Stream Restoration Design & Implementation

Greg Jennings, PhD, PE
jenningsenv@gmail.com

1. Channel morphology
2. Floodplain structure
3. Hydrologic & hydraulic analysis
4. In-stream structures
5. Habitats & vegetation
6. Site & watershed conditions
7. Monitoring, maintenance, education

Basic Science: Fluvial Geomorphology:

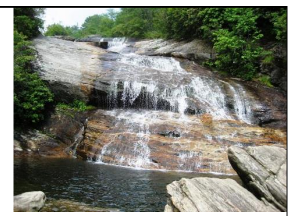
study of landforms and the fluvial processes that shape them

Fluvial Processes:

associated with flowing water, including sediment erosion, transport, and deposition

Fluvial Forms

- Bar
- Channel
- Confluence
- Cutoff channel
- Delta
- Floodplain
- Gorge
- Gully
- Meander
- Oxbow lake
- Pool
- Riffle
- Stream
- Valley
- Waterfall
- Watershed



What is a Stream?

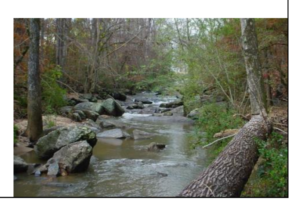
… a body of water with a <u>current</u>, confined within a <u>bed</u> and <u>streambanks</u>

Synonyms: bayou, beck, branch, brook, burn, creek, crick, kill, lick, rill, river, rivulet, run, slough, syke

Streams are conduits in the <u>water cycle</u> and also important <u>habitats</u>

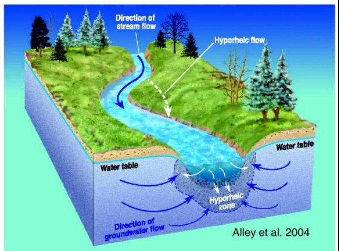
Stream: *A <u>system</u> of fluvial forms & habitats*

- Channel (bed & banks)
- Floodplain
- Water
- Sediment
- Plants & animals



Stream Connections

- Mostly downstream fluxes of energy and matter
- Lateral and vertical connections to the riparian and hyporheic zones



Courtesy of Francois Birgand, NCSU

Stream (Ecosystem) Restoration

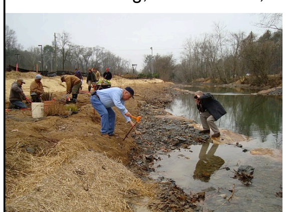
"activities that initiate or accelerate the recovery of ecosystem health, integrity, and sustainability" (*SER, 2004*)

Jasper Town Creek

Auburn UT Town Creek

Stream Restoration is a Systematic Process

1. Planning & Assessment
2. Engineering
3. Construction & Planting
4. Monitoring, Maintenance, Adjustments



Samford Univ Shades Creek

Daphne UT D'Olive Creek

Goals of Stream Restoration Projects

- Improve habitats & water quality
- Improve recreation & aesthetics
- Protect infrastructure & land value
- Educate citizens & decision-makers

Daphne UT D'Olive Creek

Samford Univ Shades Creek

Stream Restoration as a BMP

- Sediment control
- Nutrient cycling (instream & floodplain)
- Peak discharge attenuation
- Habitats (aquatic & terrestrial)
- Infrastructure protection

Standards for ecologically successful river restoration

Palmer et al., Journal of Applied Ecology, 2005, 42, 208–217

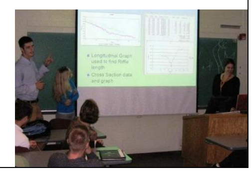
1. design of an ecological river restoration project should be based on a specified guiding image of a more dynamic, healthy river
2. river's ecological condition must be measurably improved
3. river system must be more self-sustaining and resilient to external perturbations so that only minimal follow-up maintenance is needed
4. during the construction phase, no lasting harm should be inflicted on the ecosystem
5. pre- and post-assessment must be completed and data made publicly available

Restoration Planning & Design

1. Objectives?
2. Constraints?
3. Design Approach?
4. Permitting?
5. Construction?
6. Monitoring & Maintenance?
7. Funding?

Stream Design Approaches

1. Threshold Channel
2. Alluvial Channel
   a. Regime Equations
   b. Analogy (Reference Reach)
   c. Hydraulic Geometry
   d. Analytical Models
3. Combination of Methods



Threshold Channels

Rigid Boundary

Threshold Channels

1. Rigid boundary systems
2. *Simple design approach*: select channel configuration where the stress applied during design conditions is below the allowable stress for the channel boundary

Table 8–1 General guidance for selecting the most appropriate channel design technique

Technique	Significant sediment load and movable channel boundaries	Boundary material smaller than sand size	Boundary material larger than sand size	Boundary material does not act as discrete particles	No baseflow in channel. Climate can support permanent vegetation
Allowable velocity		X			
Allowable shear stress			X		
Tractive power				X	
Grass lined/tractive stress					X
Alluvial channel design techniques	X				

8–2 (210–VI–NEH, August 2007)

Alluvial Channels

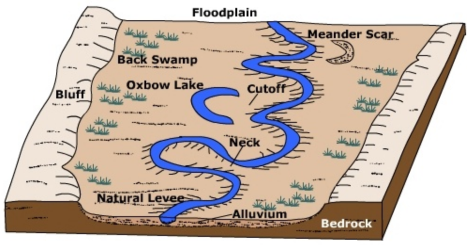
1. Movable boundary systems ("natural" streams)
2. *Complex design approach*: assess sediment continuity and channel performance for a range of flows
3. *Dependent variables:* Width, Depth, Slope, Planform
4. *Independent variables:* Sediment inflow, Water inflow, Bank composition
5. Empirical & Analytical approaches should be used concurrently

Assumption: Stream Behavior Is Predictable

- Streams evolve to a state of dynamic equilibrium
- Equilibrium is a function of flow and sediment
- Equilibrium is naturally associated with a main channel and a flood-prone area
- Channel is formed by the effective ("bankfull") discharge
- Alluvial stream meandering is predictable

Alluvial River Processes

Rivers that have reached base level develop broad valleys by erosion caused by meandering channels. The stream channel cuts through and redistributes its sediment or **alluvium** that lines the area bordering the stream.



http://www.uwsp.edu/gEo/faculty/ritter/geog101/textbook/fluvial_systems/geologic_work_of_streams.html

Sediment Transport in Alluvial Streams

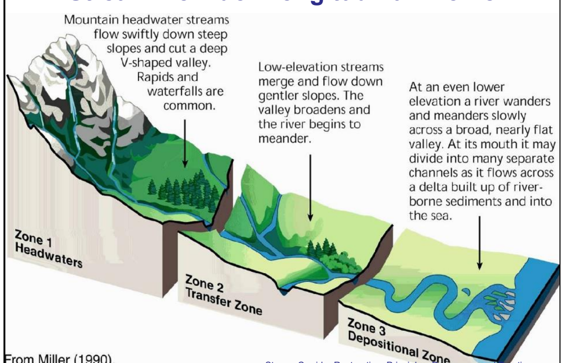
Stream Load includes:
dissolved + suspended + bed load

Capacity: maximum load that can be transported for a given discharge (increases with velocity and turbulence)

Competence: largest size material that can be transported for a given discharge

http://www.uwsp.edu/gEo/faculty/ritter/geog101/textbook/fluvial_systems/geologic_work_of_streams.html

Stream Corridor Longitudinal Profile



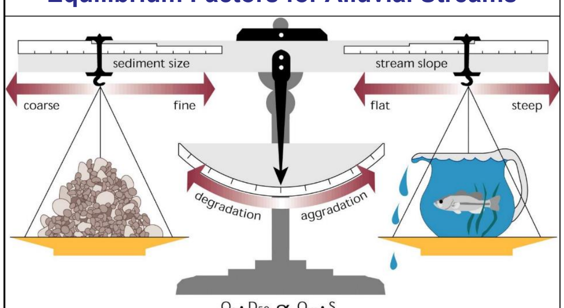
From Miller (1990).
©1990 Wadsworth Publishing Co.

Stream Corridor Restoration: Principles, Processes, and Practices. 1998. Federal Interagency Stream Restoration Working Group.

Natural Stream Channel Equilibrium *(from Leopold)*

- River has a stable *dimension, pattern and profile*
- Maintains channel features (riffles, pools, steps)
- Does not aggrade (fills) or degrade (erodes)

Equilibrium Factors for Alluvial Streams



From Rosgen (1996), from Lane, Proceedings, 1955.
Published with the permission of American Society of Civil Engineers.

Fig. 1.13 – Factors affecting channel degradation and aggradation: Concept of "Stream Balance.".
In Stream Corridor Restoration: Principles, Processes, and Practices, 10/98.
Interagency Stream Restoration Working Group (15 Federal Agencies of the US).

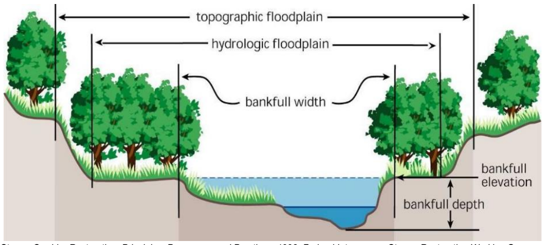
Equilibrium Controlling Variables

- Width
- Depth
- Slope
- Velocity
- Discharge
- Flow resistance
- Sediment size
- Sediment load

Leopold et al (1964)

Bankfull Stage

"corresponds to the discharge at which channel maintenance is the most effective, that is, the discharge at which moving sediment, forming or removing bars, forming or changing bends and meanders, and generally doing work results in the average morphologic characteristics" *(Dunne and Leopold,1978)*

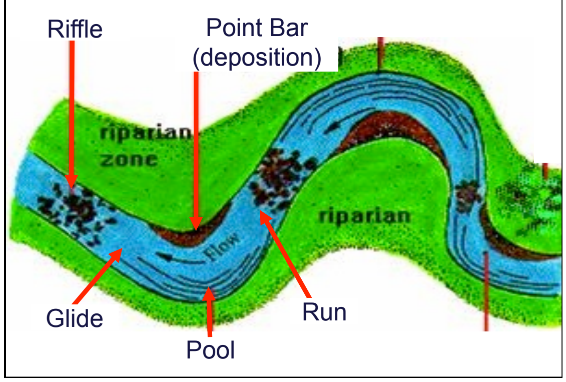


Stream Corridor Restoration: Principles, Processes, and Practices. 1998. Federal Interagency Stream Restoration Working Group.

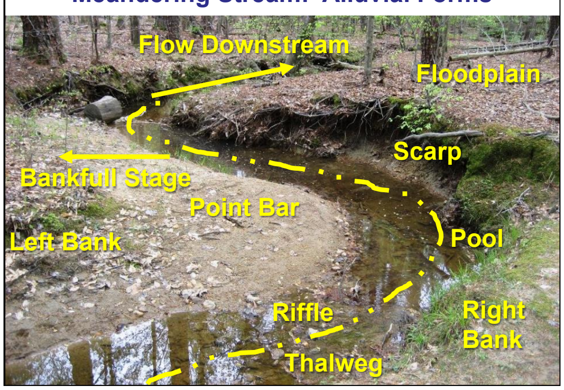
Bankfull Indicators:

Point Bars and Lateral Benches 1.2 to 1.5 ft above WS

Meandering Stream: Alluvial Forms



Meandering Stream: Alluvial Forms



Natural Channel Design: Alluvial Channels

1. Existing Conditions – valley, watershed, constraints
2. Design Parameters (Channel & Floodplain)
   a. Reference Reaches (Analogy)
   b. Completed Restoration Projects (Analogy)
   c. Hydraulic Geometry Regional Curves (Empirical)
   d. Regime Equations (Empirical)
3. Analytical Models to Test Range of Discharges

Reference Reaches:

Morphology design parameters serve as a “starting point”



Reference Reaches:

- Channels well-connected to alluvial floodplains with little evidence of incision (bank height ratios less than 1.2)
- Freely-formed meanders with alternating riffles and pools
- Streambanks and floodplains well-vegetated with no erosion
- Upstream watersheds mostly forest and agriculture
- Stable and unconfined for a length 20 times bankfull width

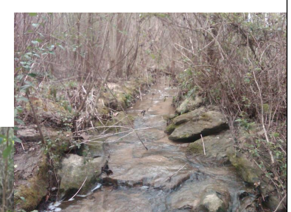

Reference Reaches:

- Upstream/downstream
- Similar watersheds
- Databases
- Historical photos


Similar bed/bank materials; hydrology; sediment inflow; slope; valley

Completed Projects:

- Upstream/downstream
- Similar watersheds
- Successes & Failures




Auburn Town Creek Park (5 years later)

Channel Evolution: *Vegetation Effects*

- Width-to-depth ratio will decrease
- Banks will steepen

As-built:

A_{bkf} = 4.5 sq ft

W_{bkf} / d_{bkf} = 7.6 / 0.6 = 13

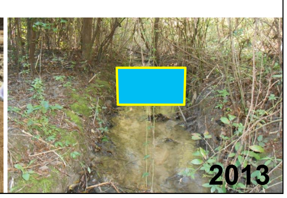
Bank Angles: 3:1

5 Years Later:

A_{bkf} = 3.8 sq ft

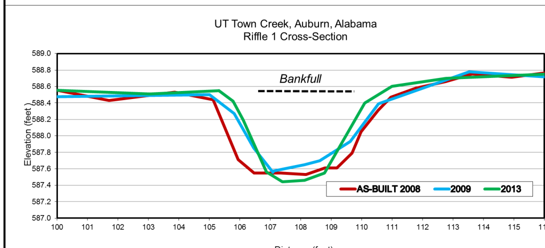
W_{bkf} / d_{bkf} = 5.4 / 0.7 = 8

Bank Angles: Near Vertical



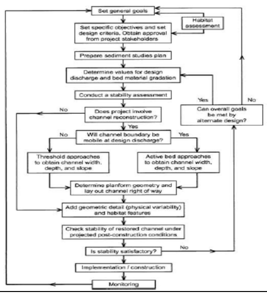
Channel Evolution: *Vegetation Effects*

- Width-to-depth ratio will decrease
- Banks will steepen



Analytical Methods to Check Design

1. Choose appropriate model
2. Assess a range of solutions
3. Use as a check



Analytical Design Approach, Shields, 2006

Restoration Components

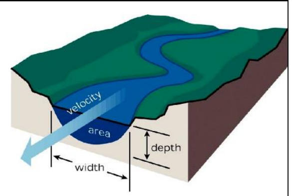
1. Channel morphology
2. Floodplain structure
3. Hydrologic & hydraulic analysis
4. In-stream structures
5. Habitats & vegetation
6. Site & watershed conditions
7. Monitoring, maintenance, education

1. Channel Morphology

- Dimension (baseflow, bankfull, flood flows)
- Pattern (meandering, straight, braided)
- Profile (bedform – riffle, run, pool, glide, step)

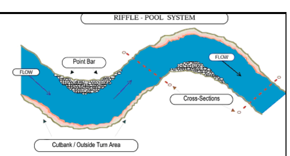
Vestavia Hills: Little Shades Creek, 2011

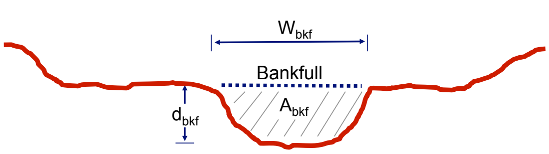
Dimension *(cross-section)*



- Area
- Width
- Depth
- Width/Depth Ratio
- Entrenchment Ratio
- Bank Height Ratio

Riffle Dimensions





Measure Bankfull Width (W_{bkf}) and Bankfull Area (A_{bkf})

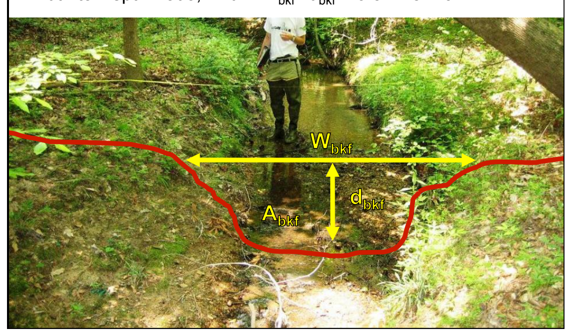
Mean Depth, $d_{bkf} = A_{bkf} / W_{bkf}$

Width to Depth Ratio, $W/d = W_{bkf} / d_{bkf}$

Bankfull Width, W_{bkf} = 9.3 ft; Bankfull Area, A_{bkf} = 13.9 ft^2

Mean Depth, $d_{bkf} = A_{bkf} / W_{bkf}$ = 13.9 / 9.3 = 1.5 ft

Width to Depth Ratio, $W/d = W_{bkf} / d_{bkf}$ = 9.3 / 1.5 = 6.2

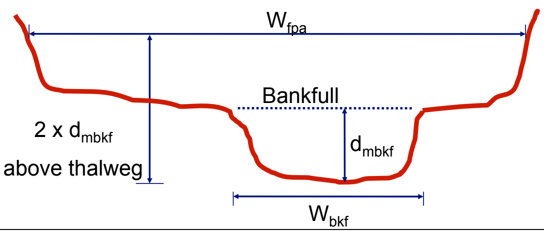


Entrenchment Ratio

$ER = W_{fpa} / W_{bkf}$

W_{fpa} = Width of Flood Prone Area measured at the elevation twice bankfull max depth above thalweg

W_{bkf} = Width of Bankfull Channel

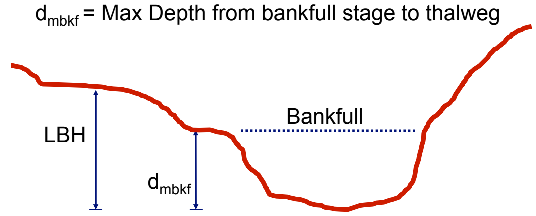


Bank Height Ratio

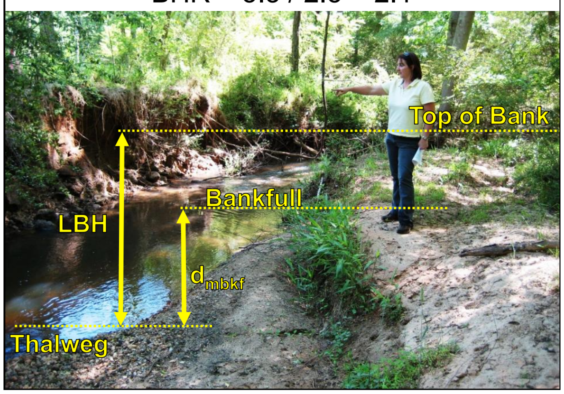
$BHR = LBH / d_{mbkf}$

LBH = Low Bank Height (Max Depth to thalweg)

d_{mbkf} = Max Depth from bankfull stage to thalweg



BHR = 5.3 / 2.5 = 2.1



Cross-Sections: 5 Riffles, 5 Pools

Riffle width, W_{bkf} = 8.0 ft (*range 6.8 to 9.4*)

Riffle cross-section area, A_{bkf} = 8.5 sq ft (*range 8.3 to 8.9*)

Mean riffle depth, $d_{bkf} = A_{bkf} / W_{bkf}$ = 1.1 ft

Width-to-depth ratio, W_{bkf} / d_{bkf} = 7.5 ft/ft

BHR = 1.1 to 1.5

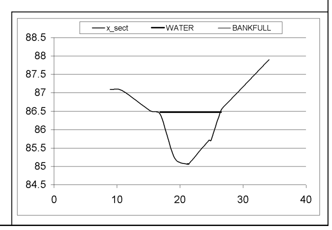
d_{mbkf} = 1.5 to 2.0 ft

d_{bkfp} = 1.3 to 2.1 ft

W_{bkfp} = 9.0 to 12.9 ft

A_{bkfp} = 11.5 to 24.2 sq ft

d_{mbkfp} = 1.8 to 3.0 ft

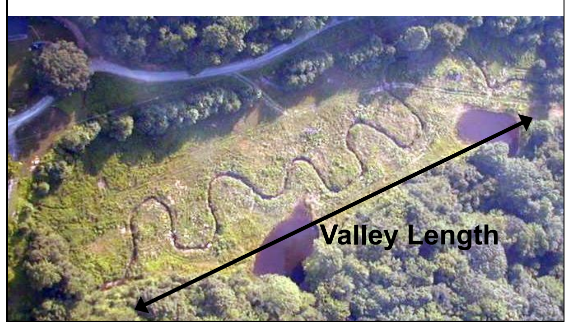


Pattern (plan form)

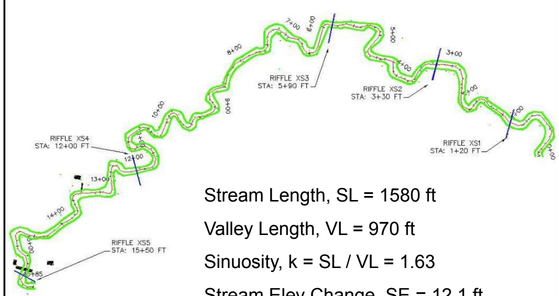
Alluvial (low-gradient) streams naturally meander across a valley with a somewhat predictable pattern

Sinuosity = stream length / valley length

K = 1850 / 980 = 1.9



Plan View – Total Station Survey, 2008



Stream Length, SL = 1580 ft

Valley Length, VL = 970 ft

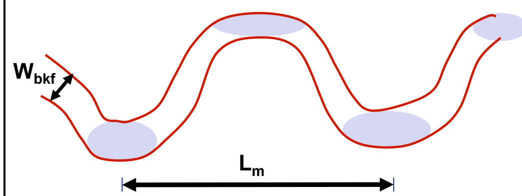
Sinuosity, k = SL / VL = 1.63

Stream Elev Change, SE = 12.1 ft

Ave WS Slope, S = SE / SL = 0.0077 ft/ft

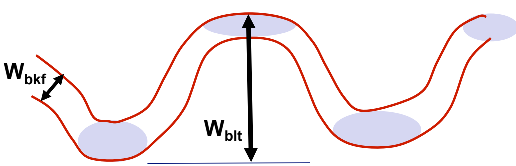
Meander length, L_m (ft)

Meander length ratio, [L_m / W_{bkf}]



Meander belt width, W_{blt} (ft)

Meander width ratio, [W_{blt} / W_{bkf}]



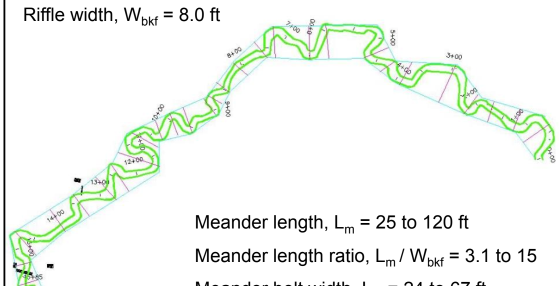
Meander Length Ratio = meander length / width = 78/15 = 5.2

Meander Width Ratio = belt width / width = 57/15 = 3.8

Radius of Curvature Ratio = radius / width = 23/15 = 1.5

Meander Lengths and Belt Widths

Riffle width, W_{bkf} = 8.0 ft



Meander length, L_m = 25 to 120 ft

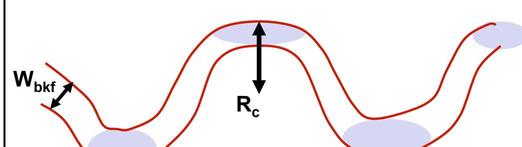
Meander length ratio, L_m / W_{bkf} = 3.1 to 15

Meander belt width, L_m = 24 to 67 ft

Meander width ratio, W_{blt} / W_{bkf} = 3.0 to 8.4

Radius of curvature, R_c (ft)

Radius of curvature ratio, [R_c / W_{bkf}]

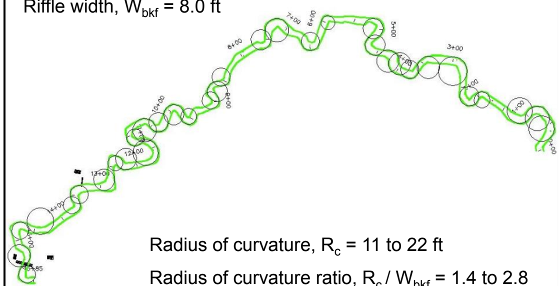


Note: Measure radius to outside bend on reference reach.

For design layout, adjust radius to centerline using ½ width.

Radius of Curvature

Riffle width, W_{bkf} = 8.0 ft

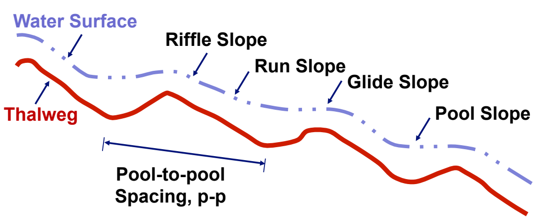


Radius of curvature, R_c = 11 to 22 ft

Radius of curvature ratio, R_c / W_{bkf} = 1.4 to 2.8

Note: R_c measured to outside bend

Profile (bedform)



Riffle Slope Ratio, S_{rif} / S_{av}

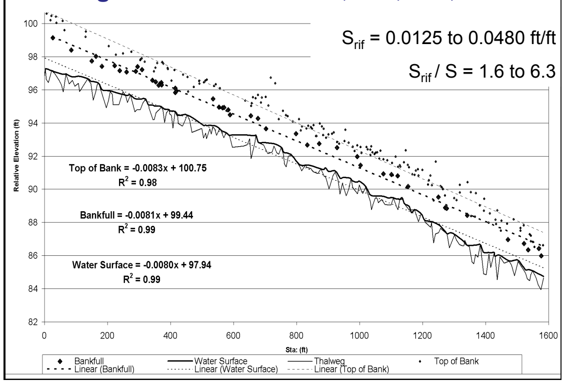
Pool Slope Ratio, S_{pool} / S_{av}

Pool-to-Pool Spacing Ratio, p-p / W_{bkf}

Longitudinal Profile: TW, WS, Bkf, TOB

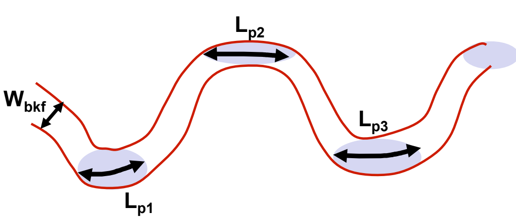
S_{rif} = 0.0125 to 0.0480 ft/ft

S_{rif} / S = 1.6 to 6.3



Pool length, L_p (ft)

Pool length ratio, [L_p / W_{bkf}]

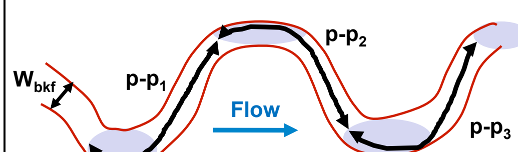


L_p = 9 to 38 ft

L_p / W_{bkf} = 1.1 to 4.8

Pool-to-pool spacing, p-p (ft)

Pool-to-pool spacing ratio, [p-p / W_{bkf}]

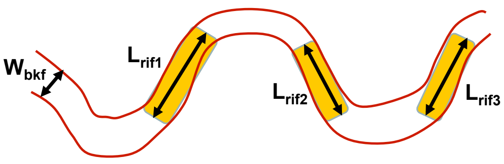


p-p = 19 to 67 ft

p-p / W_{bkf} = 2.4 to 8.4

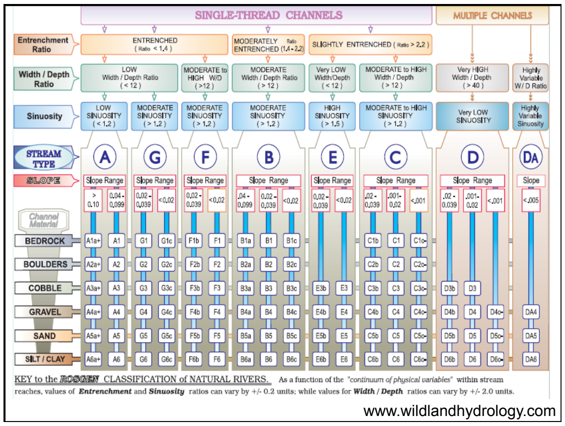
Riffle length, L_{rif} (ft)

Riffle length ratio, $[L_{rif} / W_{bkf}]$



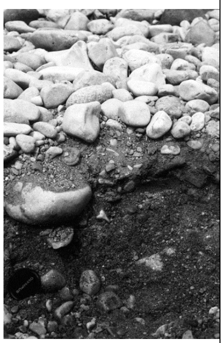
L_{rif} = 5.5 to 23.8

L_{rif} / W_{bkf} = 0.7 to 3.0



Bed Material (Substrate)

6. Silt/Clay: < 0.062 mm
5. Sand: 0.062 – 2 mm
4. Gravel: 2 – 64 mm
3. Cobble: 64 – 256 mm
2. Boulder: 256 – 2048 mm
1. Bedrock



2. Floodplain Structure

- Regular (every year) flooding to relieve stress
- Floodwater retention & riparian wetlands
- Stormwater discharge retention & treatment

2. Floodplain Structure

$ER = W_{bkf} / W_{fpa}$: Entrenchment ratio provides wide floodplain for flood energy dissipation, sediment retention & riparian habitats

$BHR = LBH / d_{mbkf}$: Bank height ratio provides floodplain access at bankfull stage consistently down valley on both banks

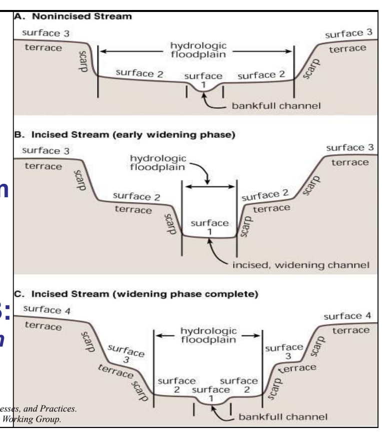
Floodplain orientation minimizes flood flow stresses (straight down valley & consistent width)

Surface topography supports floodwater retention, flow diversity & riparian habitats

Priority 1:
lift channel

Incised Stream

Priority 2 & 3:
lower floodplain



Stream Corridor Restoration: Principles, Processes, and Practices. 1998. Federal Interagency Stream Restoration Working Group.

Priority 1: Reconnect Floodplain

Replace incised channel with shallow channel raised to existing floodplain elevation

ER = 18 W/d = 12
K = 1.4 S = 0.008

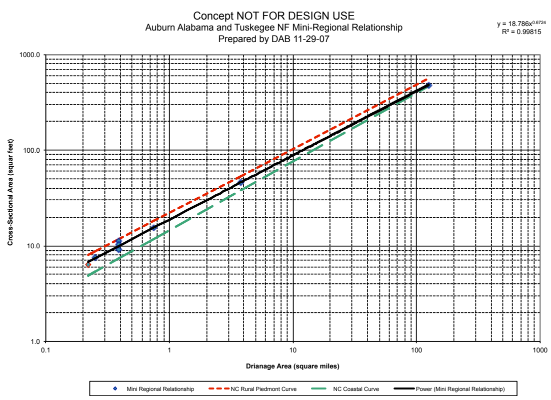
2006 Town Creek Tributary 2007

Engineering Design:

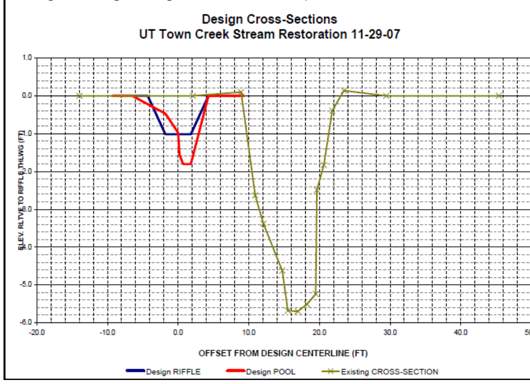
Morphological Table

David Bidelspach, PE, Stantec

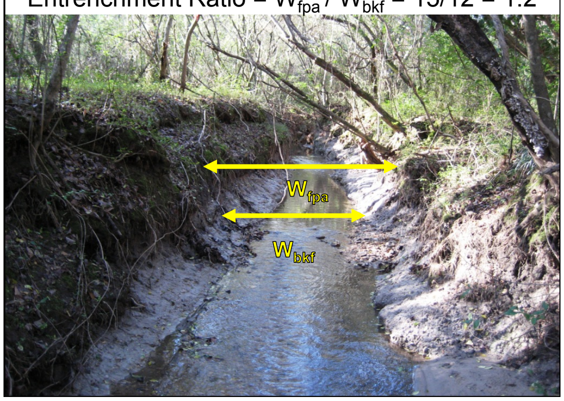
Parameter	Existing Stream			Design Stream			Reference Stream 1			Reference Stream 2		
	Min	Median	Max	Min	Median	Max	Min	Median	Max	Min	Median	Max
Stream name	Privet Creek - Auburn AL.			Privet Creek - Auburn AL.			Eva Crick - Tuskegee AL.			Sals Branch - Raleigh NC		
Stream type	G5c			E4			E5			E4		
Drainage area, DA (sq mi)	0.22			0.22			0.39			0.20		
Mean riffle depth, d_{bkf} (ft)	1.3	1.3	1.5	0.7	0.7	0.7	0.9	1.0	0.9	1.3	1.2	1.3
Riffle width, W_{bkf} (ft)	5.1	5.2	7.5	8.5	8.6	8.8	10.1	10.4	12.3	7.4	8.3	8.5
Width-to-depth ratio, $[W_{bkf}/d_{bkf}]$	4.0	3.9	5.0	12.0	12.0	12.0	11.1	10.5	13.4	5.9	6.8	6.6
Riffle cross-section area, A_{bkf} (sq ft)	6.5	7.0	11.3	6.0	6.2	6.5	9.2	10.3	11.3	9.3	10.2	11.0
Max riffle depth, d_{mbkf} (ft)	1.6	1.7	2.2	1.0	1.1	1.2	1.5	1.6	1.7	1.8	1.9	1.9
Max riffle depth ratio, $[d_{mbkf}/d_{bkf}]$	1.2	1.3	1.5	1.4	1.5	1.6	1.6	1.6	1.9	1.4	1.5	1.5
Mean pool depth, d_{bkfp} (ft)	1.5	1.5	1.5	1.4	1.7	2.1	2.2	2.4	2.6	2.4	2.7	3.5
Mean pool depth ratio, $[d_{bkfp}/d_{bkf}]$	1.2	1.1	1.0	2.0	2.4	2.8	2.4	2.4	2.8	1.9	2.2	2.7
Pool width, W_{bkfp} (ft)	6.5	6.5	6.5	10.6	10.8	11.0	10.5	10.5	10.5	11.0	14.0	15.0
Pool width ratio, $[W_{bkfp}/W_{bkf}]$	1.3	1.3	0.9	1.3	1.3	1.3	1.0	1.0	0.9	1.5	1.7	1.8
Pool cross-section area, A_{bkfp} (sq ft)	9.0	9.0	9.0	7.2	8.7	10.4	12.5	12.5	12.5	11.7	15.9	18.2
Pool area ratio, $[A_{bkfp}/A_{bkf}]$	1.4	1.3	0.8	1.2	1.4	1.6	1.4	1.2	1.1	1.3	1.6	1.7
Max pool depth, d_{mbkfp} (ft)	1.6	1.6	1.6	1.4	1.4	1.5	2.3	2.3	2.3	2.5	2.9	3.0
Max pool depth ratio, $[d_{mbkfp}/d_{bkf}]$	1.3	1.2	1.1	2.0	2.0	2.0	2.5	2.3	2.5	2.0	2.4	2.3
Low bank height, LBH (ft)	2.1	5.7	5.3	1.0	1.1	1.2	1.6	1.6	1.7	2.1	2.1	2.1
Low bank height ratio, $[LBH/d_{mbkf}]$	1.3	3.4	2.4	1.0	1.0	1.0	1.1	1.0	1.0	1.2	1.1	1.1
Width flood-prone area, W_{fpa} (ft)	50	7	12	67.9	103.5	132.5	151	210	220	114	130	148
Entrenchment ratio, ER $[W_{fpa}/W_{bkf}]$	9.7	1.4	1.5	8.0	12.0	15.0	15.0	20.2	17.9	15.4	15.7	17.4
Point bar slope (ft/ft)	0.25	0.50	0.50	0.10	0.12	0.15	0.15	0.15	0.20	0.15	0.18	0.20
Bankfull mean velocity, u_{bkf} = Q/A (ft/s)	3.1	2.9	1.8	3.3	3.2	3.1	3.8	3.4	3.1	3.2	2.9	3.2
Bankfull discharge, Q_{bkf} (cfs)	20	20	20	20	20	20	35	35	35	30	30	35
Meander length, L_m (ft)	105.0	121.0	133.0	59.4	77.6	97.1	28.0	35.0	42.0	47.0	60.0	89.0
Meander length ratio $[L_m/W_{bkf}]$	20.6	23.3	17.7	7.0	9.0	11.0	2.8	3.4	3.4	6.4	7.2	10.5
Radius of curvature, Rc (ft)	30.0	34.0	55.0	17.0	19.8	23.8	16.0	18.0	26.0	12.0	19.0	23.0
Radius of curvature ratio $[Rc/W_{bkf}]$	5.9	6.5	7.3	2.0	2.3	2.7	1.6	1.7	2.1	1.6	2.3	2.7
Belt width, W_{blt} (ft)	35.0	56.0	68.0	25.5	43.1	53.0	19.0	24.0	35.0	25.0	48.0	69.0
Meander width ratio $[W_{blt}/W_{bkf}]$	6.9	10.8	9.1	3.0	5.0	6.0	1.9	2.3	2.8	3.4	5.8	8.1
Pool length, L_p (ft)				17.0	21.6	26.5	15.0	19.0	24.0	12.0	24.0	32.0
Pool length ratio $[L_p/W_{bkf}]$				2.0	2.5	3.0	1.5	1.8	2.0	1.6	2.9	3.8
Pool-to-poo spacing, p-p (ft)				33.9	38.8	44.2	22.0	26.0	28.0	29.0	44.0	57.0
Pool-to-pool spacing ratio, $[p\text{-}p/W_{bkf}]$				4.0	4.5	5.0	2.2	2.5	2.3	3.9	5.3	6.7
Stream length, SL (ft)	1090.0	1090.0	1090.0	1200.0	1200.0	1200.0	205.0	205.0	205.0	245.0	268.0	290.0
Valley length, VL (ft)	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	160.0	160.0	160.0	151.0	183.0	168.0
Valley slope, VS (ft/ft)	0.0130	0.0130	0.0130	0.0130	0.0130	0.0130	0.0104	0.0104	0.0104	0.0110	0.0130	0.0150
Average water surface slope, S (ft/ft)	0.0119	0.0119	0.0119	0.0100	0.0100	0.0100	0.0077	0.0077	0.0077	0.0050	0.0060	0.0060
Sinuosity, k = SL/VL (ft/ft)	1.09	1.09	1.09	1.20	1.20	1.20	1.28	1.28	1.28	1.62	1.46	1.73
Riffle slope, S_{rif} (ft/ft)	0.0150	0.0150	0.0150	0.0150	0.0170	0.0225	0.0090	0.0170	0.0240	0.0080	0.0150	0.0200
Riffle slope ratio, $[S_{rif}/S]$	1.3	1.3	1.3	1.5	1.7	2.3	1.2	2.2	3.1	1.6	2.5	3.3
Run slope, S_{run} (ft/ft)										0.0180	0.0210	0.0250
Run slope ratio, $[S_{rif}/S]$										3.6	3.5	4.2
Pool slope, S_p (ft/ft)	0.0100	0.0100	0.0100	0.0000	0.0000	0.0000	0.0000	0.0005	0.0016	0.0000	0.0005	0.0013
Pool slope ratio, $[S_p/S]$	0.8	0.8	0.8	0.0	0.0	0.0	0.0	0.1	0.2	0.0	0.1	0.2
Glide slope, S_g (ft/ft)										0.0005	0.0012	0.0015
Glide slope ratio, $[S_g/S]$										0.1	0.2	0.3
Riffle length, L_{rif} (ft)	11.0	11.0	11.0	11.0	15.1	17.7	7.0	9.0	14.0	6.0	11.0	23.0
Riffle length ratio, $[L_{rif}/W_{bkf}]$	2.2	2.1	1.5	1.3	1.8	2.0	0.7	0.9	1.1	0.8	1.3	2.7
Bankfull wetted perimeter, WP (ft)	7.6	7.9	10.5	9.9	10.1	10.3	11.9	12.4	14.1	9.9	10.8	11.1
Bankfull hydraulic radius, R (ft)	0.8	0.9	1.1	0.6	0.6	0.6	0.8	0.8	0.8	0.9	0.9	1.0
Bankfull Mannings n (estimate)	0.045	0.045	0.045	0.045	0.045	0.045	0.035	0.035	0.035	0.035	0.035	0.035
Mannings bankfull discharge, Q_{bkf} (cfs)	21.1	23.4	42.9	14.2	14.9	15.8	28.9	34.0	36.4	26.8	32.5	36.1
Bankfull shear stress (lb/sf)	0.63	0.66	0.80	0.38	0.38	0.39	0.37	0.40	0.38	0.29	0.35	0.37
Shields - diameter mobilized (mm)	35	40	60	22	22	22	21	22	22	18	20	21
D_{50} (mm)	1	1	1	2	2	2	2	2	2	4	6	12
D_{84} (mm)	8	32	45	12	12	12	8	8	8	32	34	32



Engineering Design: David Bidelspach, PE, Stantec



Entrenchment Ratio = W_{fpa} / W_{bkf} = 15/12 = 1.2

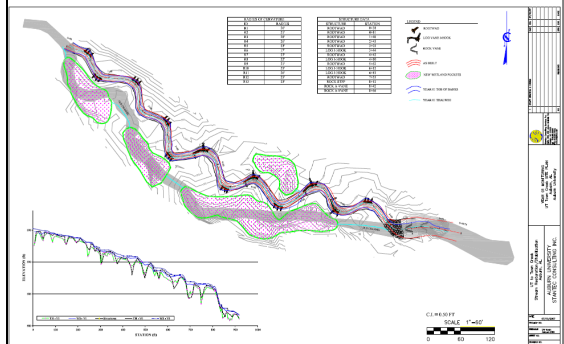


Construction:

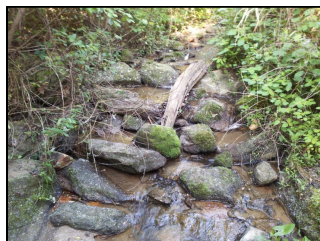
January, 2008

Entrenchment Ratio = W_{fpa} / W_{bkf} = 180/10 = 18

As-Built Survey

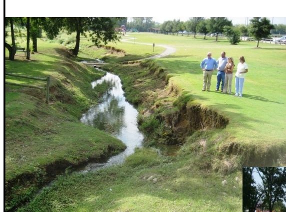


5 years after construction



5 years after construction

Montgomery White Slough (2009)



Project Mgmt: Auburn Univ

Funding: ADEM, EPA 319

Design: GMC, Jennings

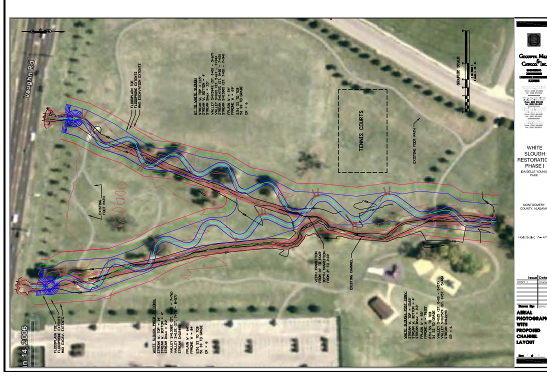
Construction: GMC

Vegetation: GMC, Auburn Univ

2008

2010

Engineering Design: William McLemore, PE, GMC



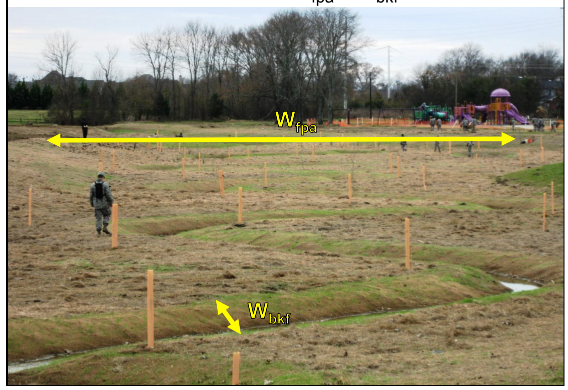
Priority 2: Reconnect Floodplain

Excavate wide floodplain and meander channel at a lower elevation

ER = 6
W/d = 11
K = 1.4
S = 0.003

2008 White Slough 2010

Entrenchment Ratio = W_{fpa} / W_{bkf} = 84/14 = 6



Priority 2: Reconnect Floodplain

Priority 2: Reconnect Floodplain

Vestavia Hills Little Shades Creek (2010)

Project Mgmt: CAWACO RC&D

Funding: ADEM, EPA 319

Design: GMC, Jennings

Construction: North State Environmental

Vegetation: Auburn Univ, NSE

2009

North State ENVIRONMENTAL

2011

Project Specs

1,900 feet stream length

30-60 feet riparian buffer

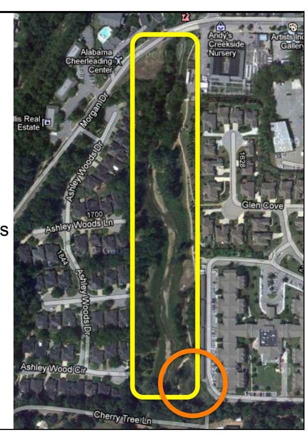
0.5 acre stormwater wetland

10 stormwater outfall channels

Sewer crossing

Greenway trail on East bank

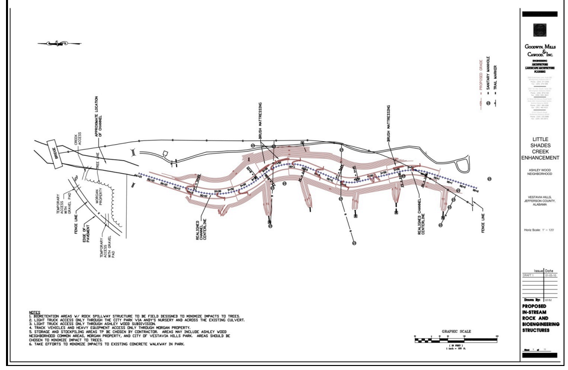
Gravel/cobble – high bedload



Project Components

1. Channel morphology
2. Floodplain structure
3. Hydrologic & hydraulic analysis
4. In-stream structures
5. Habitats & vegetation
6. Site & watershed conditions
7. Monitoring, maintenance, education

Engineering Design: William McLemore, PE



Priority 3: Excavate narrow floodplain benches in confined corridor

ER = 1.6
W/d = 19
K = 1.2
R_c/W = 2-3

Construction: Jan-Mar, 2010

Entrenchment Ratio = W_{fpa} / W_{bkf} = 60/38 = 1.6

Width to depth Ratio = W_{bkf} / d_{bkf} = 38/2 = 19

Entrenchment Ratio = W_{fpa} / W_{bkf} = 60/38 = 1.6

In-Stream Structures (11): Boulder & Log

- Grade Control
- Bank Protection
- Sediment Transport
- Habitat Enhancement

Stormwater Outfall Channels (10)

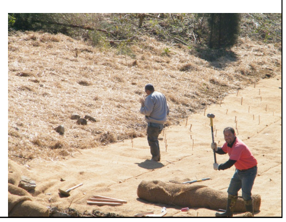
- Vegetated bio-swales (low slope)
- Rock step-pools (high slope)


Construction Practices

- Track equipment
- Spill management plan
- Staged construction phases to limit exposure


Temporary Erosion Control

- Soil prep, seed, straw
- Biodegradable matting (coir, 700g)
- Wood stakes

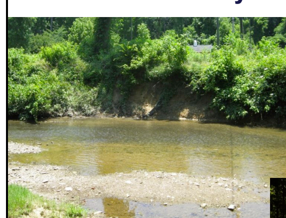
Natural Succession

Partridge Pea, *Chamaecrista fasciculata*

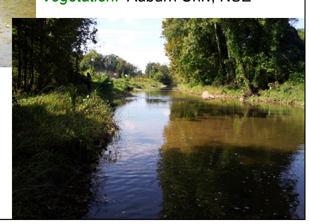
High-stress bank after repair with coir logs

Samford University Shades Creek (2011)

Project Mgmt: Samford Univ
Funding: Samford Univ
Design: LBYD, Jennings
Construction: North State Environmental
Vegetation: Auburn Univ, NSE



2010



2012

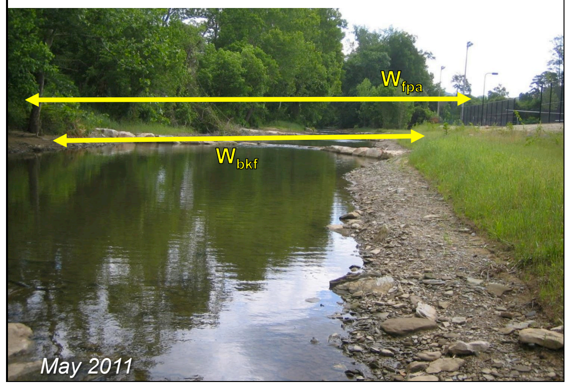
Priority 3: Excavate narrow floodplain benches in confined corridor

ER = 1.4
W/d = 15
K = 1.02
S = 0.005


Construction: Jan, 2011

North State ENVIRONMENTAL

Entrenchment Ratio = W_{fpa} / W_{bkf} = 55/40 = 1.4



Erosion Control: Seed, Straw, Matting, Wood Stakes

In-Stream Structures (10): Boulder & Log

- Grade Control
- Bank Protection
- Sediment Transport
- Habitat


Log Vane (Grade Control J-Hook)

- 70-ft long log; 30-inch diameter; root wad attached
- 3 % arm slope; 20 degree angle
- Sealed with woven geotextile & backer log
- Back filled with river cobble, gravel, sand


Log Vane (Grade Control J-Hook)

Boulder Cross-Vanes

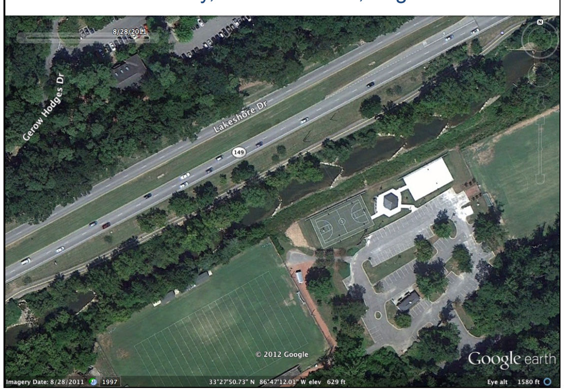
- 1 to 2 ton boulders; 3 % arm slope; 20 degree angle
- Throat extends through center half of channel
- Boulder footers; Sealed with non-woven geotextile
- Back filled with river cobble, gravel, sand

Boulder Cross-Vanes

Shades Creek Flood, March 2011

Samford University, Shades Creek, Feb 2002

Samford University, Shades Creek, Aug 2011



Floodplain Orientation:

- Straight down valley
- Consistent width to avoid contraction
- Setback from outside meander bends

3. Hydrologic & Hydraulic Analysis

Q_{bkf}: Bankfull discharge (cfs) appropriate for watershed size, sediment transport & valley conditions

$V_{av} = Q_{bkf} / A_{bkf}$: Bankfull average velocity (ft/s) appropriate for valley, soils, bed material

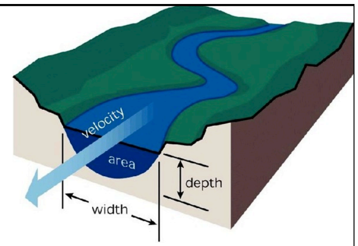
τ_{av}: Bankfull average applied shear stress (lb/ft^2) & local max stresses appropriate for sediment transport conditions & bed/bank resistance

ω_{av}: Bankfull average stream power (lb/ft/s) appropriate for sediment transport conditions

Riffle substrate size distribution appropriate for hydraulic conditions & habitats

Streambank protection to resist erosion (short-term & long-term)

Velocity & Discharge



Q = VA = Discharge (cfs)
V = Average Velocity (ft/s)
A = Cross-Section Area (ft^2)
V related to slope, channel shape, and channel roughness

Stream Corridor Restoration: Principles, Processes, and Practices. 1998. Federal Interagency Stream Restoration Working Group.

Manning Equation for Average Velocity

$$V = \frac{k}{n} R_h^{\frac{2}{3}} \cdot S^{\frac{1}{2}}$$

where:

- V is the cross-sectional average velocity (ft/s, m/s)
- k is a conversion constant equal to 1.486 for U.S. customary units or 1.0 for SI units
- n is the Gauckler-Manning coefficient (independent of units)
- R_h is the hydraulic radius (ft, m)
- S is the slope of the water surface or the linear hydraulic head loss (ft/ft, m/m) ($S = h_f / L$)

$$R_h = \frac{A}{P}$$

where:

- R_h is the hydraulic radius (m)
- A is the cross sectional area of flow (m^2)
- P is wetted perimeter (m)

Manning's n for Channels (Chow, 1959).

Type of Channel and Description	Minimum	Normal	Maximum
Natural streams - minor streams (top width at floodstage < 100 ft)			
1. Main Channels			
a. clean, straight, full stage, no rifts or deep pools	0.025	0.030	0.033
b. same as above, but more stones and weeds	0.030	0.035	0.040
c. clean, winding, some pools and shoals	0.033	0.040	0.045
d. same as above, but some weeds and stones	0.035	0.045	0.050
e. same as above, lower stages, more ineffective slopes and sections	0.040	0.048	0.055
f. same as "d" with more stones	0.045	0.050	0.060
g. sluggish reaches, weedy, deep pools	0.050	0.070	0.080
h. very weedy reaches, deep pools, or floodways with heavy stand of timber and underbrush	0.075	0.100	0.150
2. Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stages			
a. bottom: gravels, cobbles, and few boulders	0.030	0.040	0.050
b. bottom: cobbles with large boulders	0.040	0.050	0.070

"Open-Channel Hydraulics, originally published in 1959, has been described as one of the best textbooks ever written. It's clear descriptions of timeless fundamental principles make Chow a classic. Anyone wanting to learn, to teach, and to work with water and fluids must own a copy."

Shear Stress: *fluid force per unit area acting on the channel bed*

$\tau_{av} = \gamma R S$ = Average Shear Stress (lb/ft^2)
γ = Unit Weight of Water = 62.4 lb/ft^3
R = Hydraulic Radius (ft) = A_{bkf} / P
S = Average Water Surface Slope (ft/ft)
A_{bkf} = Riffle Cross-Section Area (ft^2)
P = Wetted Perimeter (ft) = $W_{bkf} + 2 * d_{bkf}$ (approx)

Unit Stream Power: *rate of energy loss to the channel bed per unit area*

$\omega_{av} = V \tau_{av}$ = Average Unit Stream Power (lb/ft/s)

V = Average Velocity (ft/s)

Bankfull Conditions: Clinton Creek

A = 15 ft^2	R = 1.1 ft	S = 0.0117 ft/ft
n = 0.040	V = 4.2 ft/s	Q = 63 cfs
τ = 0.77 lb/ft^2	ω = 3.2 lb/ft/s	

Competence = 60-200 mm

Stream Competence *(www.epa.gov/WARSSS)*

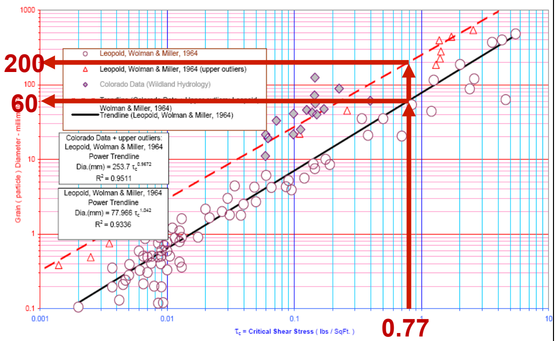


Figure 126. Critical Shear Stress (tc: Range .001 to 10) Required to Initiate Movement of Grains (particles), revised for Colorado Rivers.