Detention Basin Design for Stream Stability

June 23, 2022

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Sustainable Streams, LLC

Sustainable Streams LLC
Science · Service · Solutions

Geomorphic Stability Fundamentals

Stream Function Pyramid as a Framework for Stream Management

Cumulative Impacts

Biological

Physicochemical

Geomorphology

Hydraulics

Hydrologic

(Adapted from Harmon et al., 2012)

Streams Tend Toward Equilibrium

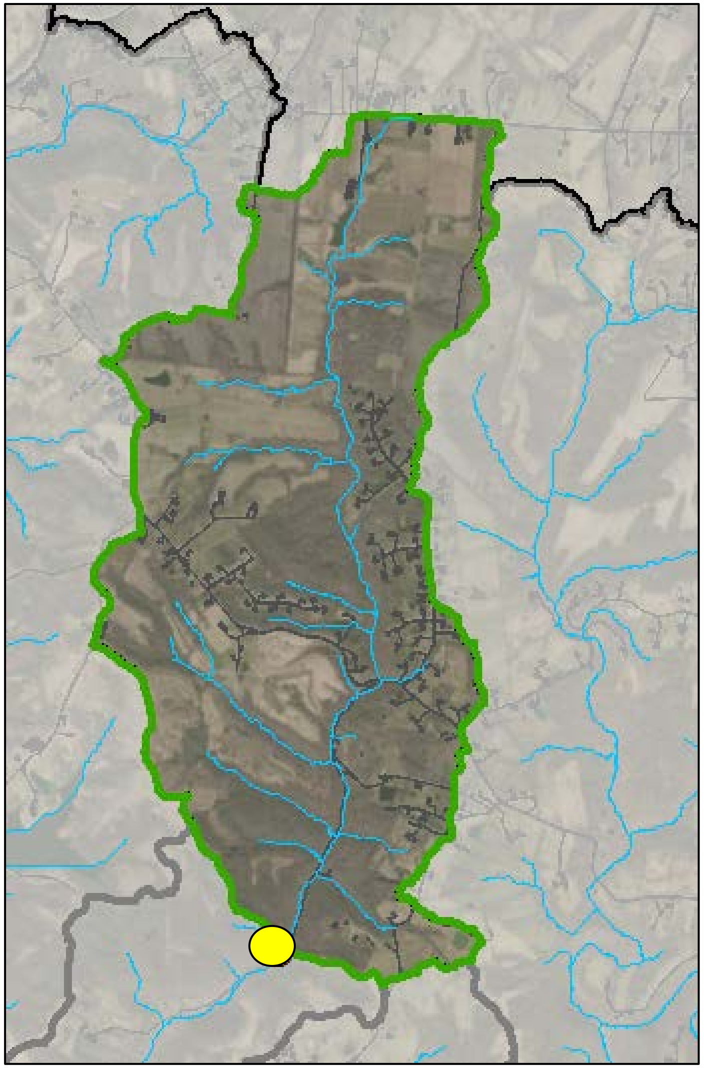
Resistance α Erosion

Sediment Supply in Balance with Water Supply and Slope

Qs, d_{50} Q, S

Adapted from Lane (1955)

Stream Flow in Undeveloped Watershed



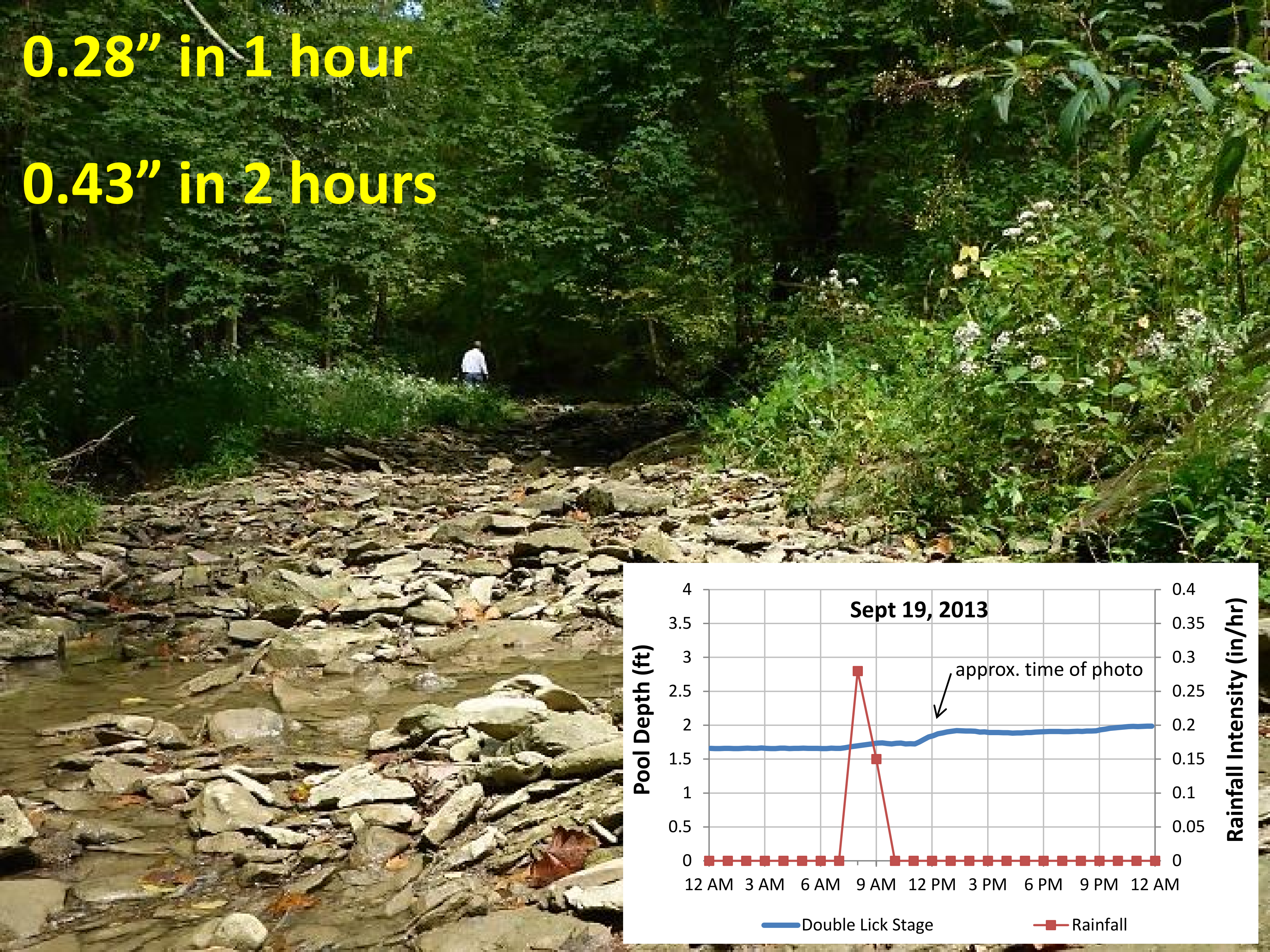
Double Lick Creek

1.8 square miles, 3% impervious

Outstanding State Resource Water

0.28” in 1 hour

0.43” in 2 hours



Stream Flow Downstream of Conventional Development

Sand Run

2.2 square miles, 29% impervious

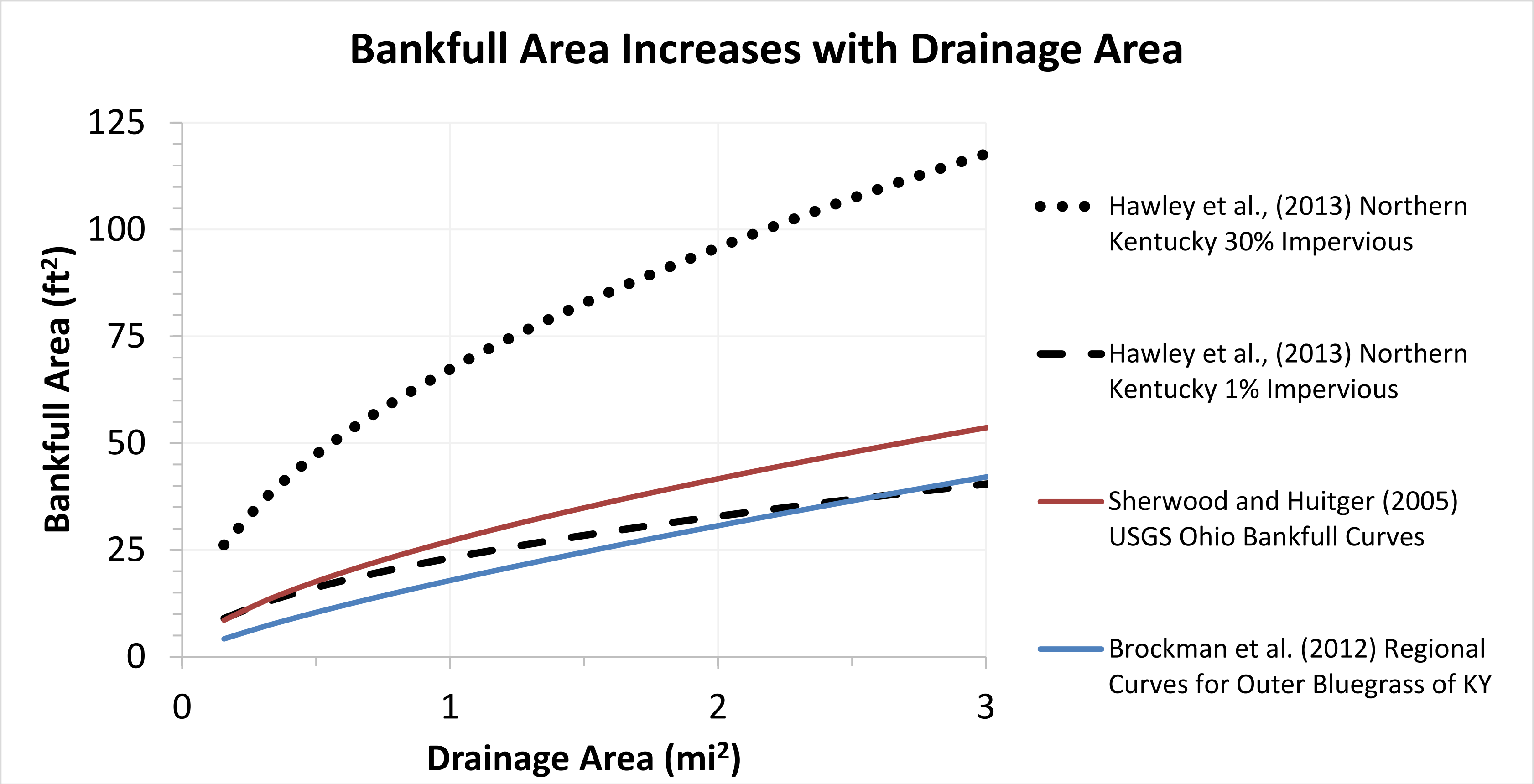
Sand Run

08/28/2008 11:14

0.3” in 1 hour

06/10/2009 08:26

More Water = Larger Channels
More Storm Water = Larger Urban Streams



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

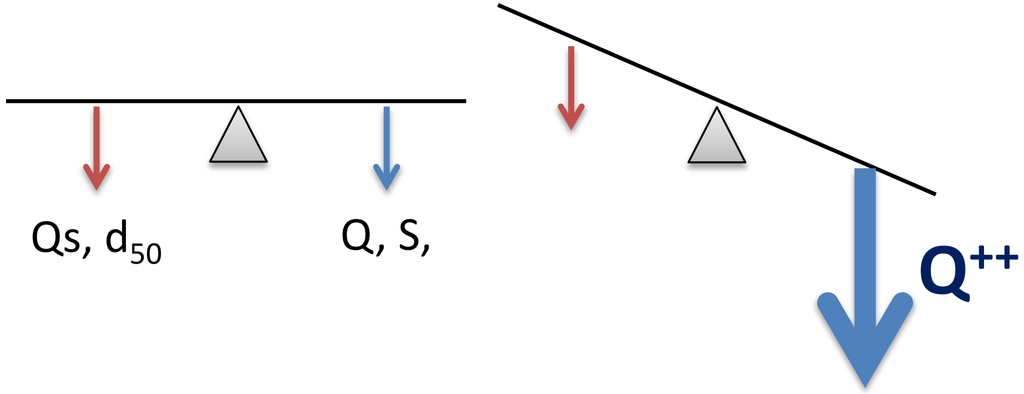
Conventional Stormwater Designs → Unstable Streams

Stable:

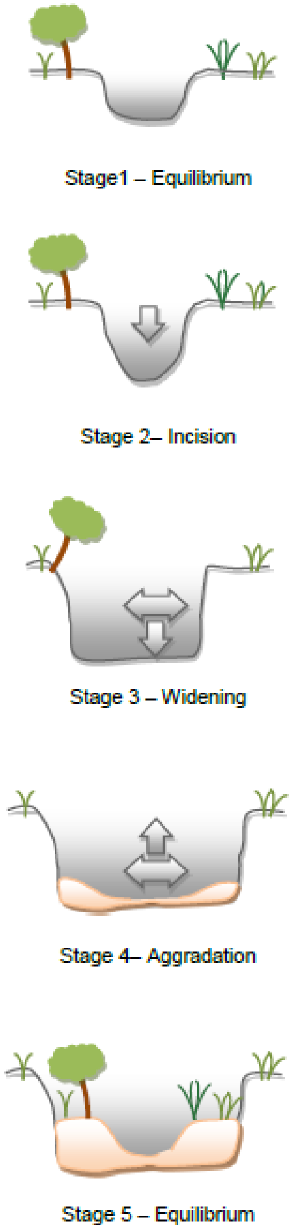
resistance α erosion

Urban (Unstable):

resistance << erosion



Adapted from Lane (1955)



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

Conventional Stormwater Designs → Unstable Streams

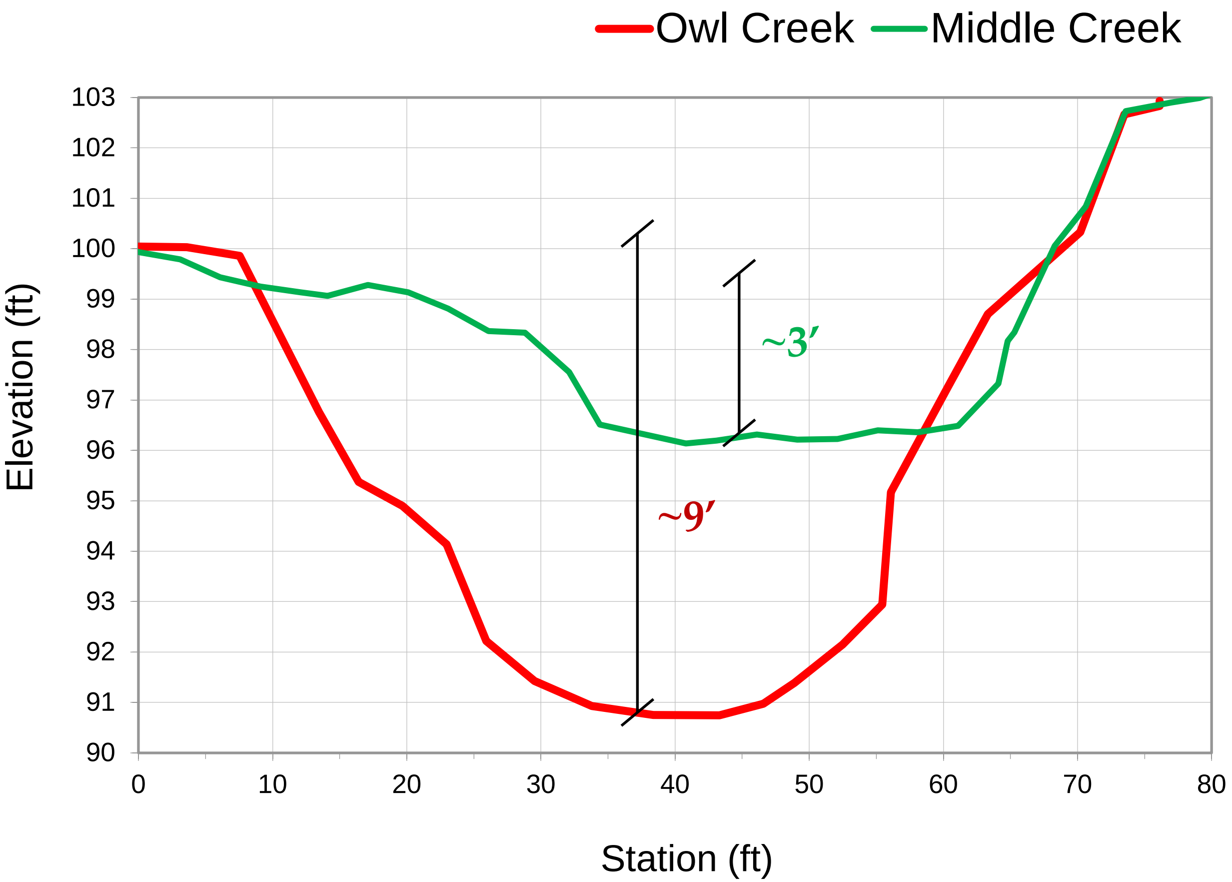
Middle Creek (3.3 mi^2)

0.6% Impervious

Owl Creek (3.7 mi^2)

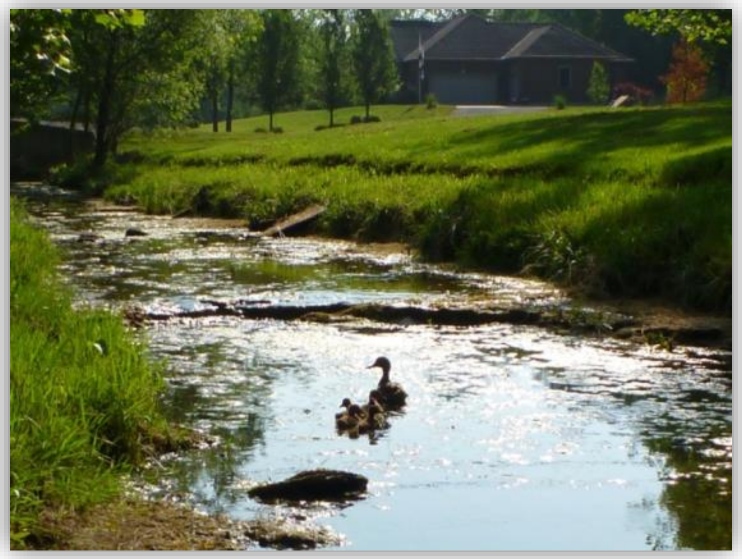
9% Impervious

Conventional Stormwater Designs → Unstable Streams



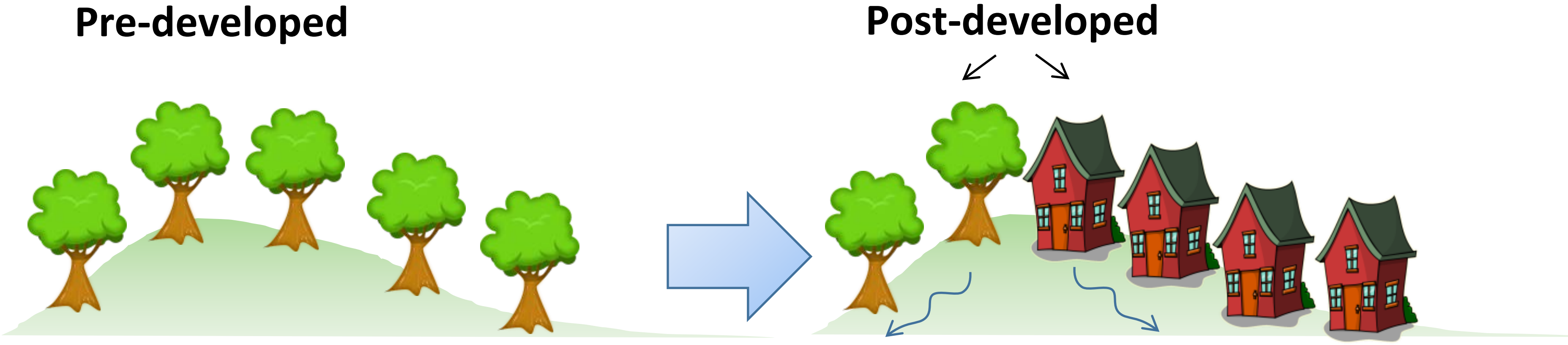
Unstable Streams
Impact Resources and Waste $$$

- Aquatic habitat
- Water quality
- Private property
- Infrastructure



Why Are All Stormwater Investments Not Preventing Stream Erosion?

Historical Stormwater Management Has Not Been Protective of Aquatic Biodiversity



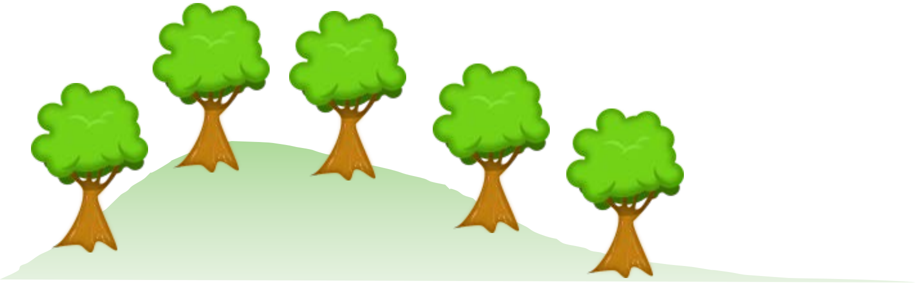
Pre-developed

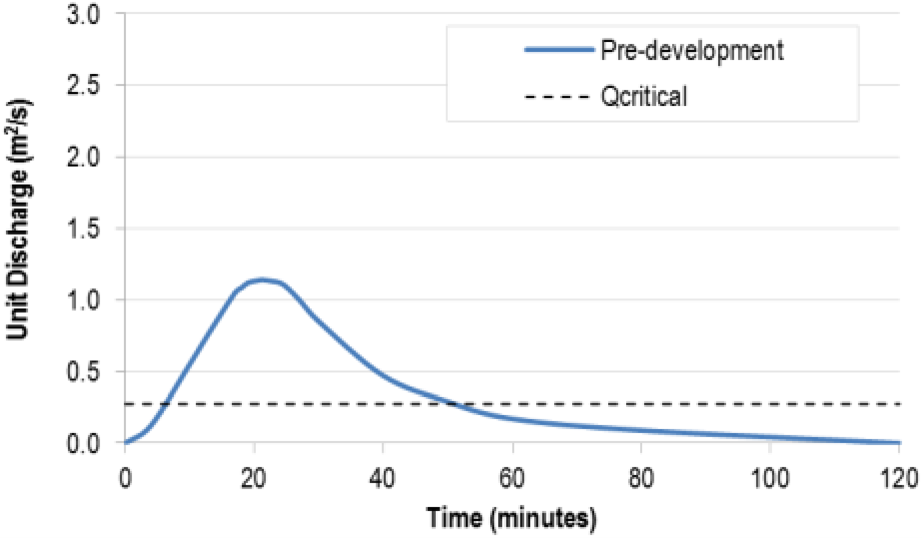
Post-developed

Data from 73 Northern Kentucky monitoring sites across a range of development styles, including peak matching detention/retention basins.

Figure from Hawley et al. (2016, Freshwater Science)

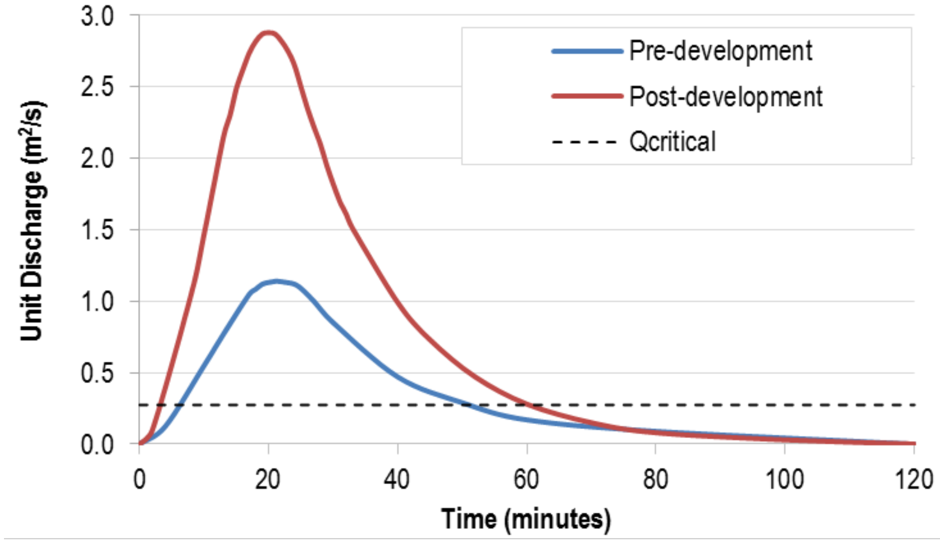
History of Stormwater Management





Analysis of the 2-yr, 2-hr storm from Fort Collins, CO by Bledsoe (2002), Journal of Water Resources Planning and Management

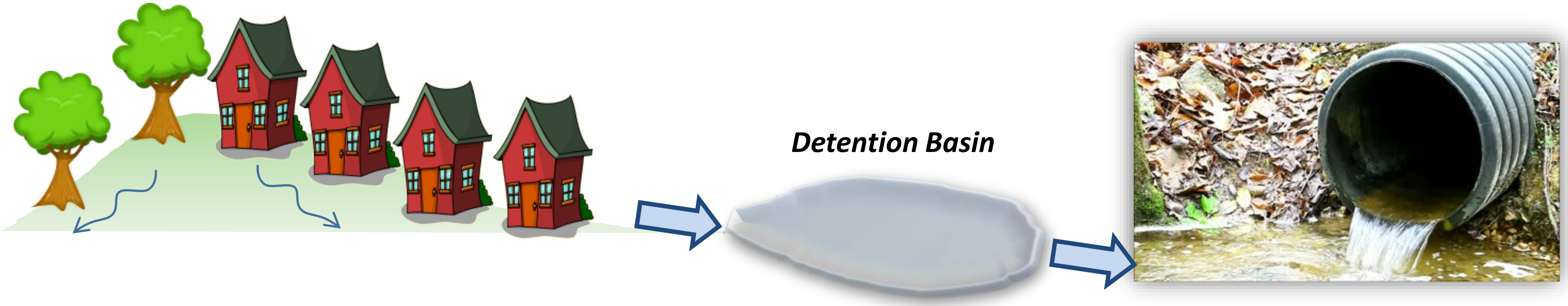
Pre ~1980s

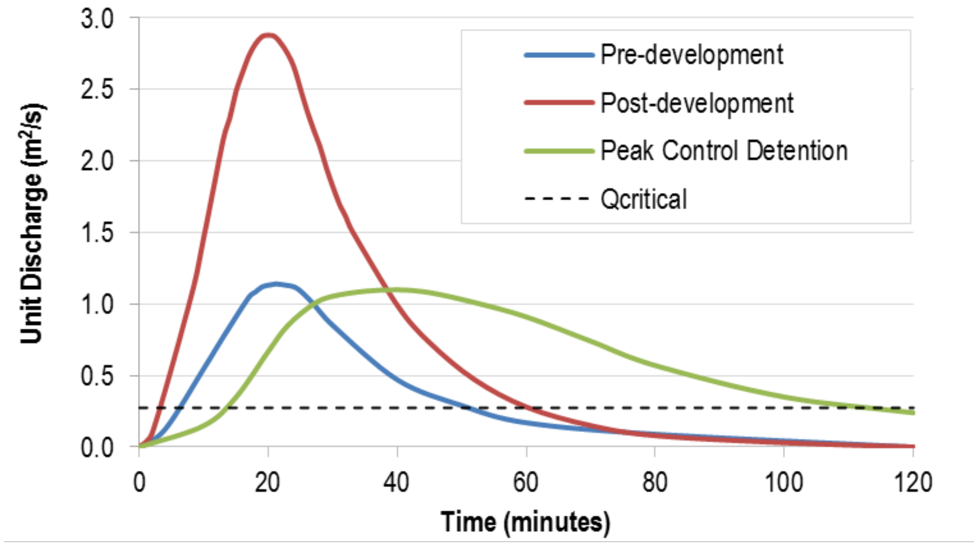


Analysis of the 2-yr, 2-hr storm from Fort Collins, CO by Bledsoe (2002), Journal of Water Resources Planning and Management


1041A

Post ~1980 / ~2000





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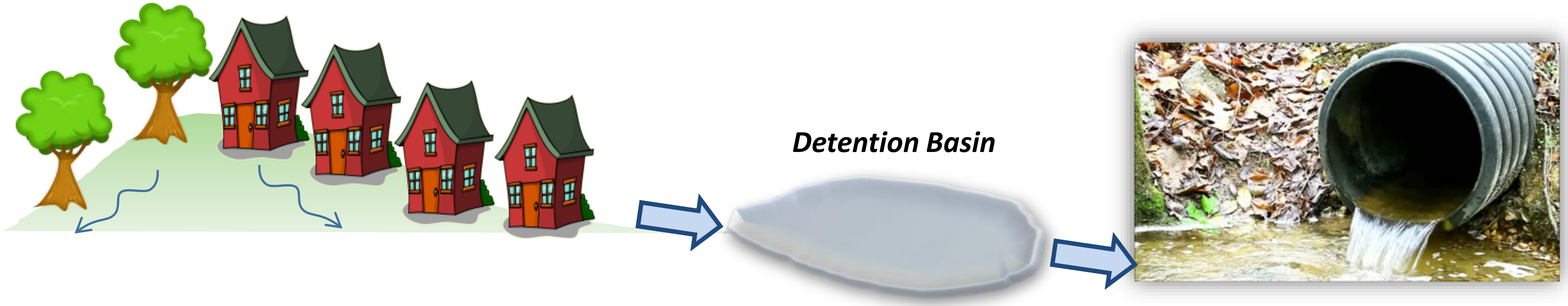
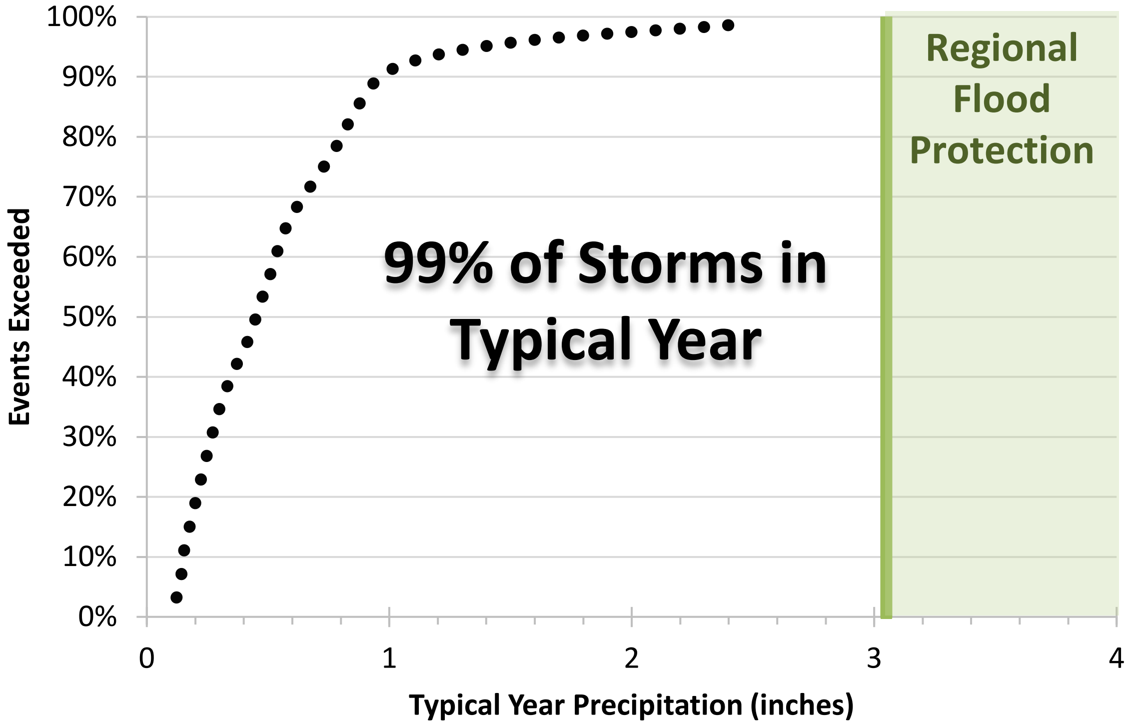




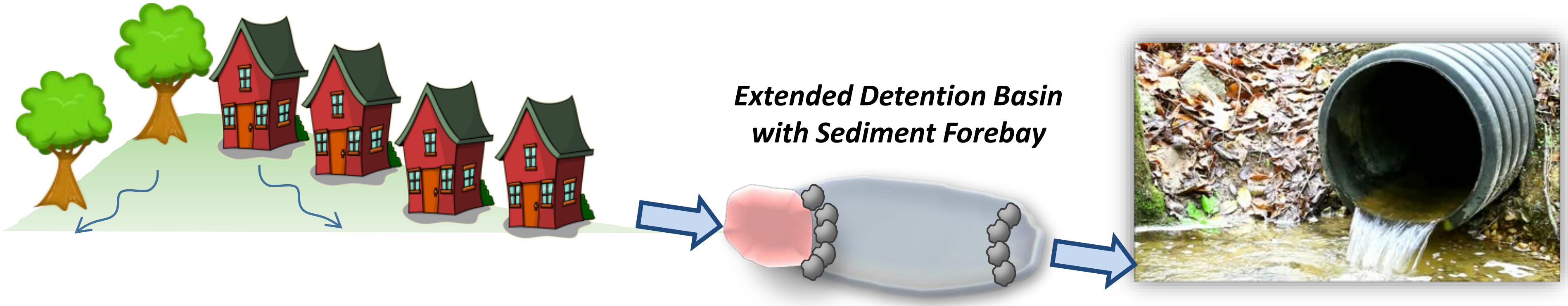
Adapted from Hawley (2012)

0.3” in 1 hour

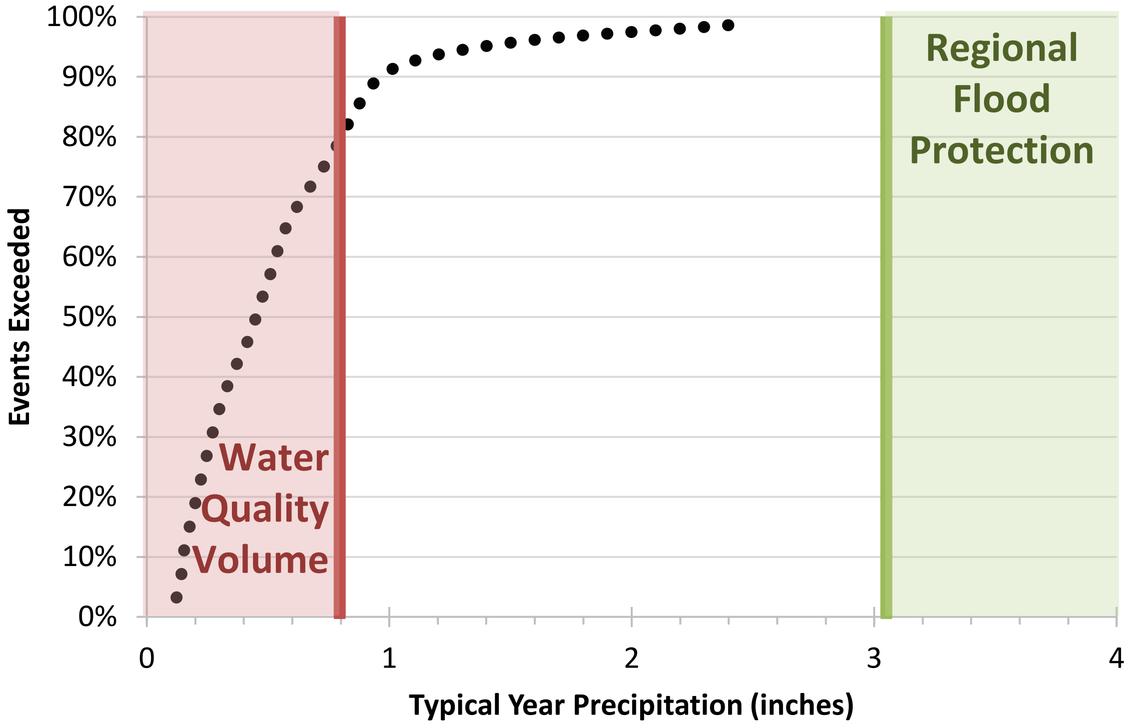
2.2 mi^2, 29% impervious

06/10/2009 08:26

Post ~2000 / ~2015

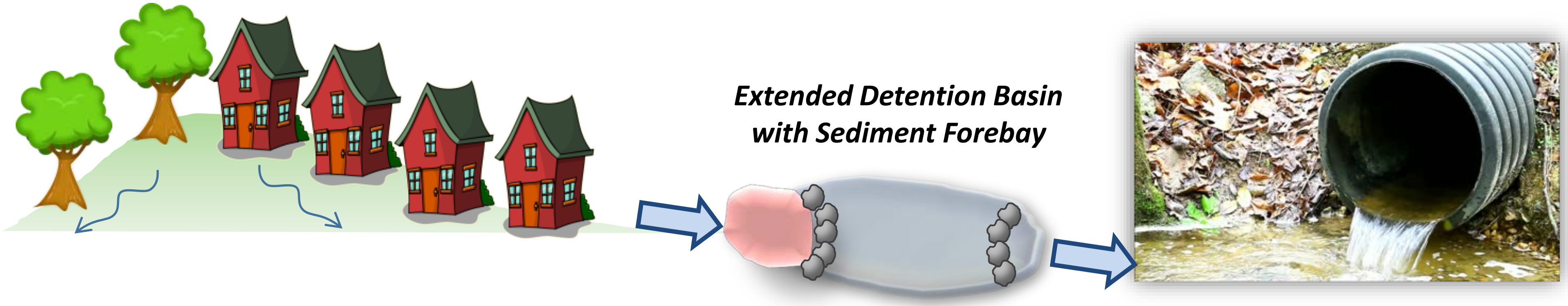


Extended Detention Basin with Sediment Forebay



Adapted from Hawley (2012)

Post ~2000 / ~2015



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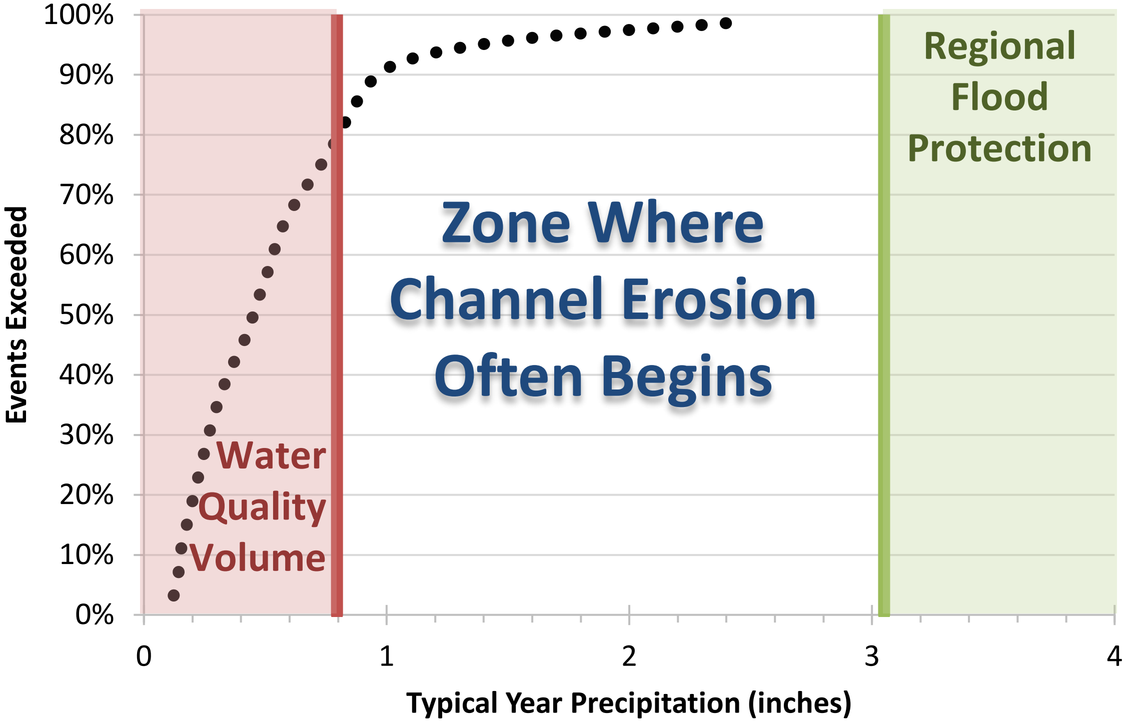
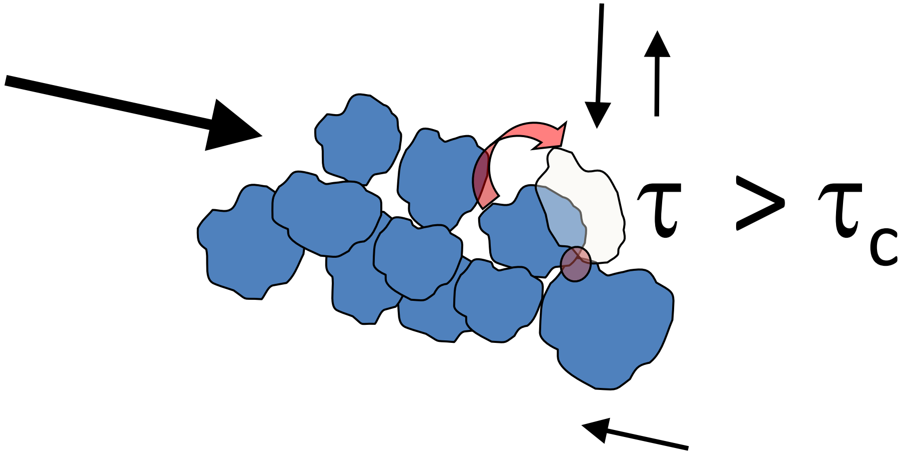


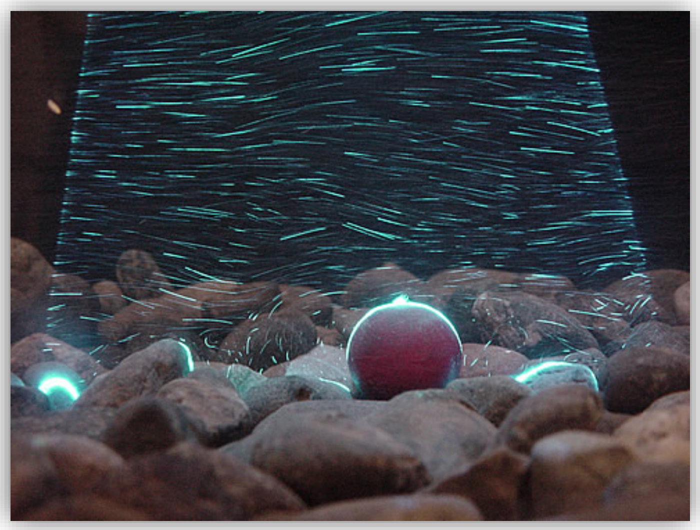
Adapted from Hawley (2012)

Introduction of $Q_{critical}$

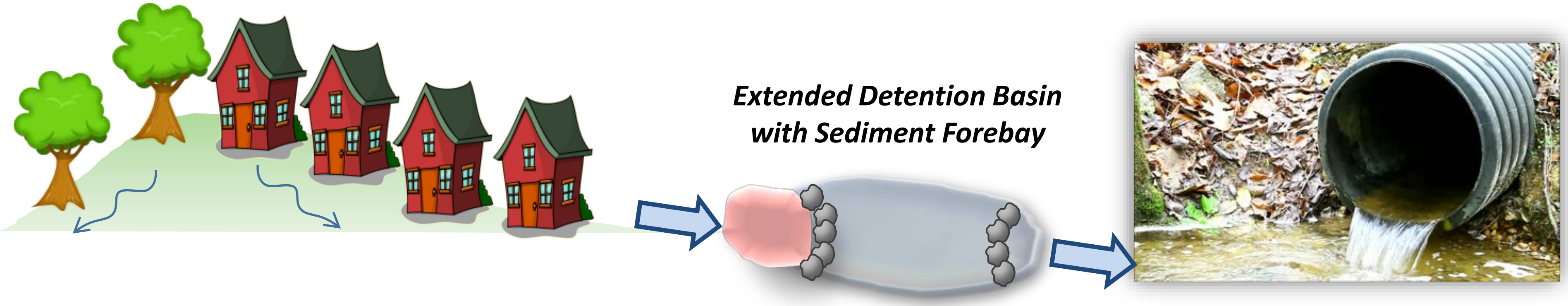
The Critical Discharge for Stream Bed Erosion



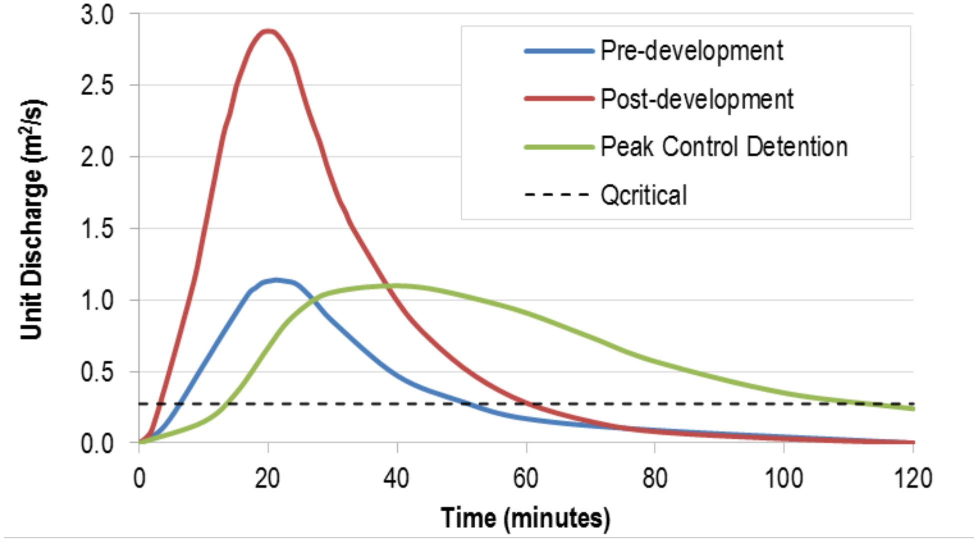
$\tau > \tau_c$



Post ~2000 to ~2015



Extended Detention Basin with Sediment Forebay



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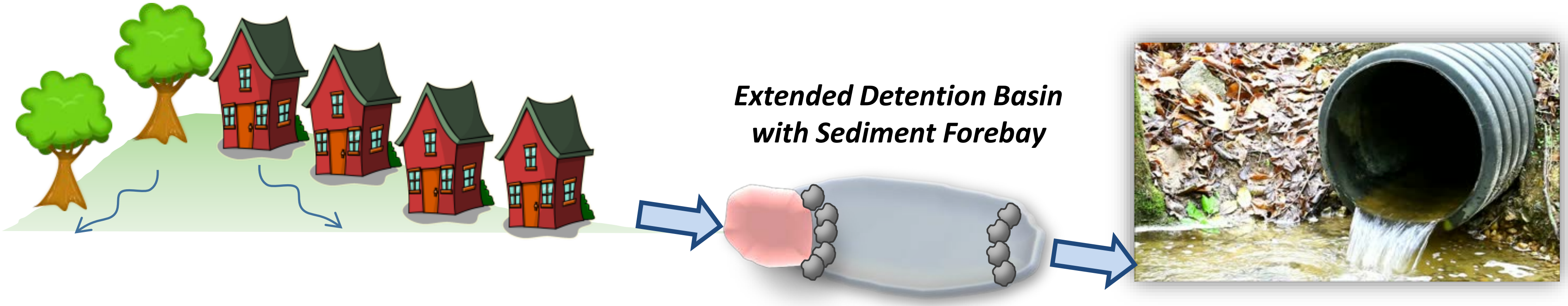
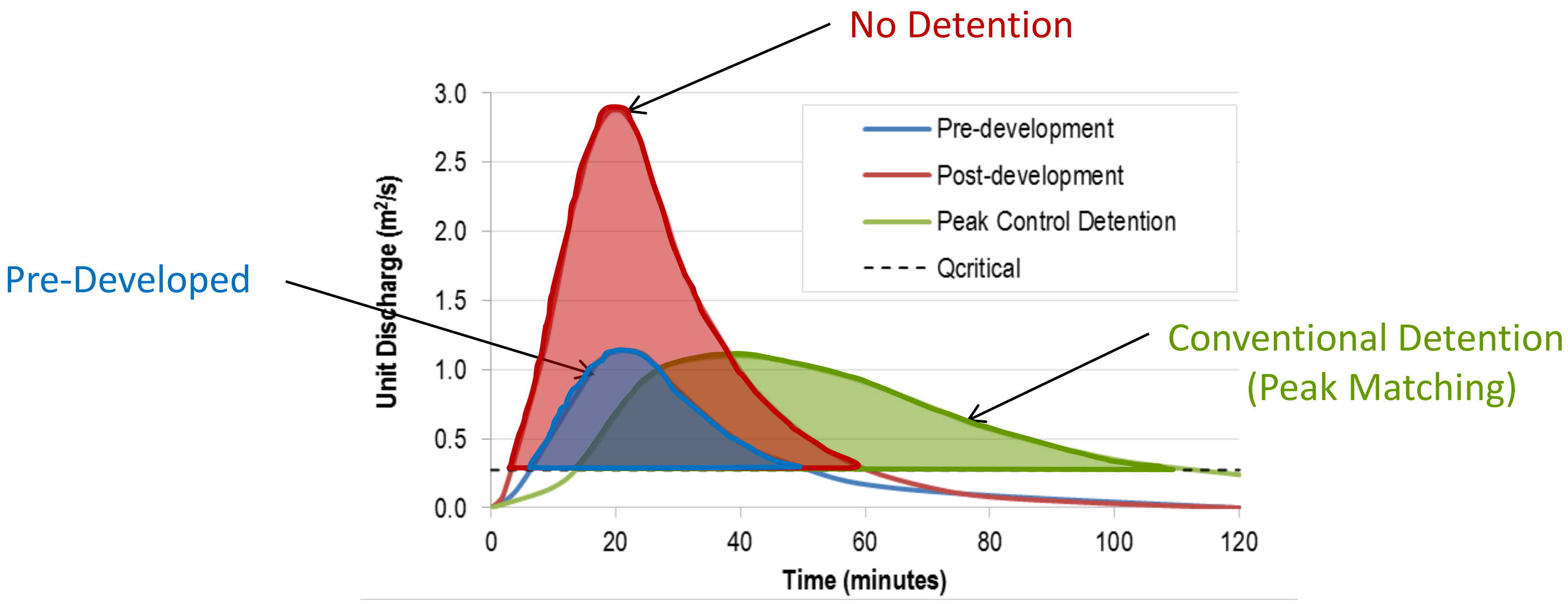
Journal of Water Resources Planning and Management

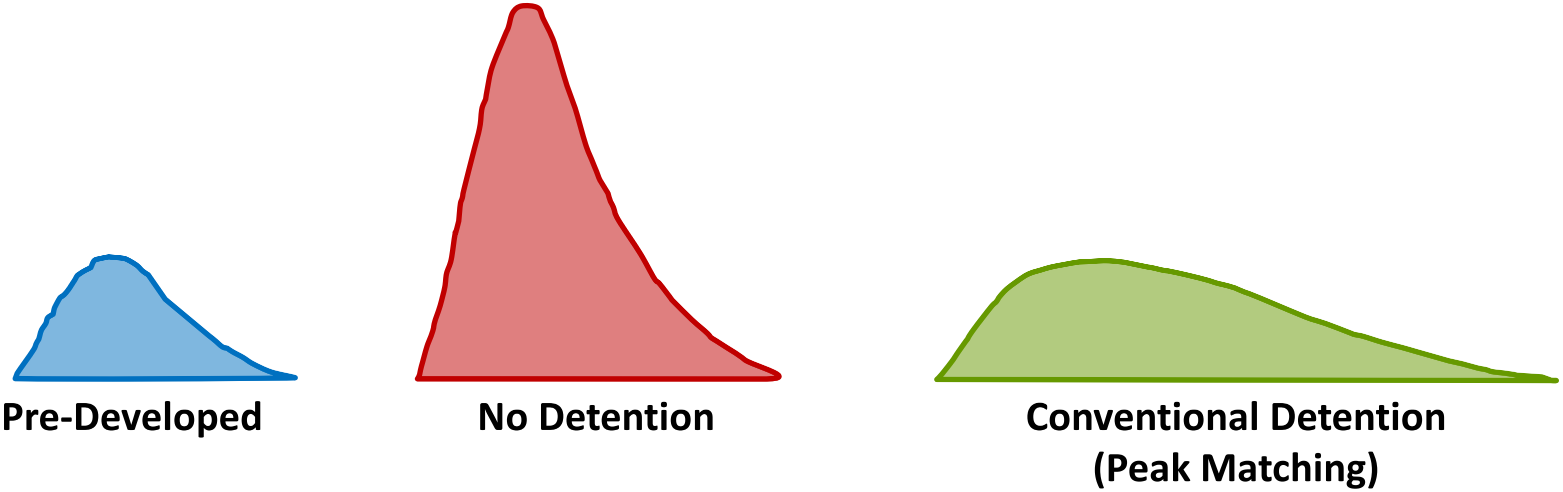
Post ~2000 to ~2015





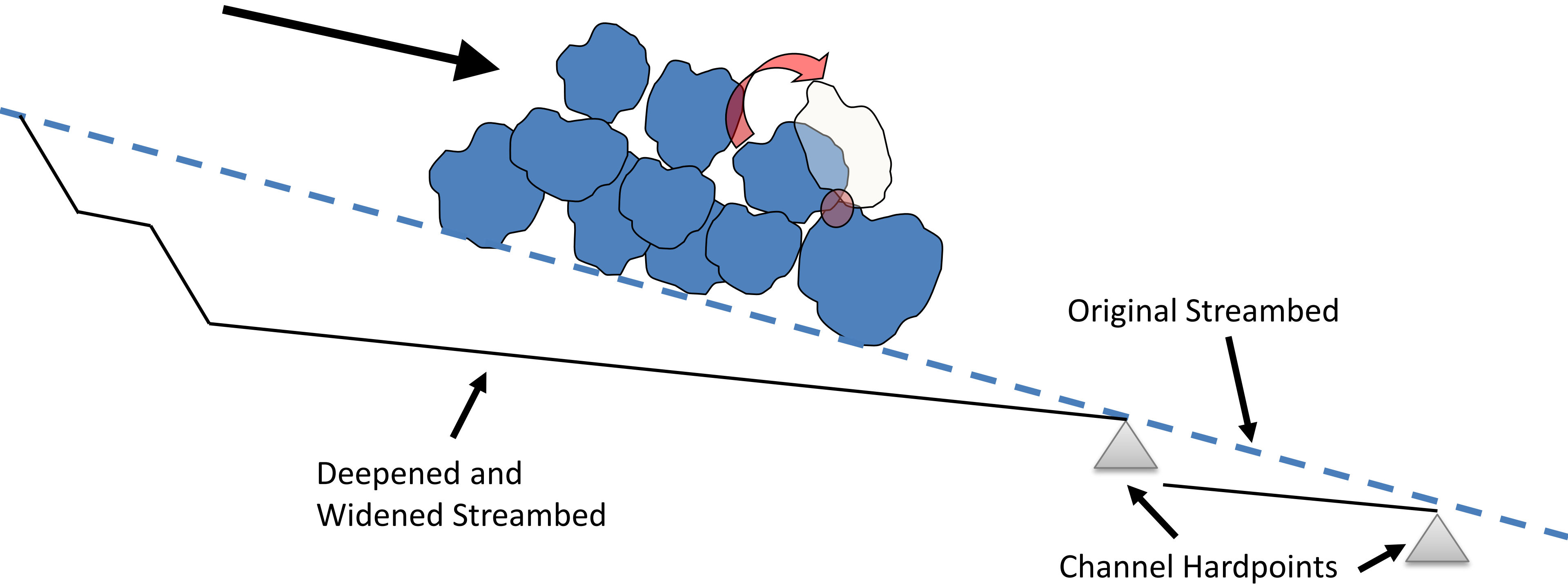
Analysis of the 2-yr, 2-hr storm from Fort Collins, CO by Bledsoe (2002),
Journal of Water Resources Planning and Management

Conventional Detention = *More Erosion* than Pre-Developed Conditions

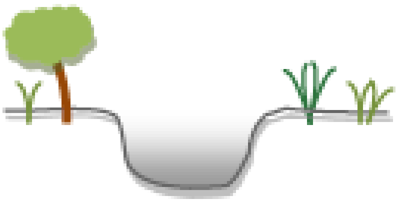


Excess Erosion of Streambed Can Lead to:

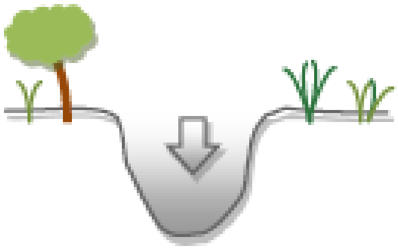
- **Stream Deepening & Widening**
- **Water Quality Impacts**
- **Biological Disturbance**



Increased Bed Erosion → Incision (Downcutting)

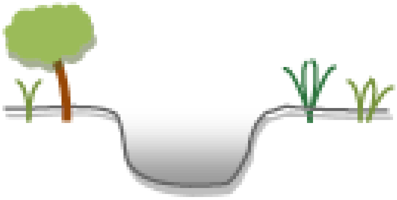


Stage1 – Equilibrium



Stage 2– Incision

Incision → Taller Banks → Bank Failure



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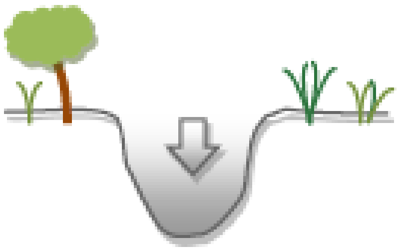
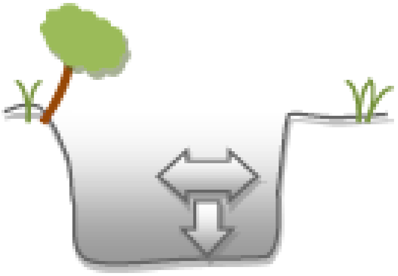
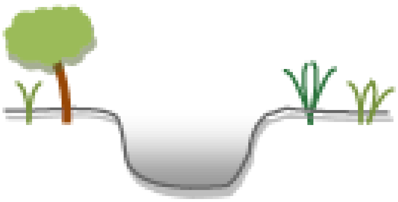


Stage 2– Incision



Stage 3 – Widening

Bank Failure → Widening



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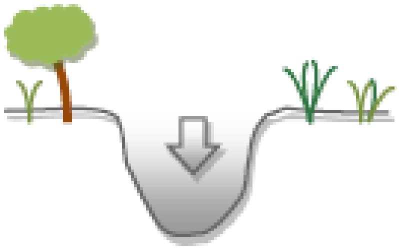
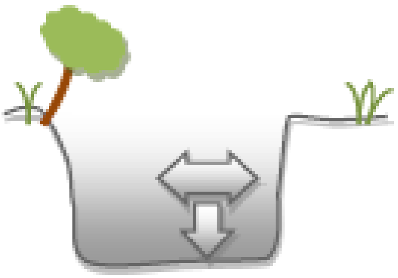
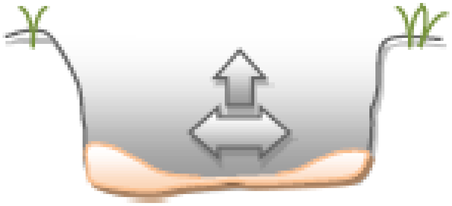


Stage 2– Incision

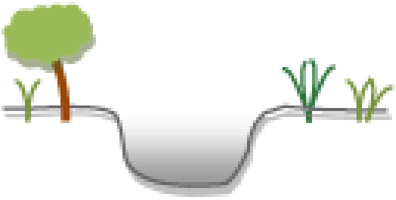


Stage 3 – Widening

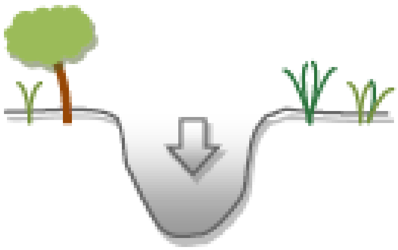


Stage 4– Aggradation

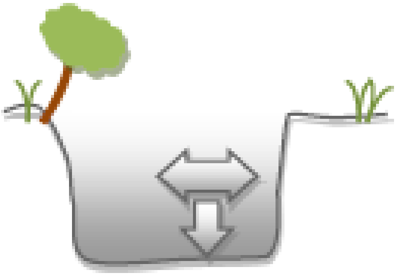
→Large Amounts of Erosion Before Returning to Equilibrium



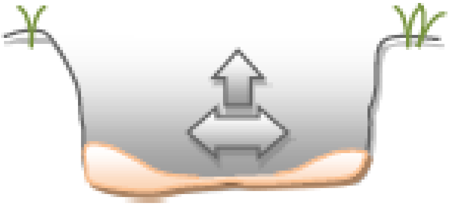
Stage1 – Equilibrium



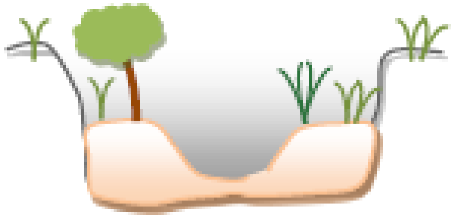
Stage 2– Incision



Stage 3 – Widening



Stage 4– Aggradation



Stage 5 – Equilibrium

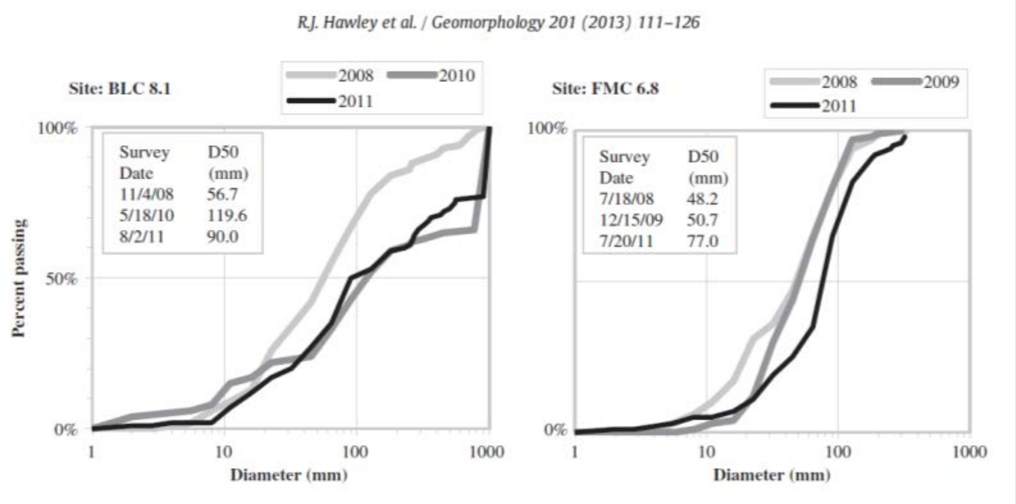
Adapted from Schumm et al. (1984) and Hawley et al. (2012)

Achieving $Q_{critical}$ Means that Storms ≤ 2-year No Longer Cause Stream Downcutting

- ✓ Protects Our Natural Resources
- ✓ Protects Our Infrastructure
- ✓ Protects Our Property
- ✓ Satisfies Regulations

How can New Detention BMPs be Designed for Stream Stability?

$Q_{critical}$ Needs to Be Calibrated to Your Streams



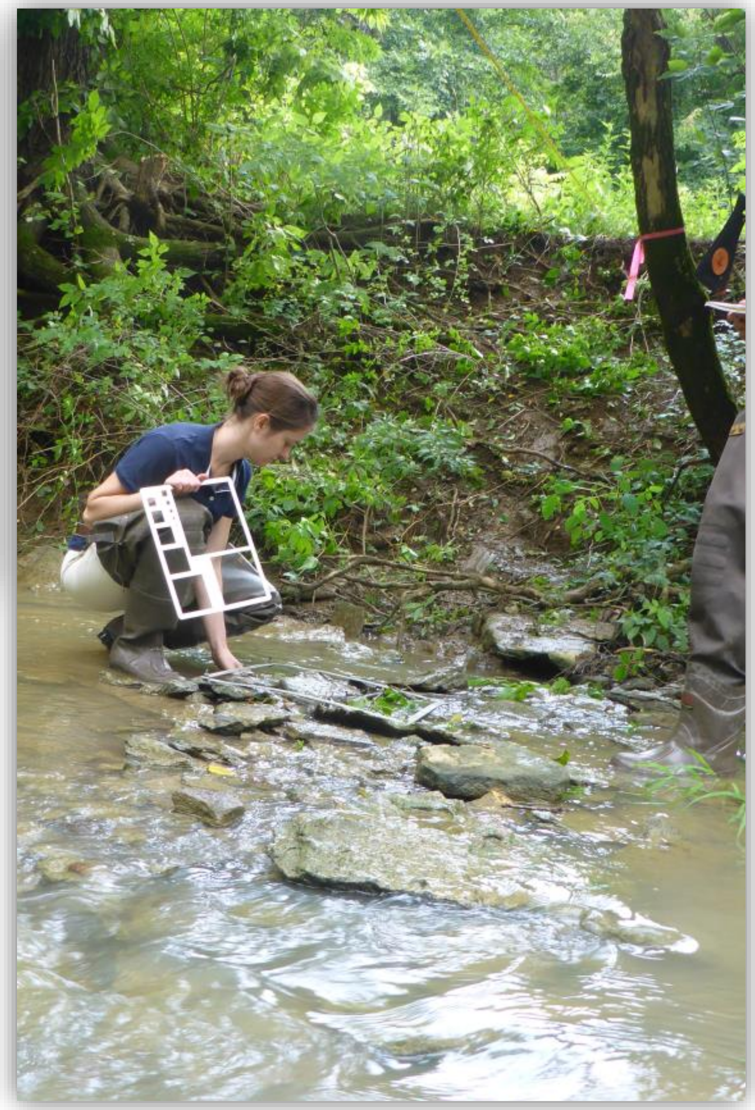
R.J. Hawley et al. / Geomorphology 201 (2013) 111–126

Site: BLC 8.1

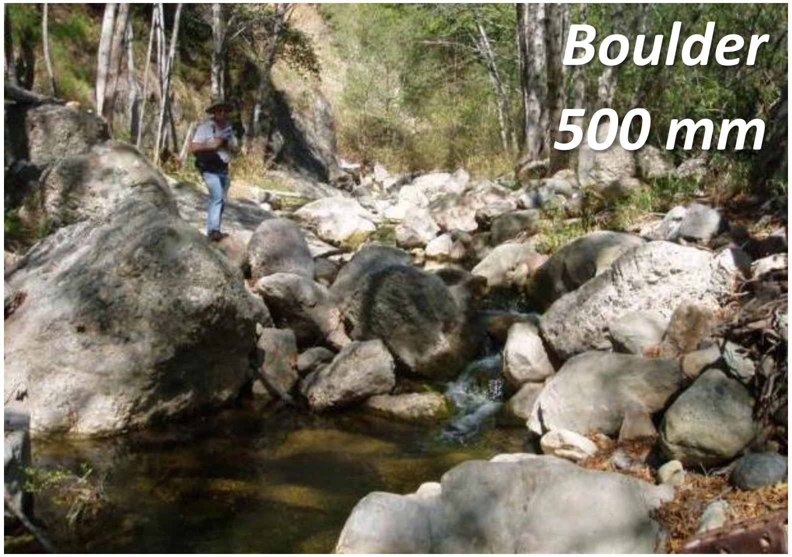
Survey Date	D50 (mm)
11/4/08	56.7
5/18/10	119.6
8/2/11	90.0

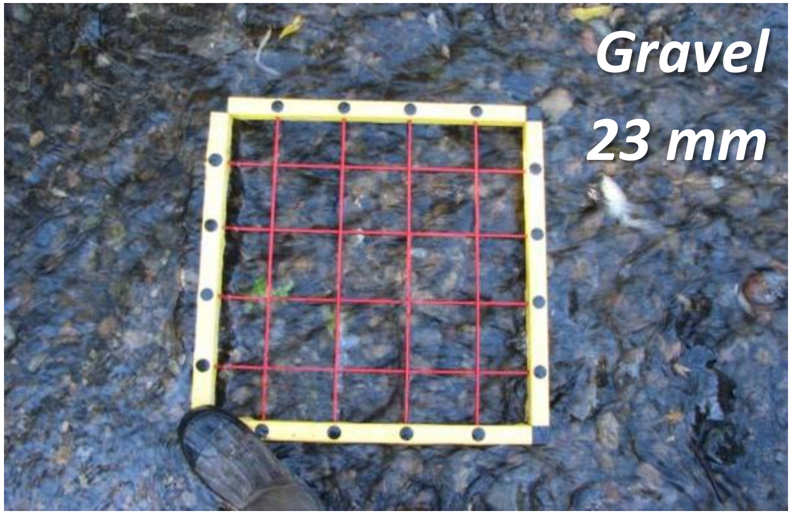
Site: FMC 6.8

Survey Date	D50 (mm)
7/18/08	48.2
12/15/09	50.7
7/20/11	77.0



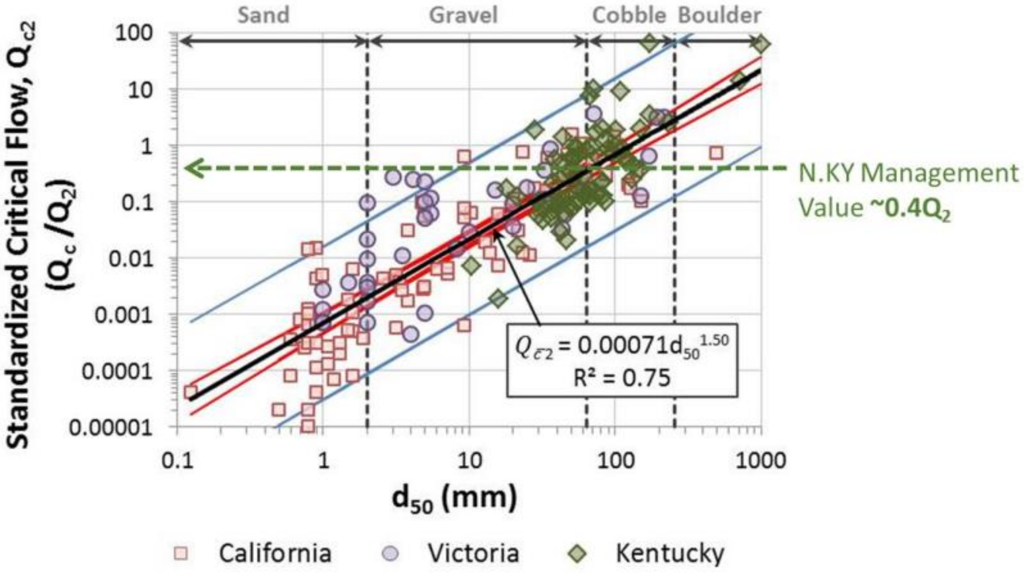
Sediment Transport Regimes Vary By Stream/Region





First Step is to Calculate $Q_{critical}$

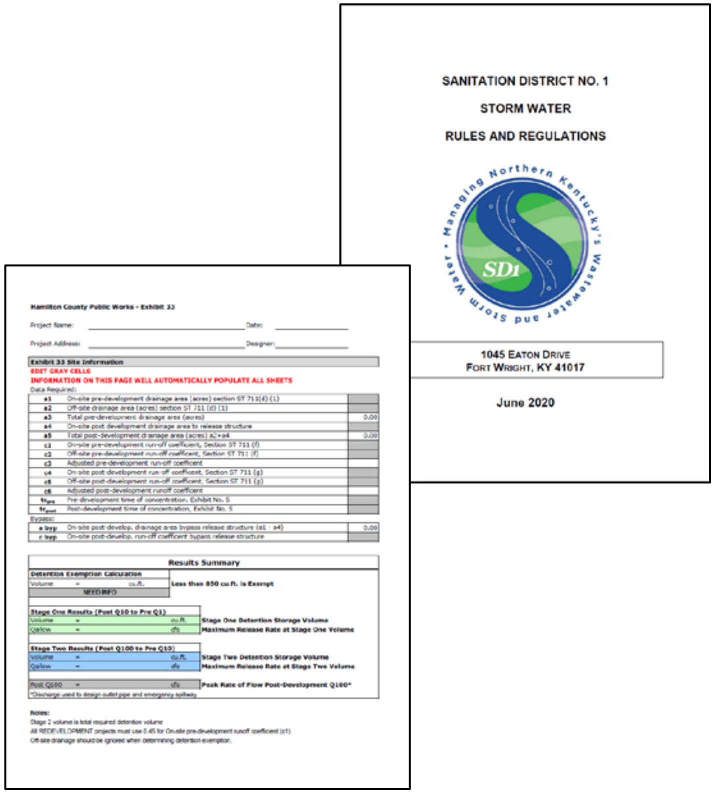
- $Q_{critical}$ is calculated as a fraction of the **undeveloped** 2-year flow (Q_2)
- N.KY $Q_{critical}$ typically **~$0.4Q_2$ to ~$0.5Q_2$**
- SCS, Rational, and USGS Rural methods acceptable



Adapted from Hawley and Vietz (Forthcoming, Freshwater Science)

Model Existing & Proposed Conditions

1. **Flood Control:**
   - Meet local flood criteria
   - e.g., Post-development < Pre-development peak for 2- to 100-year events
2. **Water Quality:**
   - Meet local water quality criteria
   - e.g., first 0.8 inches
3. **Channel Protection:**
   - 2-year peak flow < $Q_{critical}$



SANITATION DISTRICT NO. 1

STORM WATER

RULES AND REGULATIONS

1045 Eaton Drive
Fort Wright, KY 41017

June 2020

Hamilton County Public Works - Exhibit 33

Project Name: ______________________ Date: __________

Project Address: ______________________ Designer: __________

Exhibit 33 Site Information

EDIT GRAY CELLS

INFORMATION ON THIS PAGE WILL AUTOMATICALLY POPULATE ALL SHEETS

Data Required:

a1	On-site pre-development drainage area (acres) section ST 711(d) (1)	
a2	Off-site drainage area (acres) section ST 711 (d) (1)	
a3	Total pre-development drainage area (acres)	0.00
a4	On-site post development drainage area to release structure	
a5	Total post-development drainage area (acres) a2+a4	0.00
c1	On-site pre-development run-off coefficient, Section ST 711 (f)	
c2	Off-site pre-development run-off coefficent, Section ST 711 (f)	
c3	Adjusted pre-development run-off coefficent	
c4	On-site post development run-off coefficent, Section ST 711 (g)	
c5	Off-site post-development run-off coefficent, Section ST 711 (g)	
c6	Adjusted post-development runoff coefficent	
tc_{pre}	Pre-development time of concentration, Exhibit No. 5	
tc_{post}	Post-development time of concentration, Exhibit No. 5	

Bypass:

a byp	On-site post-develop. drainage area bypass release structure (a1 - a4)	0.00
c byp	On-site post-develop. run-off coefficent bypass release structure	

Results Summary

Detention Exemption Calculation

Volume = cu.ft. **Less than 850 cu.ft. is Exempt**

NEED INFO

Stage One Results (Post Q10 to Pre Q1)

Volume = cu.ft. **Stage One Detention Storage Volume**

Qallow = cfs **Maximum Release Rate at Stage One Volume**

Stage Two Results (Post Q100 to Pre Q10)

Volume = cu.ft. **Stage Two Detention Storage Volume**

Qallow = cfs **Maximum Release Rate at Stage Two Volume**

Post Q100 = cfs **Peak Rate of Flow Post-Development Q100***

*Discharge used to design outlet pipe and emergency spillway

Notes:

Stage 2 volume is total required detention volume

All REDEVELOPMENT projects must use 0.45 for On-site pre-development runoff coefficent (c1)

Off-site drainage should be ignored when determining detention exemption.

Example:
Bioretention Basin

http://www.water-research.net/urbanstormwaterbmp.htm

Non-optimized Bioretention Basin

Step	Basin Type	Outlet Structure Optimized?	Basin Footprint (SF)	Estimated Excavation (CY)
1. Flood Control Only	Traditional DB	Yes	3,848	2,510
2. Flood/Water Quality	Bioretention	Yes	**3,318**	**2,832**
3. Flood/WQ/$Q_{critical}$	Bioretention	**No**	**5,027**	**3,846**

Poor Optimization from Flood Control and Water Quality Only

- ~50% larger footprint
- ~35% larger volume
- ~0.5 additional design hours

Optimized Bioretention Basin

Step	Basin Type	Outlet Structure Optimized?	Basin Footprint (SF)	Estimated Excavation (CY)
1. Flood Control Only	Traditional DB	Yes	3,848	2,510
2. Flood/Water Quality	Bioretention	Yes	**3,318**	**2,832**
3. Flood/WQ/$Q_{critical}$	Bioretention	**Yes**	**3,318**	**2,832**

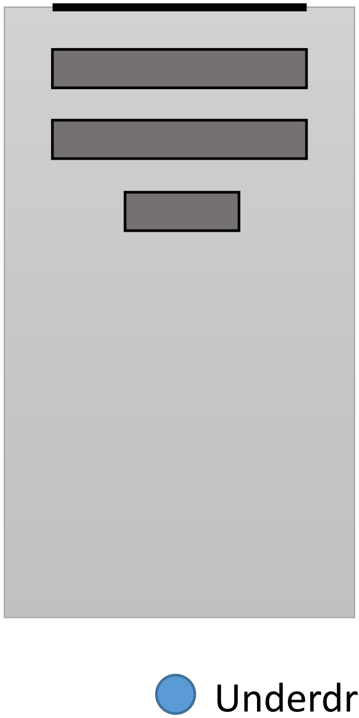
Good Optimization to Meet $Q_{critical}$

- 0% larger footprint
- 0% larger volume
- 2 additional design hours

Bioretention Basin

Optimization of Outlet Control Structure

Non-Optimized



Top Grate

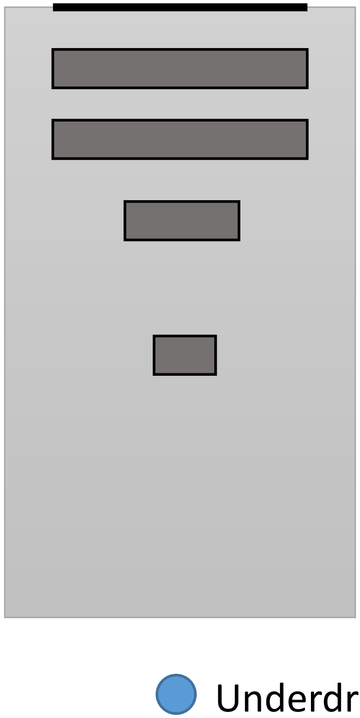
Window x 2

Window x 2

Window

Underdrain

Multiple Iterations



Top Grate

Window x 3

Window

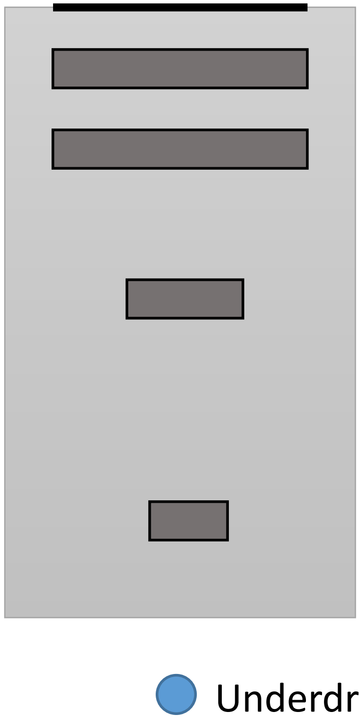
Window

Window

Underdrain

…

Optimized



Top Grate

Window x 2

Window x 2

Window

Window

Underdrain

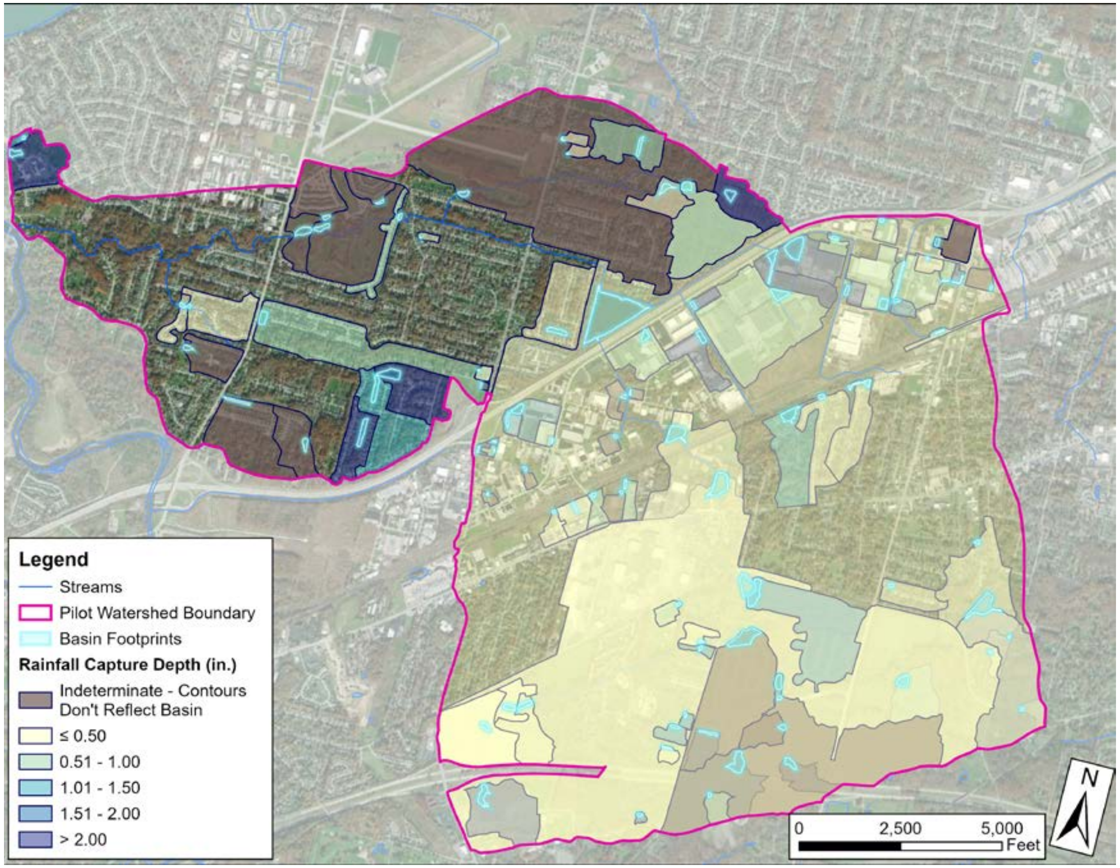
How can Detention Basins be Retrofitted for Stream Stability?

Retrofitting Existing Detention Basins Offers A Cost-effective Approach to Mitigate Existing Impacts

Strategy	Cost per Acre Treated	Notes
Distributed GI	~$50,000	King Co. (2013) pilot study
Stream Restoration	~$5,000	Equivalent of ~$200-300 per foot
New Detention	~$3,000	Hawley et al., 2012
Retrofit Detention	**~$500**	"Detain H2O" (2019 Patent) ~$10,000 installed

Adapted from Hawley et al. (2017)

Lessons Learned from Previous Retrofit Studies



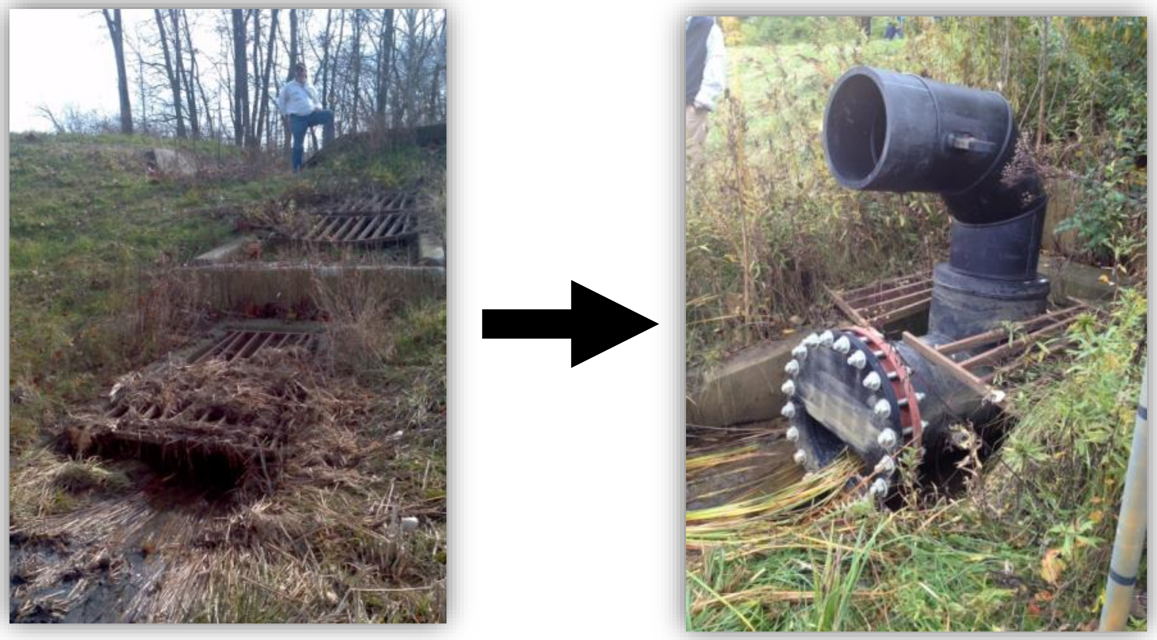
- Level of control that coincided with inducing geomorphic recovery:
  - Effectively managing ~25-50% of the impervious area
  - Effectively managing ~5-10% of the drainage area
- Timing of development that coincides with adequate freeboard for economical retrofits (***this will vary by community***):
  - "Recent imperviousness" e.g., imperviousness that was added between ~2001 and 2016 +/-
  - Helps to quickly find subwatersheds in GIS that may have lots of economical retrofits

Maintain Existing Level of Service

1. **Flood Control**
    - Contain same events within the basin as provided with original design
2. **Water Quality?**
    - Many retrofitted basins were originally designed before water quality requirements
    - Talk to the local regulating body
3. **Channel Protection**

Can Retrofitting Induce Stream Recovery?

Lessons from a Pilot Retrofit



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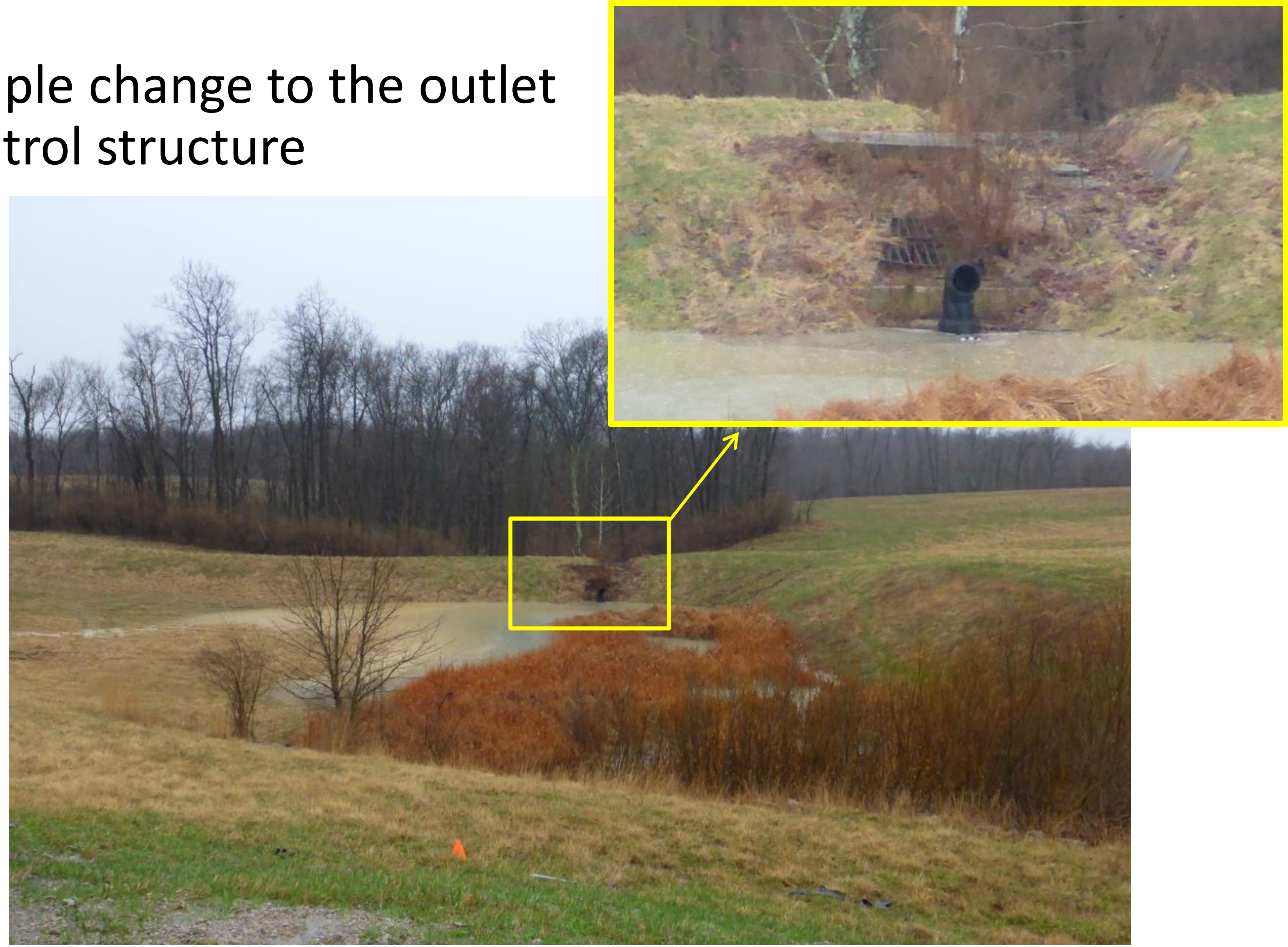
Soil Conservation Districts of Kentucky
The Soil is in our Hands

SD1

United States Environmental Protection Agency

2013 Pilot Retrofit

Simple change to the outlet control structure



2013 Pilot Retrofit

- Restrict flows < $Q_{critical}$ to the extent feasible
  - $Q_{critical} = 0.38$ m^3/s (13.4 ft^3/s)

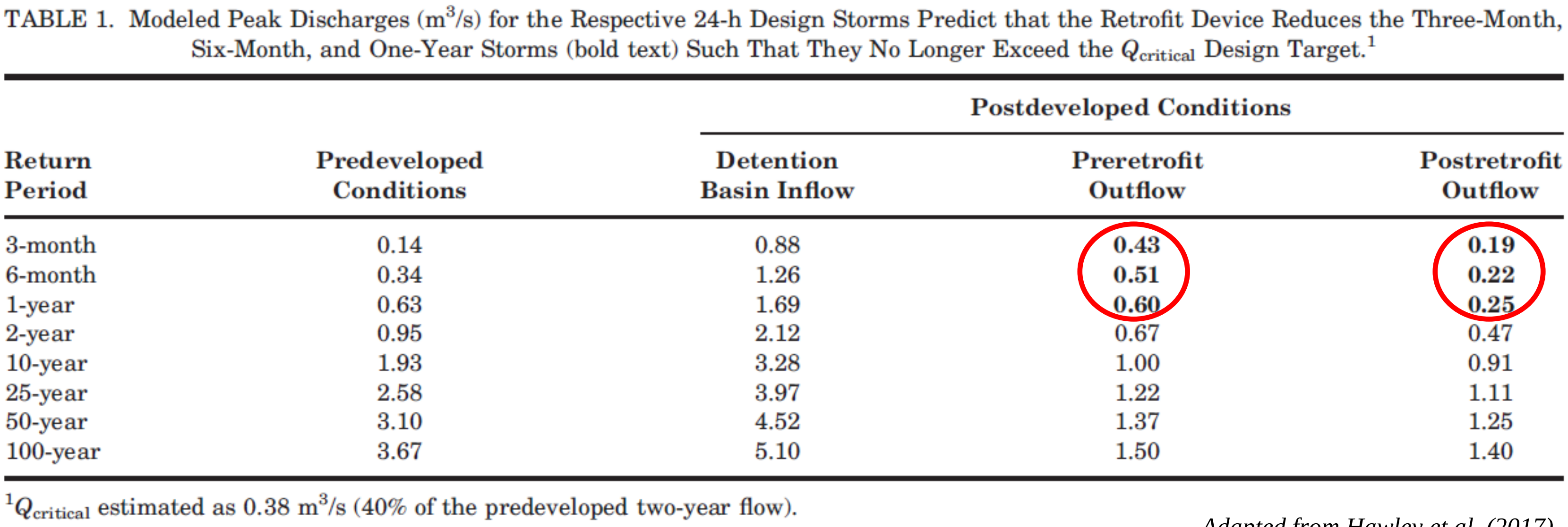


TABLE 1. Modeled Peak Discharges (m^3/s) for the Respective 24-h Design Storms Predict that the Retrofit Device Reduces the Three-Month, Six-Month, and One-Year Storms (bold text) Such That They No Longer Exceed the Q_{critical} Design Target.[1]

		Postdeveloped Conditions		
Return Period	**Predeveloped Conditions**	**Detention Basin Inflow**	**Preretrofit Outflow**	**Postretrofit Outflow**
3-month	0.14	0.88	**0.43**	**0.19**
6-month	0.34	1.26	**0.51**	**0.22**
1-year	0.63	1.69	**0.60**	**0.25**
2-year	0.95	2.12	0.67	0.47
10-year	1.93	3.28	1.00	0.91
25-year	2.58	3.97	1.22	1.11
50-year	3.10	4.52	1.37	1.25
100-year	3.67	5.10	1.50	1.40

[1] Q_{critical} estimated as 0.38 m^3/s (40% of the predeveloped two-year flow).

Adapted from Hawley et al. (2017)

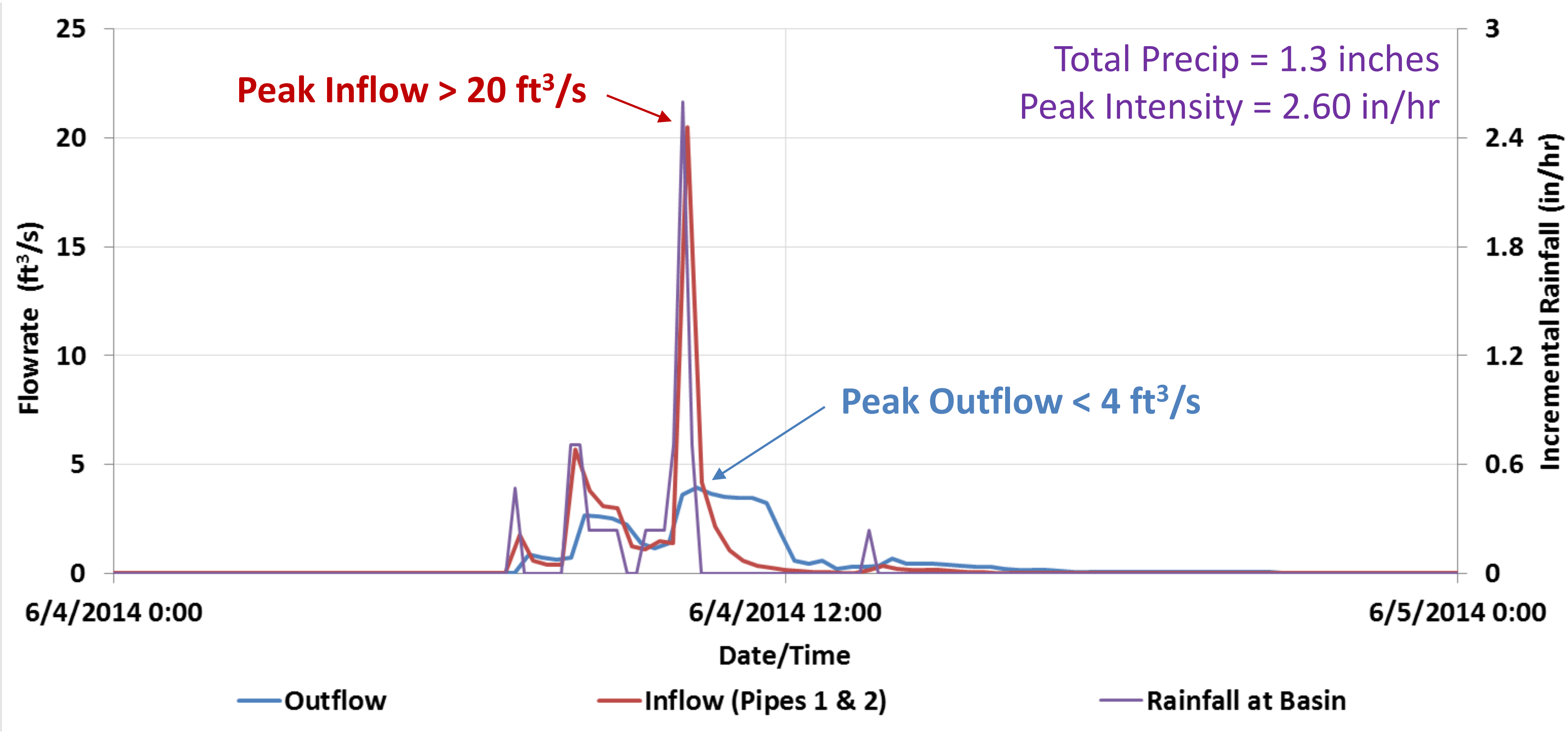
Post-retrofit outflow:

All design storms < pre-retrofit outflow

3-mo, 6-mo, and 1-yr storms < $Q_{critical}$

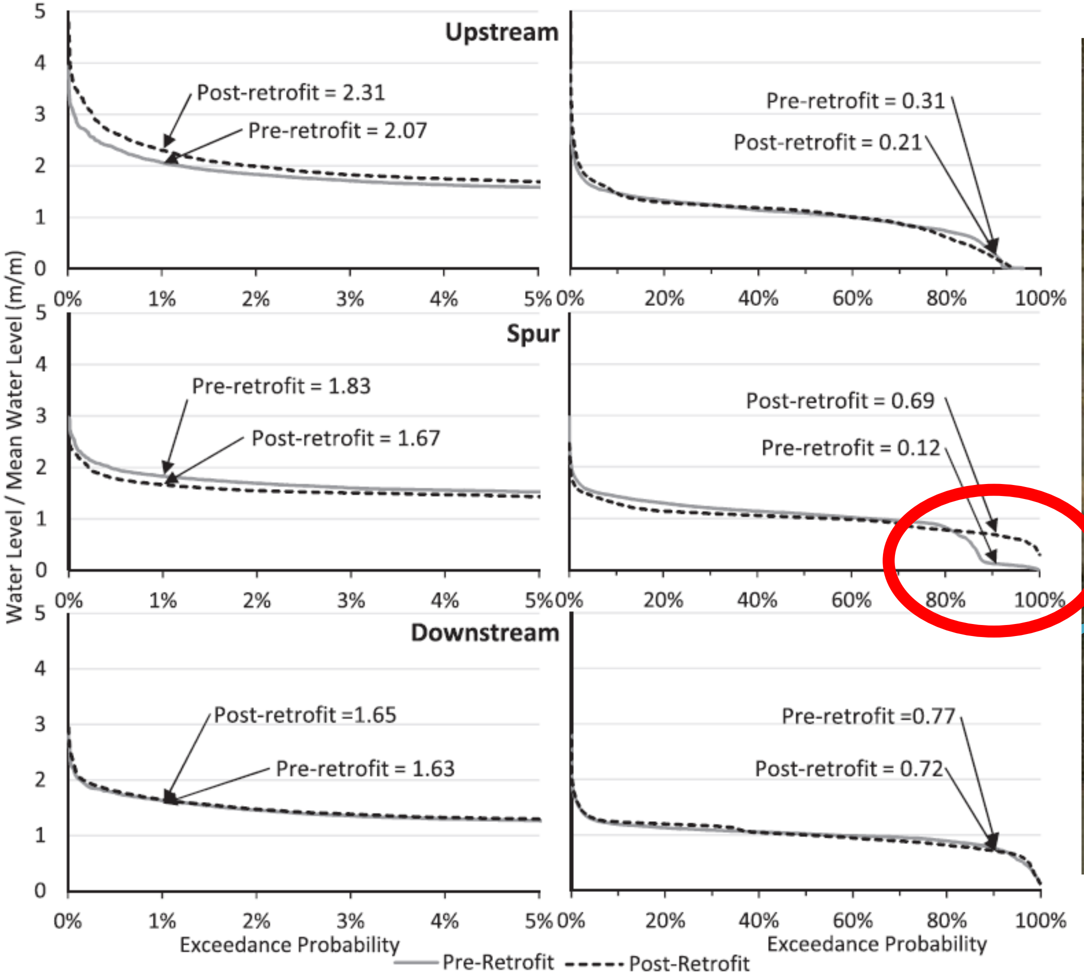
2013 Pilot Retrofit

Post-installation Monitoring



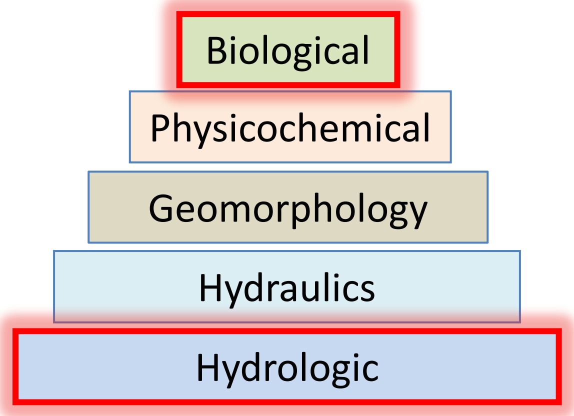
Adapted from Hawley et al. (2017)

Restoration of Both High and Low Flows



Adapted from Hawley et al. (2017)

Restoration of Baseflows Supports Ecological “Lift”



Biological

Physicochemical

Geomorphology

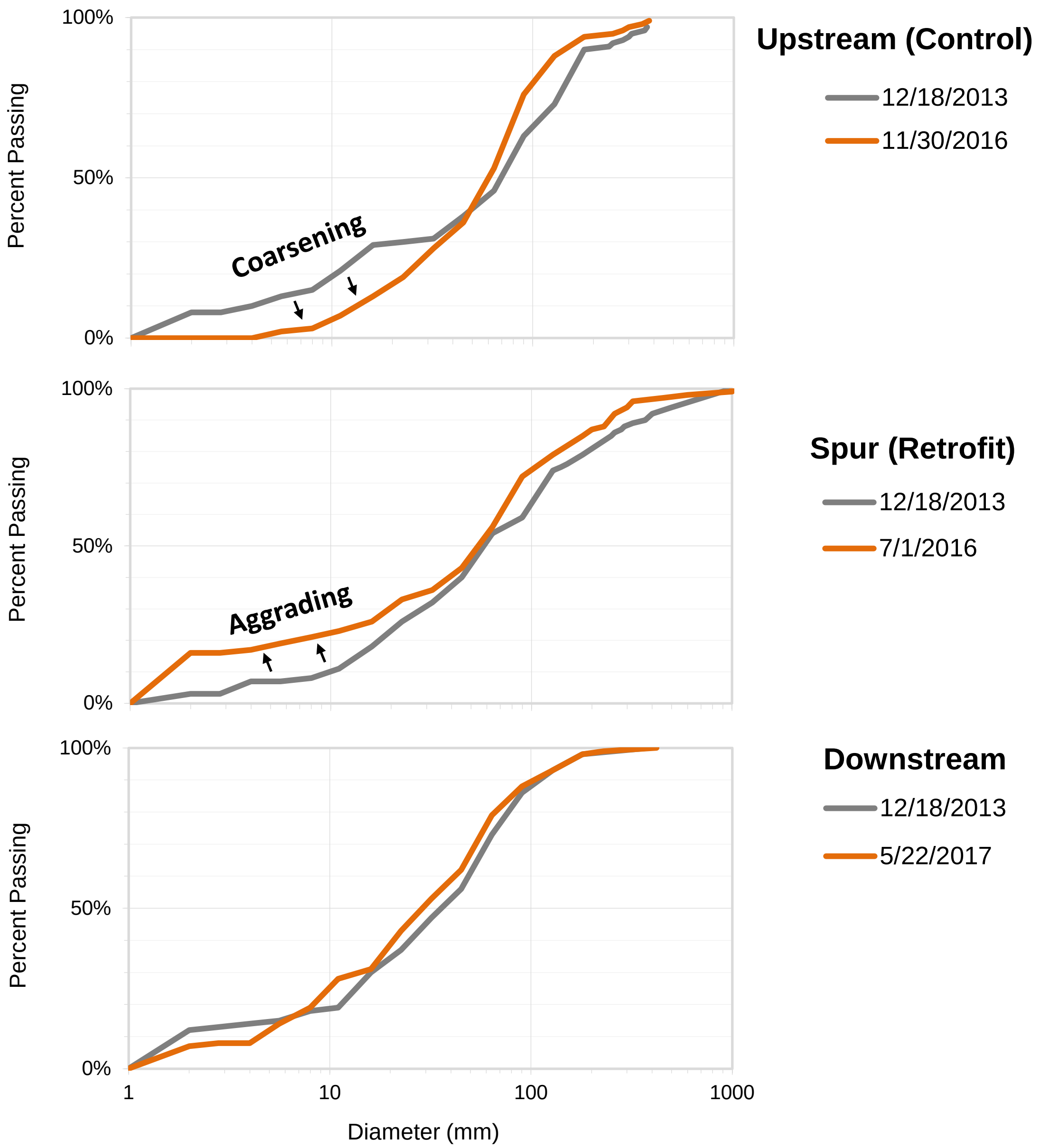
Hydraulics

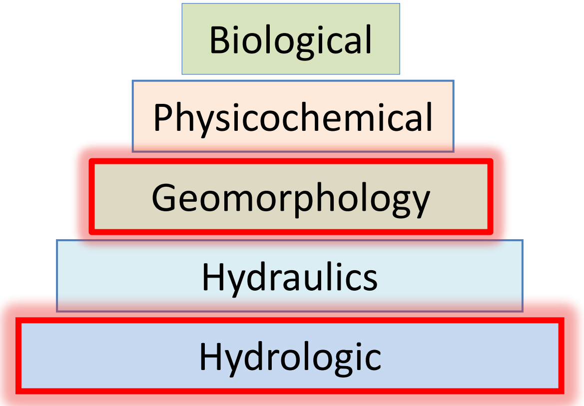
Hydrologic

~Dozen native minnows in 1st pool immediately downstream of the outfall on 9/16/16 (2 circled). Flow was evident coming out of the basin despite the dry/hot week

Adapted from Hawley (2018)

Restricted High Flows Reduces Streambed Erosion





Biological

Physicochemical

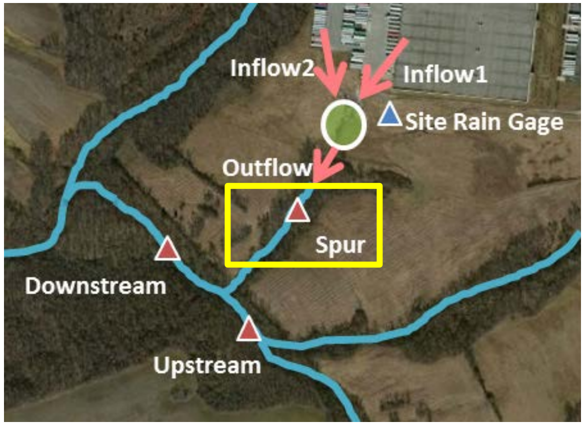
Geomorphology

Hydraulics

Hydrologic

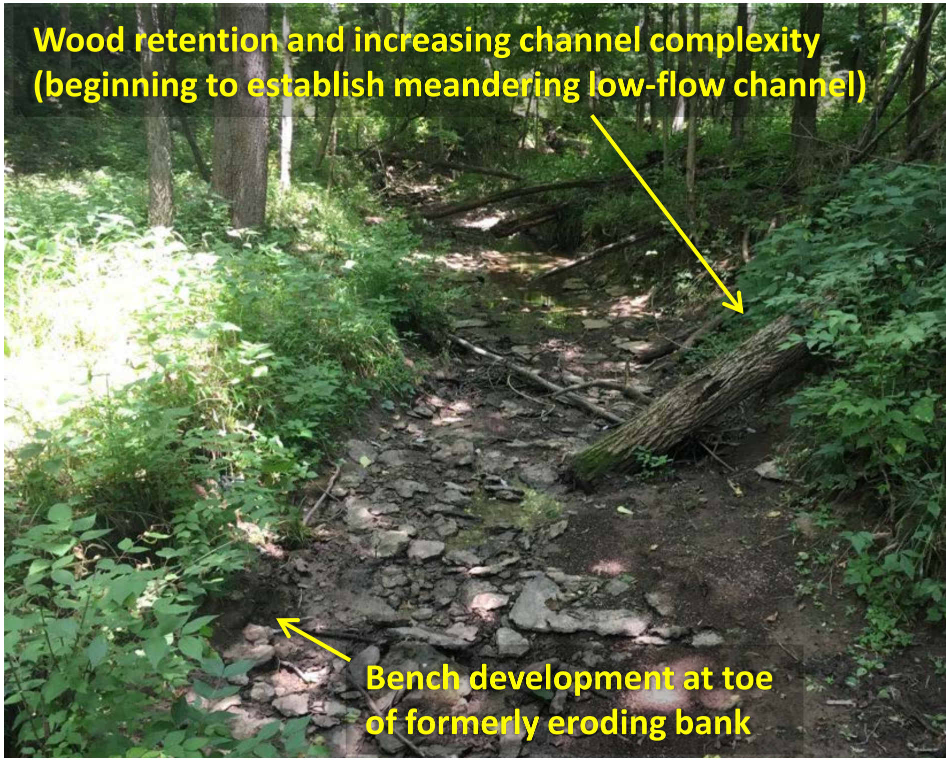
Adapted from Hawley et al. (2020)

→ Improved Bank Stability & Habitat in Spur




Eroding banks and channel widening

8/26/13 Looking upstream

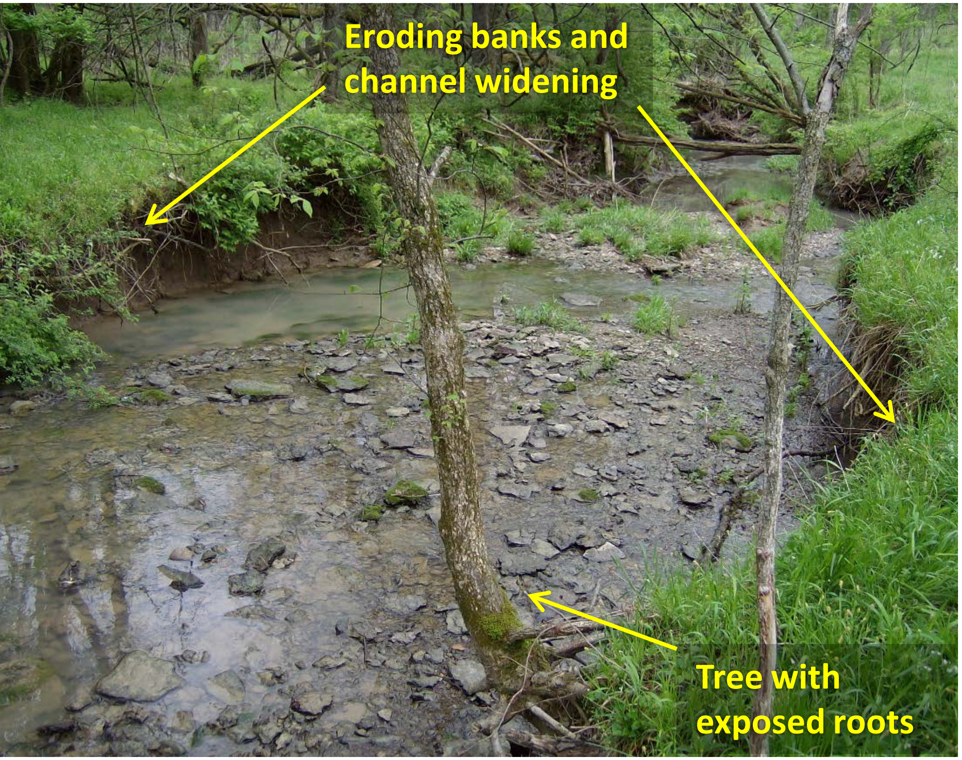

Wood retention and increasing channel complexity (beginning to establish meandering low-flow channel)

Bench development at toe of formerly eroding bank

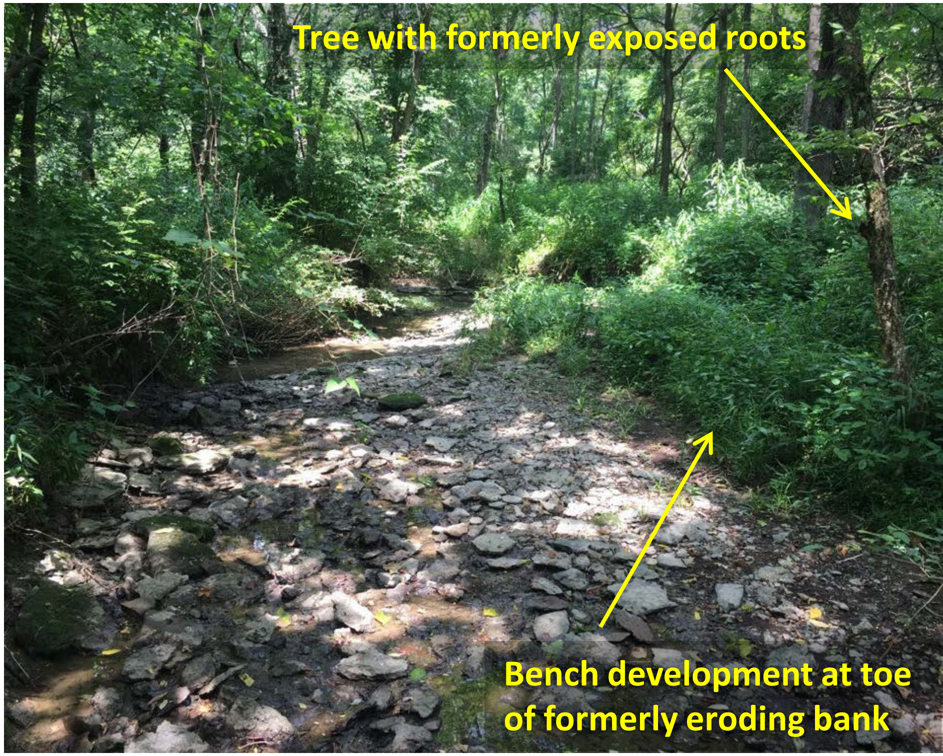
7/8/19 Looking upstream

Adapted from Hawley (2022), Urban Ecosystems

→ Improved Bank Stability & Habitat Downstream



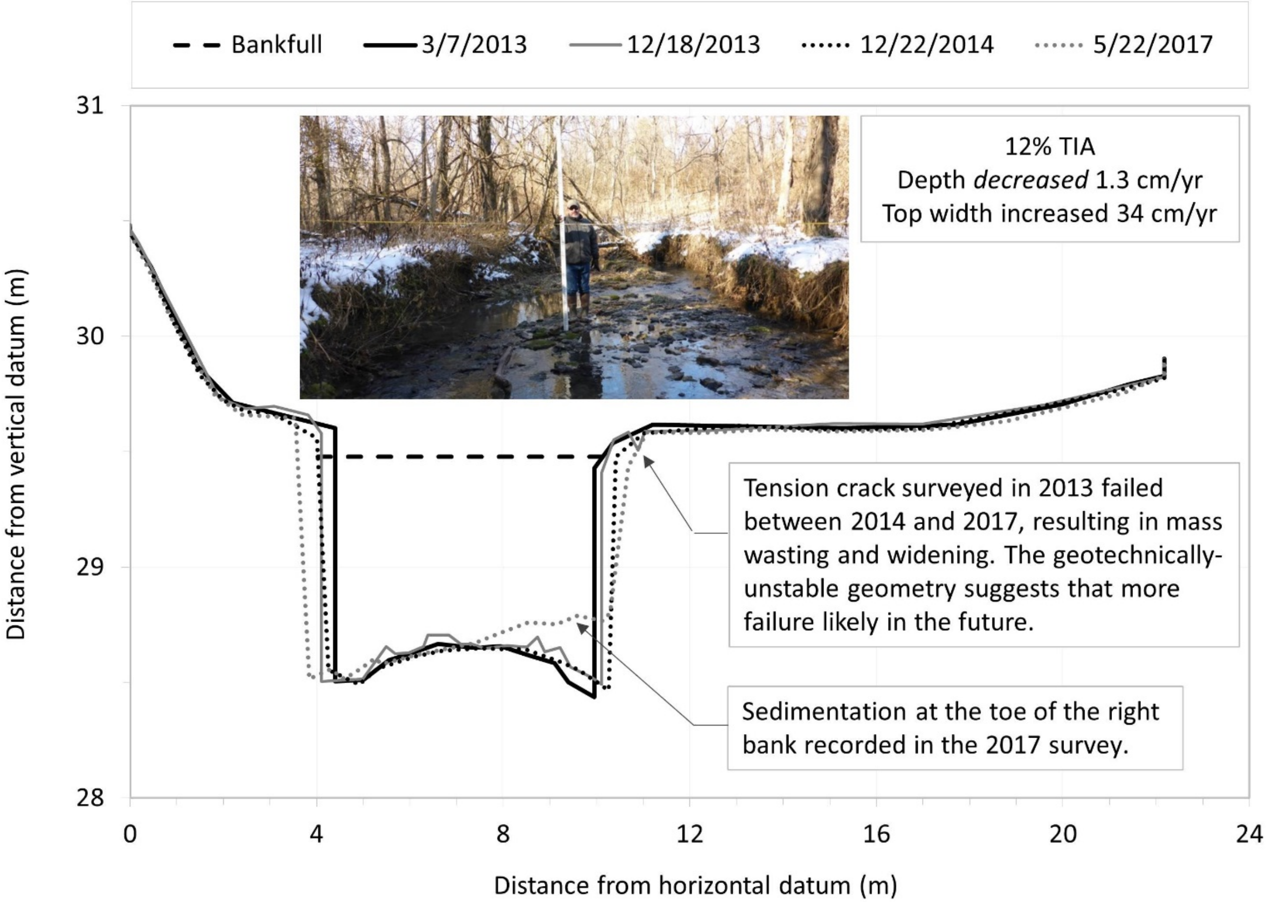
4/29/13 Looking downstream



7/8/19 Looking downstream

Adapted from Hawley (2022), Urban Ecosystems

→ Downstream Improvements Captured by Channel Surveys



12% TIA
Depth *decreased* 1.3 cm/yr
Top width increased 34 cm/yr

Tension crack surveyed in 2013 failed between 2014 and 2017, resulting in mass wasting and widening. The geotechnically-unstable geometry suggests that more failure likely in the future.

Sedimentation at the toe of the right bank recorded in the 2017 survey.

Adapted from Hawley et al. (2020)

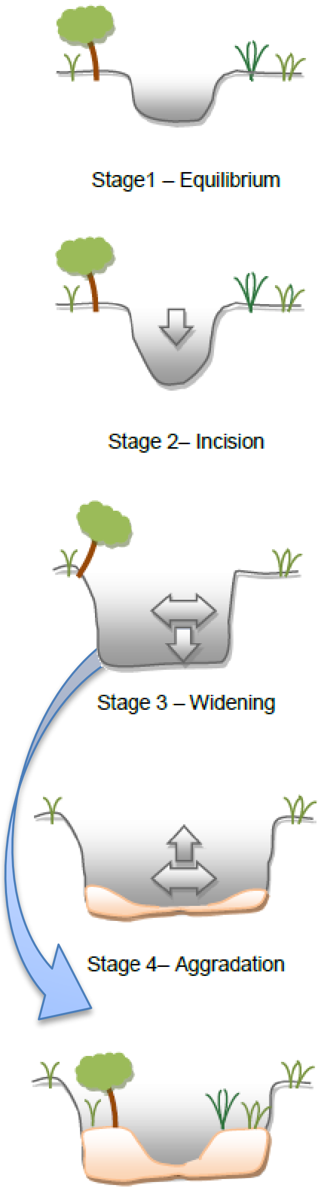
→ Worsening Stability & Habitat Upstream (Control Site)

8/26/13 Looking downstream

7/8/19 Looking downstream

Adapted from Hawley (2022), Urban Ecosystems

Habitat Recovery



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

4/15/13 **RBP 113 (Poor)**

11/5/19 **RBP 143 (Avg)**

Spur Site

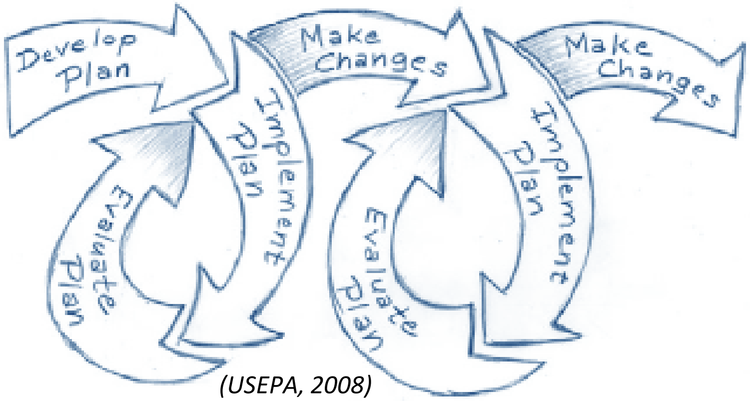
RBP 109 (Poor) **4/29/13**

RBP 146 (Avg) **11/5/19**

Downstream Site

Adapted from Hawley (2022), Urban Ecosystems

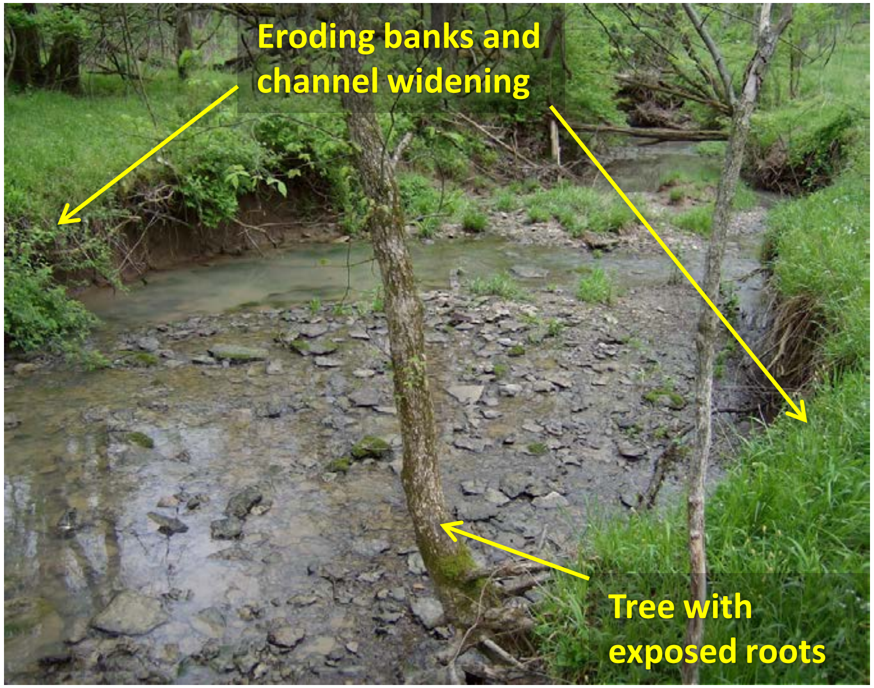
Adaptive Management, Including Monitoring, Is Highly Recommended

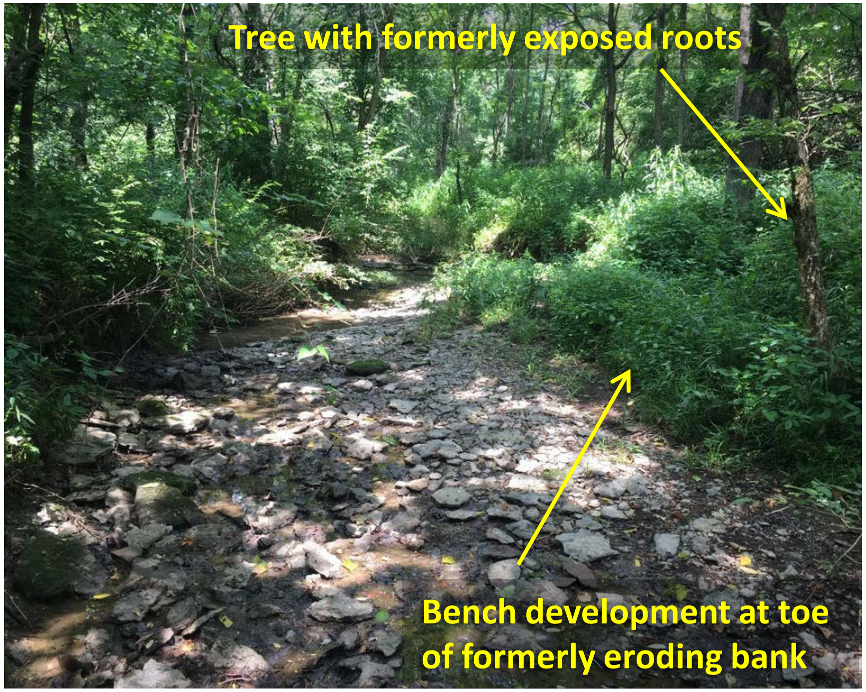


(USEPA, 2008)

- Trajectories of geomorphic recovery should be visually apparent

→ *simple photo station monitoring can be an effective monitoring approach*





Adapted from Hawley (2022)

Proactive Efforts Can Prevent Future Problems

- Include Channel Protection Considerations on Projects
- Optimize Rules and Regulations for New and Re-development
- Locate Watersheds for Cost-effective Retrofit Implementation

Questions?