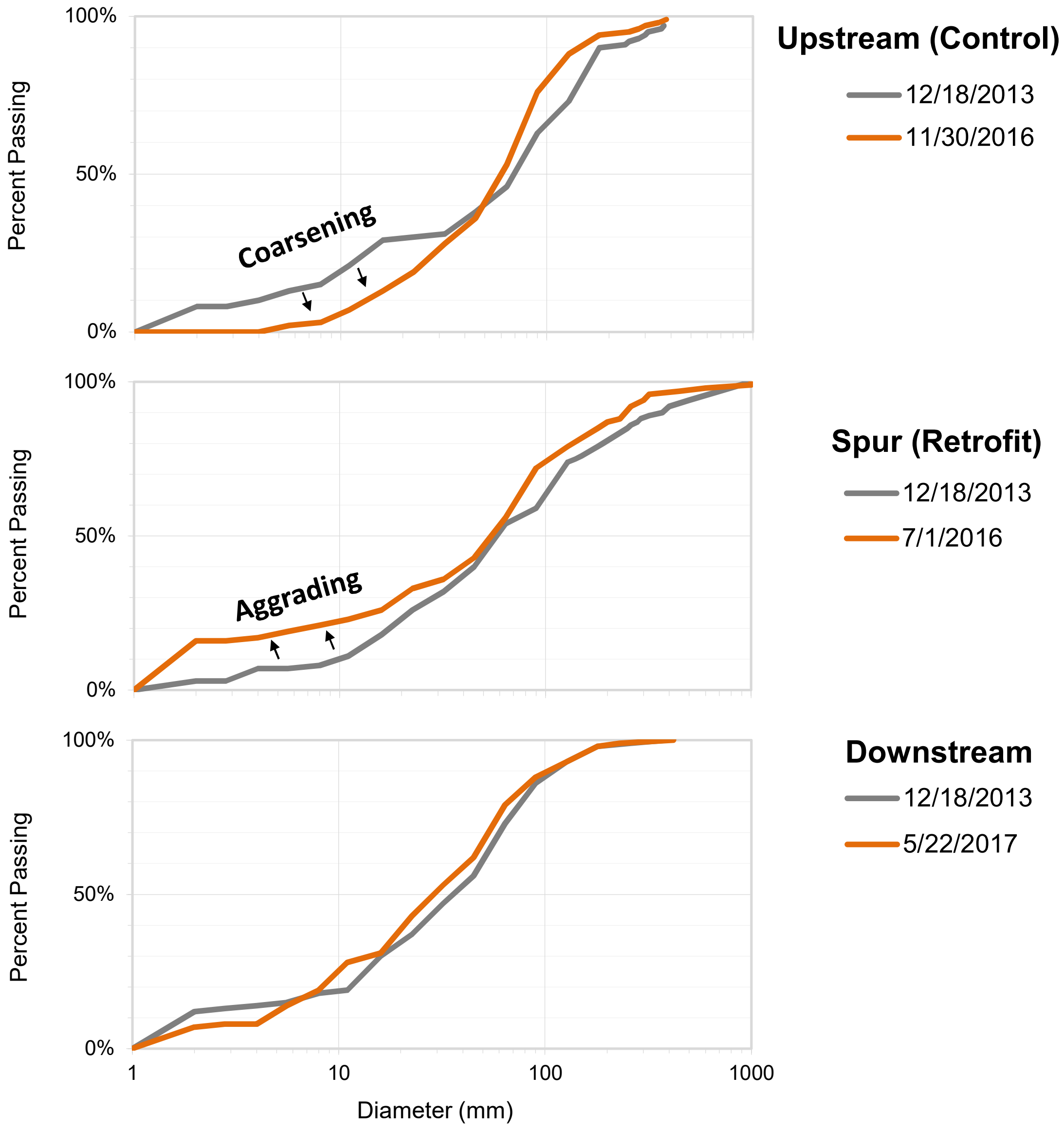
Hydrologic Restoration

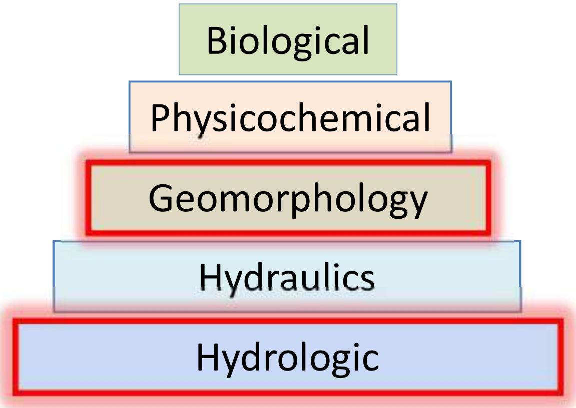


Adapted from Hawley et al. (2017)

Detention Basin Retrofits

Geomorphic Recovery

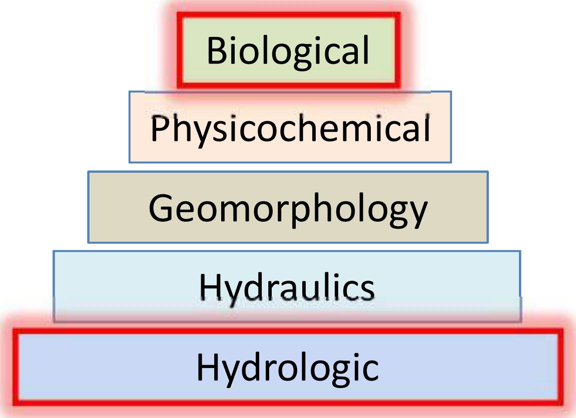




Adapted from Harman et al. (2012)

Detention Basin Retrofits

Ecological Lift



Biological

Physicochemical

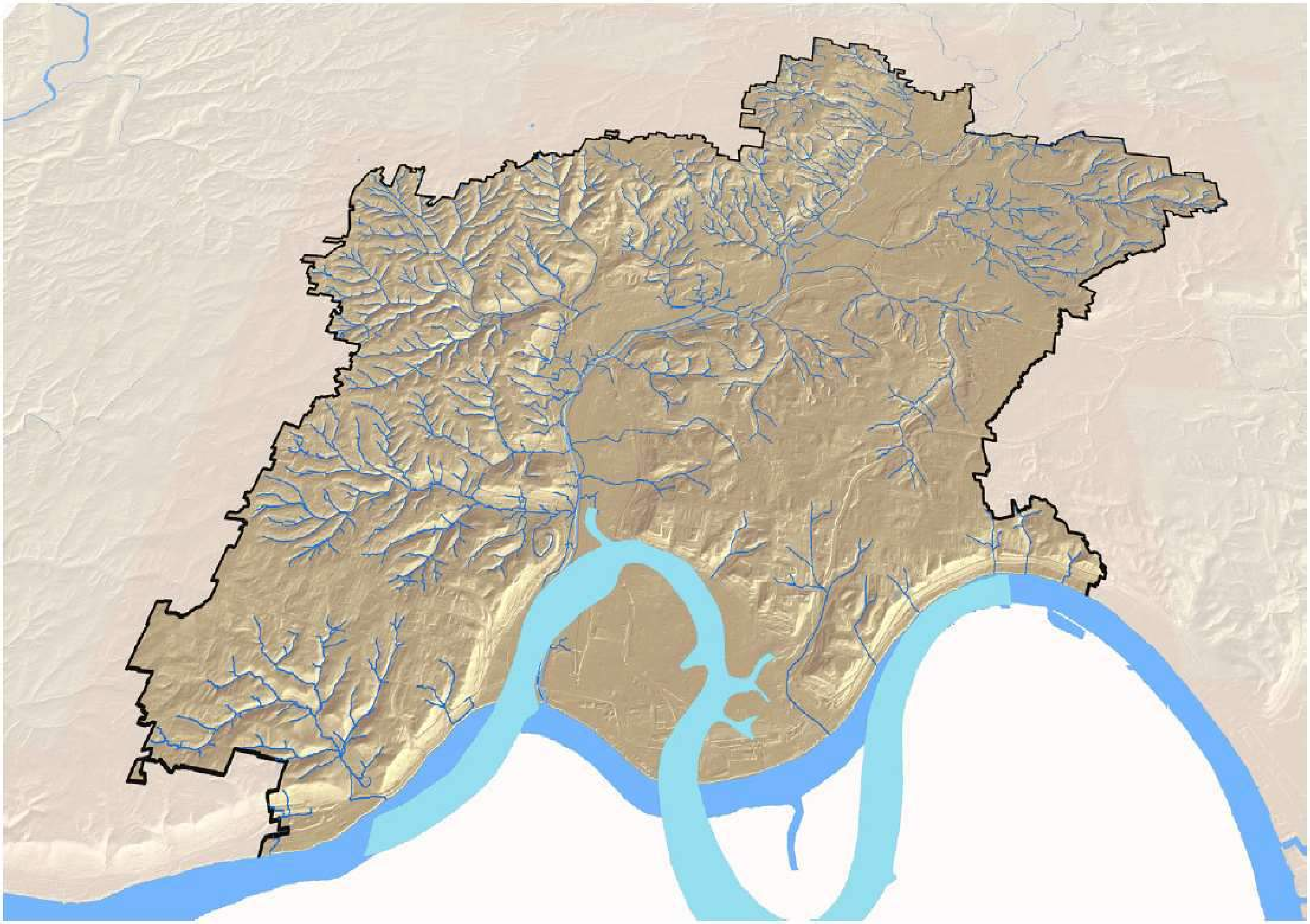
Geomorphology

Hydraulics

Hydrologic

Adapted from Harman et al. (2012)

Stream Daylighting

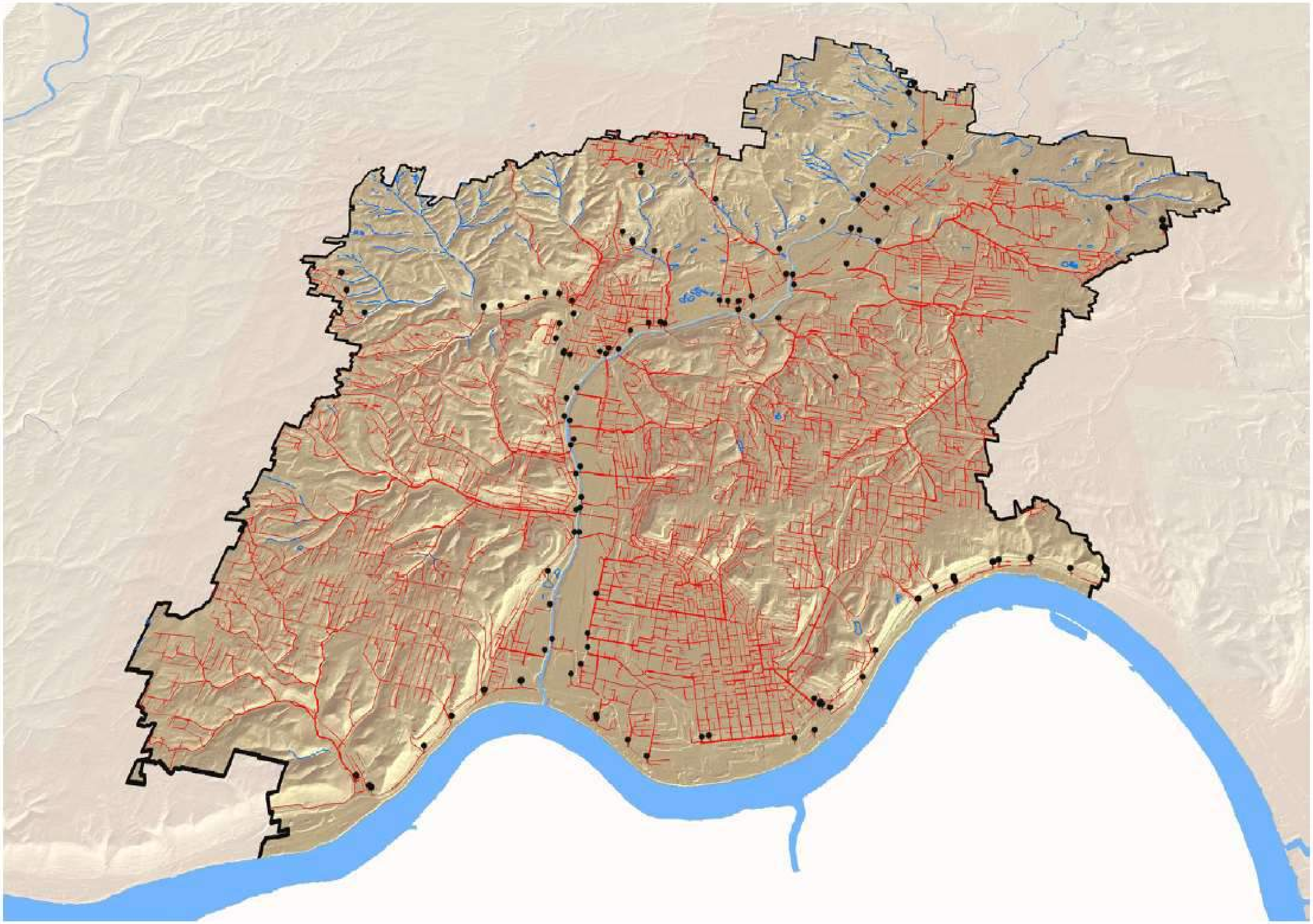


Pre-development Water Flow Patterns in Lower Mill Creek

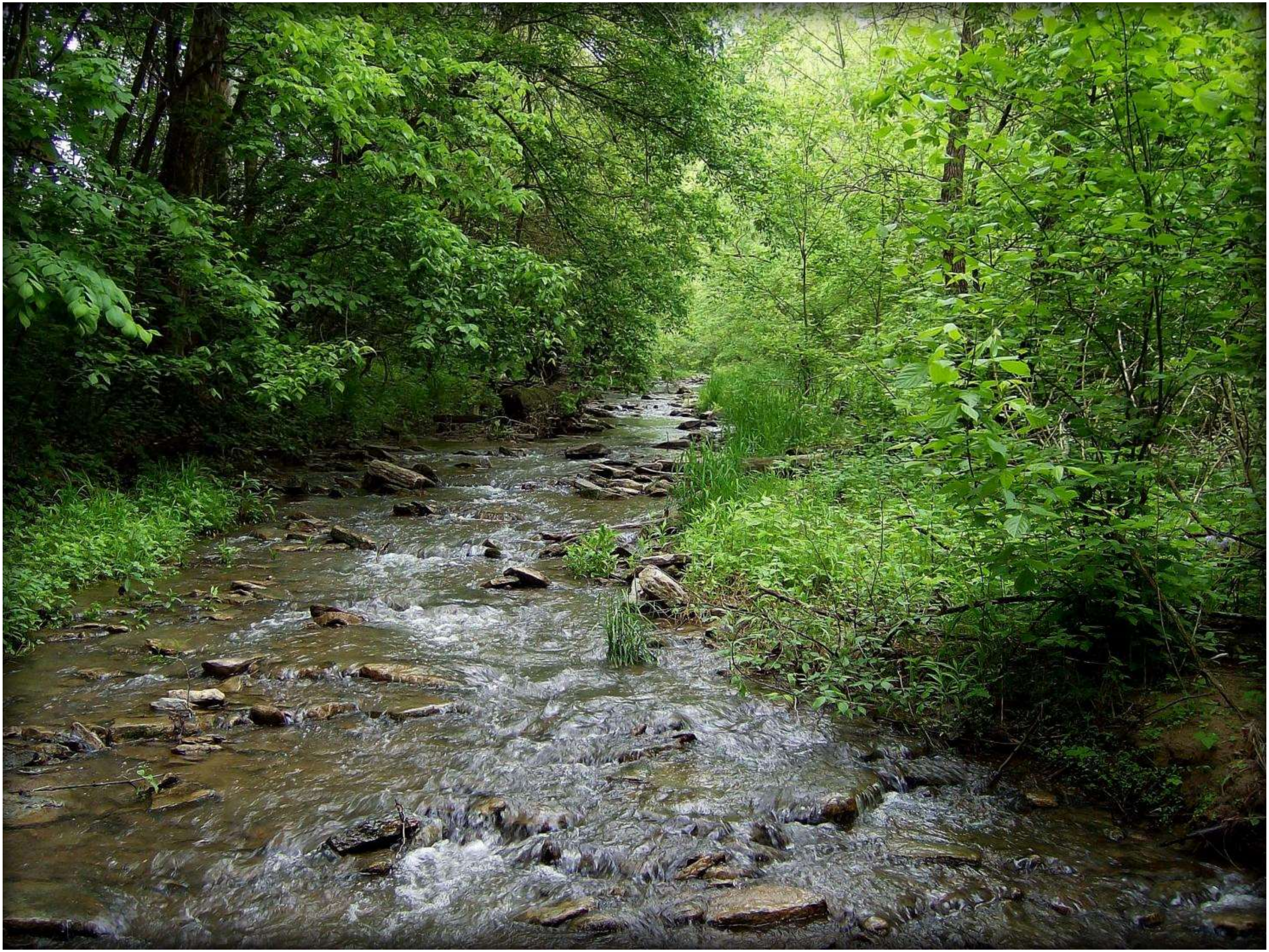
More than 300 miles of streams once flowed freely through the Lower Mill Creek area.

🟫 Lower Mill Creek Watershed

🟦 Ancient Ohio River



Today's Water Flow Patterns *Many of the streams became combined sewers. Today, only 75 miles of natural streams remain, with more than 600 miles of combined sewers.*

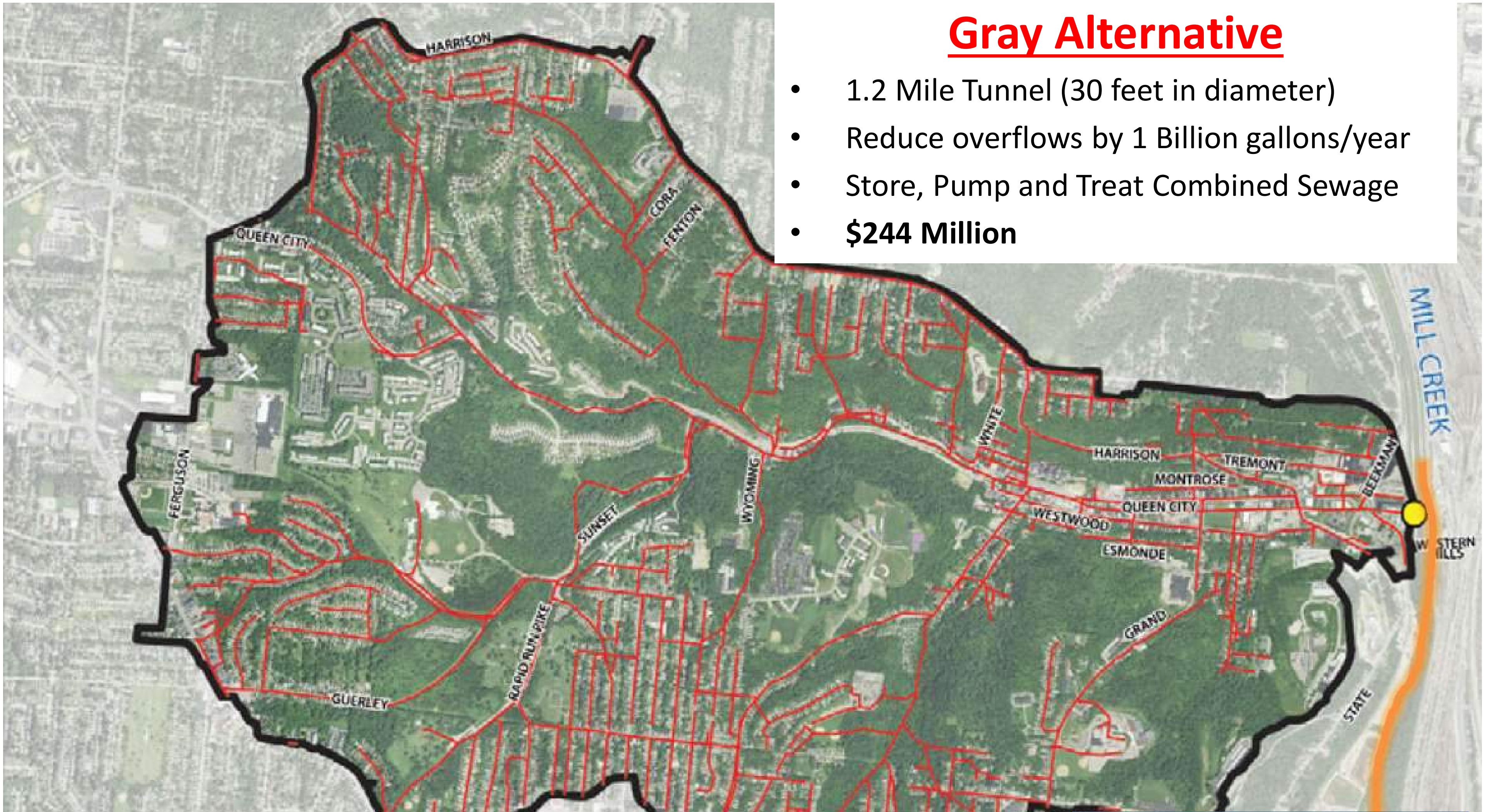


Brick sewer from the 1800s

CSO #005 in South Fairmount under dry and wet weather conditions.

Gray Alternative

- 1.2 Mile Tunnel (30 feet in diameter)
- Reduce overflows by 1 Billion gallons/year
- Store, Pump and Treat Combined Sewage
- **$244 Million**



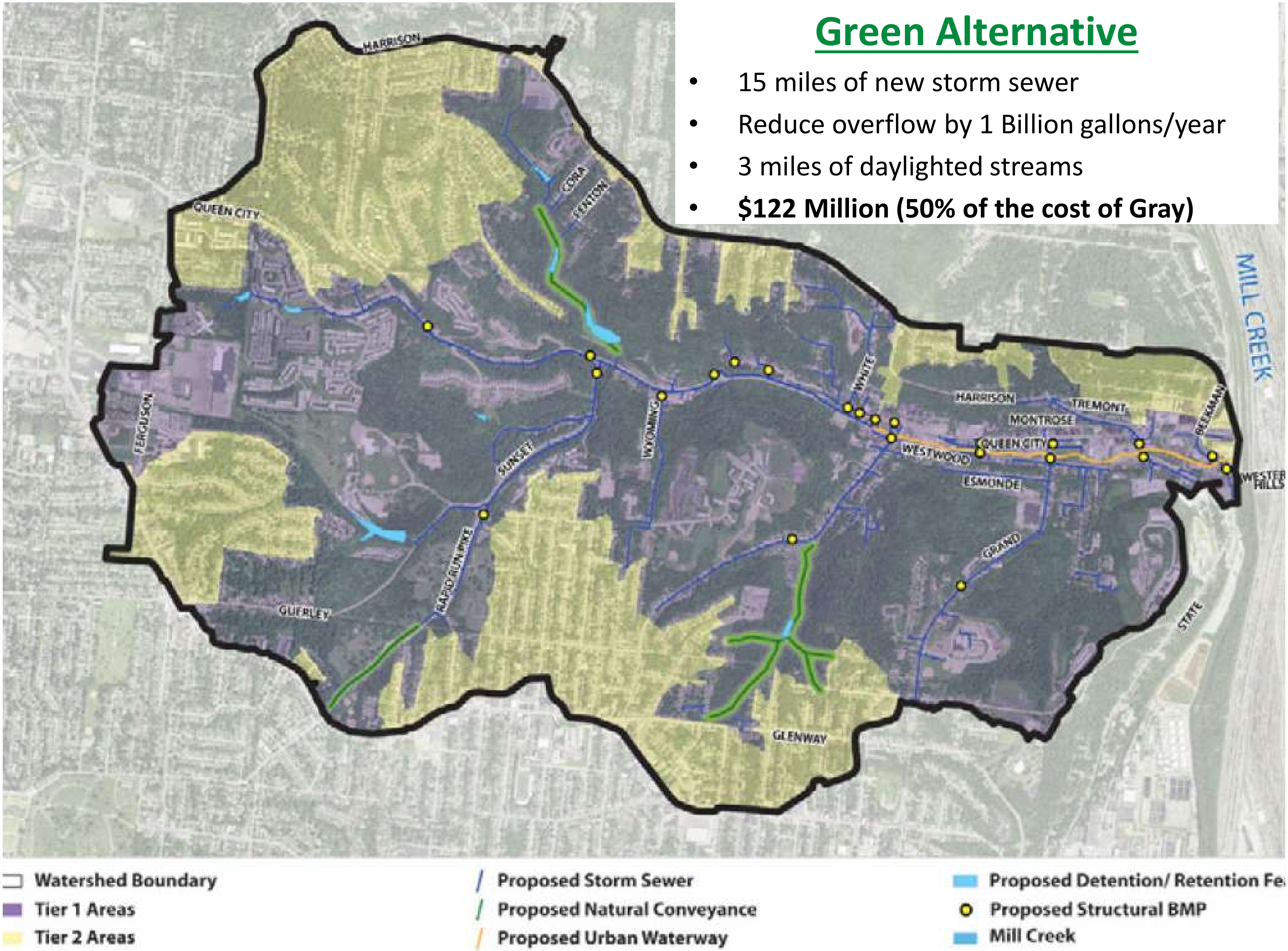
▭ **Watershed Boundary** / **Existing Combined Sewer**

Existing combined sewer system in the Lick Run Watershed

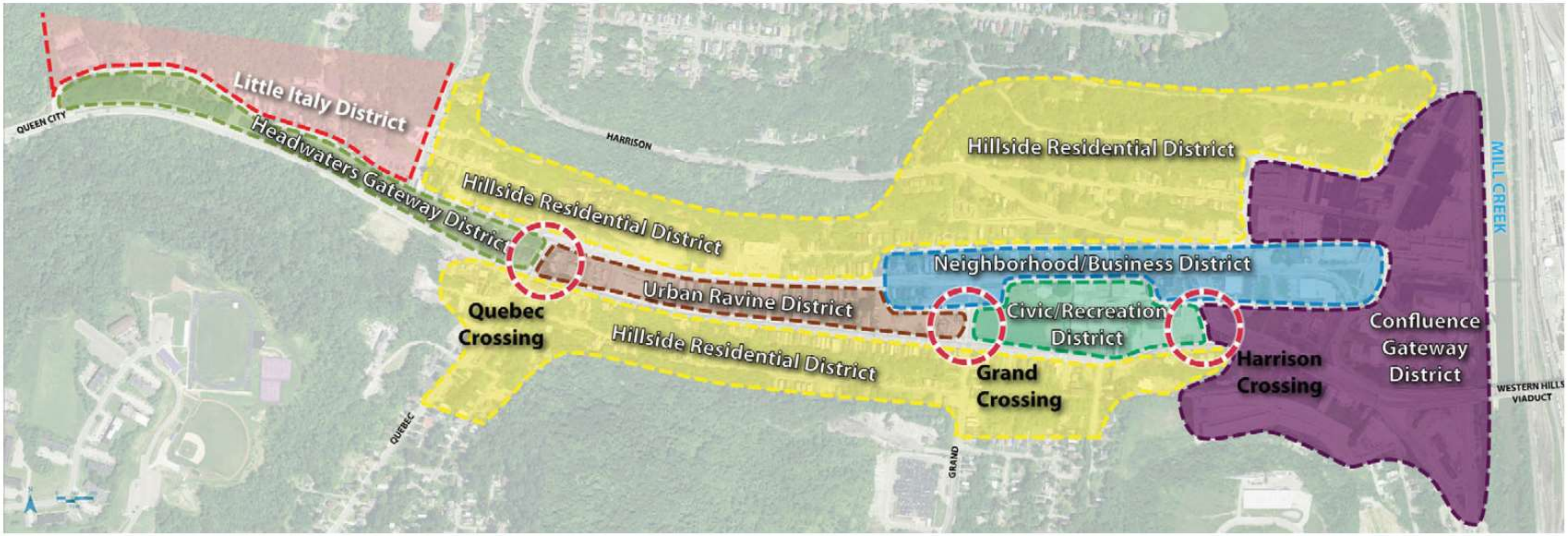
A look inside a tunnel.

Green Alternative

- 15 miles of new storm sewer
- Reduce overflow by 1 Billion gallons/year
- 3 miles of daylighted streams
- **$122 Million (50% of the cost of Gray)**



Redevelopment



Lick Run Neighborhood Districts

Residential/Mixed-Use Gathering Space

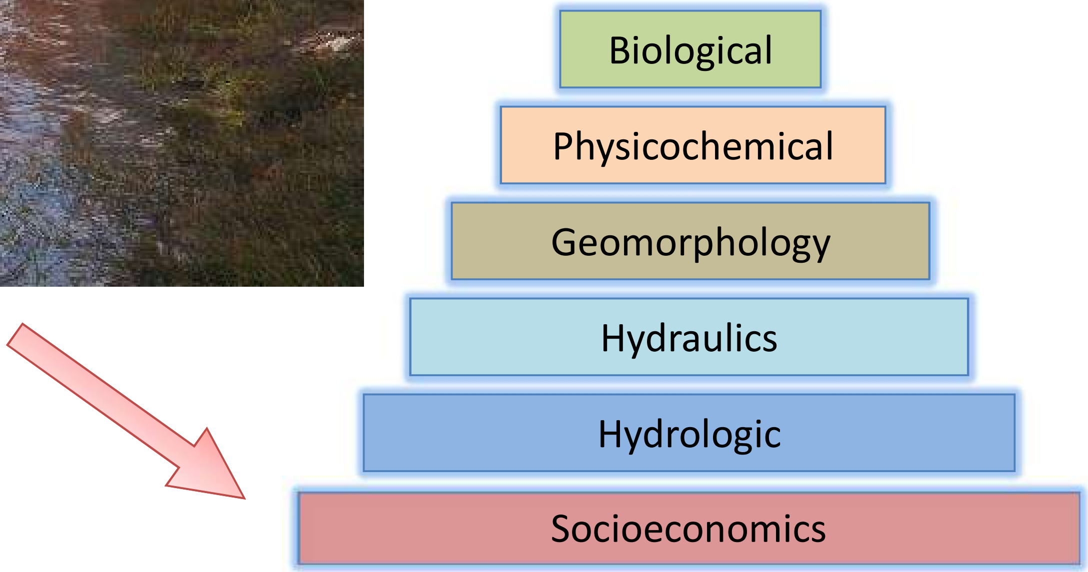
Existing Small Scale Residences in the Lick Run Watershed

Bike Lanes

Stormwater Planters/Street Trees

Successfully Incorporating Socioeconomic Factors → Greater Environmental Outcomes (i.e. Smith et al. 2016)

Adapted from Hawley (2018)



Biological

Physicochemical

Geomorphology

Hydraulics

Hydrologic

Socioeconomics

Adapted from Harman et al. (2012)

Thank You!

Sustainable Streams LLC

Science · Service · Solutions

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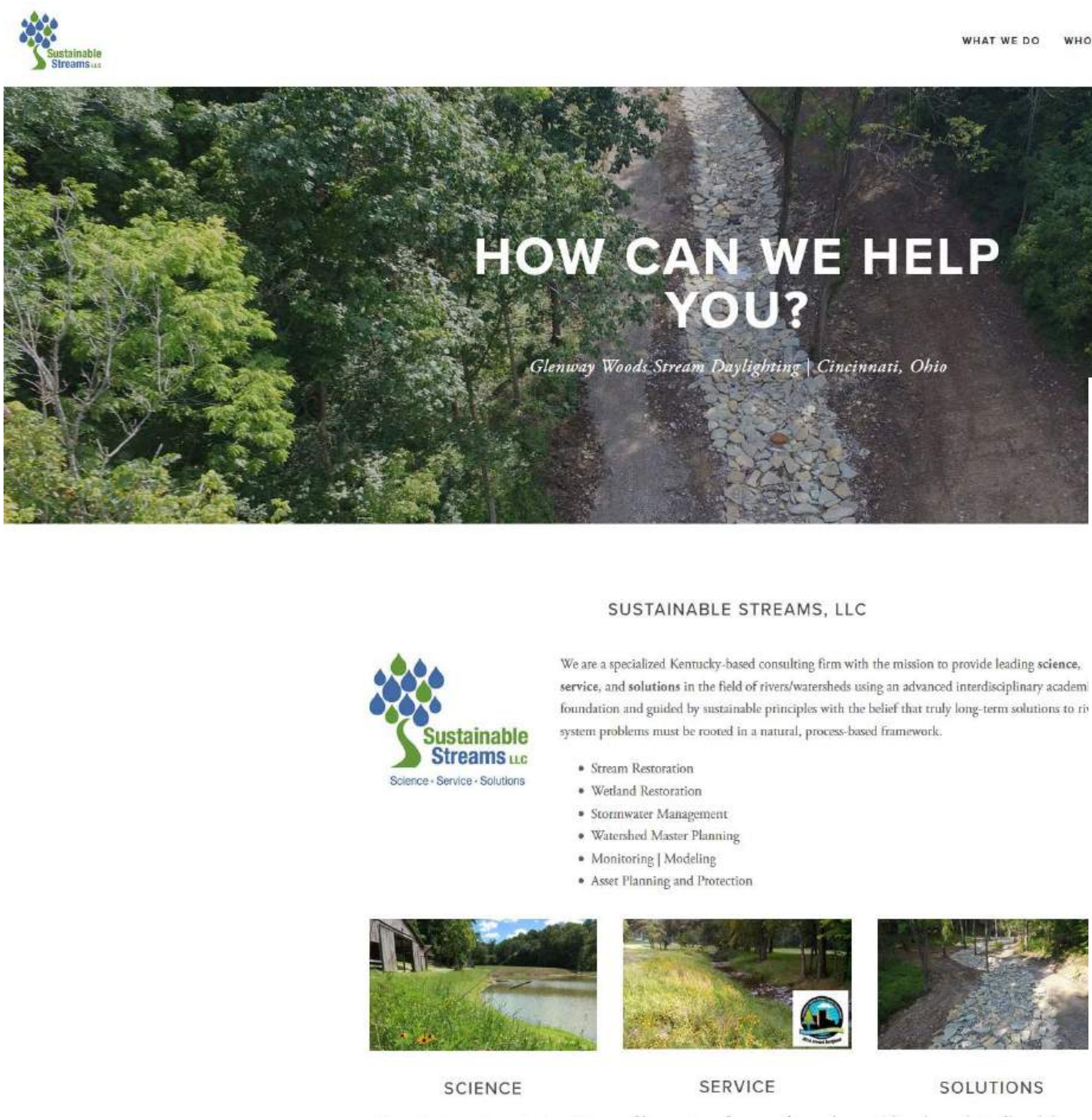
Resources



HOW CAN WE HELP YOU?

Glenway Woods Stream Daylighting | Cincinnati, Ohio

SUSTAINABLE STREAMS, LLC

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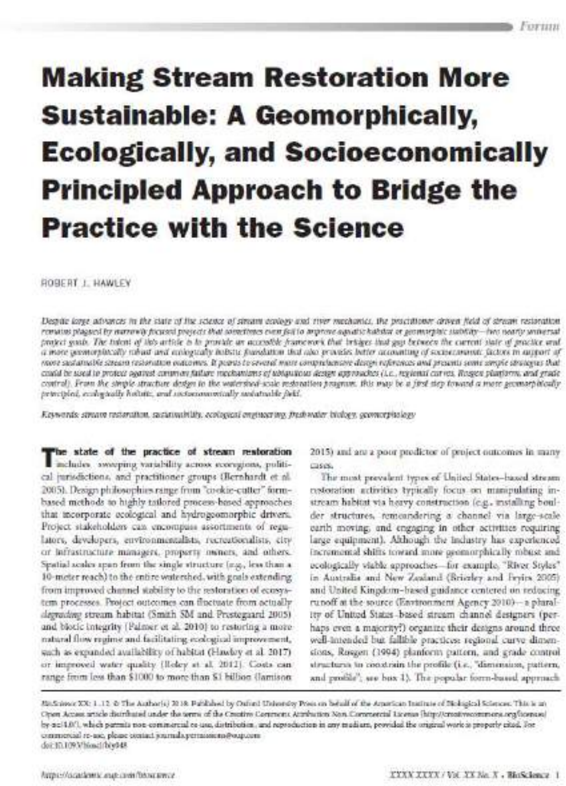
- Stream Restoration
- Wetland Restoration
- Stormwater Management
- Watershed Master Planning
- Monitoring | Modeling
- Asset Planning and Protection

SCIENCE

SERVICE

SOLUTIONS



Making Stream Restoration More Sustainable: A Geomorphically, Ecologically, and Socioeconomically Principled Approach to Bridge the Practice with the Science

ROBERT J. HAWLEY

Despite large advances in the state of the science of stream ecology and river mechanics, the practitioner-driven field of stream restoration remains plagued by narrowly focused projects that sometimes even fail to improve aquatic habitat or geomorphic stability—two nearly universal project goals. The intent of this article is to provide an accessible framework that bridges that gap between the current state of practice and a more geomorphically robust and ecologically holistic foundation that also provides better accounting of socioeconomic factors in support of more sustainable stream restoration outcomes. It points to several more comprehensive design references and presents some simple strategies that could be used to protect against common failure mechanisms of ubiquitous design approaches (i.e., regional curves, Rosgen planform, and grade control). From the simple structure design to the watershed-scale restoration program, this may be a first step toward a more geomorphically principled, ecologically holistic, and socioeconomically sustainable field.

Keywords: stream restoration, sustainability, ecological engineering, freshwater biology, geomorphology

The state of the practice of stream restoration includes sweeping variability across ecoregions, political jurisdictions, and practitioner groups (Bernhardt et al. 2005). Design philosophies range from "cookie-cutter" form-based methods to highly tailored process-based approaches that incorporate ecological and hydrogeomorphic drivers. Project stakeholders can encompass assortments of regulators, developers, environmentalists, recreationalists, city or infrastructure managers, property owners, and others. Spatial scales span from the single structure (e.g., less than a 10-meter reach) to the entire watershed, with goals extending from improved channel stability to the restoration of ecosystem processes. Project outcomes can fluctuate from actually *degrading* stream habitat (Smith SM and Prestegaard 2005) and biotic integrity (Palmer et al. 2010) to restoring a more natural flow regime and facilitating ecological improvement, such as expanded availability of habitat (Hawley et al. 2017) or improved water quality (Roley et al. 2012). Costs can range from less than $1000 to more than $1 billion (Jamison 2015) and are a poor predictor of project outcomes in many cases.

The most prevalent types of United States–based stream restoration activities typically focus on manipulating in-stream habitat via heavy construction (e.g., installing boulder structures, remeandering a channel via large-scale earth moving, and engaging in other activities requiring large equipment). Although the industry has experienced incremental shifts toward more geomorphically robust and ecologically viable approaches—for example, "River Styles" in Australia and New Zealand (Brierley and Fryirs 2005) and United Kingdom–based guidance centered on reducing runoff at the source (Environment Agency 2010)—a plurality of United States–based stream channel designers (perhaps even a majority?) organize their designs around three well-intended but fallible practices: regional curve dimensions, Rosgen (1994) planform pattern, and grade control structures to constrain the profile (i.e., "dimension, pattern, and profile"; see box 1). The popular form-based approach

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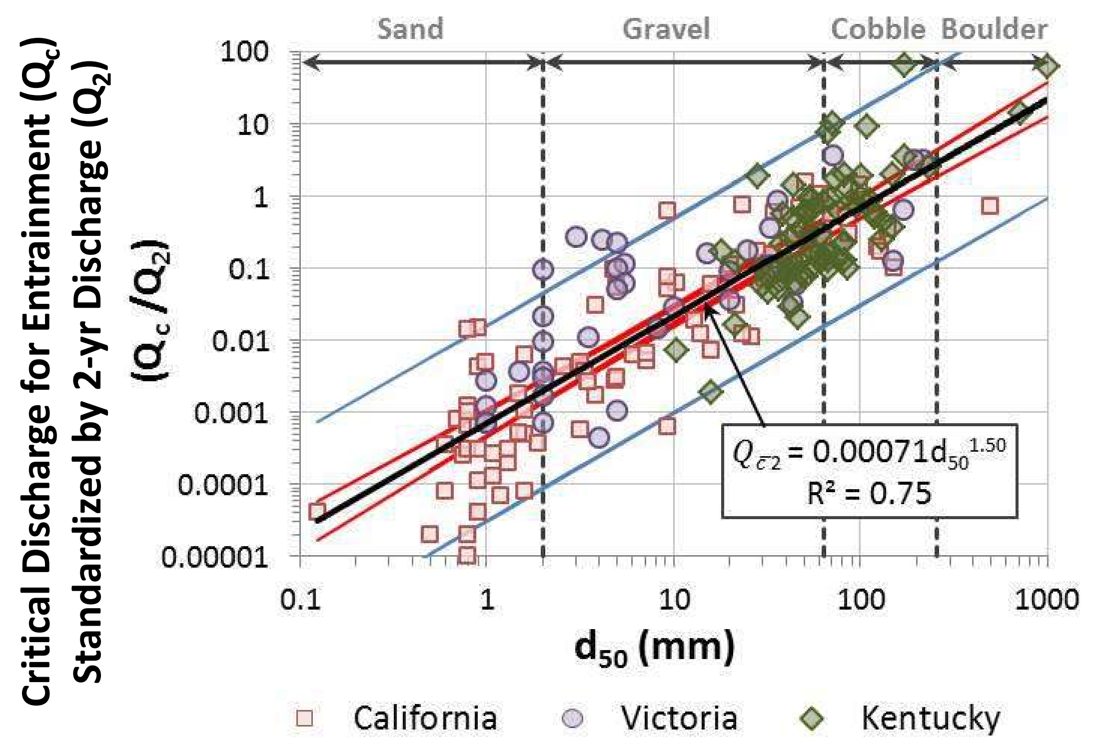
doi:10.1093/biosci/biy048

Bed Material Entrainment Threshold (Critical Discharge, Q_c) Varies by Orders of Magnitude across Size Classes



Adapted from Hawley and Vietz 2016, Freshwater Science

$Q_{critical}$ Calibrated to Stream/Region

Simple Sediment Monitoring Cost-Effectively Supports Equilibrium Design

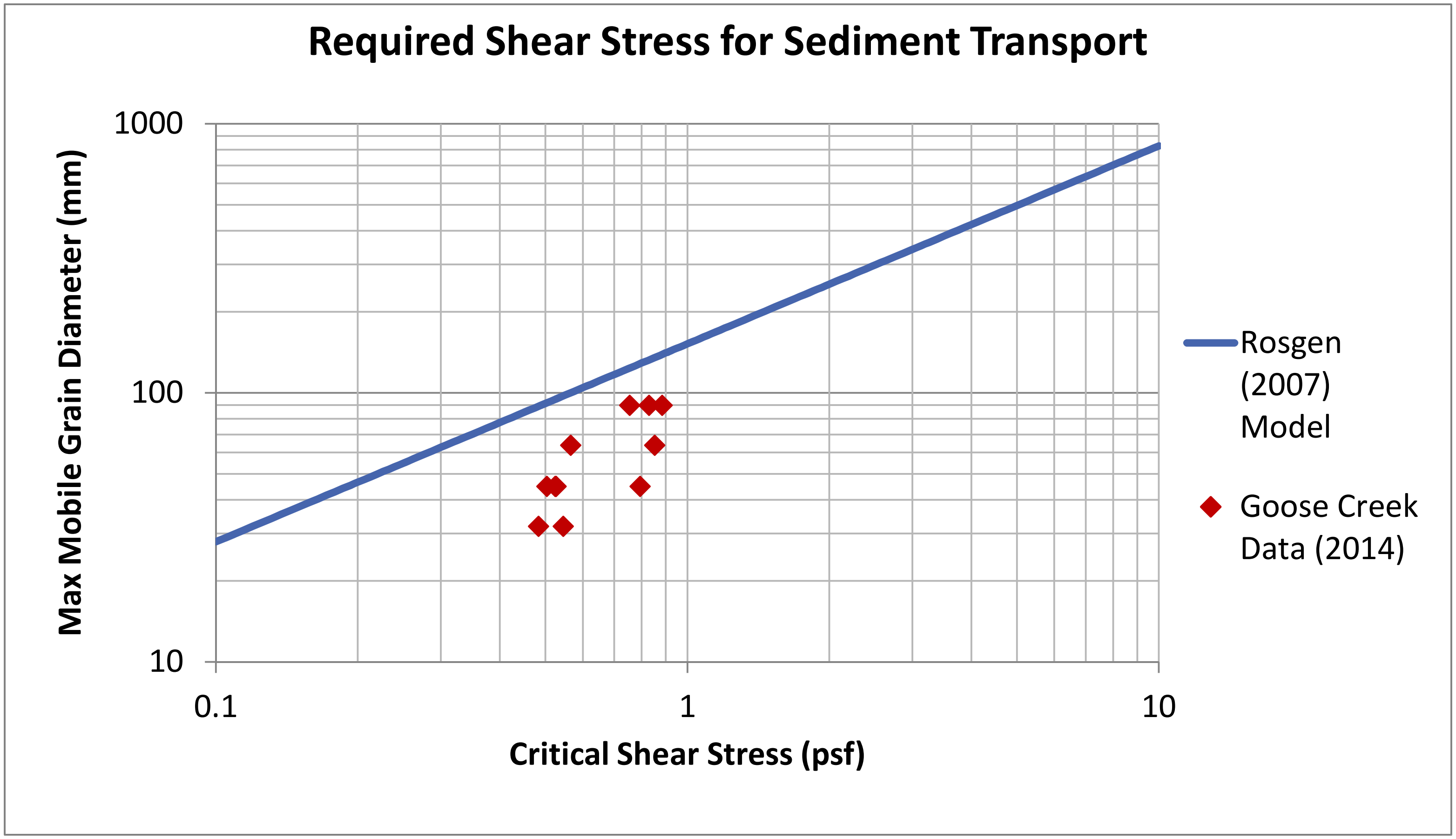
Tributary of Blue Spring Creek

"Using a few transport samples to calibrate your transport estimate is the single most effective thing you can do to increase accuracy."

– Wilcock et al., 2009

Goose Creek

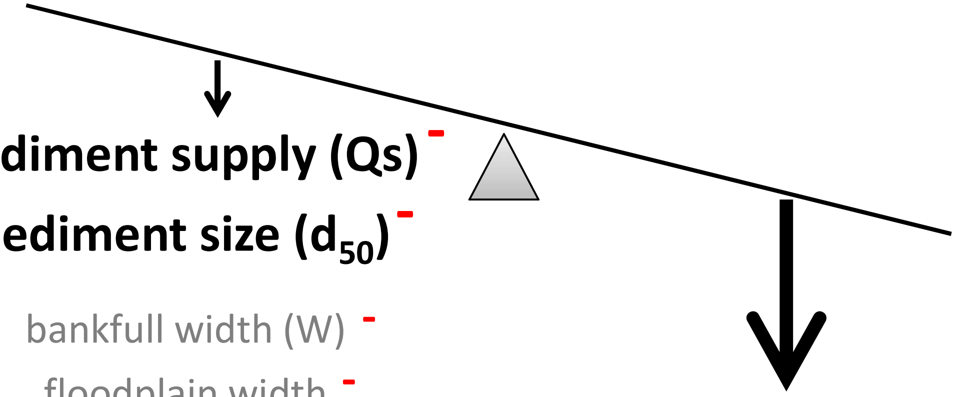
Goose Creek Data Show the Value in Calibrating Designs to the Specific Stream



Designing Considering Only Rosgen's Model Could Have Under-designed Goose Creek, Causing Sediment Aggradation and Instability

Tipping the Scales

Resistance << Erosion



dams **sediment supply (Qs)** $^{-}$

gravel mining **sediment size (d$_{50}$)** $^{-}$

channelization bankfull width (W) $^{-}$

floodplain encroachment floodplain width $^{-}$

grade control

bank strength $^{-}$

riparian removal

vegetation $^{-}$…

discharge (Q) $^{+}$ urbanization & deforestation

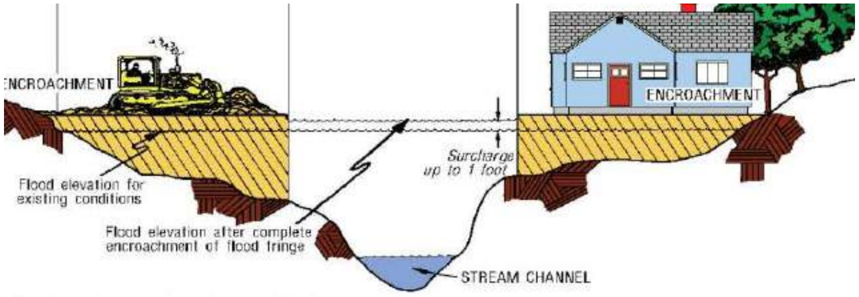
slope (S) $^{+}$

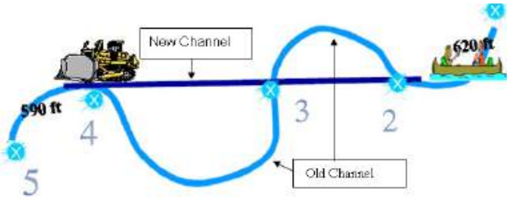
channelization

bankfull depth (y) $^{+}$

floodplain depth $^{+}$ floodplain encroachment

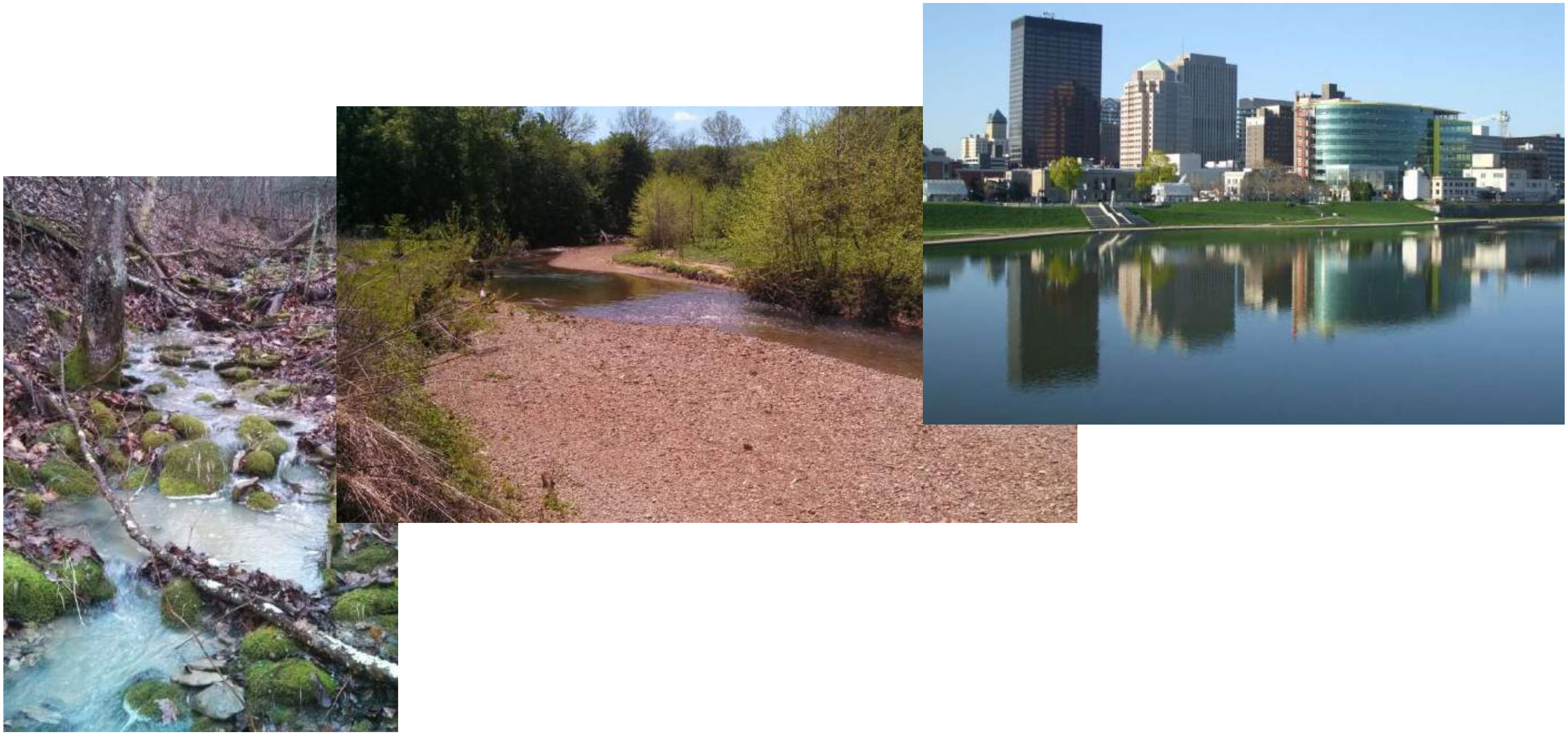
valley slope …





“Regional Curves”

- More Water = Bigger Channels (typically)

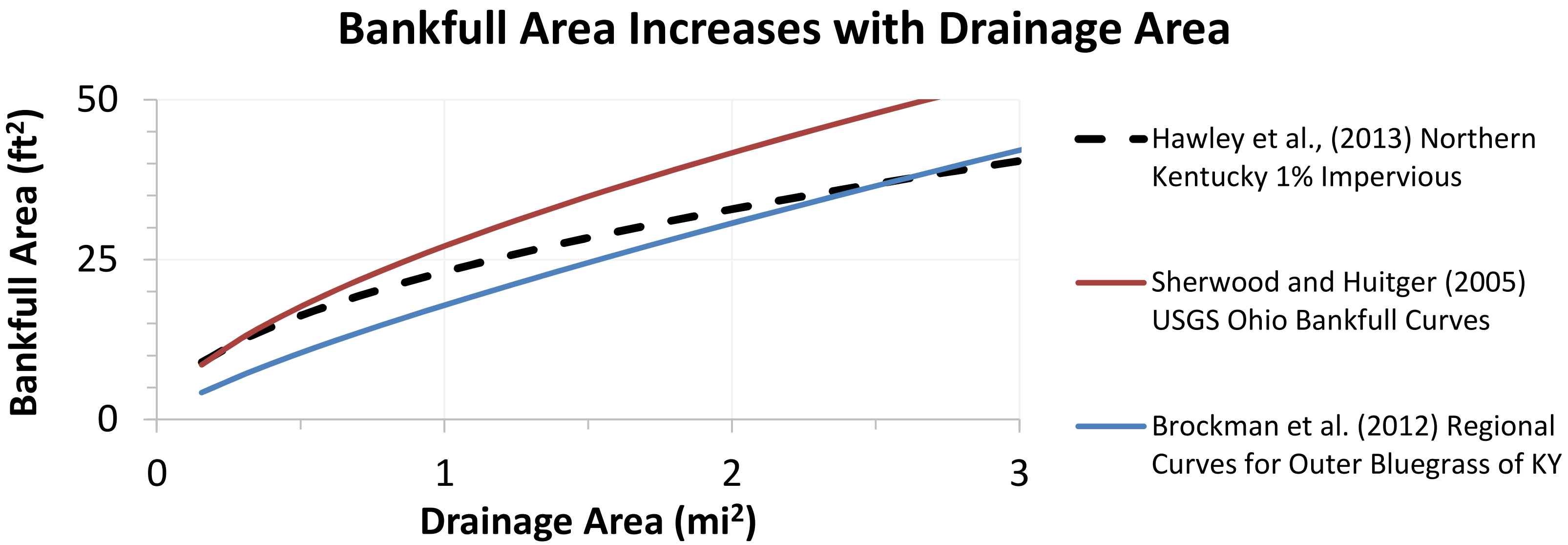


More Drainage Area = Larger Channels (typically)

$W \propto Q^{0.5}$ (most environments; Knighton, 1998)

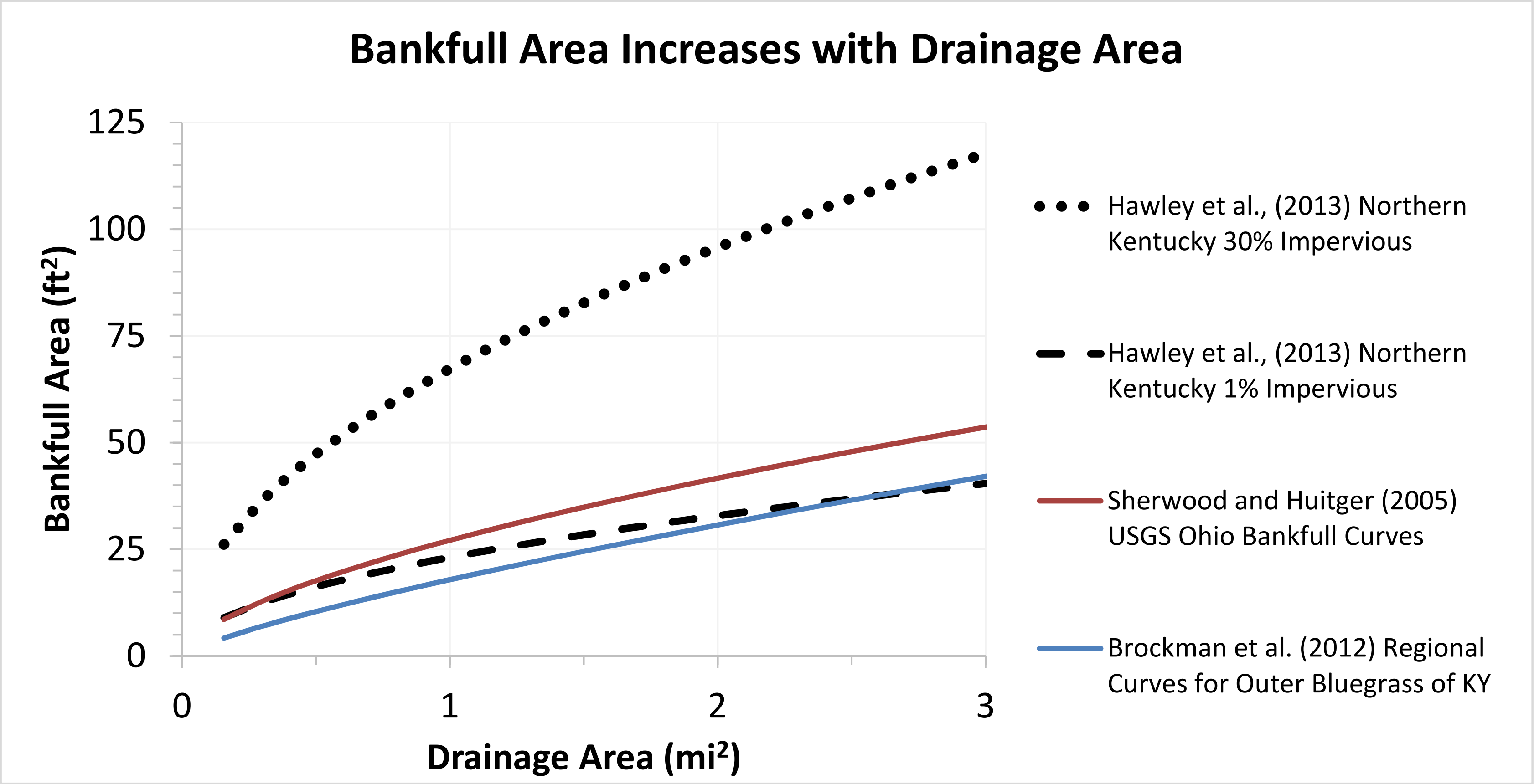
$Q \propto DA^{b}$ (USGS regional curves)

$\rightarrow W \propto DA^{\sim 0.5*b}$



Adapted from Smith et al. (2016, Freshwater Science)

More Water = Larger Channels
More Stormwater = Larger Urban Streams



Adapted from Smith et al. (2016, Freshwater Science)

Undeveloped vs. Developed Watersheds

Biological
Physicochemical
Geomorphology
Hydraulics
Hydrologic

Middle Creek (3.3 mi^2)
Undeveloped (0.6% Impervious)

Owl Creek (3.7 mi^2)
Developing (9% Impervious)

Undeveloped vs. Developed Watersheds

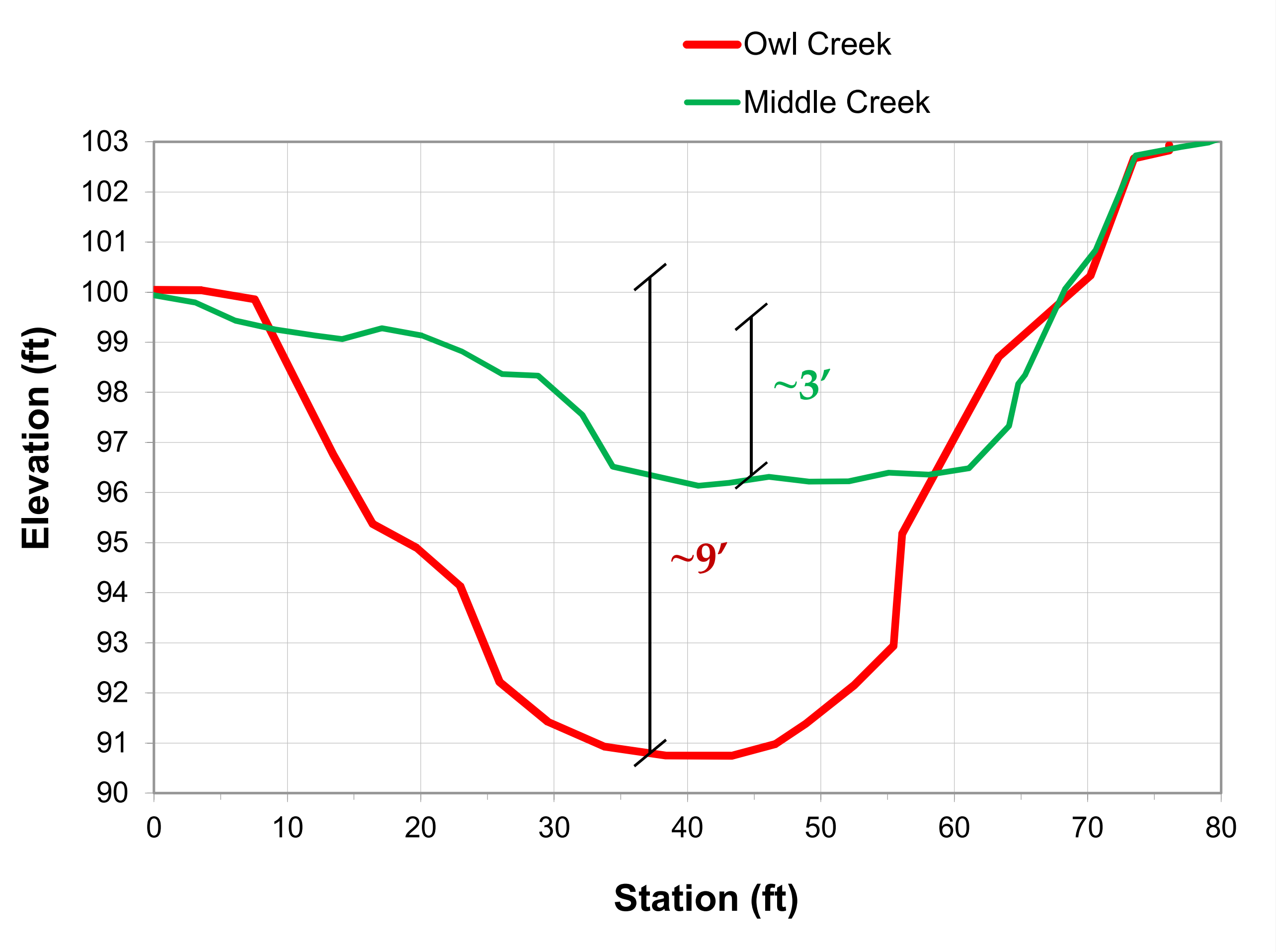
Biological

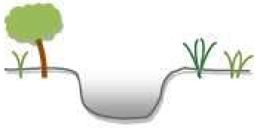
Physicochemical

Geomorphology

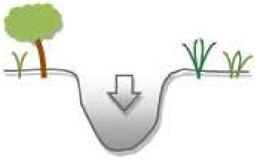
Hydraulics

Hydrologic

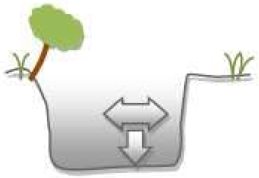




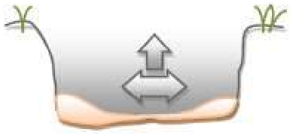
Stage1 – Equilibrium



Stage 2– Incision



Stage 3 – Widening



Stage 4– Aggradation

Stage 5 – Equilibrium

Channel Evolution Sequence in Response to Increased Flows from Urbanization, Adapted from Schumm et al. (1984) and Hawley et al. (2012)