CIVIL & ENVIRONMENTAL ENGINEERING
COLORADO SCHOOL OF MINES

3. Engineered Streambeds for Water Quality Enhancement in Urban Streams

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Reinventing the Nation's Urban Water Infrastructure [ReNUWIt]
Colorado School of Mines

MINES
NM STATE UNIVERSITY
NSF
EPA United States Environmental Protection Agency

Quarterly Meeting of the South Platte River Urban Water Partnership
19 February 2019

Potential Applications

- Urban Streams & Stormwater channels (right, Golden CO)
- Stream restoration (example later)
- Rural streams
- Acid mine drainage (bottom right)
- Agricultural ditches (below)
- Any polluted ditch or channel

Urban Stormwater & Water Pollution

In USA, storm runoff responsible for

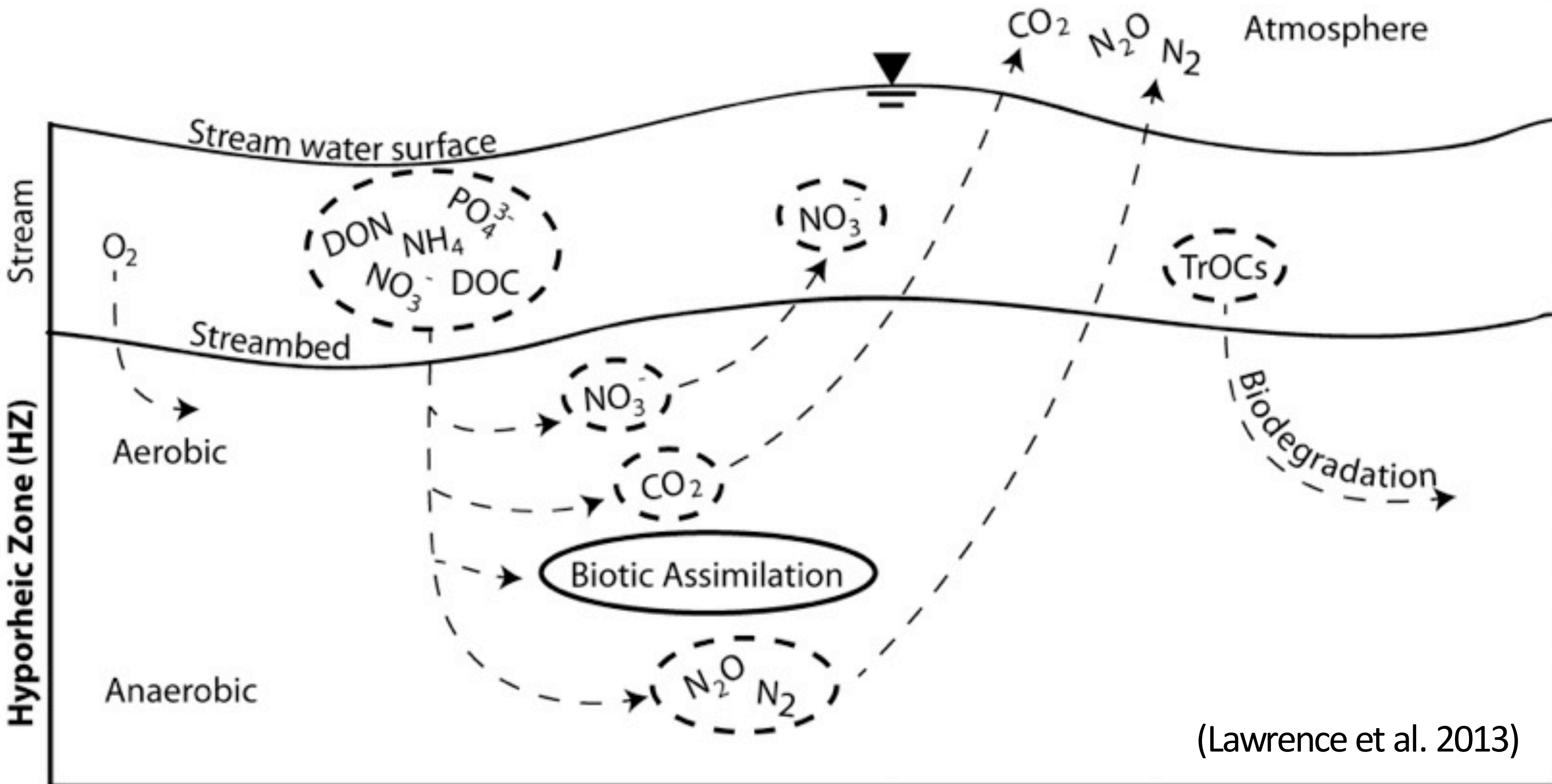
- 47% of impaired ocean shoreline miles **(EPA 1999)**
- 46% of impaired estuary areas
- 22% of impaired lake areas
- 14% of impaired river miles

Scientific Motivation

Motivation and scientific basis is the **hyporheic zone (HZ),** or "streambed", which is the connection between surface water and groundwater in streams.

Figure B-3: Groundwater System Involving the Hyporheic Zones (Alley et. al 2002)

Hyporheic Zone: The River's Liver



- Biogeochemical hotspot
- Requires exchange and proper residence times (RT)

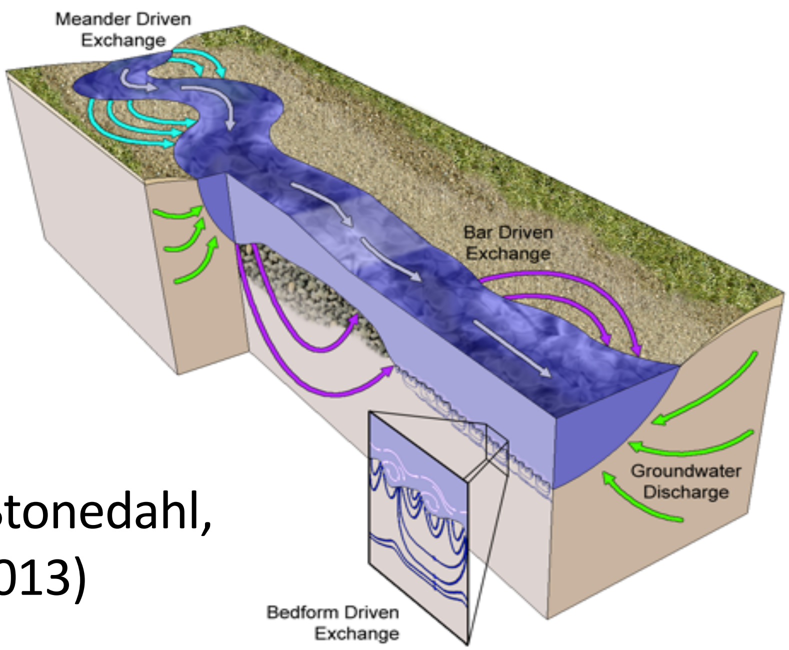
Streams have a Natural Treatment System

Stream Pollution: nutrients, metals, pathogens, organics

Hyporheic zone (HZ) / Streambed has potential to serve as a pollutant treatment unit.

However, **exchange** & **residence time** not usually sufficient to remove urban water pollutants

Stream Restoration Best Mgmt. Practices (BMPs)



(Stonedahl, 2013)

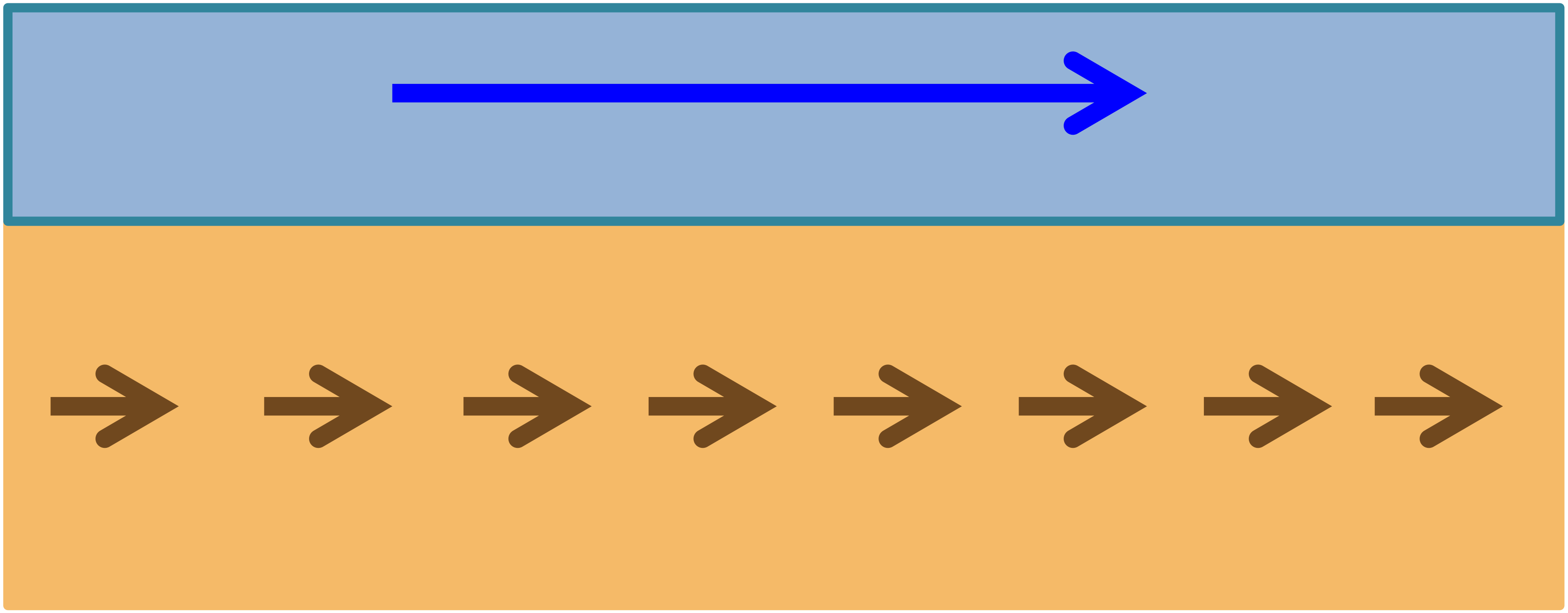
Low Head Dam/Weir

J Hook

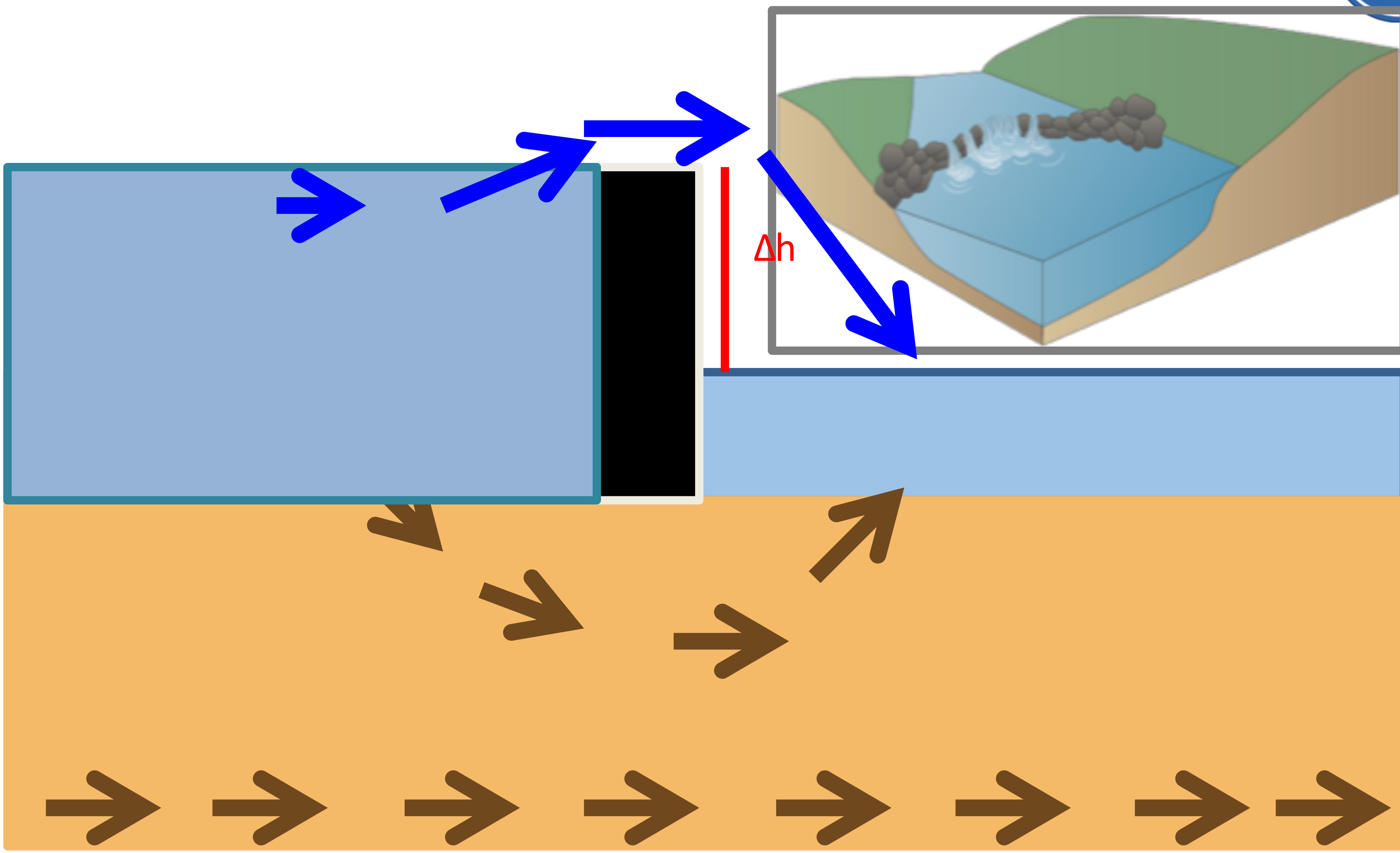
Cross-Vane

Surface Water Exchange with Streambed

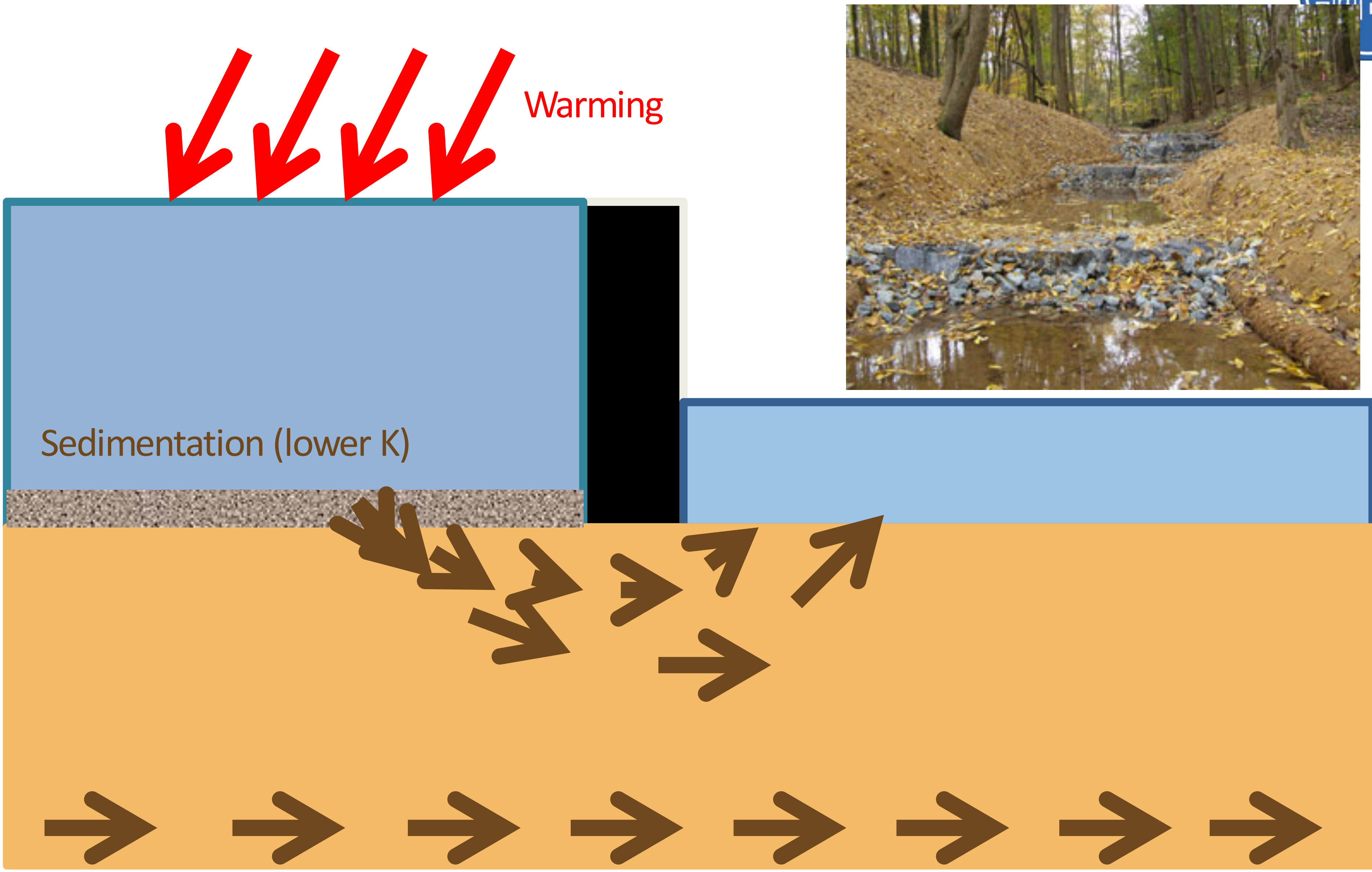
For urban streams, if the streambed is homogeneous, there is little exchange from stream to HZ. Boulders, woody debri, pools, meanders, and stream topography cause some flow into HZ.



Stream Restoration: Structures that cause ponding



Structures that cause ponding



Need HZ "Best Management Practices" (BMP)

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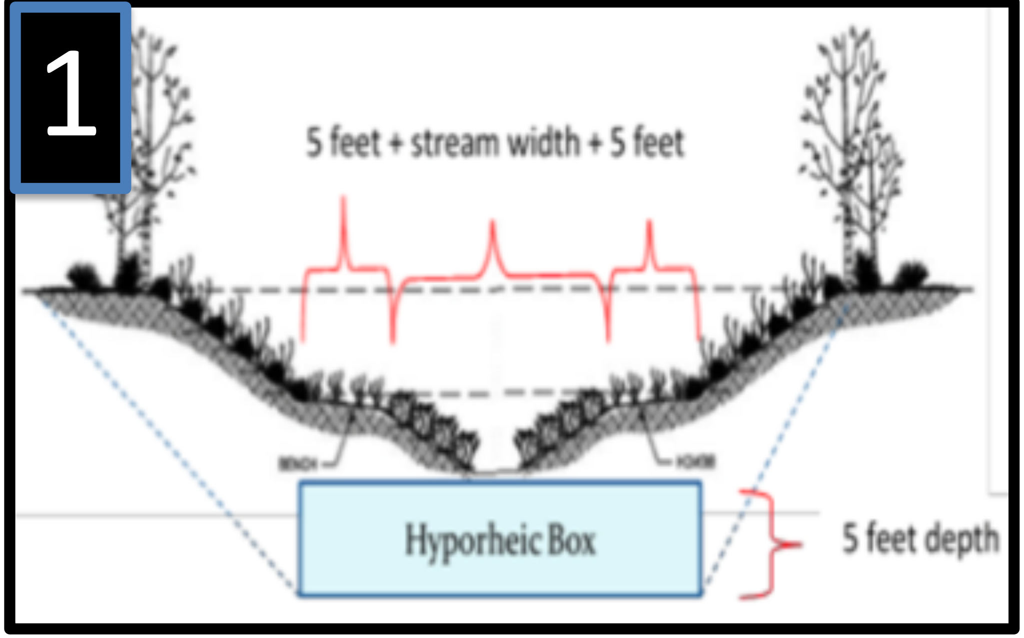

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WERF-IT13: Stream Restoration as a BMP: Crediting Guidance

Prepared by
Wright Water Engineers, Inc.
Geosyntec Consultants, Inc.
Colorado State University
University of Georgia

Under Support From
Water Environment Research Foundation
Urban Drainage and Flood Control District, Denver CO

DRAFT April 2016

3

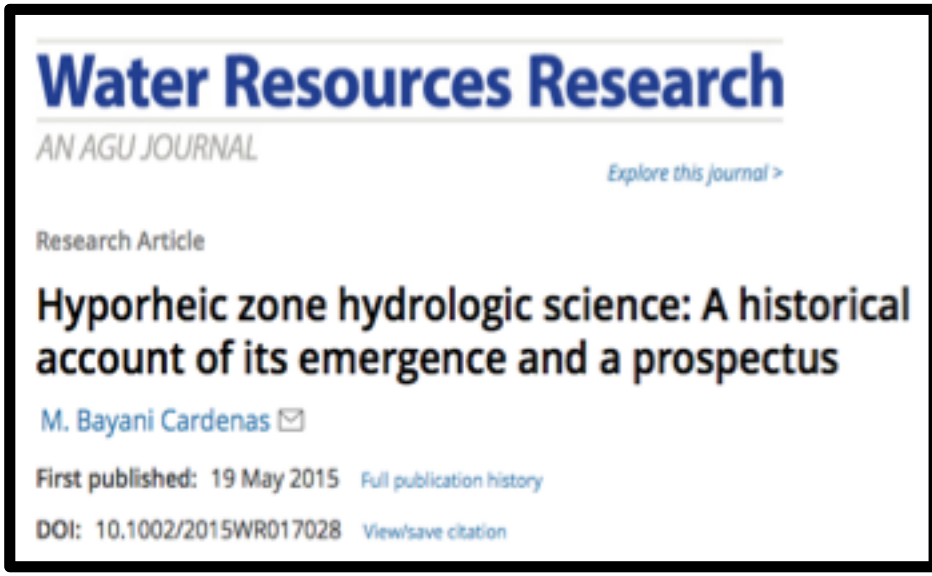
American Rivers
Rivers Connect Us®

CALIFORNIA LAW RECOGNIZES MEADOWS AND FORESTS AS WATER INFRASTRUCTURE

Governor Brown signed AB 2480, which recognizes California's watersheds as water infrastructure.

Luke Hunt, Ph.D. | October 4, 2016

State of the Science



Water Resources Research

AN AGU JOURNAL

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Research Article

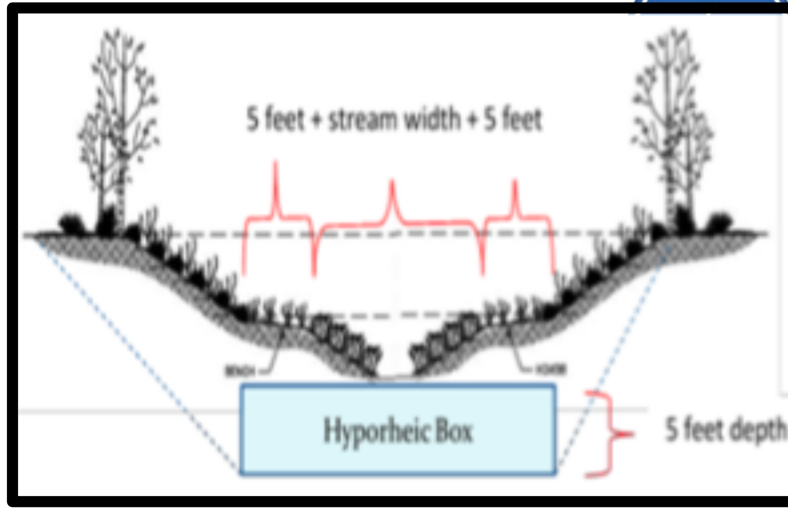
Hyporheic zone hydrologic science: A historical account of its emergence and a prospectus

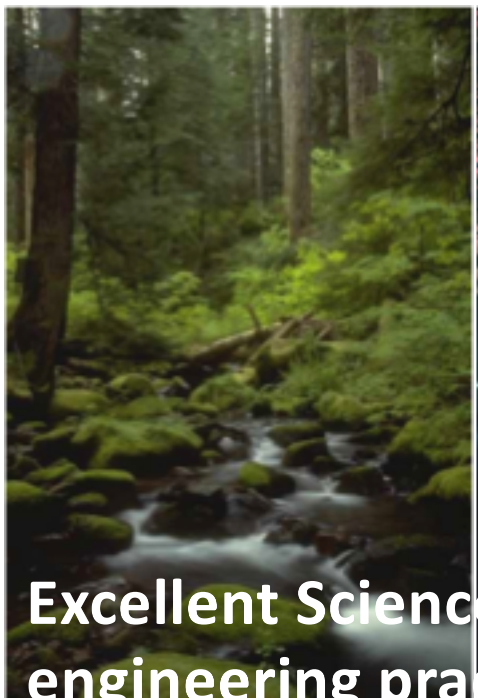
M. Bayani Cardenas

First published: 19 May 2015 Full publication history

DOI: 10.1002/2015WR017028 View/save citation

State of the Practice





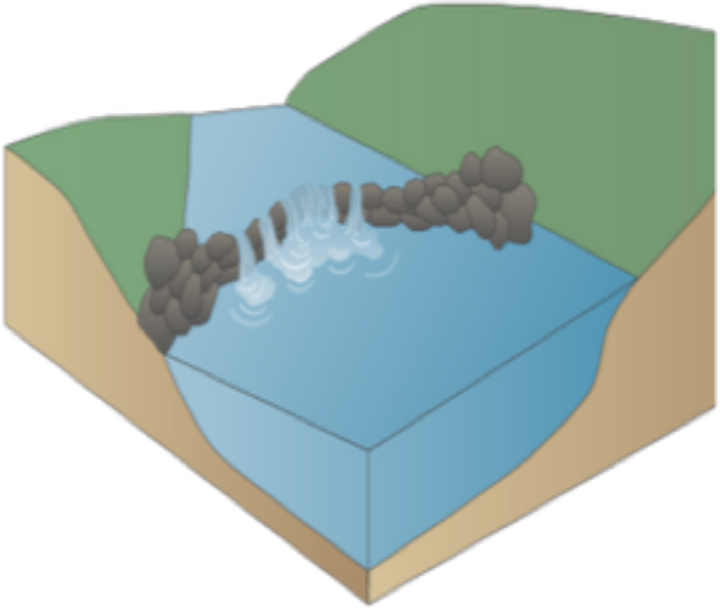
Excellent Science has not been translated into engineering practice for water quality improvement

Most BMPs not effective for pollutant removal

- Not enough volume exchange or residence time. –e.g., Azinheira et al. (2014); Hester et al. (2016)

- Heterogeneous HZ, exchange localized, residence times too short. - e.g., Gordon et al. (2013)

- No existing HZ BMP has been consistently effective at reach-scale
- No BMP explicitly controls HZ residence times



- Natural—like structures in the stream are not reliable to create exchange in the HZ,
- Surface BMPs designed to create flow in HZ are not highly effective

Why not engineer the HZ?

Engineer the Streambed to Improve Treatment of Contaminants of Interest.


Stormwater in Tucker Gulch. Golden, CO

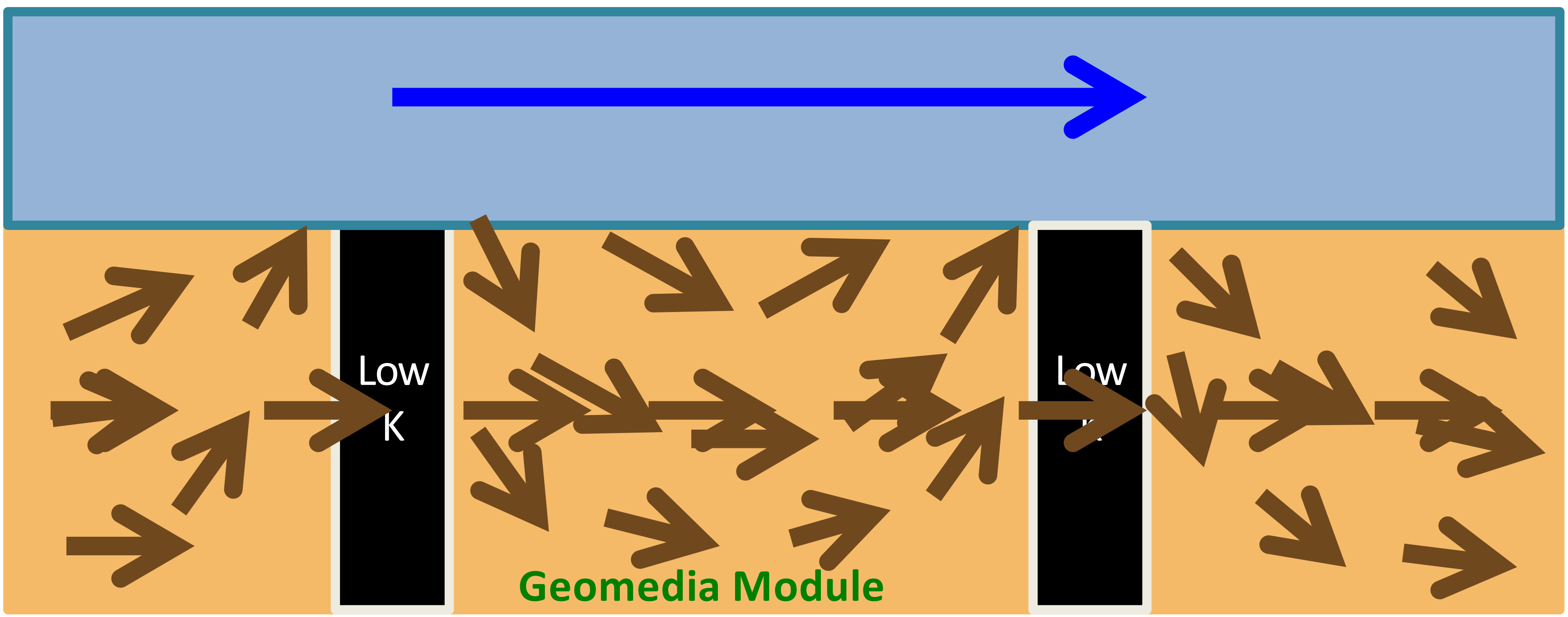
Stormwater channels are ubiquitous, and integrate stormwater from entire urban sub-watersheds

Treatment in a stormwater channel is more effective than point-source BMPs.

Place hydraulic / geomedia structures in the streambed to exchange water and cause contaminant removal

Engineer the Streambed

- **Install HZ structures to enhance subsurface flow.**
- **Optimize volume exchanged & hydraulic residence time**
- **Geomedia designed to treat specific contaminants**

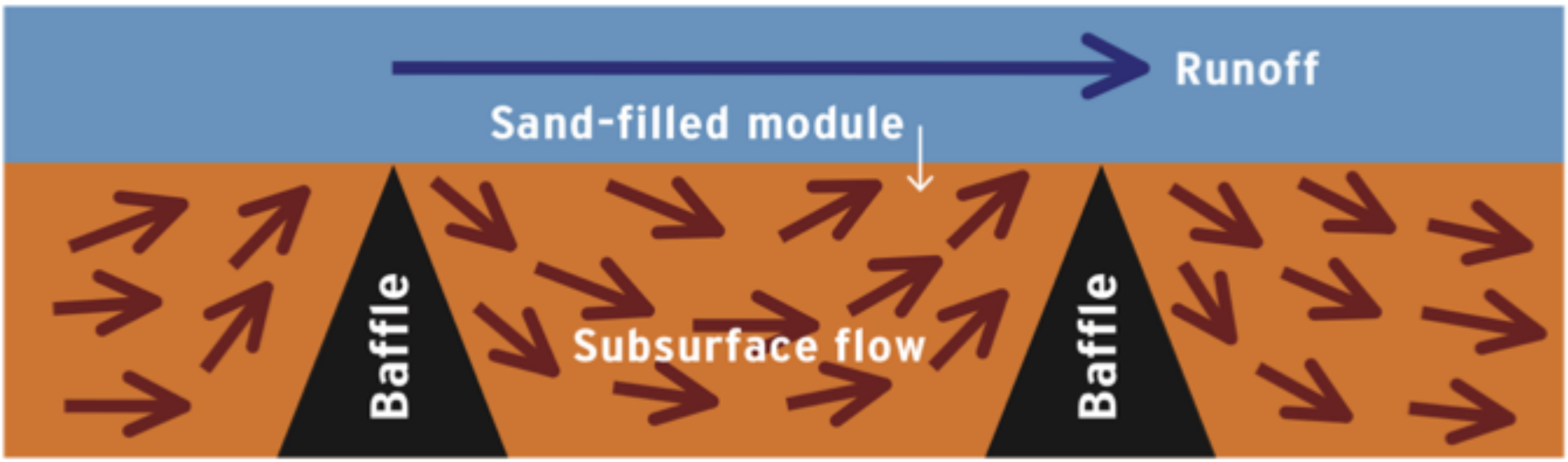


BIOHYDROCHEMICAL ENHANCEMENTS
for Streamwater Treatment (BEST)

BEST: Engineered Streambeds

Biohydrochemical Enhancements for Streamwater Treatment

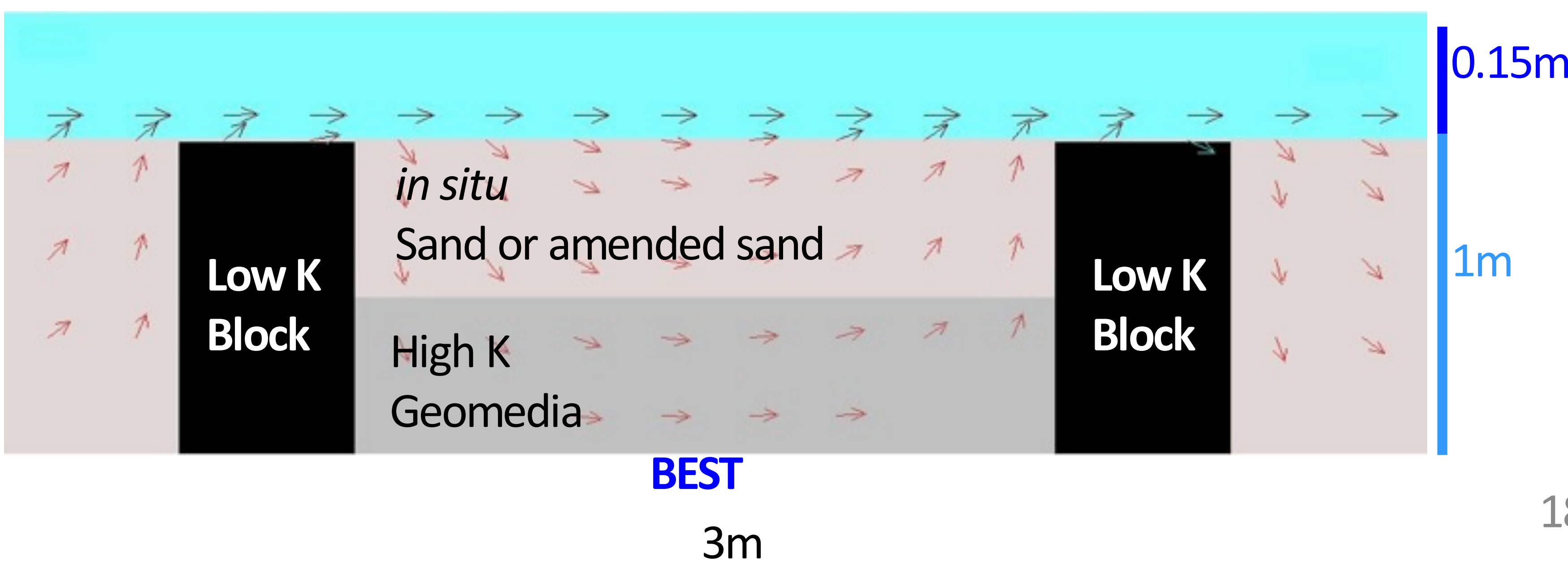
- Baffle walls enhance mixing
- Sand filters pollutants from runoff
- Repeat in Series



Pollutants removed as runoff flows through sand.

Numerical Modeling for Design

- Need sufficient exchange volume, residence (reaction) time for removal, treatment also depends on stream flow.
- Evaluate design parameters (slope, K of modules, porosity, …..)
- Model calculates volume exchange and residence time



Pollutant Transformations in Geomedia

Contaminants can be removed by irreversible sorption, by geochemistry, and microbial activity.

Need exposure to porous media (where the microbes do the work, sorption, etc.)

Some pollutants are transformed under oxic conditions (aerobic) – fuel components, pharmaceuticals, ammonium, pesticides, etc.

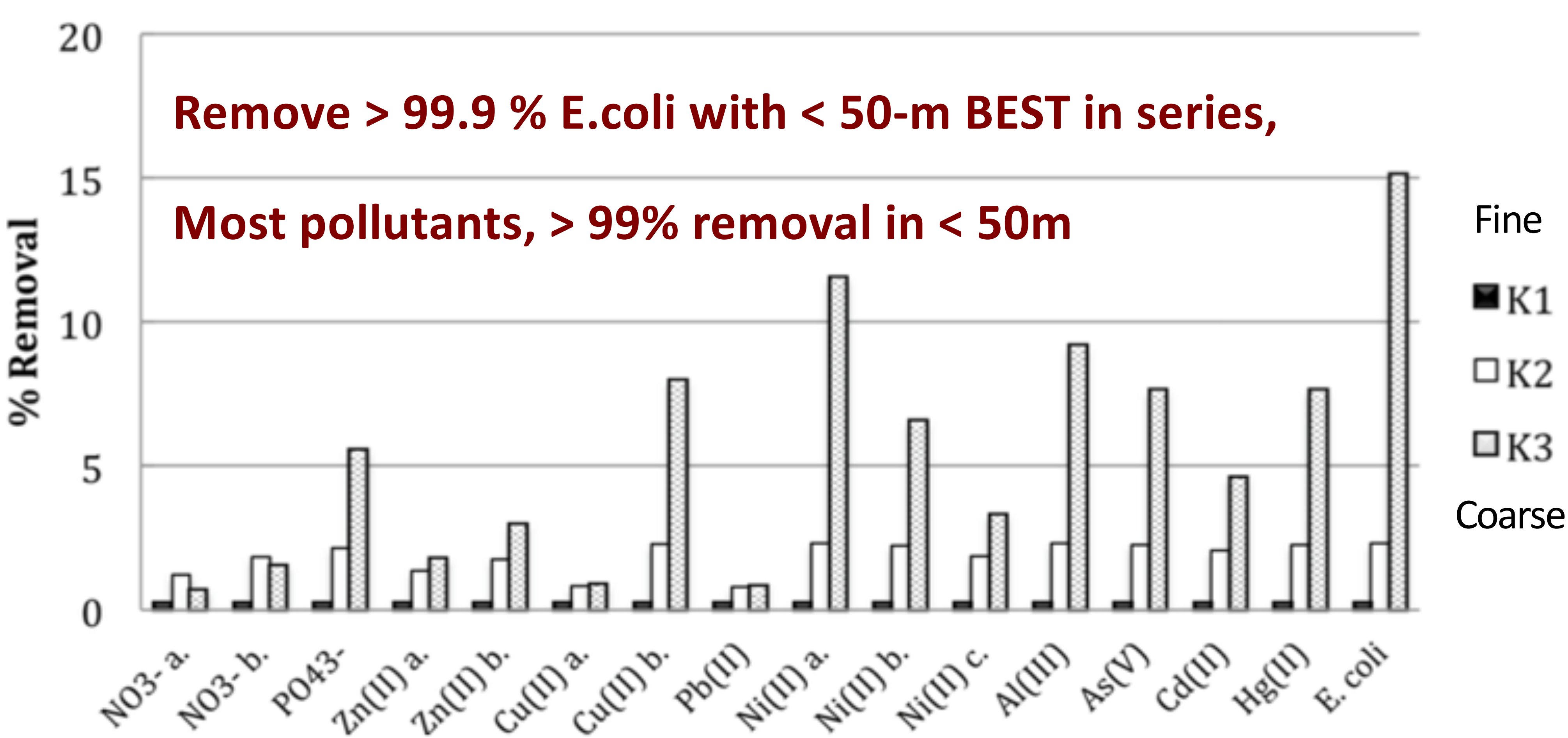
Some are transformed in anoxic conditions (anaerobic), such as nitrate to nitrogen gas

Model pollutant removal using 1st -order rate constants ($\lambda_{Geomedia}$) from literature

	Geomedia	k (hr^{-1})	Reference
NO_3^-	Natural Sediments	0.38	Gomez et al. 2012
NO_3^-	Woodchips	0.63	Robertson 2010
PO_4^{3-}	Biochar	0.155	Yao et al. 2011
Zn(II)	Green Sands	0.040	Lee et al. 2004
Zn(II)	ZVI	0.070	Wilkin & McNeil 2003
Cu(II)	Mn-oxide sands	0.019	Han et al. 2006
Cu(II)	ZVI	0.270	Wilkin & McNeil 2003
Pb(II)	Mn-oxide sands	0.018	Han et al. 2006
Ni(II)	ZVI	0.606	Moraci and Calabrò 2010
Ni(II)	ZVI/pumice mixture	0.197	Moraci and Calabrò 2010
Ni(II)	ZVI	0.080	Wilkin & McNeil 2003
Al(III)	ZVI (peerless)	0.350	Wilkin & McNeil 2003
As(V)	ZVI	0.250	Wilkin & McNeil 2003
Cd(II)	ZVI	0.120	Wilkin & McNeil 2003
Hg(II)	ZVI	0.250	Wilkin & McNeil 2003
E. coli	IOCS	4.240	Zhang et al. 2010

Modeling Results – Contaminant Removal

- Percent (%) removal *per module* (2 m length)
- Assumes 2 m wide, 2 L/s channel, K = fine to coarse sand



Cd(II), Zn(II), nitrate, and Pb(II) require 55.5, 85.5, 138, and 293 m of length

Nitrogen, Pathogens: Measure $\lambda_{Geomedia}$

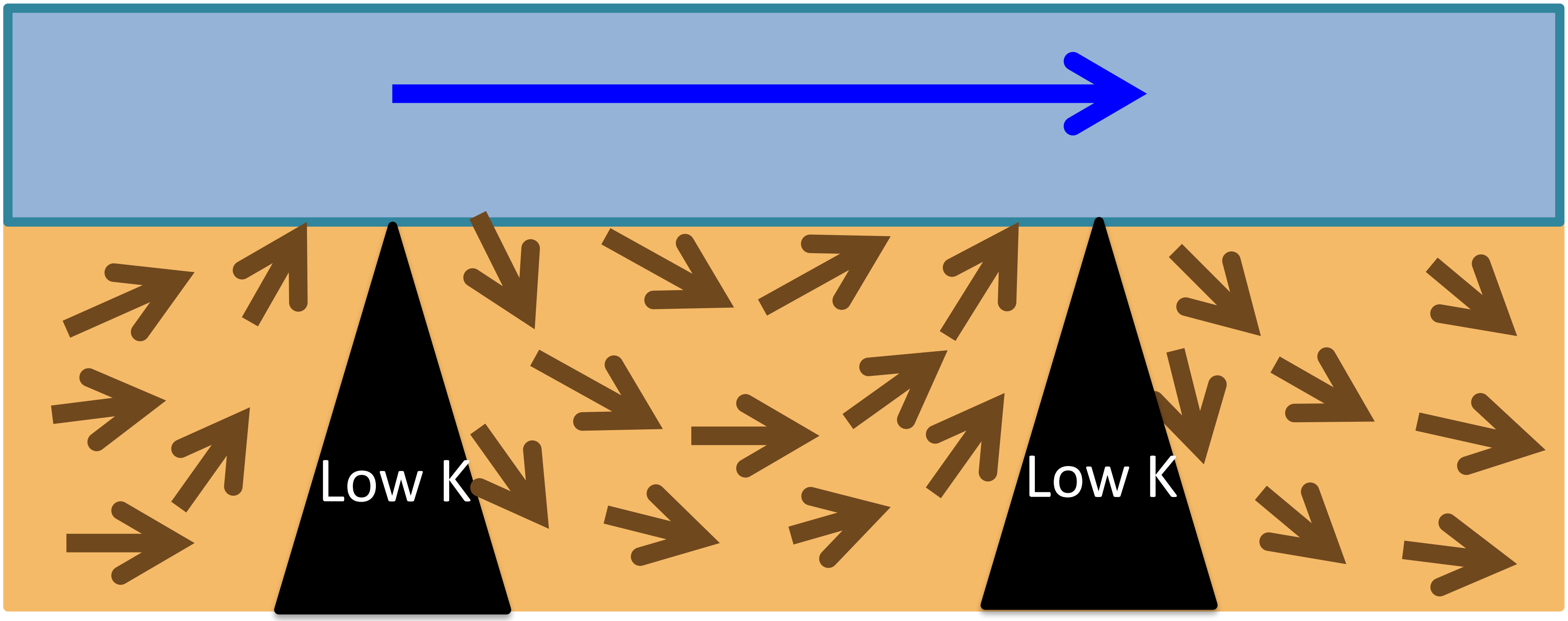
- Precisely define reaction rate constants (λ)
- Apply to model to optimize geomedia modules for implementation

Measured reaction rates larger than stated in literature.

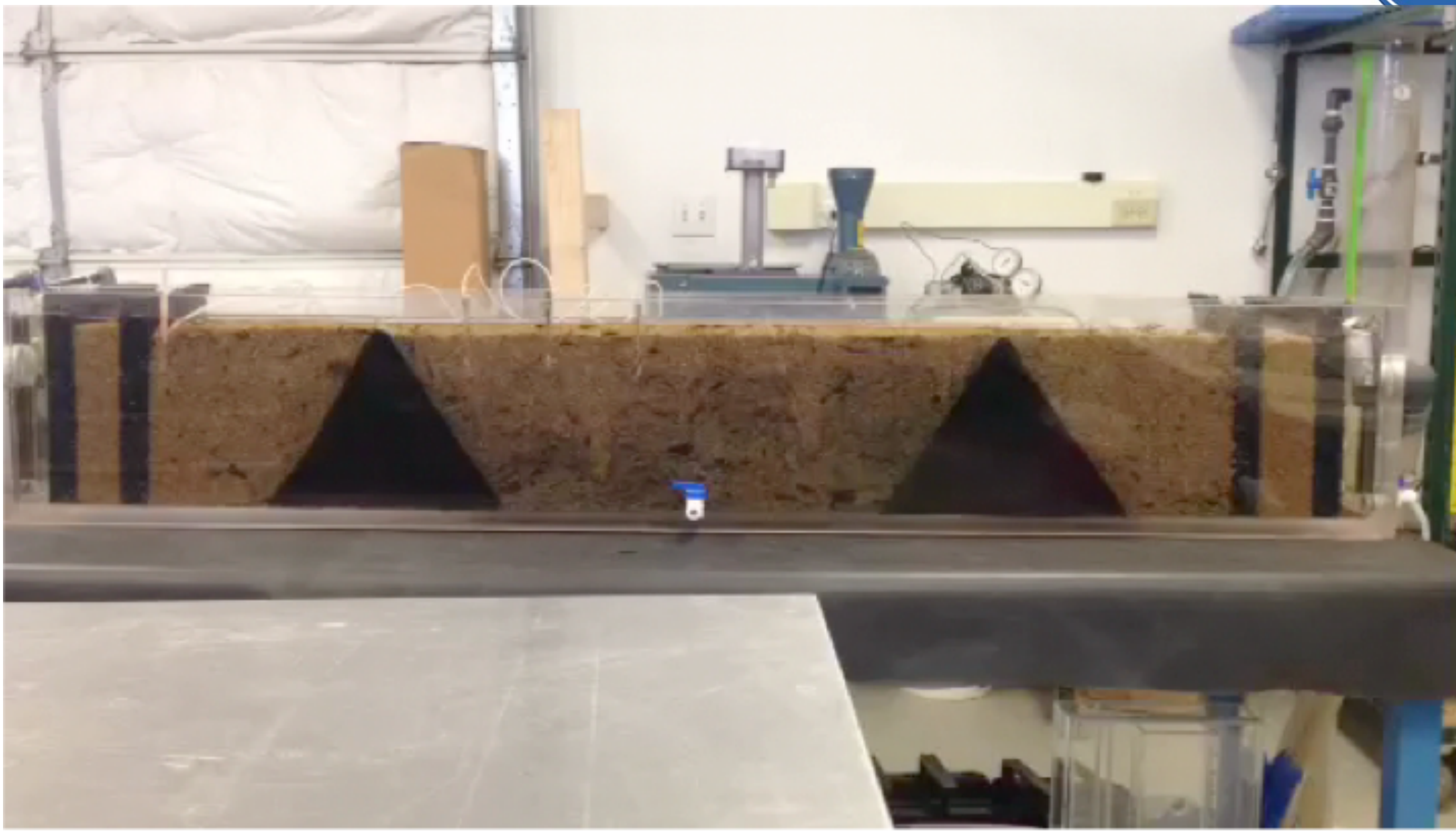
Maybe we can achieve significant removal over ~ 100 m

2-D Laboratory Experiments

BEST: "**B**iohydrochemical **E**nhancements for **S**treamwater **T**reatment"



2-D "Tank" Experiments



Pilot Tests: Constructed Streams – Mines Park

Mines Park Water Reclamation Test Site at Colorado School of Mines

BEST Modules: Biohydrochemical Enhancement for Streamwater Treatment

Implementation-scale BEST: woodchip-sand geomedia designed to treat nitrogen and pathogens.

Test Bed: Mines Park Constructed Streams

- Adjustable flow: 3-25 gpm (0.2–1.5 L/s)
- Sand-only “control” and “BEST” streams, 15m each
- Dosed with reclaimed water or stormwater
- Evaluate Tracers, N, Atrazine, Metals, Pesticides, Trace Organics

Pilot Scale Field Tests – Initial Result
Best vs. Sand-Only Control

Water Exchange

BEST is 150% more effective

Atrazine Removal,

BEST is 200% more effective

Nitrogen Removal

BEST is 200% more effective for NH4, and 50% more effective for NO3 removal (can be improved)

Model Comparison to Actual Urban Streams

- **Conduct conservative and reactive tracer tests** in BEST pilot facility to quantify transport and aerobic microbial chemical transformation (surrogate for some pesticides, ammonia, BTEX components, etc)
- Use **reaction, transport, and storage model -** (calibrated with tracer test data)
- **Simulate longer reaches with BEST modules**
- **Concrete channel** with no HZ
- **Two urban Rocky Mountain streams** from Gooseff et al. (2007).

Tracer Tests in Constructed Stream:
Resazurin (Raz)

Raz **Rru**

- **Raz** degrades irreversibly to Resorufin (**Rru)** in oxic (aerobic) HZ sediments.
- Rru degrades in anaerobic environment
- Reaction negligible in surface water at practical time scales.

THE UNIVERSITY of NEW MEXICO

From R. González-Pinzón

Center for Water and the Environment

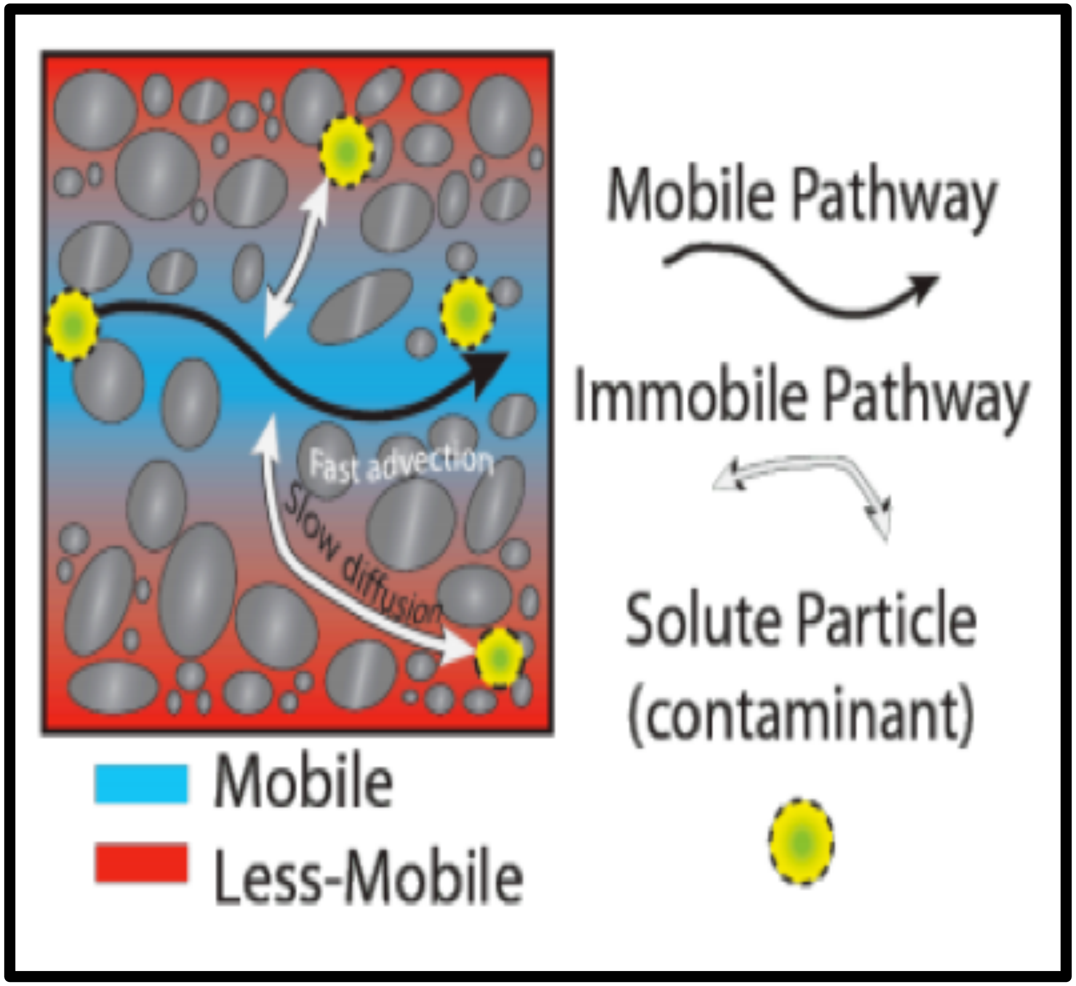
Rezazurin Transformation to Resorufin

Transformation is a measure of residence time and contaminant transformation.

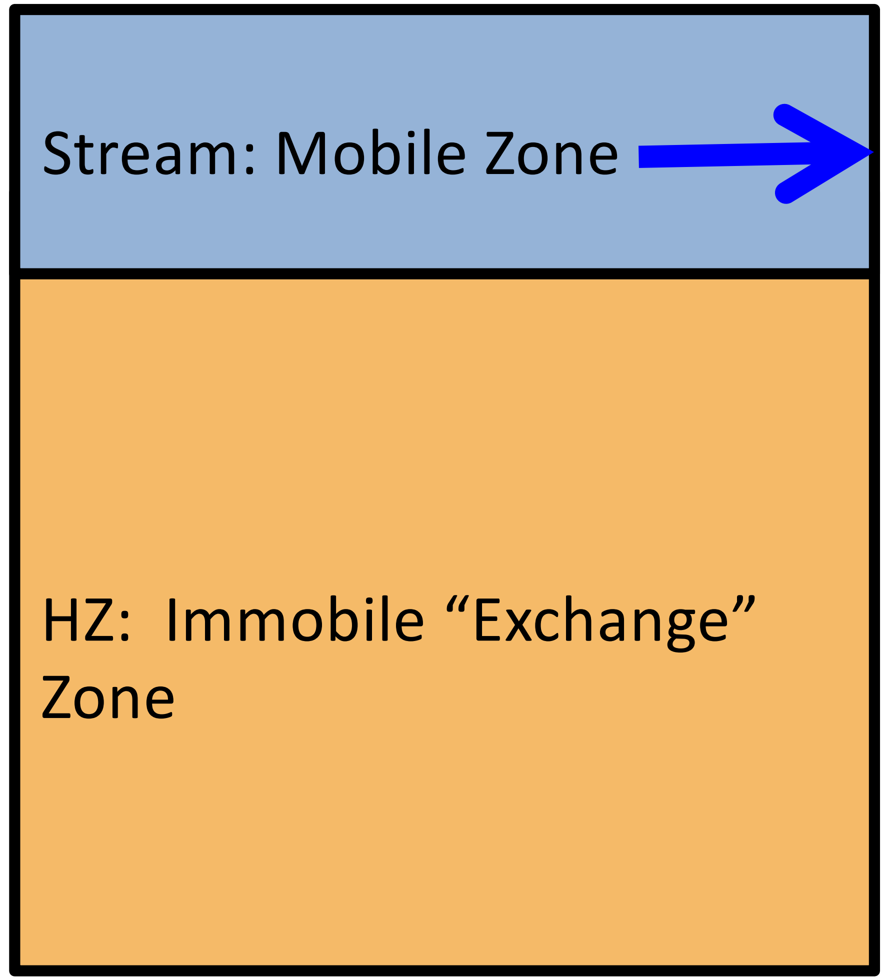
Oxic (Aerobic) reactions remove many fuel constituents, pesticides, pharmaceuticals, ammonia

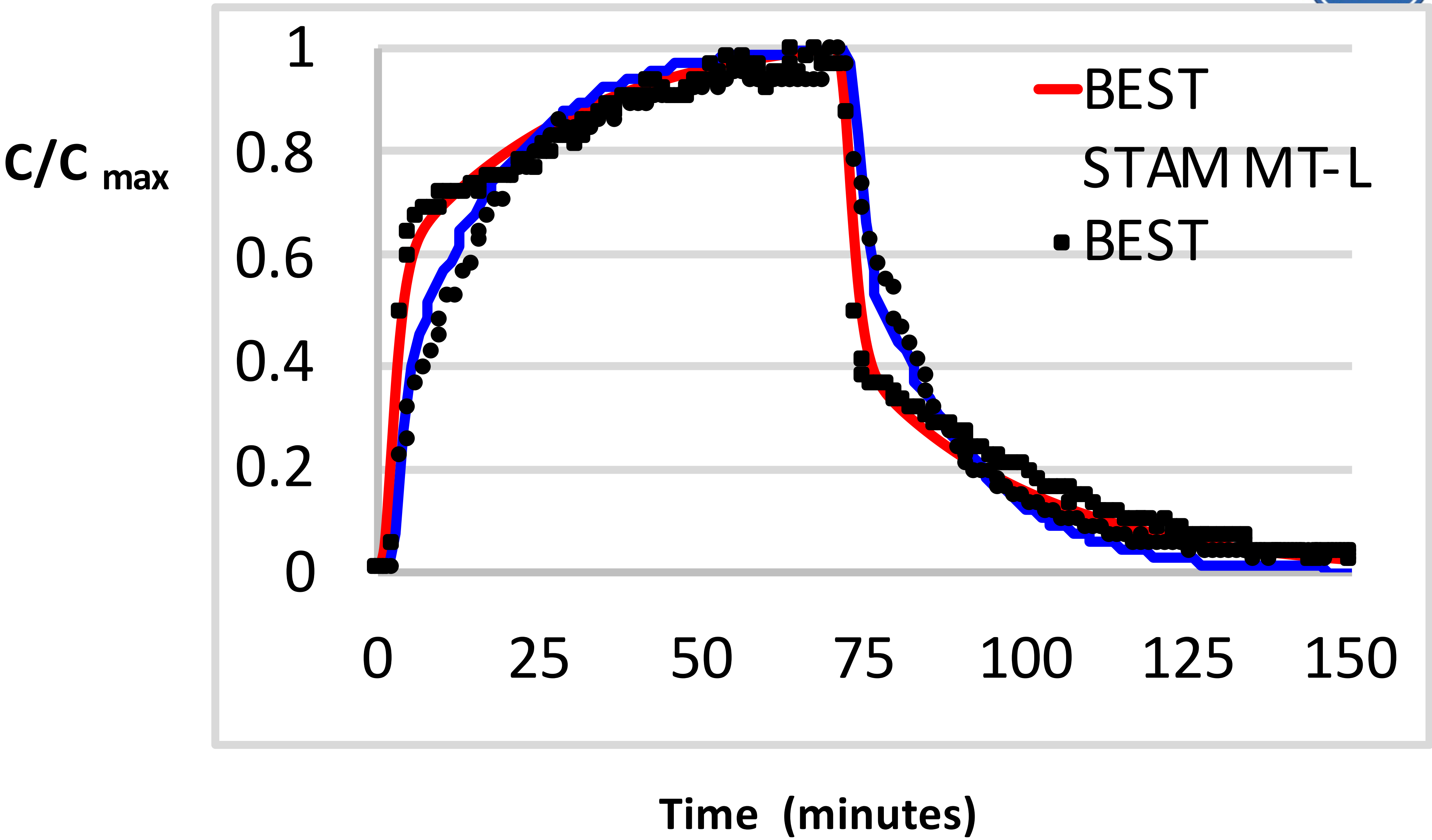
Anoxic (Anaerobic) reactions remove some organic pollutants and nitrate

Analyze Tests using STAMMT-L Model (Haggerty, 2009), then "what if" simulations

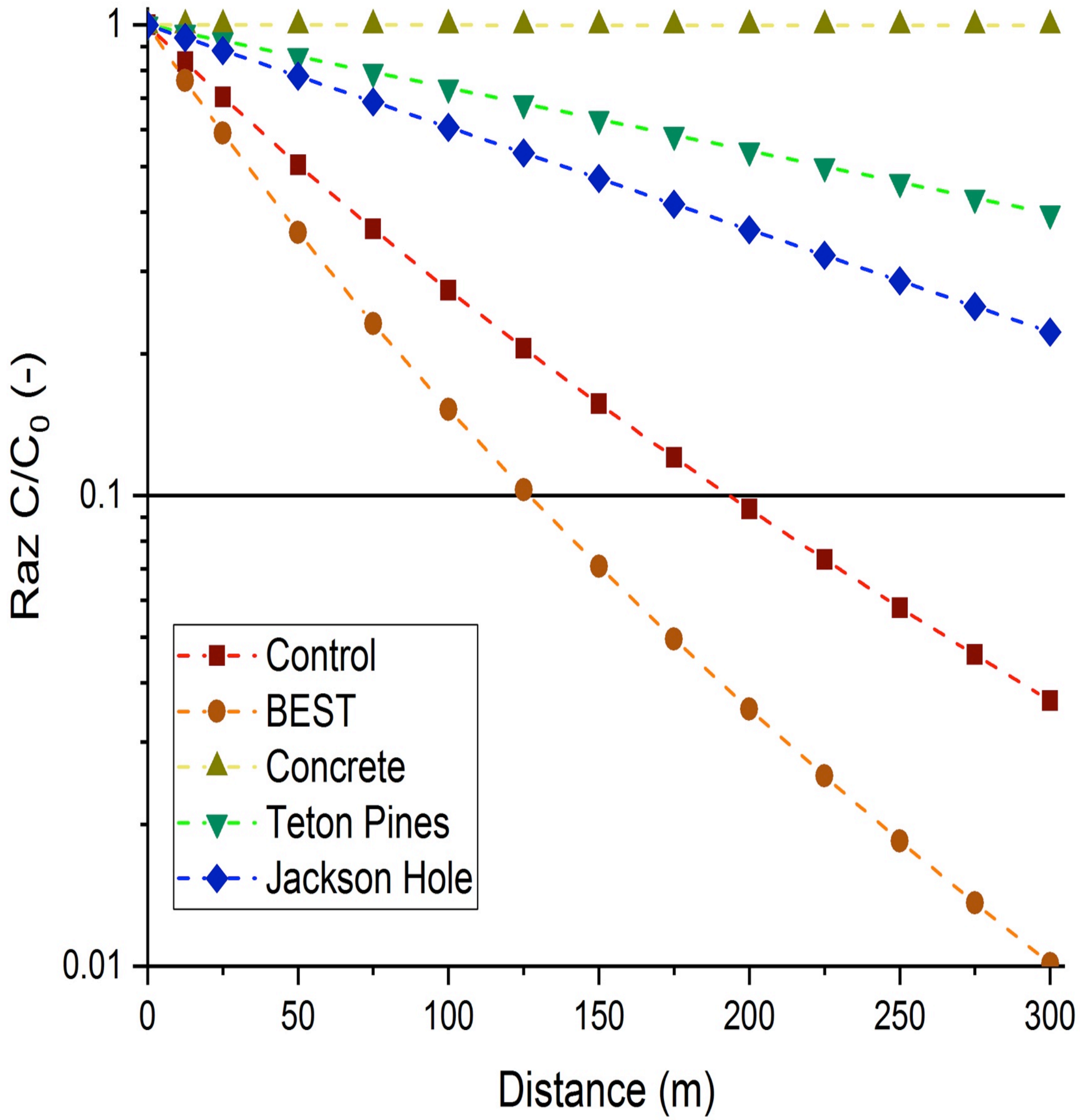


(Singha, 2015)




C/C max
1
0.8
0.6
0.4
0.2
0
0
25
50
75
100
125
150
Time (minutes)
BEST
STAM MT-L
BEST

Model Results



C/Co on y-axis is pollutant concentration divided by Initial concentration.

Distance for 99% removal

- **Concrete: > 20,000 m**
- **Urban Stream 1: 750 m**
- **Urban Stream 2: 1500 m**
- Control: 190m
- **BEST: 125m**

Implementation in the Field

BEST (and BMPs in general) are more practical to implement at relatively small flows.

Urban

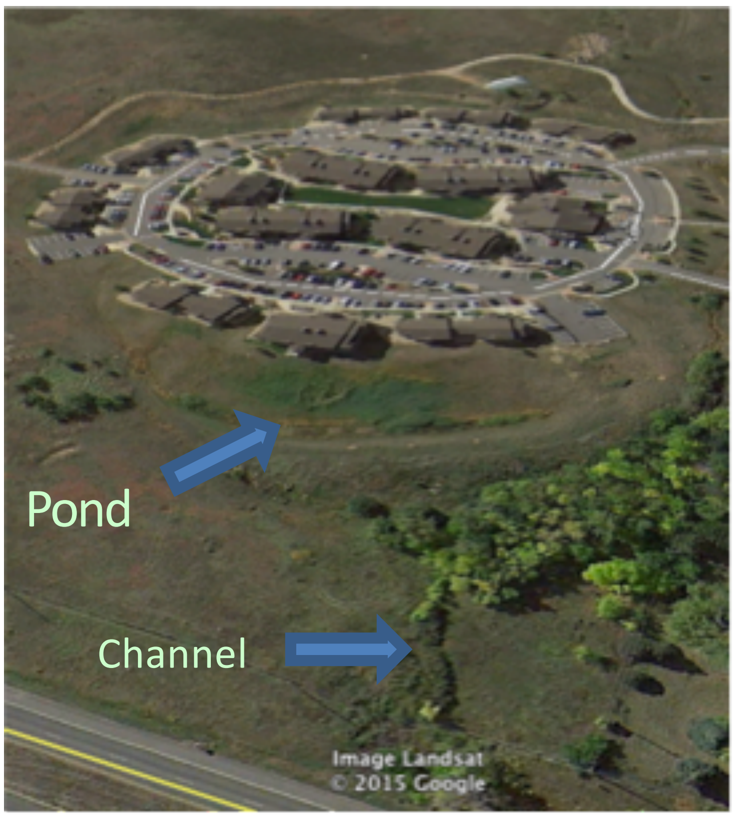
Urban

Rural

Urban Waterways Low Hanging Fruit: Outlets of Stormwater Detention Ponds

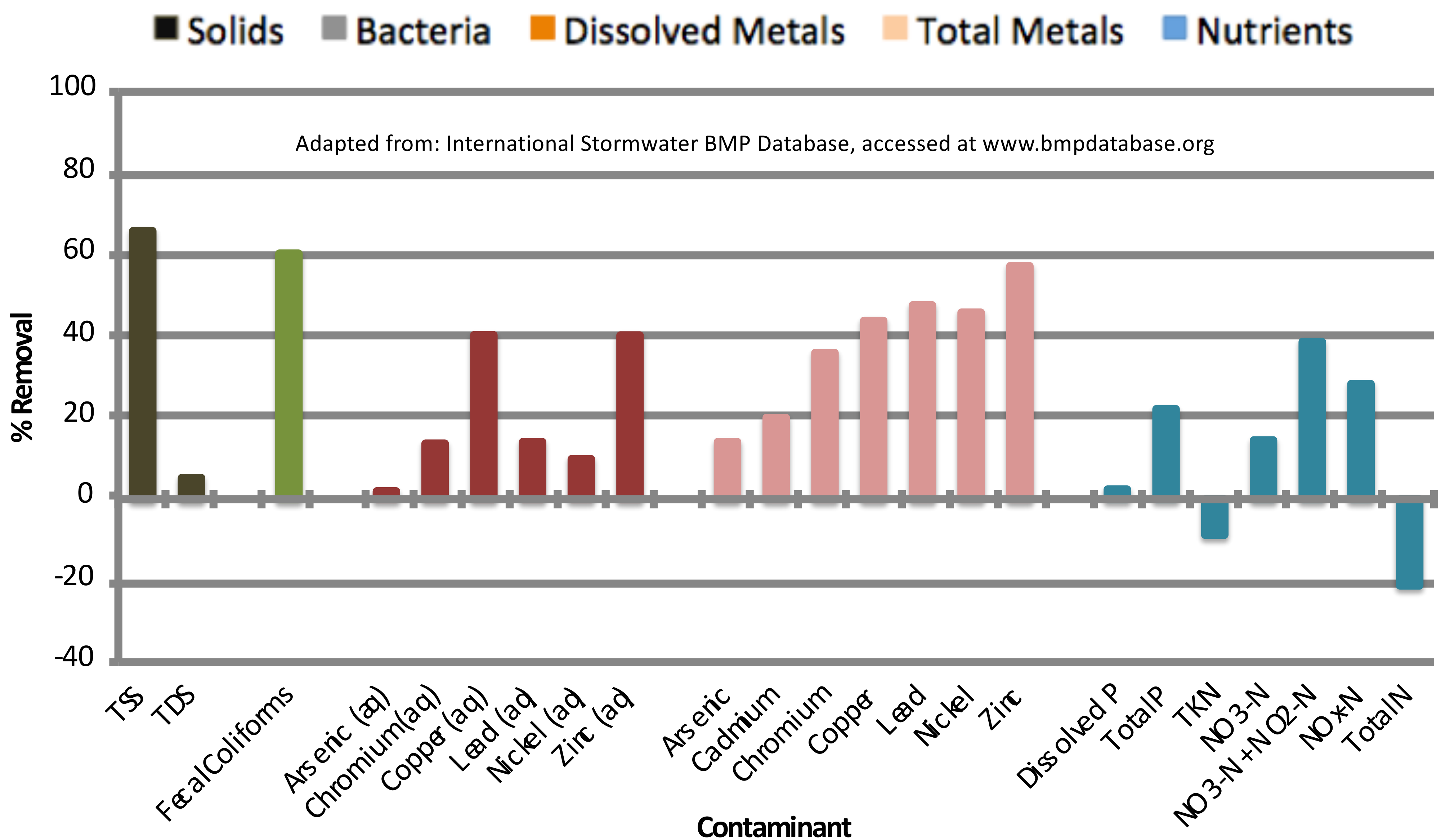
Outlet channel has modulated flow
Some settling (pre-treatment) in pond

BEST protected from siltation and scouring



Town of Golden (pop. 16,000) has more than 200 detention ponds

Contaminant Attenuation by Detention Ponds

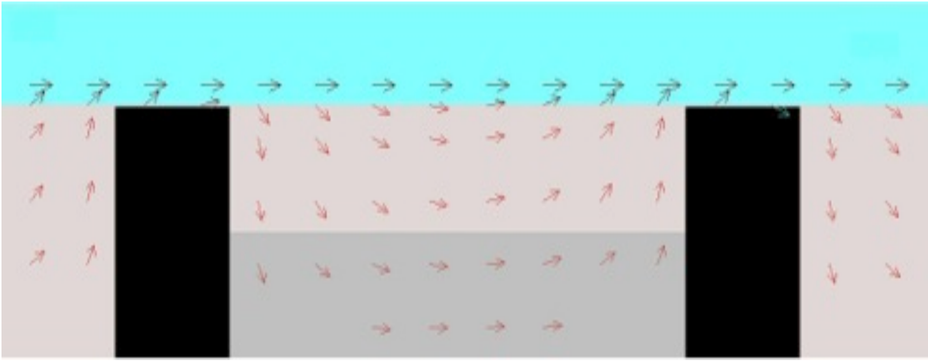


Good removal of sediment-bound pollutants, but poor treatment of dissolved pollutants

Treatment Train: BEST + Detention Ponds

Detention Pond attenuates:
- TSS
- Sediment-bound contaminants

BEST designed to treat:
- Nutrients (N, P)
- Pathogens
- Dissolved Metals



BEST treatment of entire design storm, slowly released from pond

Example: Detention Pond Outlet on Campus

Q = 0.25 to 5 L/s (actual)
10 mg/L NO_3^- (hypothetical)

60-m of BEST yields

- $NO_3^- < 1$ mg/L when $Q \leq 3$L/s
- $NO_3^- < 5$ mg/L when $Q \leq 5$L/s

Cost:

- $ 8000 - material cost
- $ 2500 - construction labor
- **$ 10,500 total**

BEST: $120 per kg N removed

Wetland: $1550 per kg N

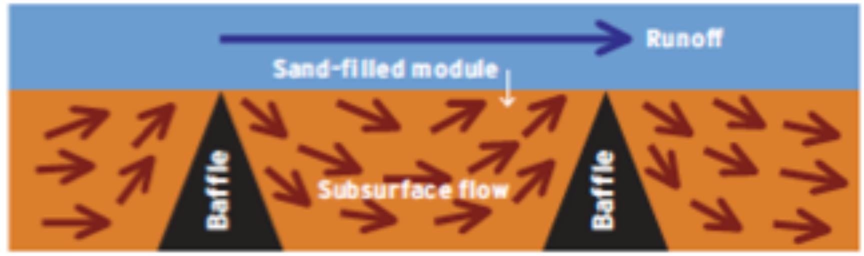
Current Field Installation with City of Golden

Treating stormwater exiting a detention pond – pollutants of concern are bacteria and metals.

Public education poster installed at City of Golden Facility

BEST: Engineered Streambeds
Biohydrochemical Enhancements for Streamwater Treatment

- Baffle walls enhance mixing
- Sand filters pollutants from runoff
- Repeat in Series



Pollutants removed as runoff flows through sand.

BIOHYDROCHEMICAL ENHANCEMENTS for Streamwater Treatment (BEST)

Stormwater Concern
This area is part of the storm drainage system and is designed to collect stormwater – rain and snow melt – and release into Clear Creek, untreated. Pollutants are transported in stormwater as rain and snowmelt flow across surfaces such as lawns, roads and parking lots, picking up substances such as fertilizers, pesticides, oil and sediments before entering Clear Creek. Pollutants that enter the creek degrade the quality of our drinking water source and the quality of fish and wildlife habitats.

What To Do? Treat Pollutants
This site is a partnership between the **City of Golden** and **Colorado School of Mines (CSM)** to treat pollutants from stormwater before they reach Clear Creek.

How To Do It? BEST
Stormwater from the parking lot flows through a swale into a detention pond. These features slow runoff allowing sediment to settle out. However, dissolved pollutants like fertilizers and metals remain in the runoff. To treat dissolved pollutants, researchers at CSM invented BEST, a streambed engineering technique. BEST cleans runoff through a series of sand-filled modules separated by baffles. The baffles enhance mixing between the surface and subsurface water, increasing the amount of water that flows through the sand-filled modules. The sand within the subsurface acts as a filter to physically remove pollutants and enhances microbial reactions to remove pollutants.

Questions?
Contact CSM at best@mines.edu or Golden at esdiv@cityofgolden.net.

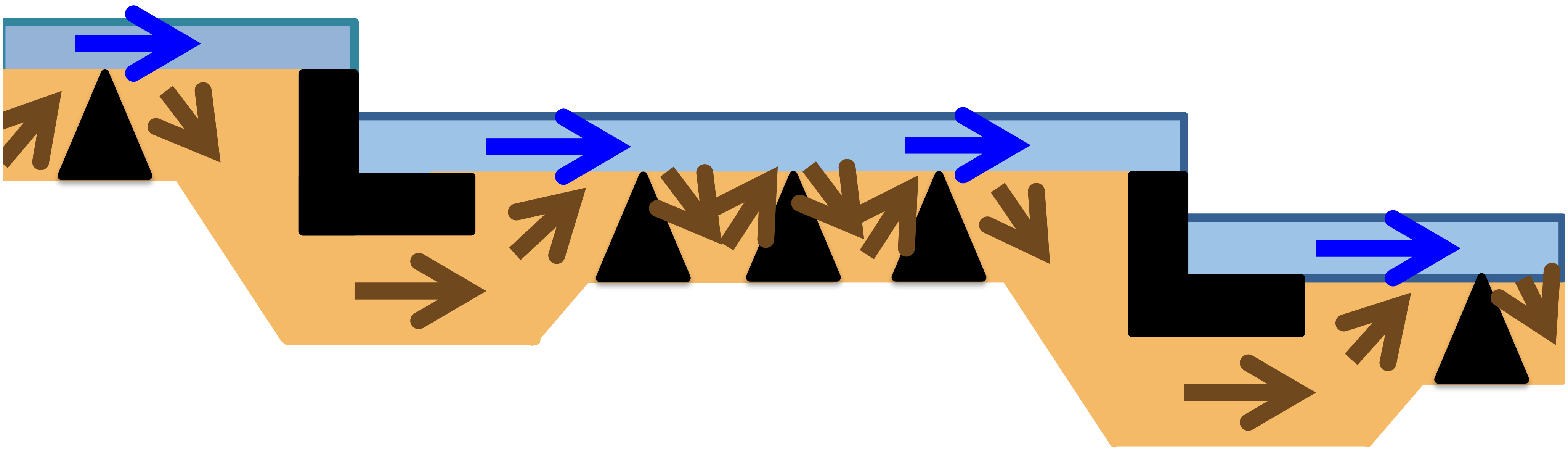
City of Golden PUBLIC WORKS DEPARTMENT
MINES
ReNUWIt URBAN WATER INFRASTRUCTURE

Collaboration with Seattle Public Utilities
Thornton Creek in Seattle, WA

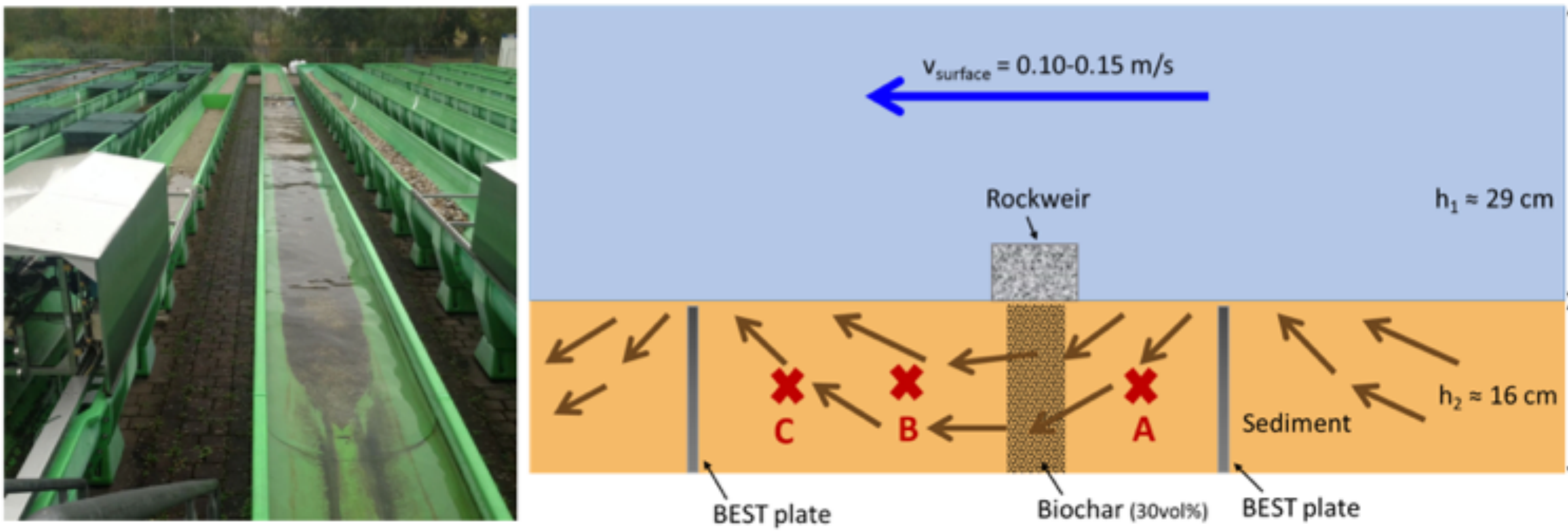
How can a hyporheic zone be designed to optimize contaminant attenuation?

Collaboration with Seattle Public Utilities

- Improved structure cross-vane function
- Distributed hyporheic exchange in between cross-vanes



Collaboration with HYPOTRAIN: an European Organization studying the Hyporheic Zone

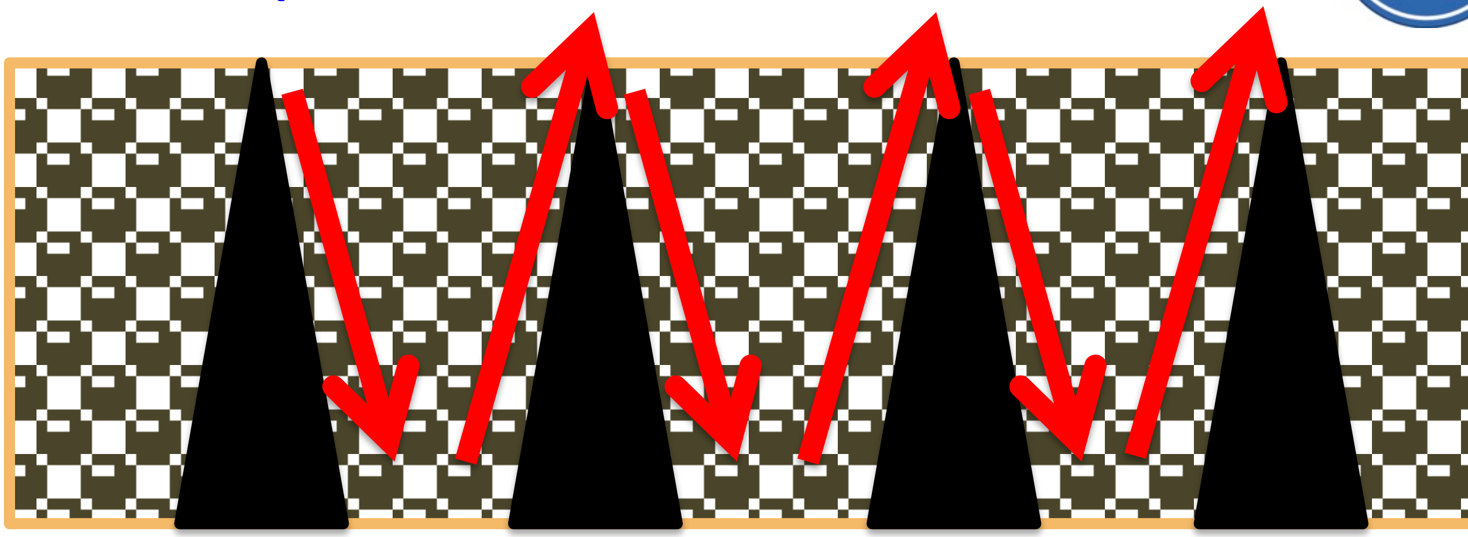


Left: Field site in Berlin, Germany, used for studying the fate of diabetes medication Metformin in BEST amended with biochar. Right: Schematic of experimental flume set-up, where Locations A, B, and C denote HZ sampling locations (via MINIPOINT samplers).

What's next?
Customize BEST for specific reactions

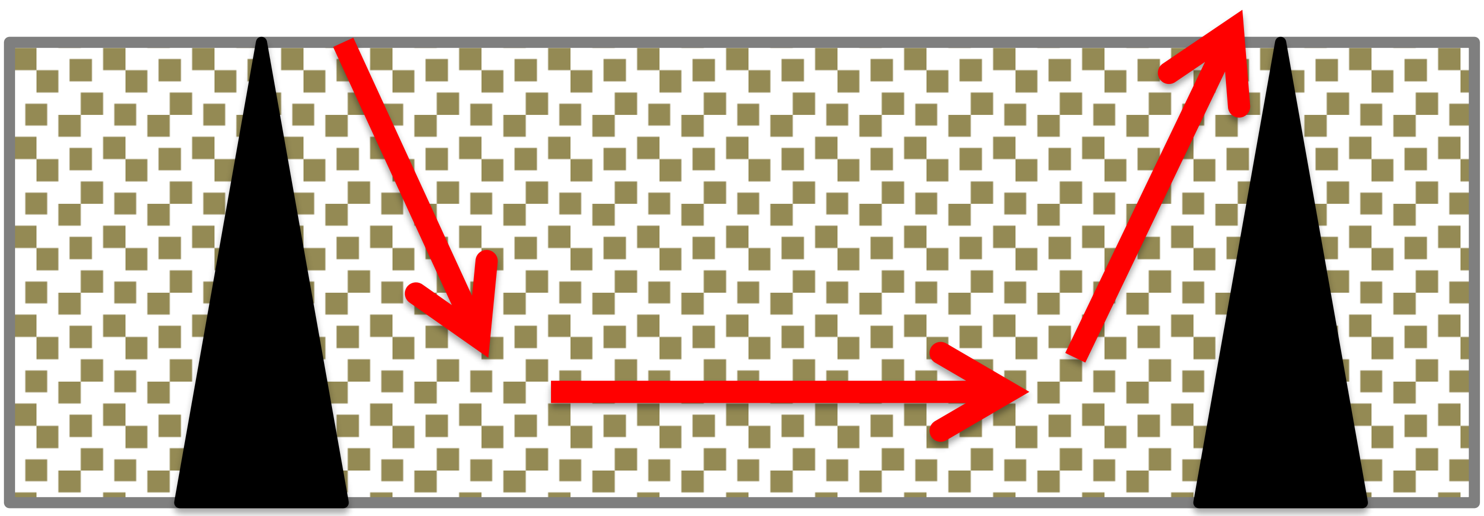
Nitrification

- Short RT (~30 min)
- Coarse sand - woodchips



Denitrification

- Long RT (~3hr)
- Medium sand & woodchips

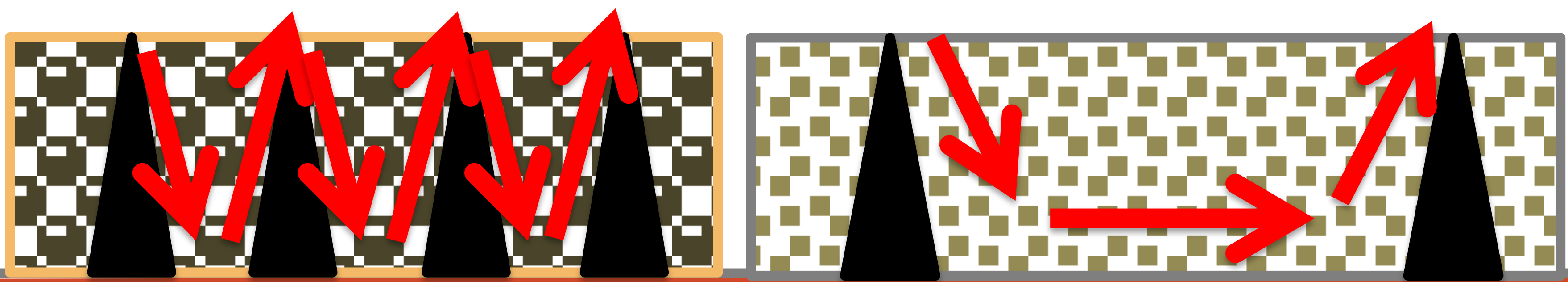


Other Applications

- Stream restoration (top)
- Rural streams (right)
- Acid mine drainage (bottom center)
- Agricultural ditches (below)
- Any polluted ditch or channel

Conclusions & Discussion

- BEST increased hyporheic transient storage compared to control.
- BEST streams shows potential for treatment of aerobic-transformed pollutant, nutrients, and atrazine compared to the control condition, but contaminant removal should be further studied and optimized.
- Not a silver bullet, but part of a treatment-train solution, and a novel means of constraining hyporheic residence times to match reaction timescales of interest.
- Future work - optimize BEST design for specific reactions.



Conclusions: Engineered BEST Modules for Stormwater Treatment


Stormwater in Tucker Gulch. Golden, CO

BEST modules are a novel BMP to attenuate nonpoint source contaminants in urban streams / channels.

Harness ubiquitous stormwater channels for overall water quality improvements.

BEST channels in series to treat multiple contaminants

Questions?

jmccray@mines.edu

Herzog, S. P., Higgins, C. P., and **J. E. McCray** (2015). Engineered streambeds for induced hyporheic flow: Enhanced removal of nutrients, pathogens, and metals from urban streams, *ASCE J. Environ. Enginrng*, 142(1) 10.1061/(ASCE)EE.1943-7870.0001012

Herzog, S.P., Singha, K., Higgins, C.P., **McCray, J.E.**, 2018. Performance of engineered streambeds for inducing hyporheic transient storage, *Environ. Sci. & Technol*. DOI: 10.1021/acs.est.8b01145

Peter, K., Herzog, S., Tian, Z., Wu, C., **McCray, J.E.**, Lynch, K., Kolodziej, E. 2018. Removal of emerging organic contaminants in an engineered hyporheic zone, in press, *Water Research*

Lawrence, J.E., …**McCray, J.E**. (2013). **Enhancing water quality and improving aquatic habitat by active management of the hyporheic zone in urban streams**, *Environ. Engrng. Science,* 30(8), 480-501.