Long-term Study of the Effectiveness of In-stream Structures near Bridges for Streambank Stability

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Background

- 82% of bridges in the U.S. transverse streams (Lagasse et al. 1995)
- Bank scour is the leading cause of bridge failure
  - 53% of bridge failures (Wardhana and Hadipriono 2003)
- $1 billion dollars annually spent on streambank stabilization and restoration (Bernhardt et al. 2005)
  - 50% of projects are unsuccessful (O’Niel and Fitch 1992)

Thornburgh 2013

Webster 2002

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In-stream structures can stabilize banks and decrease erosion

Kellner Jetties

- Work by slowing flow of water and allowing sediment to settle out
- Use peaked in 1950s and 1960s
- Up to $\frac{2}{3}$ reduction in stream velocity (Army Corps of Engineers 1963)
- Work best in wide, shallow rivers with high sediment content

(ODOT 1950)

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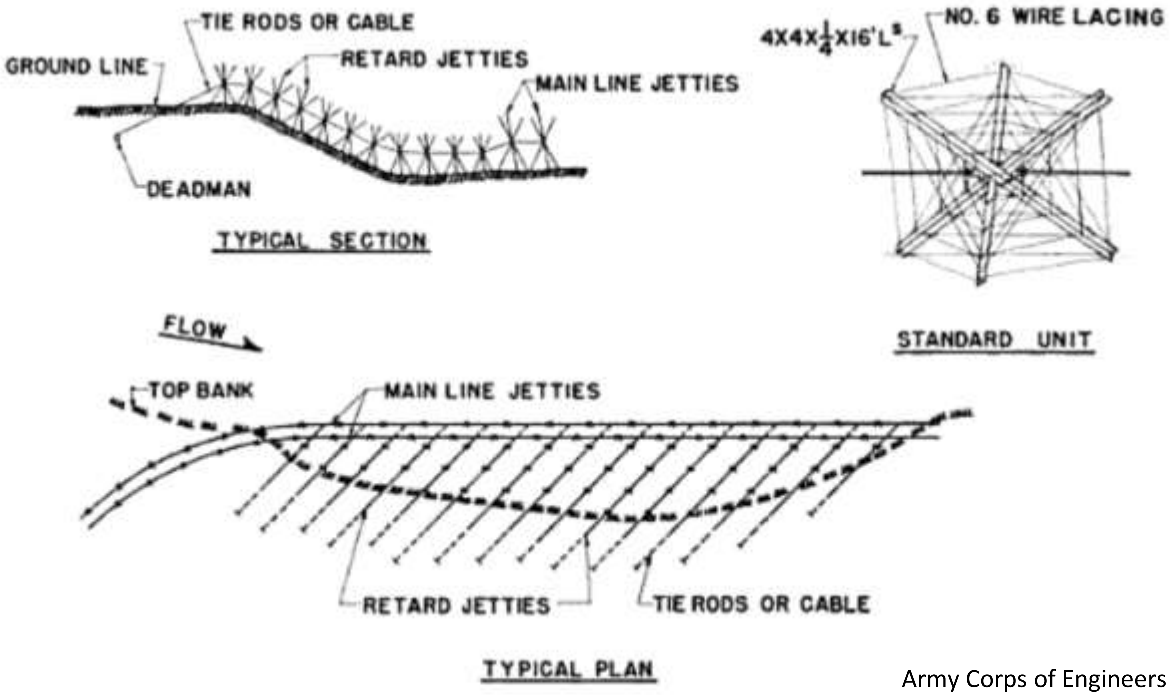
Kellner Jetties Design

- Steel jacks tied together with cables
- Lifetime of 50 years (Army Corps of Engineers 1963)

Parameter	Criteria
Number of Diversion (Main) Lines	2
Angle of Retard Lines to Diversion Lines	45-70^{o}
Spacing between Retard Lines	125-250ft



Army Corps of Engineers 1963

Pile Diversions

- Work by diverting flow
  - Create sandbars between them
- Easily worn by the elements
- Not often used anymore since technology has advanced

Harp and Thomas 1989

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Rip Rap

- Common revetment that covers bank
- Results vary (Lindsey et al. 1982)
- Often installed in conjunction with other structures
- Empirical relationships optimize the stone size (Keown et al. 1977)
- Layer thickness > maximum stone diameter (Keown et al. 1977)

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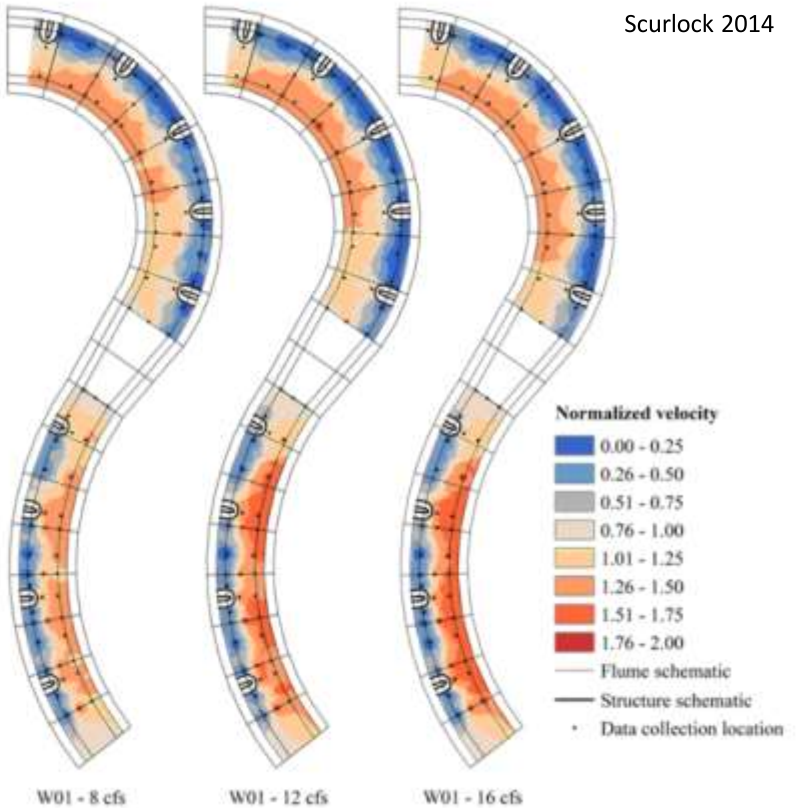
Bendway Weirs

- Rip-rapped structures
- Work by diverting flow
  - Create sandbars between them
- Centerline and inner bank velocity significantly increase with installation
  - Velocity between weirs 40% of maximum velocity prior to installation (Scurlock 2014)

Thornton et al. 2007

Scurlock 2014



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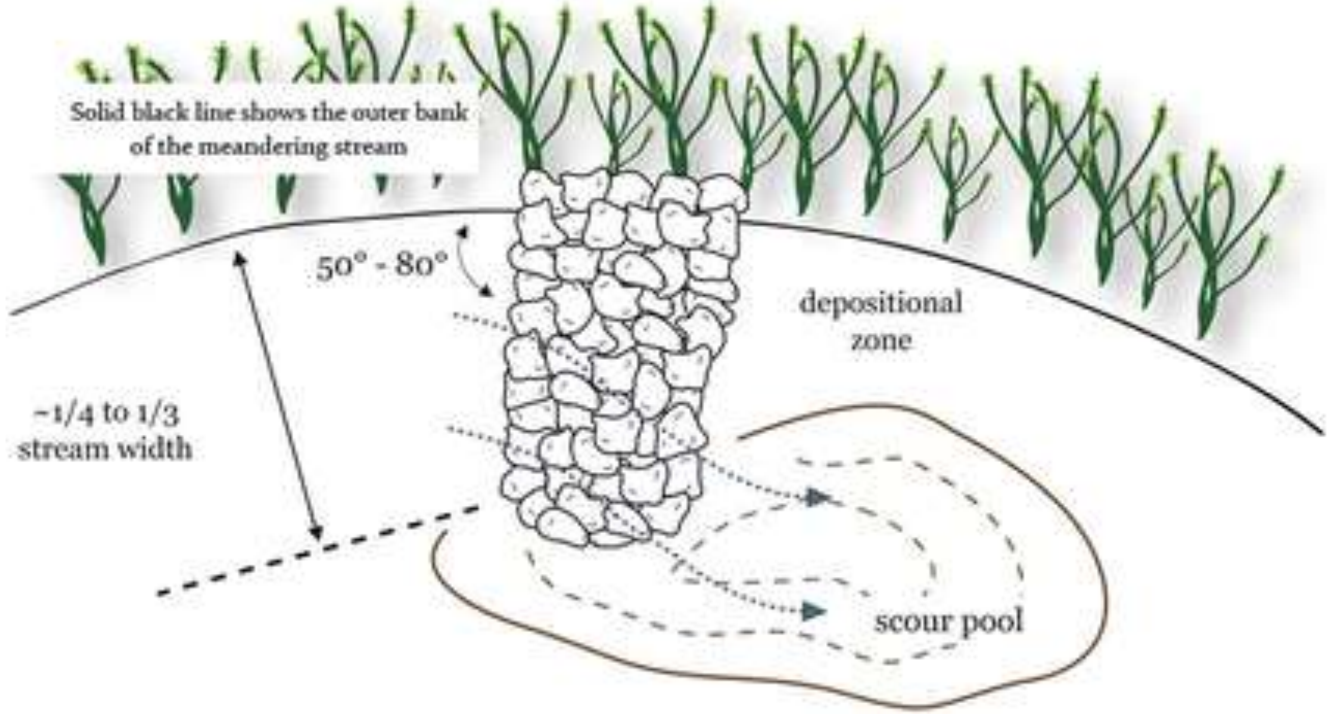
Bendway Weirs Design

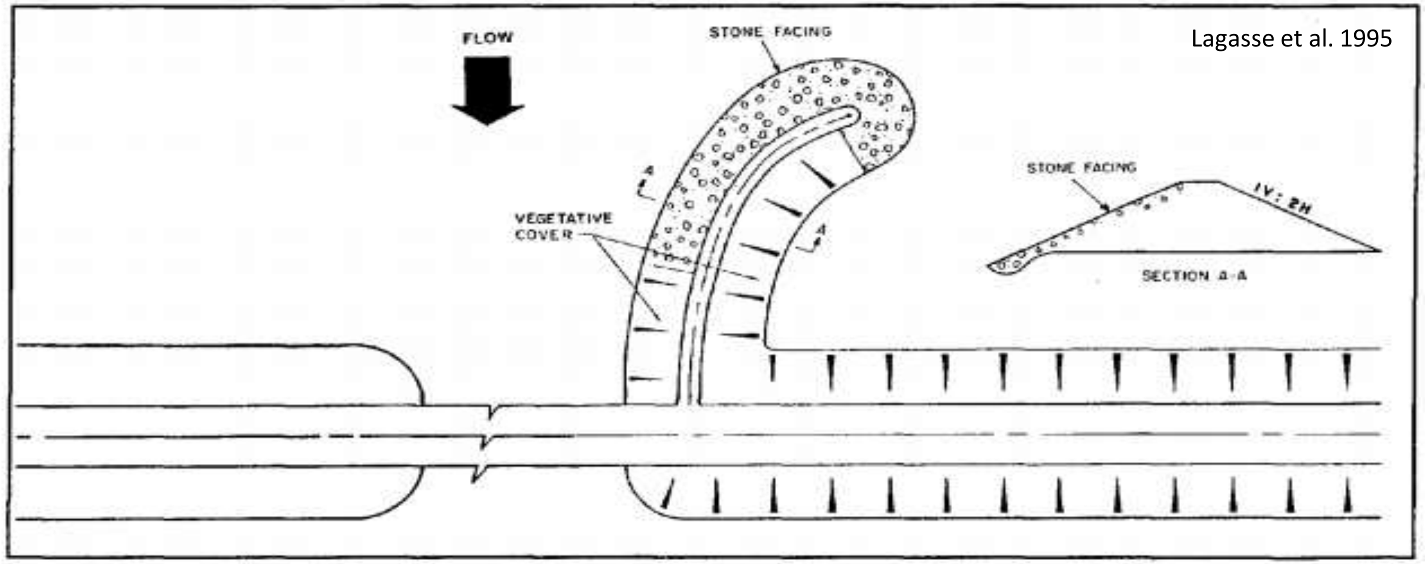
- Length is $\frac{1}{4}$ to $\frac{1}{3}$ of stream width
- 50º-80º angle with bank
- Multiple in series, spaced to optimize stagnant flow (Scurlock 2014)



Khosronejad et al. 2017

Spur Dikes

- Rip-rapped structures
- Located immediately upstream of bridge abutment
  - Guide stream under bridge
- Designed so water at high flow does not top them (Karaki 1960)



Lagasse et al. 1995

Other Structures

Gabion Baskets

- Revetment, covers bank
- Rocks in wire cages
- Not recommended for sandy banks (Freeman and Fischenich 2000)

Rock Drop

- Artificial riffle-pool pattern
- Regulates slope to decrease bank erosion and stream incision

Previous Studies (1971 and 1989)

- Evaluated over 20 sites with in-stream structures
  - Rip-rap
  - Kellner jetties
  - Spur dikes
  - Pile diversions
- Qualitative evaluation
  - Photos
  - Narrative descriptions
  - Detailed sketches

BANK PROTECTION

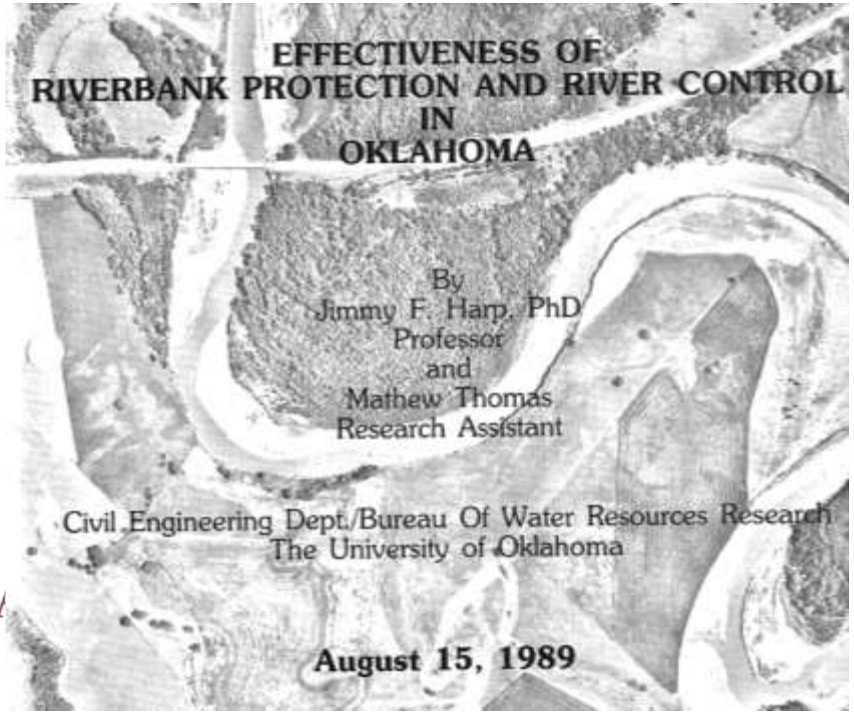
and

RIVER CONTROL

in

Federal Highway Administration
Oklahoma Division

1971


EFFECTIVENESS OF
RIVERBANK PROTECTION AND RIVER CONTROL
IN
OKLAHOMA

By
Jimmy F. Harp, PhD
Professor
and
Mathew Thomas
Research Assistant

Civil Engineering Dept./Bureau Of Water Resources Research
The University of Oklahoma

August 15, 1989

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Objectives

- Continue a long-term study of in-stream structures
- Gather quantitative data to evaluate the structures
- Determine factors that impact the success of different in-stream structures
- Establish a standard methodology

Methods

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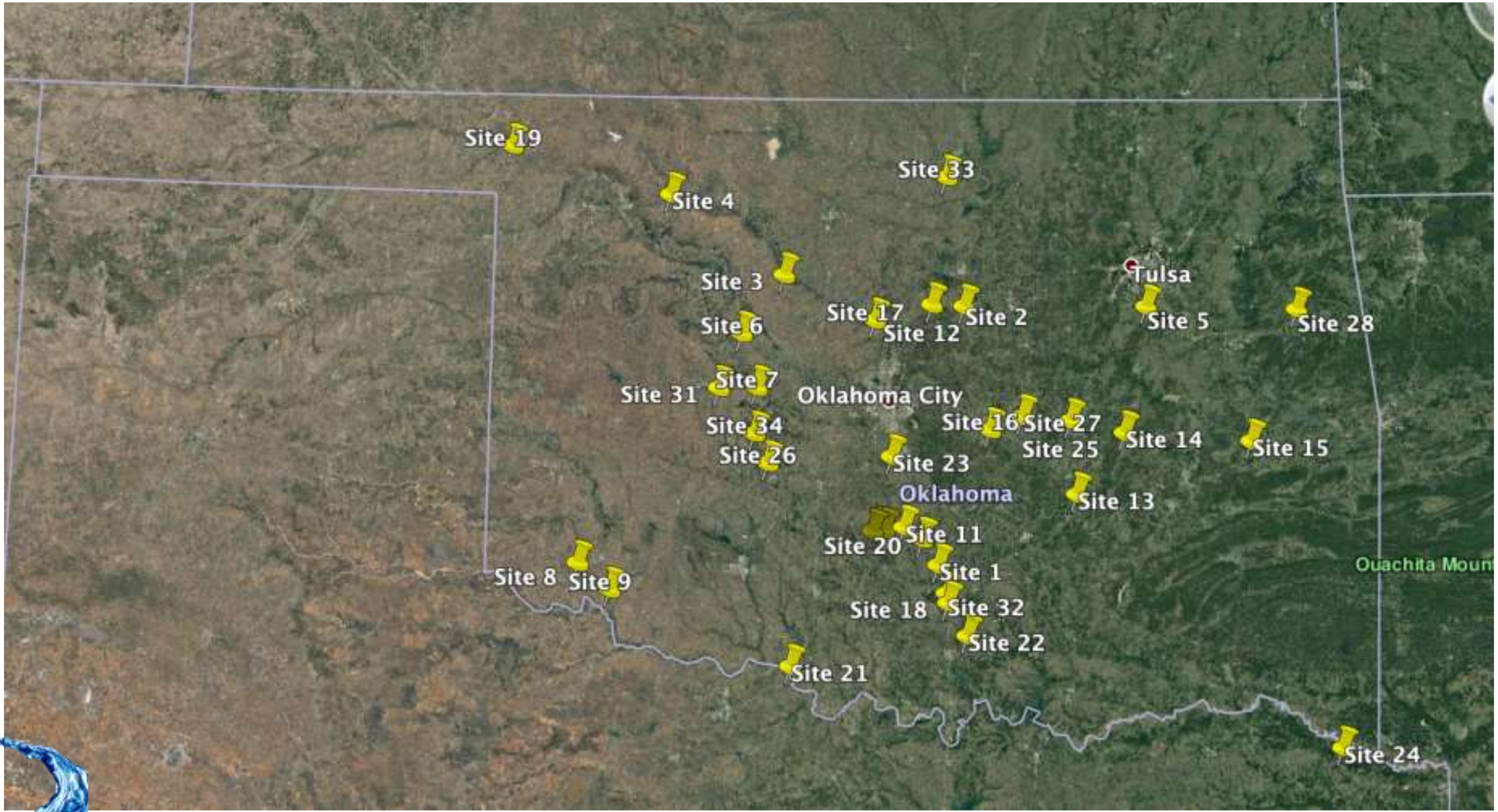
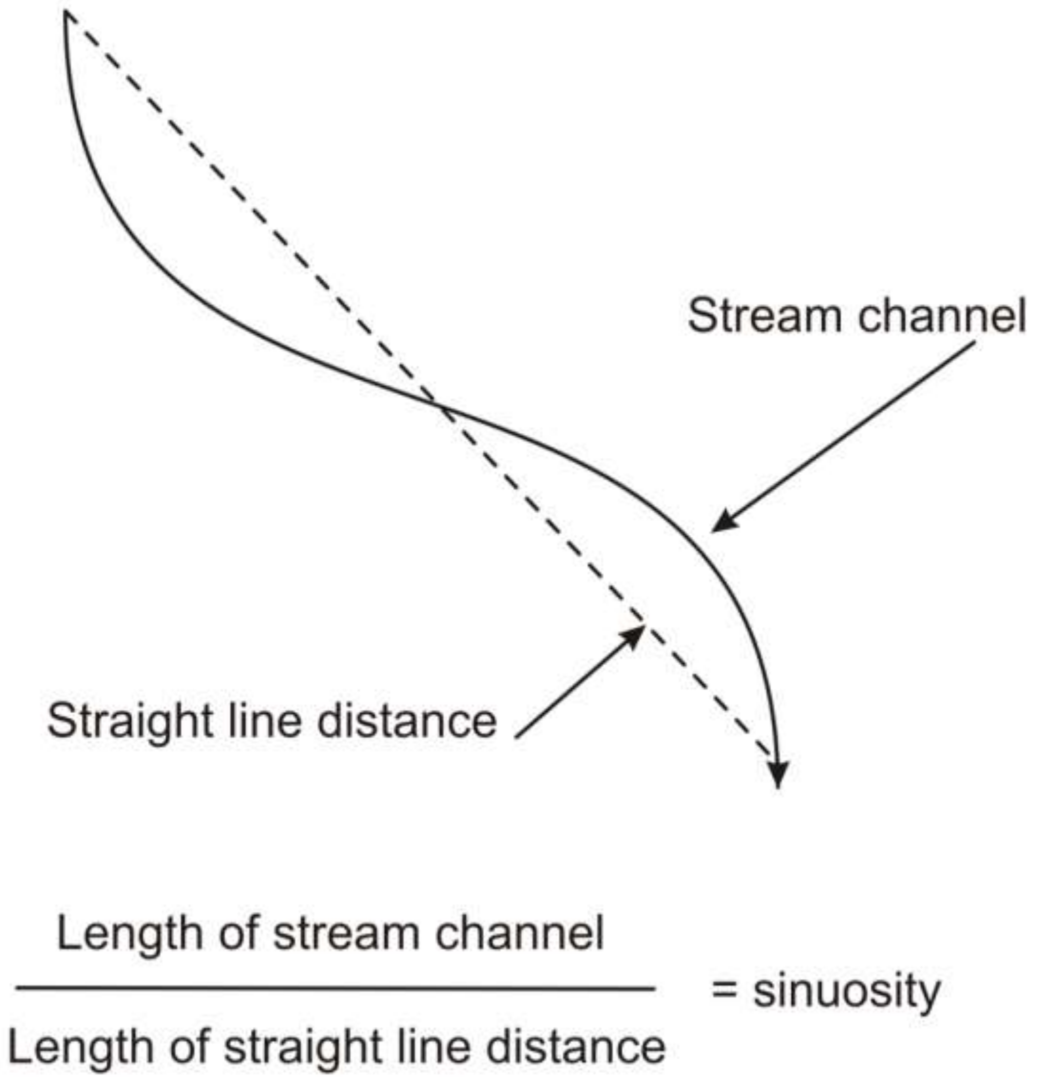
Site Locations



Remote Data Collection

- Average streamflow
  - USGS StreamStats (2020)
- Sinuosity
  - Aerial images (GoogleEarth 2020)
- Watershed land use – National Land Cover Database (2016)
  - Percent watershed developed



Channel Sinuosity 2014

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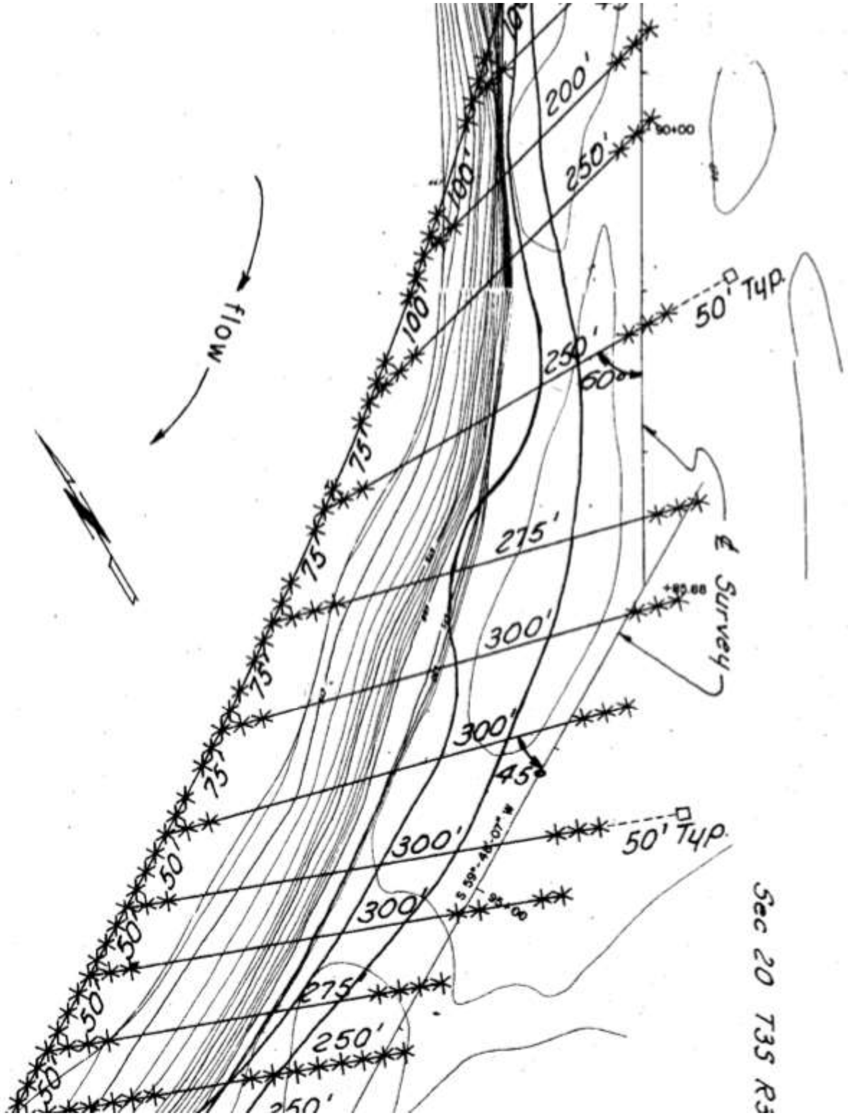
Remote Data Collection

- Kellner jetty angles
  - Average angle between thalweg and Kellner jetty retard lines
  - Plans
  - Old reports
  - Aerial images
  - Oldest available angle
- Depth to Bedrock
  - Arithmetic mean
  - Minimum
  - Coefficient of variation



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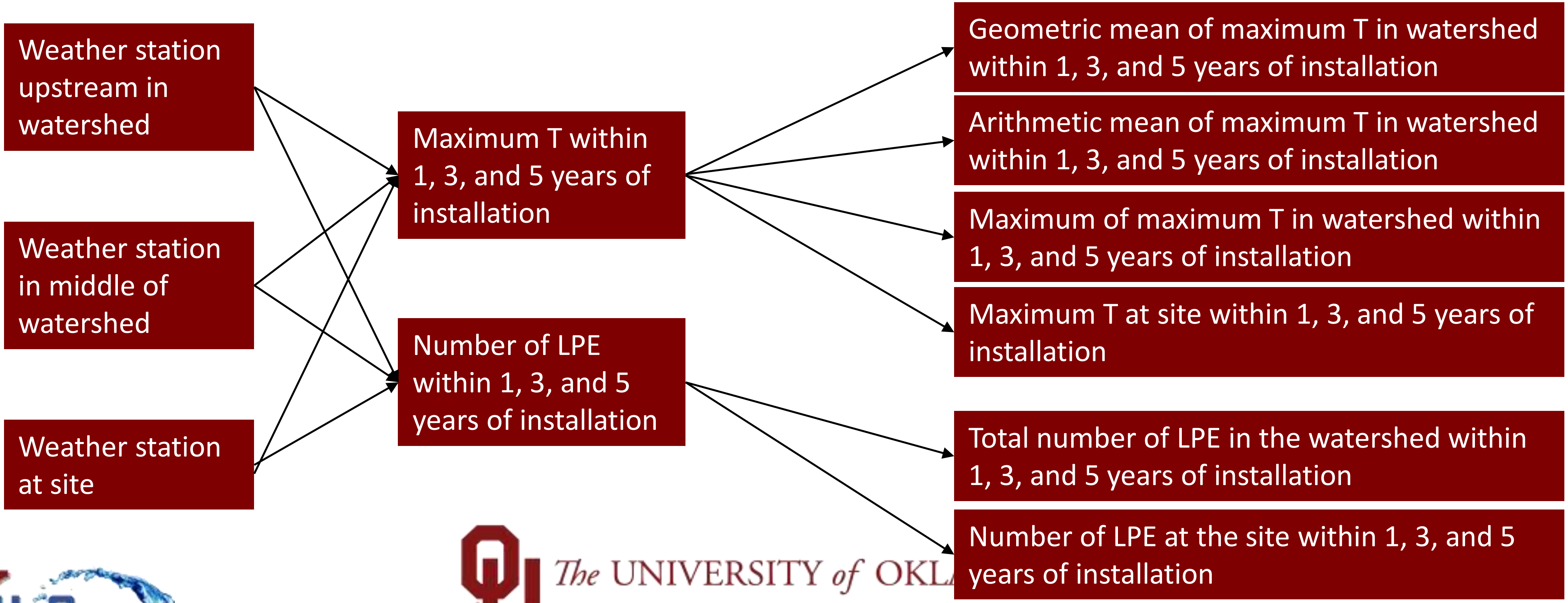
Remote Data Collection

- Historical precipitation data
  - Collected from National Oceanic and Atmospheric Administration (NOAA) climate data online
  - LPE = large precipitation event, >0.5in within 24 hours; T = return period



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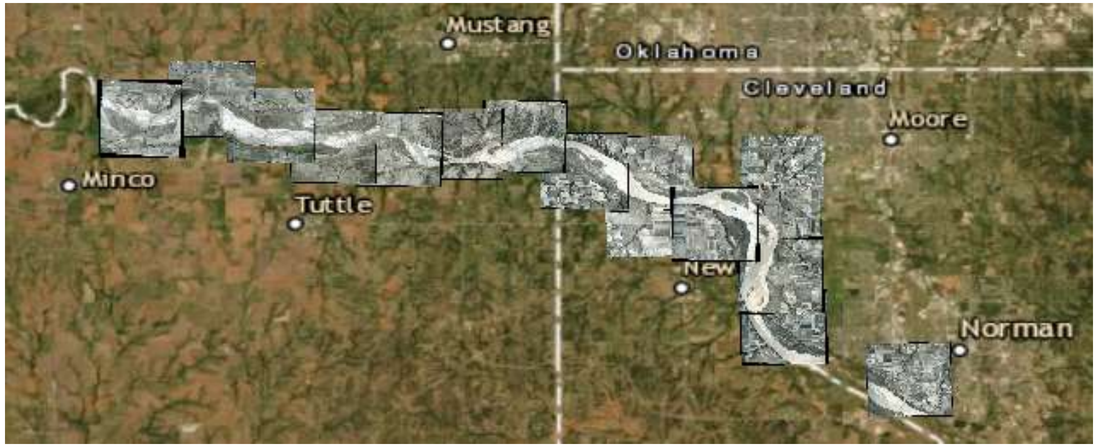
Remote Data Collection

- Historical aerial images
  - Collected from different years from the Oklahoma Aerial Photo Inventory (2019)
  - Georeferenced to at least 3 points on a current map

- Thalweg movement
  - At bridge crossing
  - From time of installation to 2020
  - Historical images and bridge plans compared to 2020 field surveys



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Field Data Collection

- Longitudinal profile
- Cross sections
- Velocity profiles
- Near-bank stress
- Bank erosion hazard index
- Sediment samples and particle size distribution
- Photos

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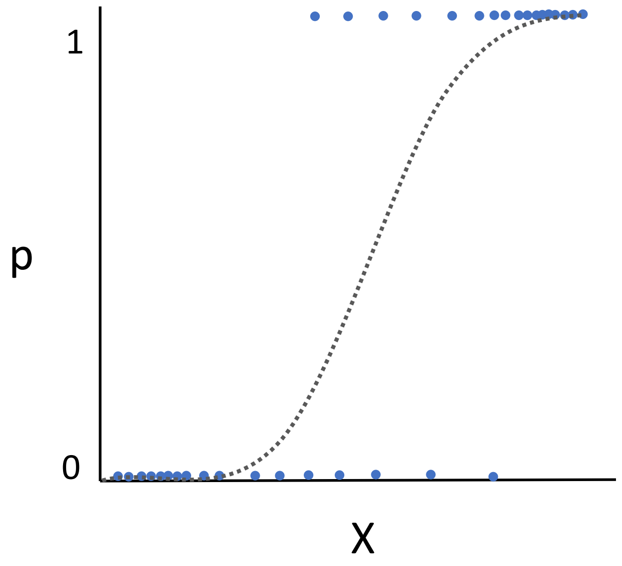
Statistical Analysis

- Correlation matrix
- Linear regressions
- Logistic regressions
  - Suited for binary dependent variables
  - Logit = log odds of proportion of positive outcomes
  - Coefficients used to calculate logit



$$logit(p) = log_e(\frac{p}{1-p})$$

$$logit(p) = a + C_1x_1 + C_2x_2 \ldots + C_nx_n$$

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Analysis

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Bendway Weirs

- 4 sites
- 17-21 years old, 19 years old on average
- 100% successful
- Largest precip return period in watershed = 24 years

	% clay	% sand	% silt	% gravel	d_{10} (mm)	d_{40} (mm)	C_u	C_c
Average	4.0	82	13	1.4	0.02	0.12	4.6	1.6
Minimum	1.4	79	5.8	0.01	0.04	0.09	3.9	0.7
Maximum	4.9	86	16	6.8	0.07	0.19	5.9	2.1

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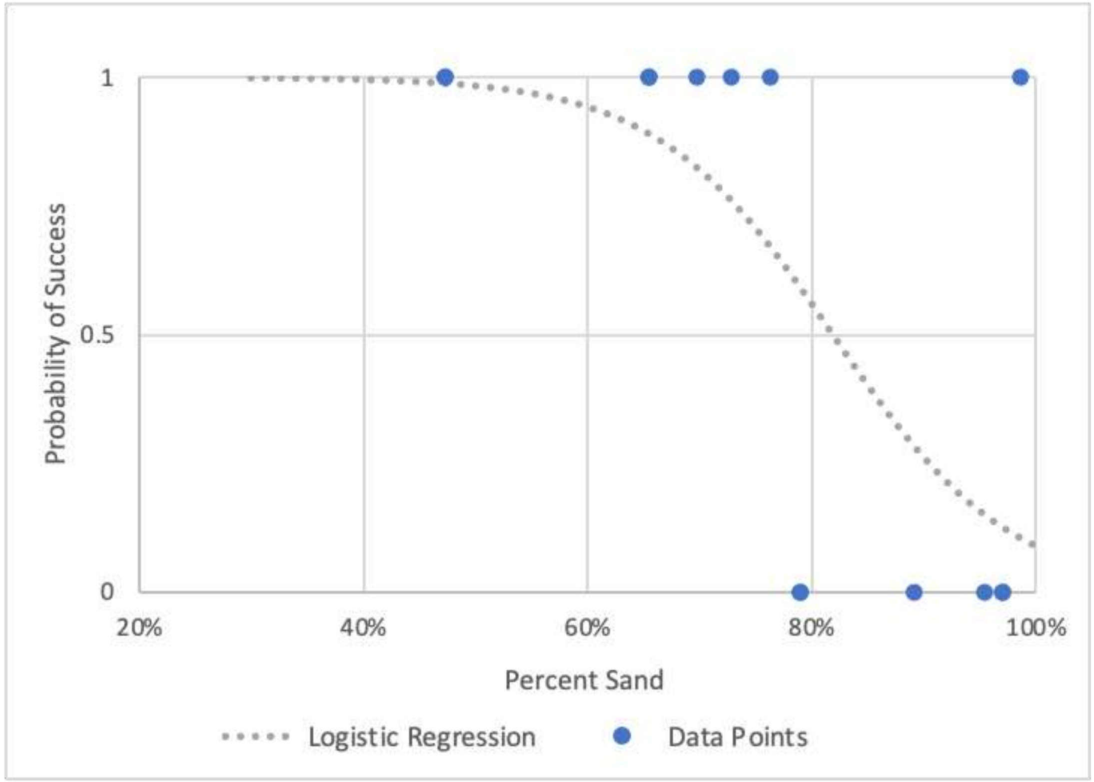
Pile Diversions

- 10 sites, 14 installations
- 52-71 years old, 63 years old on average
- Most were badly damaged
- Deemed failure if stream eroded behind pile diversions
- 57% successful (8/14 successful)
- Percent sand and precipitation within first three years correlated to their success



Harp and Thomas 1989

	Coefficient	p Value
Intercept	10.5	0.049
Percent Sand (as a fraction)	-12.8	0.049

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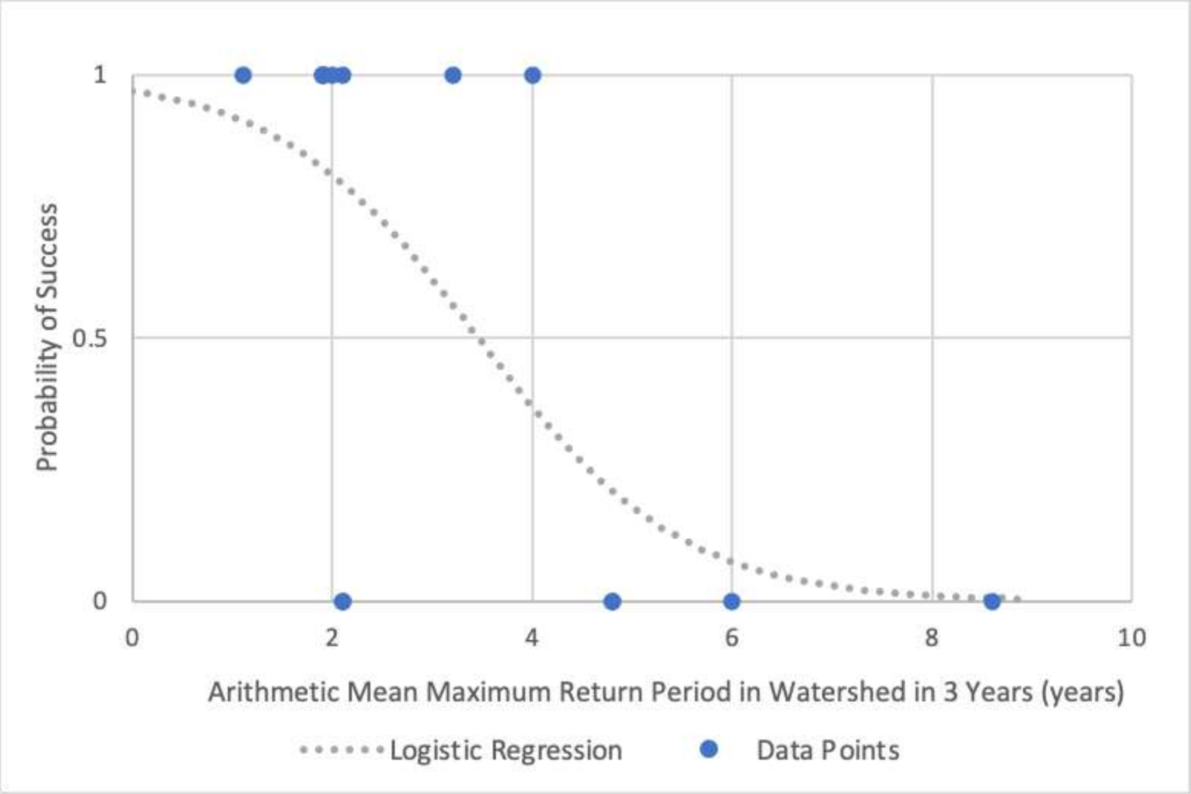
Pile Diversions

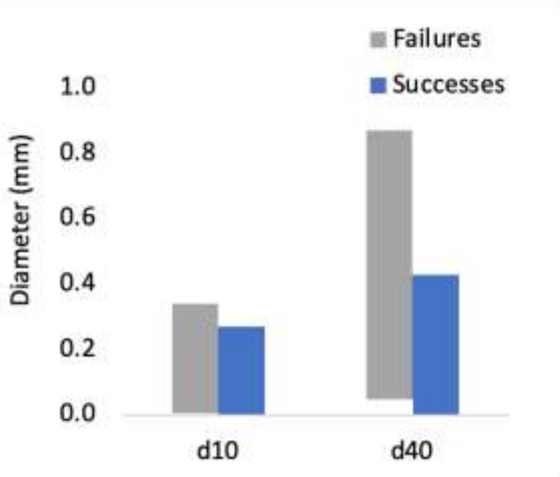
	Coefficient	p Value
Intercept	3.42	0.047
Arithmetic Mean Maximum Return Period in the Watershed within Three Years of Installation (years)	-0.99	0.065

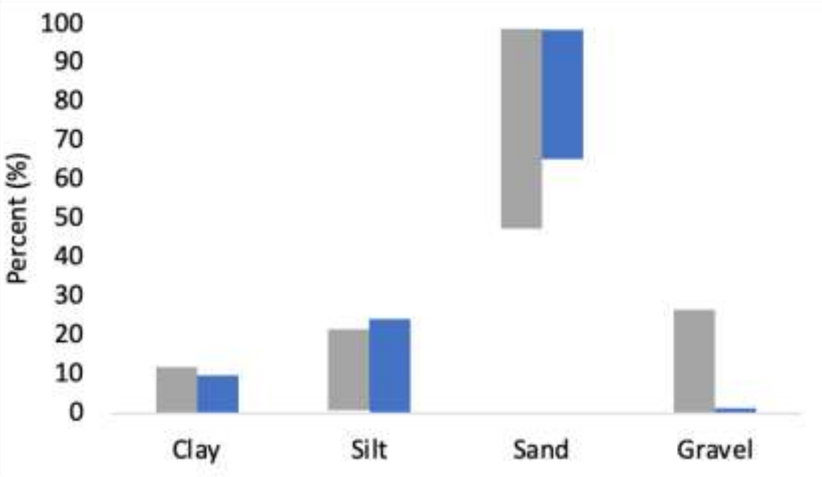
- Precipitation events cause damage to pile diversions
- Storms within 3 years of installation lead to failure
- Maximum mean return period = 8.6 years



Rip Rap

- 12 sites, 13 installations
- 32-70 years old, 54 years old on average
- Deemed failure if washed away
- 46% successful (6/13 successful)
- No significant regressions





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Spur Dikes

- 7 sites, 8 installations
- 49-64 years old, 62 years old on average
- Deemed failure if stream cut behind it
- One failure
  - Old bridge abutment rip rapped to be used as a spur dike
- Largest return period in watershed = 68 years

	% clay	% sand	% silt	% gravel	d_{10} (mm)	d_{40} (mm)	C_u	C_c
Average	6.6	70	16	8.1	0.06	0.19	85	4.0
Minimum	0.0	47	0.6	0.4	0.001	0.04	4.5	0.7
Maximum	12	86	24	27	0.34	0.87	461	15

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Kellner Jetties

- 22 sites, 28 installations
- 17-94 years old, 61 years old on average
- Deemed failure if stream eroded through jetty field
- 79% successful (22/28 successful)
- Site 21 had largest thalweg movement
  - Kellner jetties washed away
  - Bridge washout

Site	Oldest KJ Angle (degrees)	Thalweg Movement (ft)
5	30	-440
6	30	-30
8	30	-150
11	40	-30
17	45	-320
21	60	2950

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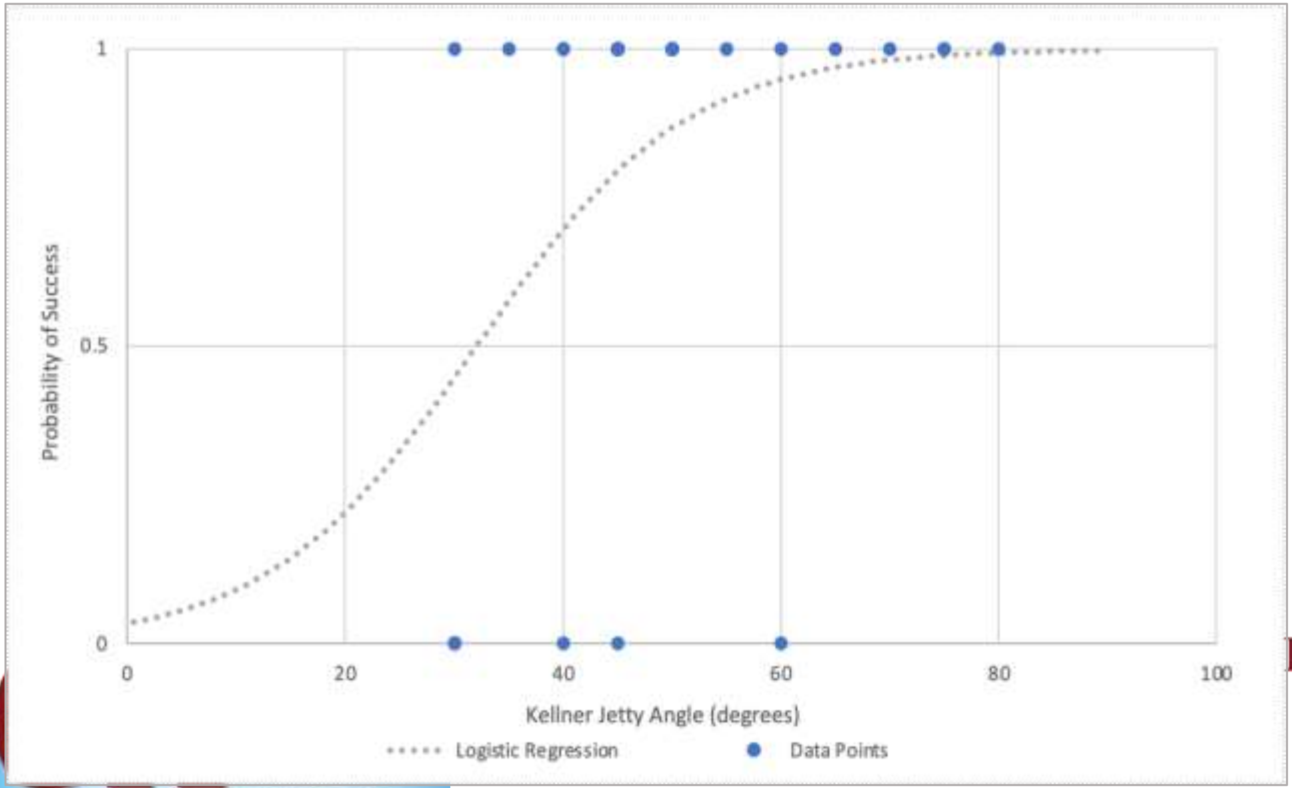
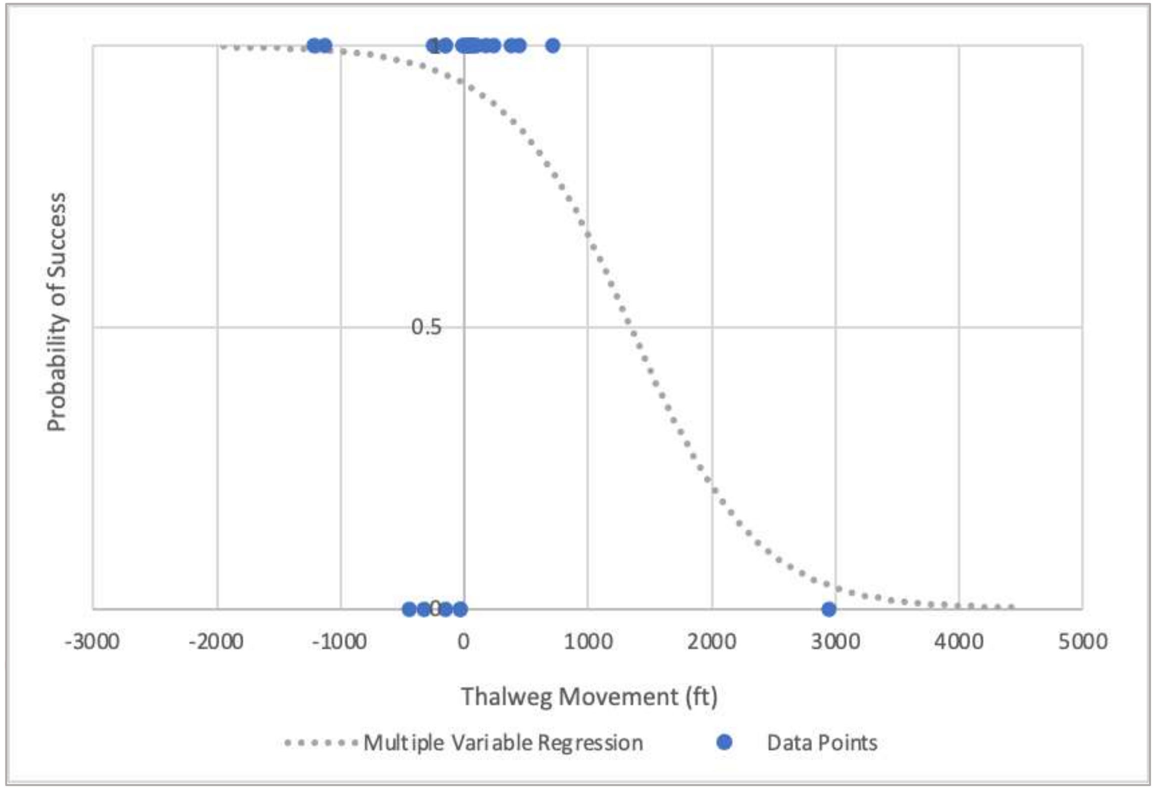
Kellner Jetties with Site 21

	Coefficient	p Value
Intercept	-3.35	0.17
Oldest Kellner Jetty Angle (degrees)	0.104	0.068

	Coefficient	p Value
Intercept	-3.33	0.062
Oldest Kellner Jetty Angle (degrees)	0.101	0.057
Thalweg Movement	-0.0013	0.035



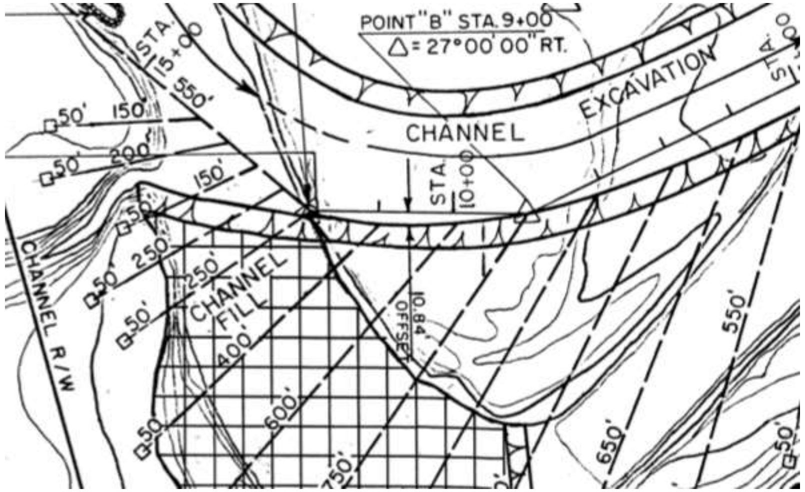


Kellner Jetties without Site 21

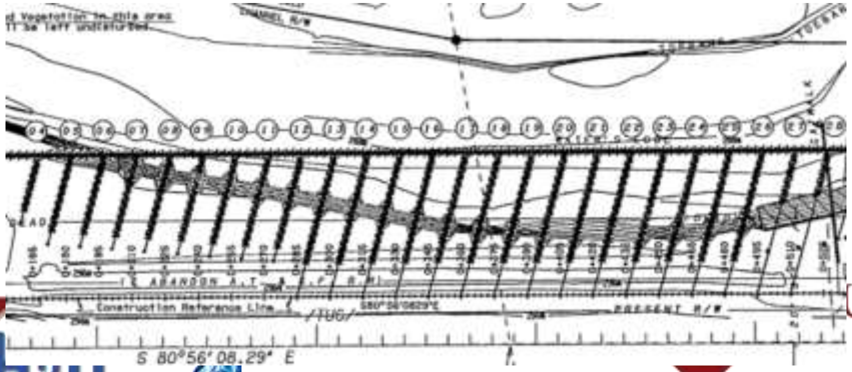
- Higher angle between Kellner jetties and thalweg, more likely to succeed

	Coefficient	p Value
Intercept	-7.18	0.045
Oldest Kellner Jetty Angle (degrees)	0.213	0.020
Thalweg Movement	0.00145	0.41

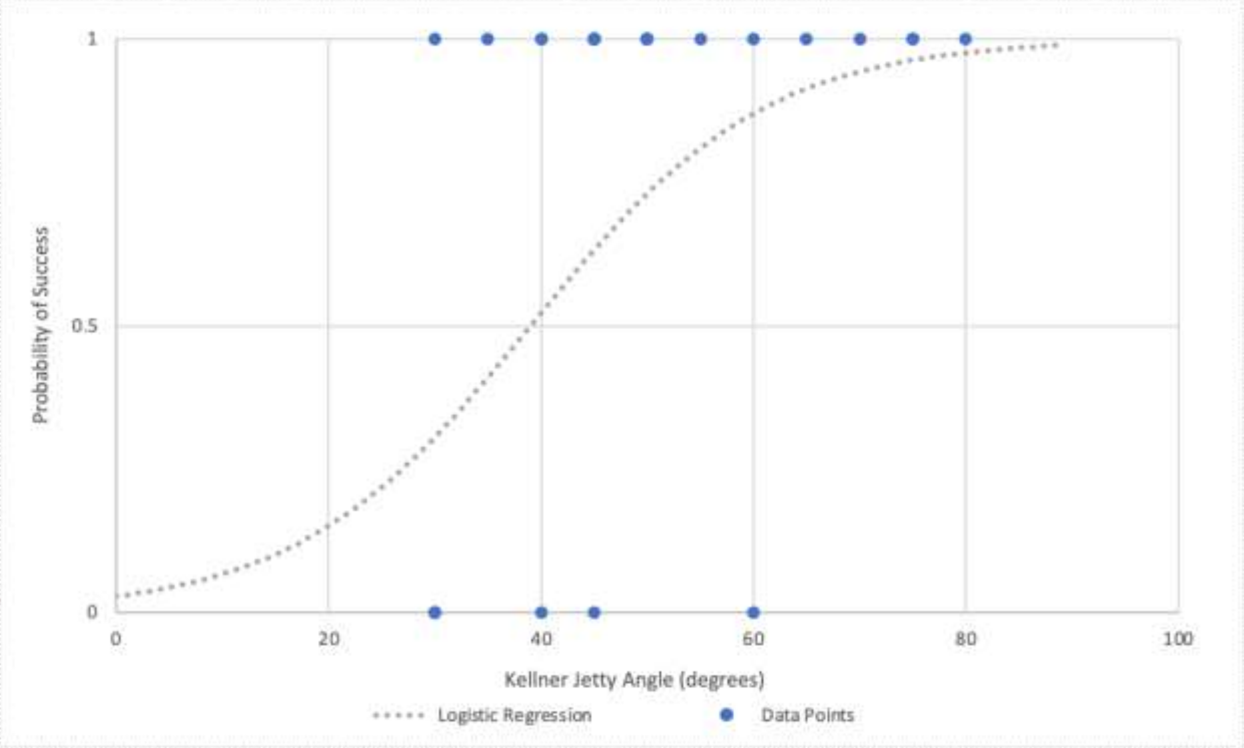
	Coefficient	p Value
Intercept	-3.54	0.044
Oldest Kellner Jetty Angle (degrees)	0.091	0.022



40° 1988



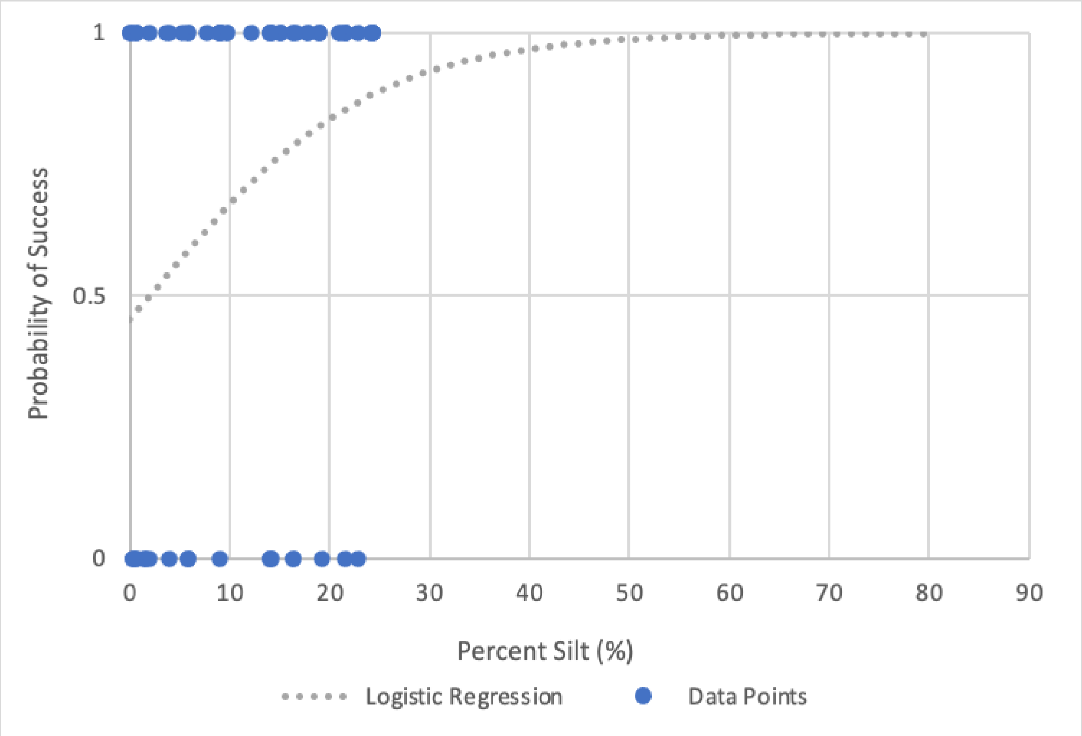
75° 1999



All Structures

- 30 sites, 79 structures
- 68% success rate (54/79 successful)
- Percent silt in bank material was only significant variable
- Higher silt, higher probability of success
  - Carried in streams, settles out in structures
  - Higher organic content
  - Supported by literature (Army Corps of Engineers 1963; Abad et al. 2008; Scurlock 2014)

Variable	Coefficient	p Value
Intercept	-0.183	0.66
Percent Silt (as a fraction)	9.05	0.007



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Variables Not Significantly Correlated with Success and Failure

- Depth to bedrock
- Precipitation at site
- Sinuosity
- Watershed land use
- Stream slope
- Bank erosion hazard index
- Near-bank stress

Long-Term Evaluation

- Compared success of structures in 1971, 1989, and 2021
- Of structures that failed, 73% failed within 20 years of installation
  - 97% were within 50 years
- Potential causes of long-term success:
  - Sediment fills in
  - Vegetation develops

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Acknowledgements

- Graduate Student Lead: Adella Kuster
- Co-PIs: Grant Graves, Keith Strevett and Jeff Volz
- Funding: Oklahoma Department of Transportation
- ODOT Partner: Leslie Lewis
- Assistance: Oklahoma Water Survey undergraduates and staff

Thank you

Questions?

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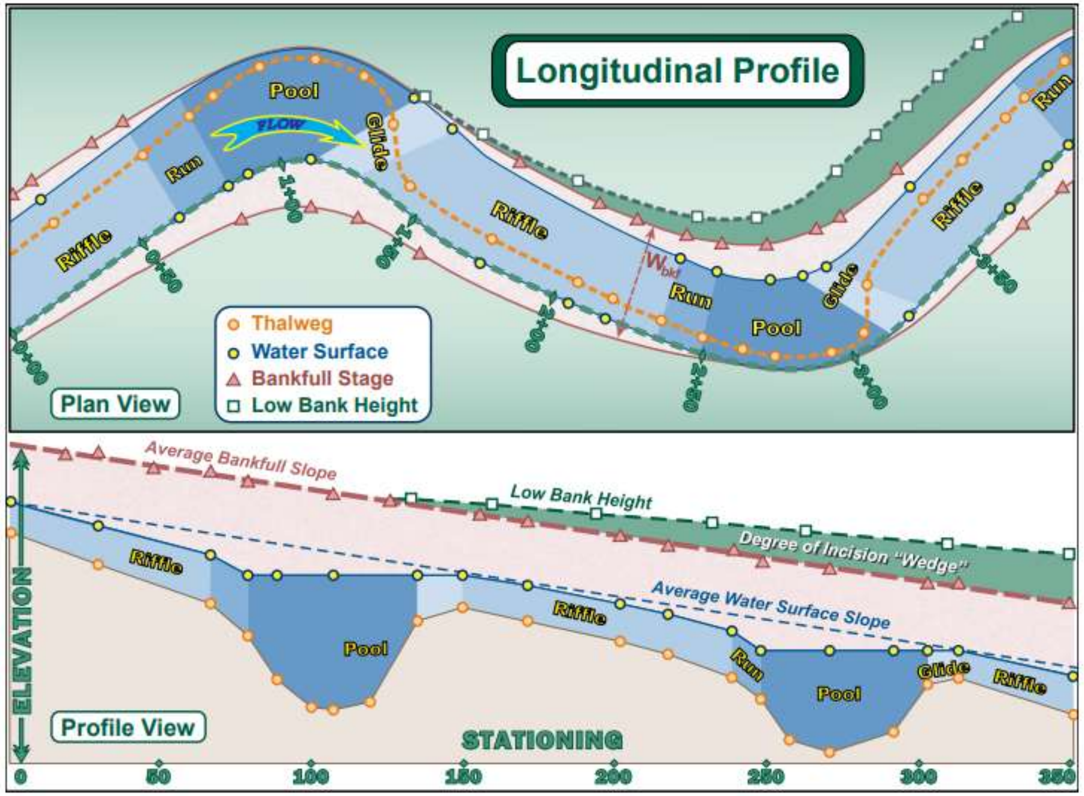
Other Structures

- Gabion baskets successful at less sandy site
  - Sunk into sand
  - Common problem with gabion baskets (Freeman and Fischenich 2000)
- Rock drop structures were both successful

Geomorphology

- Quantifies river channel morphological patterns
- Includes many variables
  - Land use
  - Hydrologic data
  - Stream slope
  - Sinuosity
  - Bank slope
  - Riffle-pool spacing
- Impacts streambank stability and effectiveness of in-stream structures (Smith and Patrick 1979; Keefer et al. 1990)



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Field Data Collection

- Longitudinal profile
  - Survey along thalweg using Topcon ES Total Station
  - Upstream of structures to bridge crossing
  - Data points taken every 20-40 feet
  - Water depths collected at each point
  - Riffle-pool patterns
  - Stream slope
  - Lateral location of thalweg

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Field Data Collection

- Cross sections
  - Surveyed perpendicular to stream using Topcon ES Total Station
  - Taken at structures, at local riffle, and at bridge
  - Data points every 5-10 feet
  - Water depths taken at every point

- Velocity profiles
  - Taken at each cross section using a Sontek S5 acoustic Doppler current profiler (ADCP)
  - Near-bank stress rating based on velocity gradient

Rating	Very Low	Low	Moderate	High	Very High	Extreme
Velocity Gradient (ft/sec/ft)	<0.50	0.50-1.00	1.01-1.60	1.61-2.00	2.01-2.40	>2.40

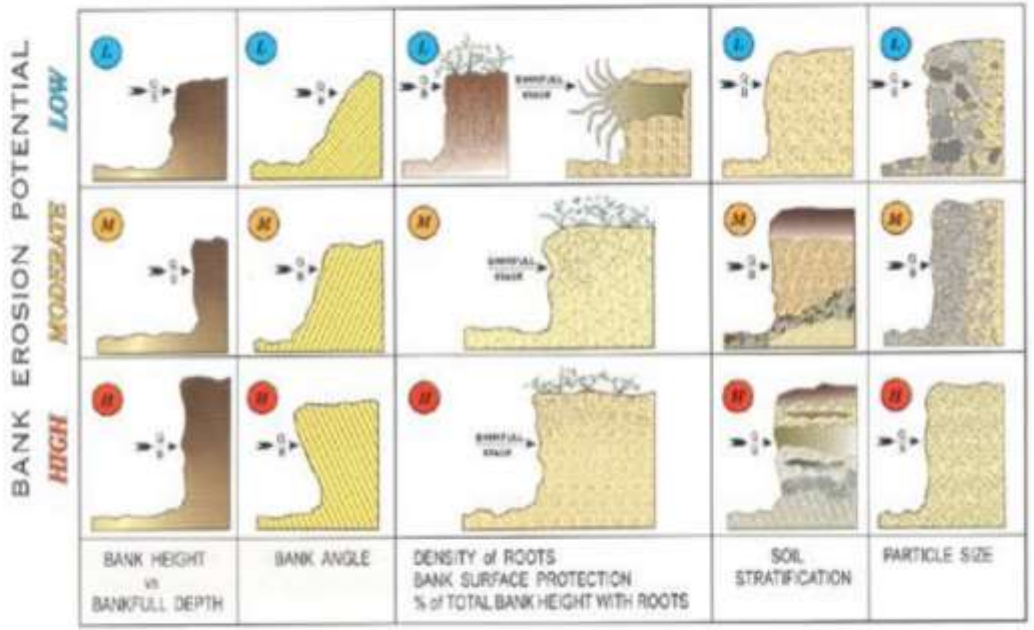
Field Data Collection

- Modified Bank Erosion Hazard Index (BEHI) (Rosgen 2014)

BEHI Category	Score	Root depth/bank height (%)	Root Density (%)	Surface Protection (%)	Bank Angle (degrees)	Total
Very low	1	90-100	80-100	80-100	0-20	<6
Low	3	50-89	55-79	55-79	21-60	6-12
Moderate	5	30-49	30-54	30-54	61-80	13-20
High	7	15-29	15-29	15-29	81-90	21-28
Very High	8.5	5-14	5-14	10-14	91-119	29-34
Extreme	10	<5	<5	<10	>119	>34

Material Adjustment	
Bedrock	Automatically very low
Boulder	Automatically low
Cobble	-10
Gravel	5
Sand	10
Silt/Loam	0
Clay	-20

Stratification Adjustment	
No Layer	0
Single Layer	5
Multiple Layers	10



Stream Bank Erodibility Factors (Rosgen 1993d)

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Field Data Collection

- Sediment samples
  - Taken at each bank of concern
  - Particle size distribution
    - ASTM D7928
    - ASTM D6913
  - Sediment factors used in statistical analyses
    - d_{10}
    - Uniformity coefficient (C_u) $C_u = d_{60}/d_{10}$
    - Coefficient of curvature (C_c) $C_c = d_{30}^2/(d_{10} * d_{60})$
    - Percent gravel
    - Percent sand
    - Percent silt
    - Percent clay

USCS Particle Classification	Clay	Silt	Sand	Gravel
Particle Size (mm)	<0.002	0.002-0.05	0.05-2.0	>2.0

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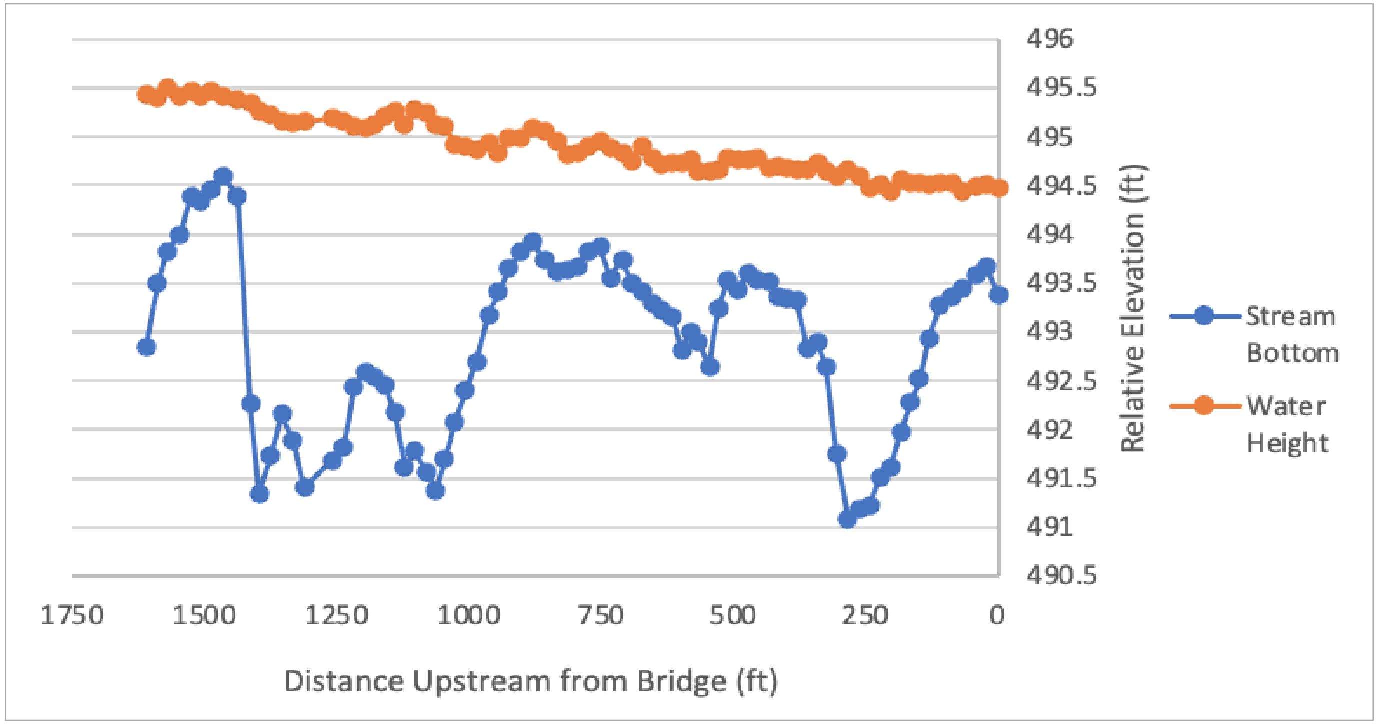
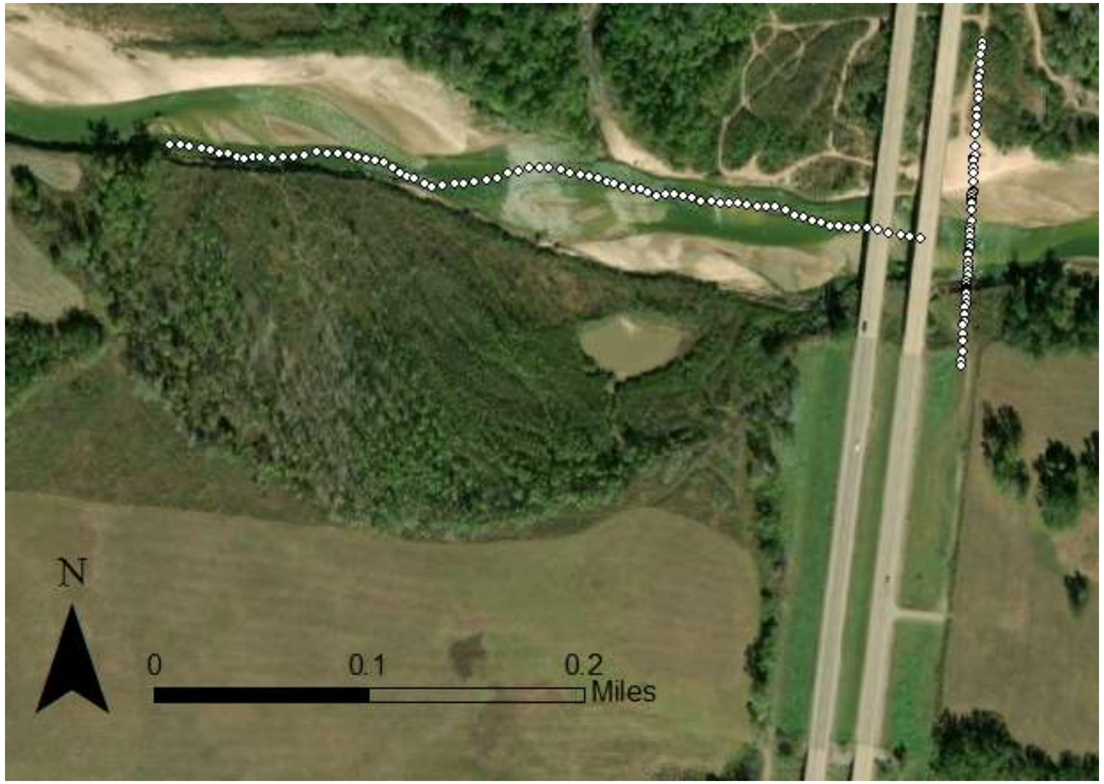
Results

Longitudinal Profile

Site 27 – North Canadian River and S.H. 99, Seminole county





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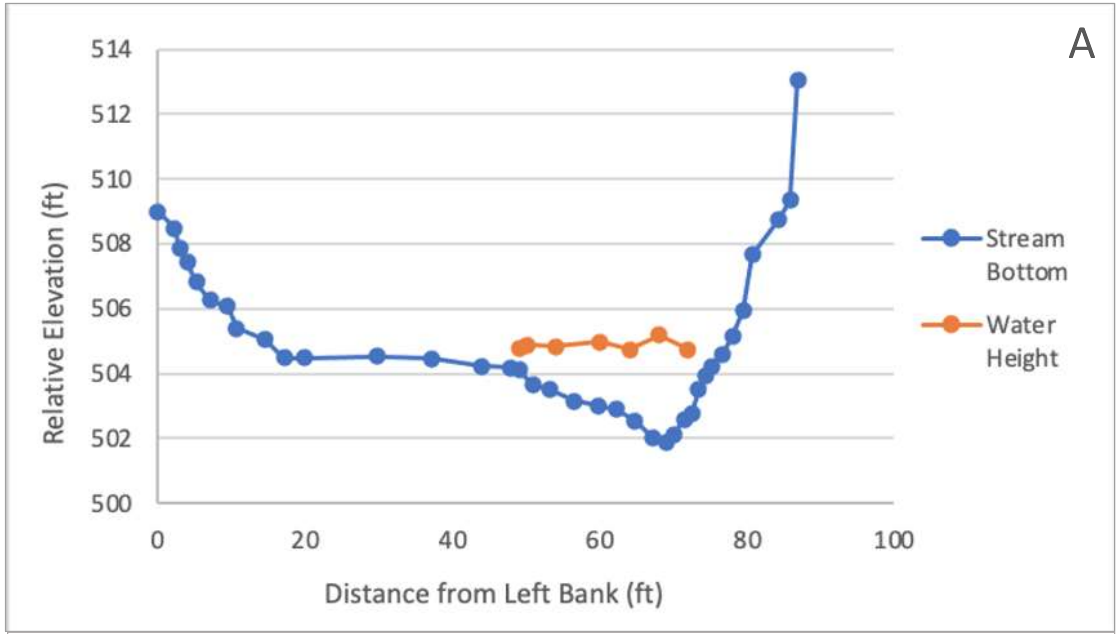
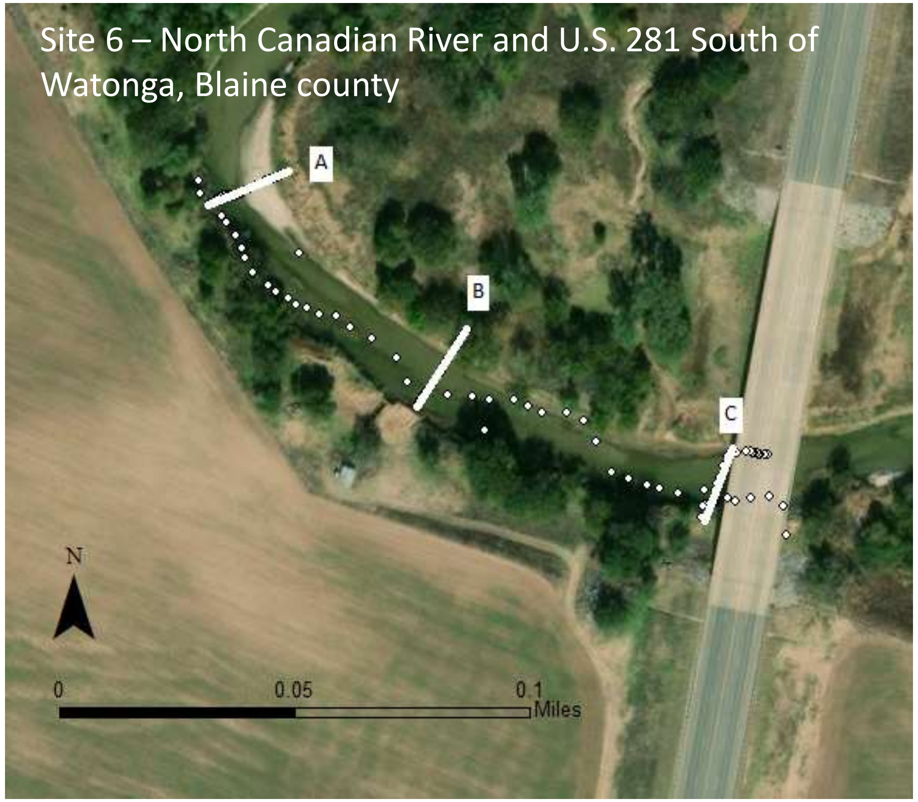
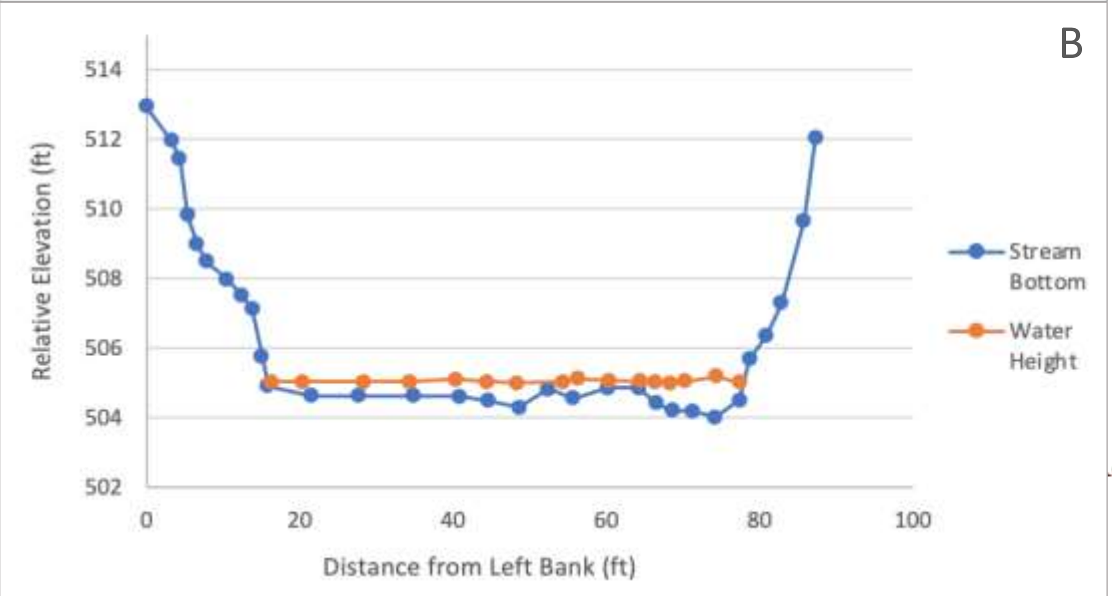
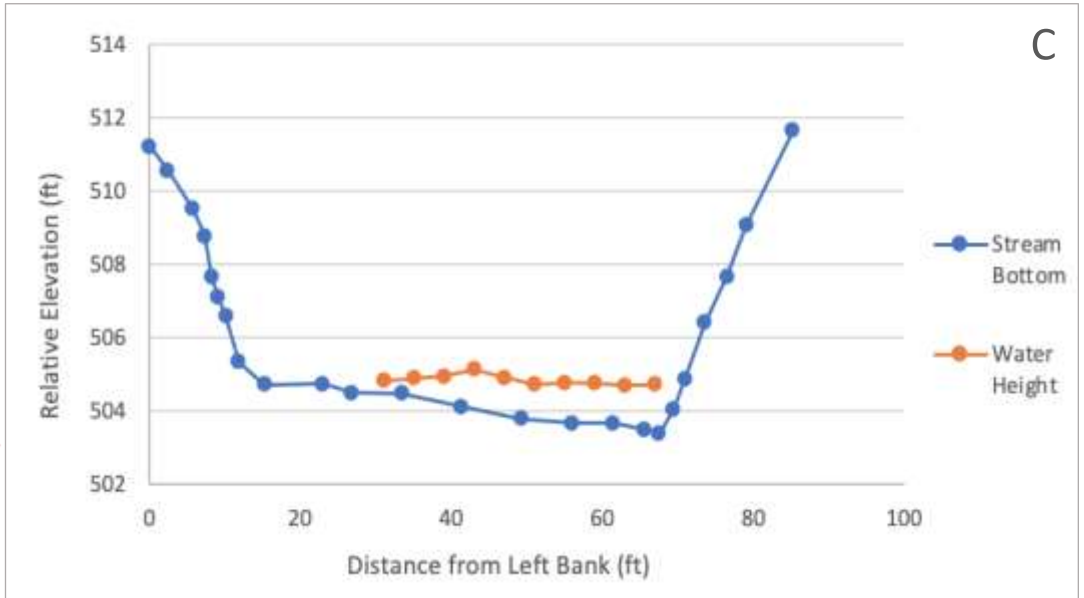
Cross Sections





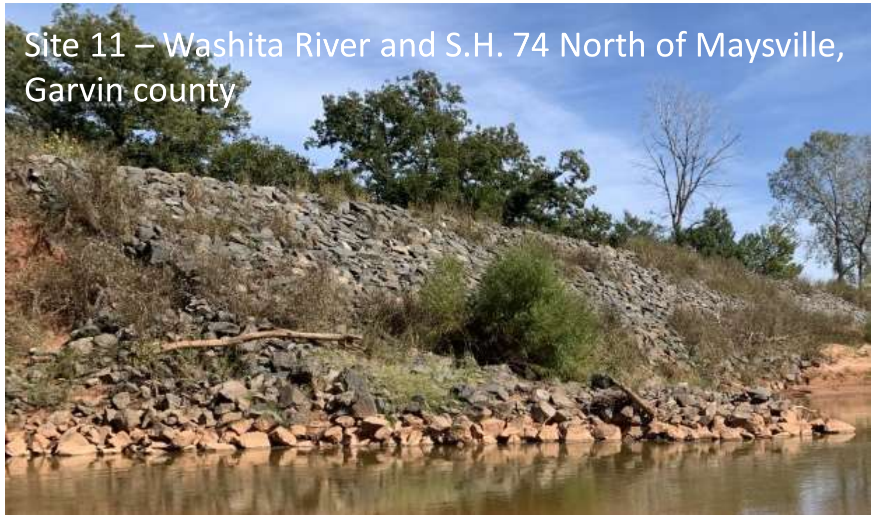




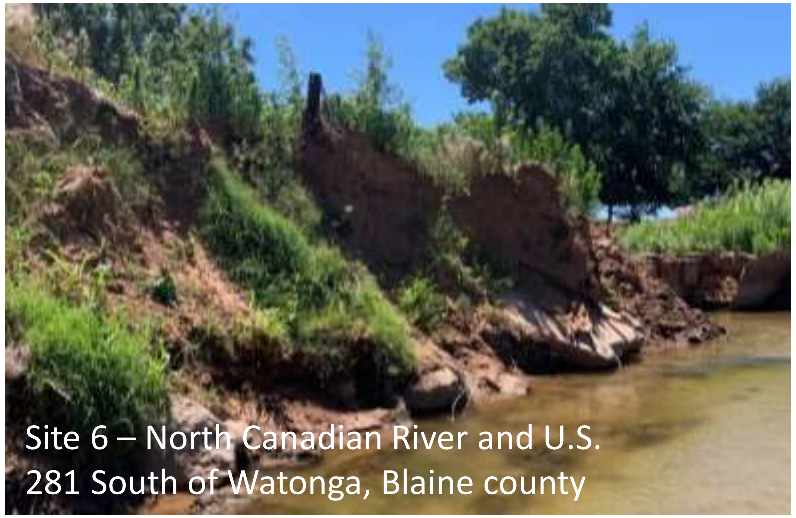
Bank Erosion Hazard Index

	Average	Minimum	Maximum
Rating	20.5	5.5	32
Category	Moderate-High	Very Low	Very High

Very Low



Moderate



Very High

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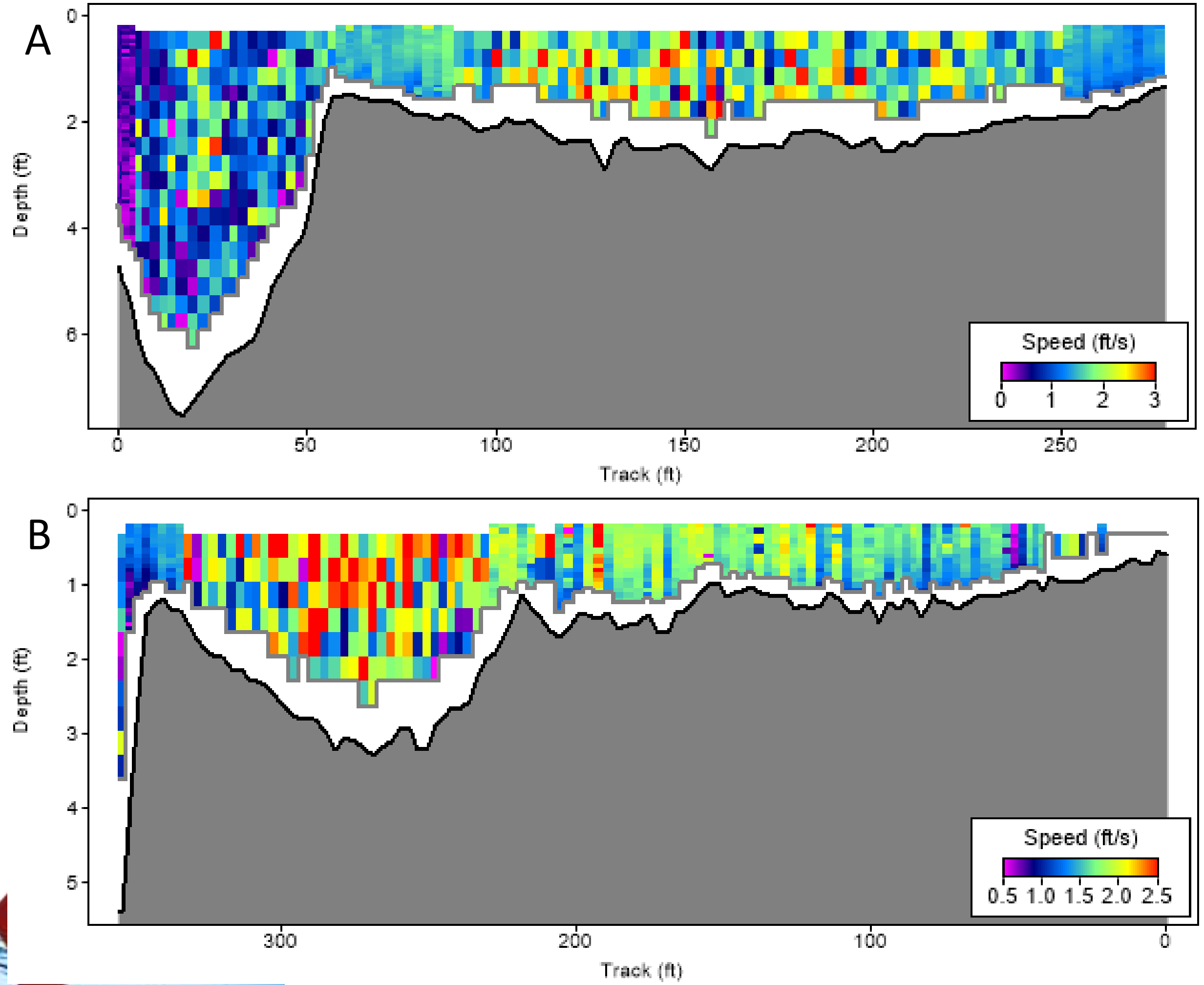
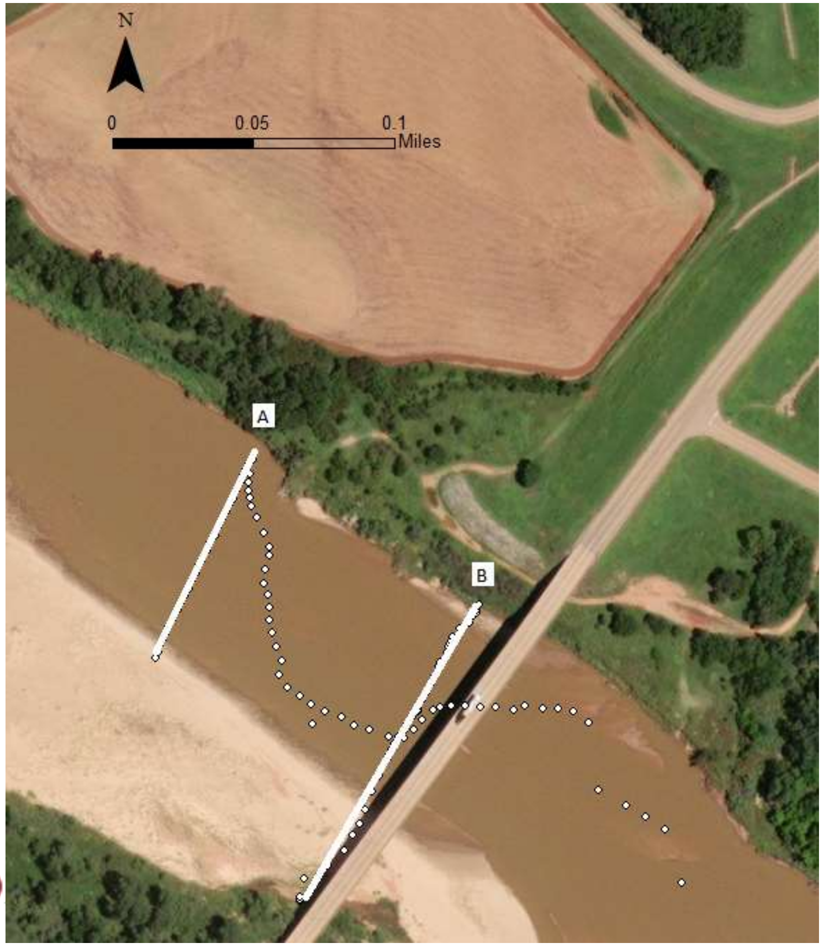
Velocity Profiles

Site 12 – Cimarron River and S.H. 33 North of Coyle, Logan county



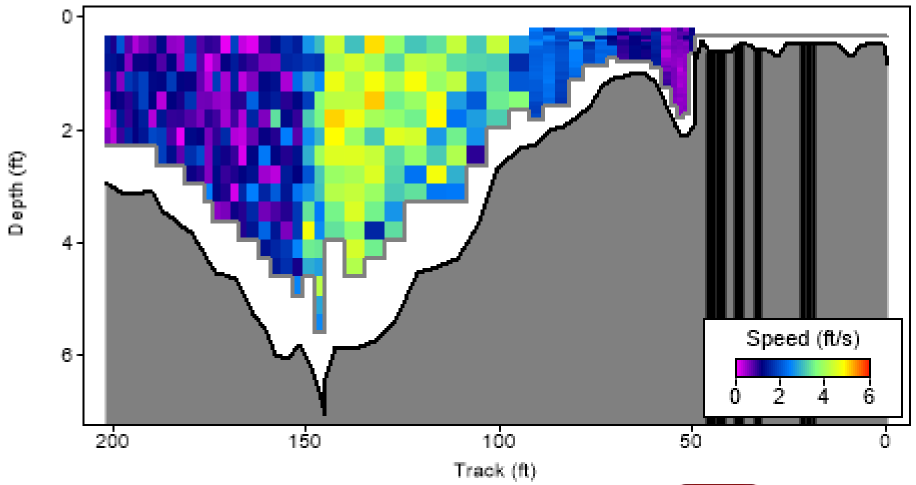


Near-Bank Stress

	Average	Minimum	Maximum
Rating	0.37	0.05	1.9
Category	Very Low	Very Low	High

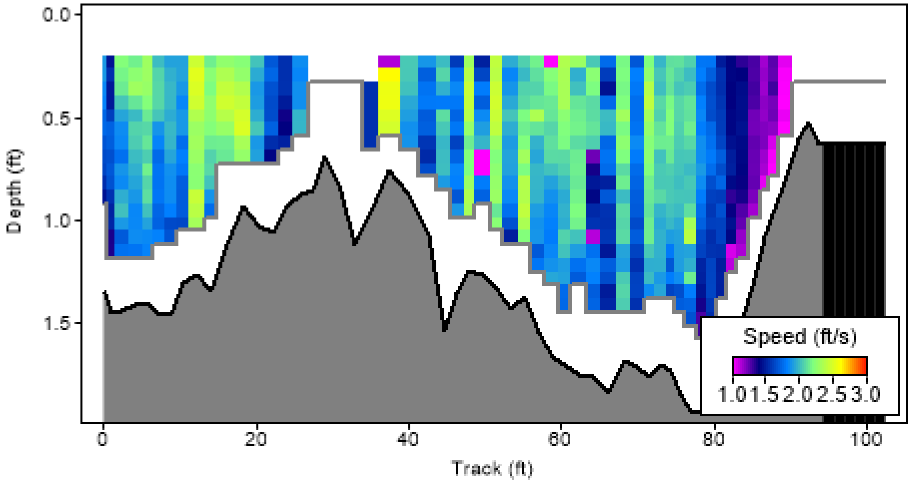
Very Low (Left)

Site 1 – Washita River and U.S. 77 NW of Wynnewood, Garvin county



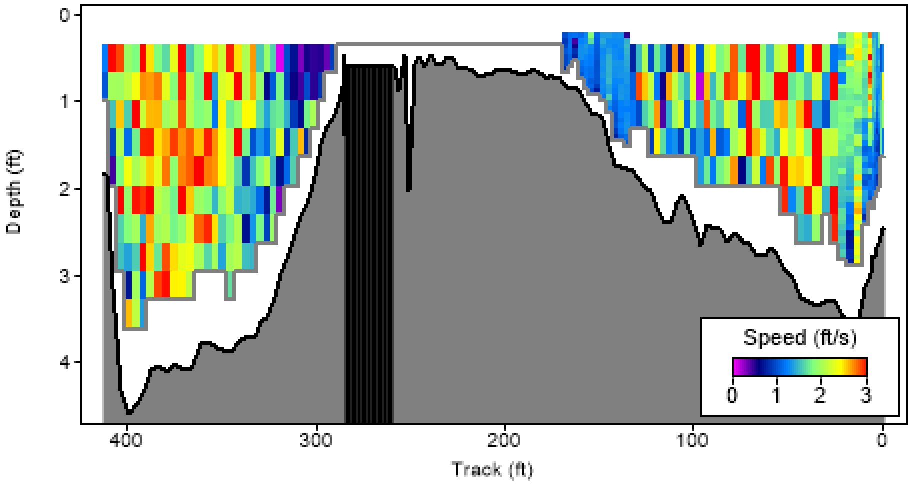
Low (Left)

Site 27 – North Canadian River and S.H. 99, Seminole county



High (Left)

Site 2 – Cimarron River and U.S. 177 south of Perkins, Payne county



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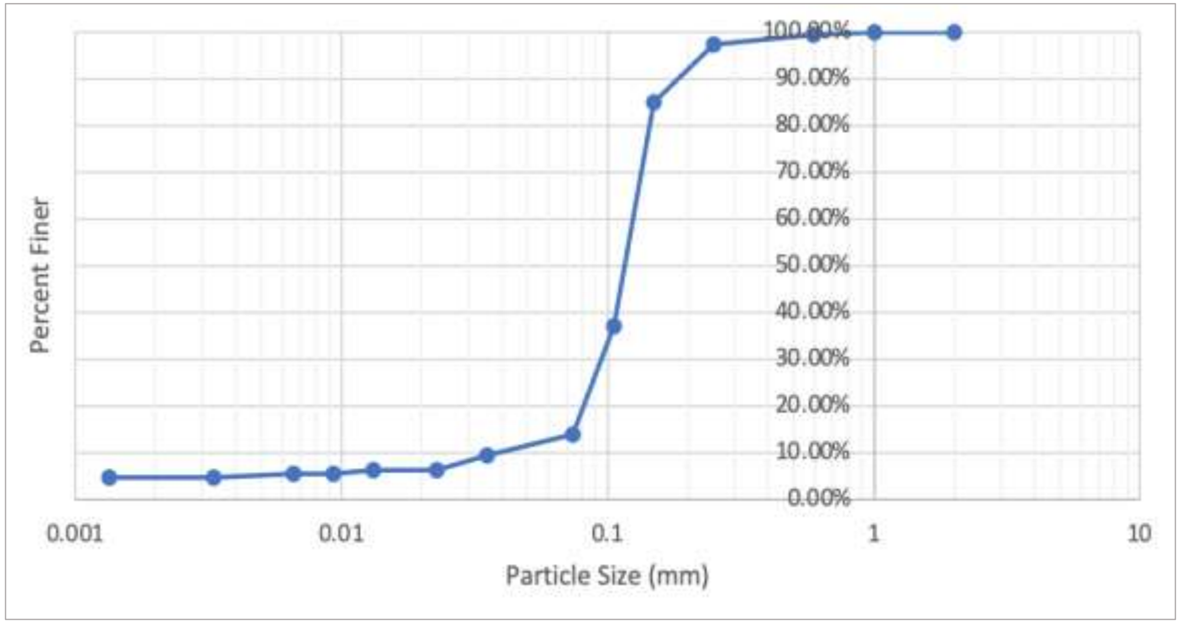
Particle Size Distributions

d_{10} (mm)	d_{40} (mm)	C_u	C_c
0.04	0.11	3.5	1.4

Loamy Sand

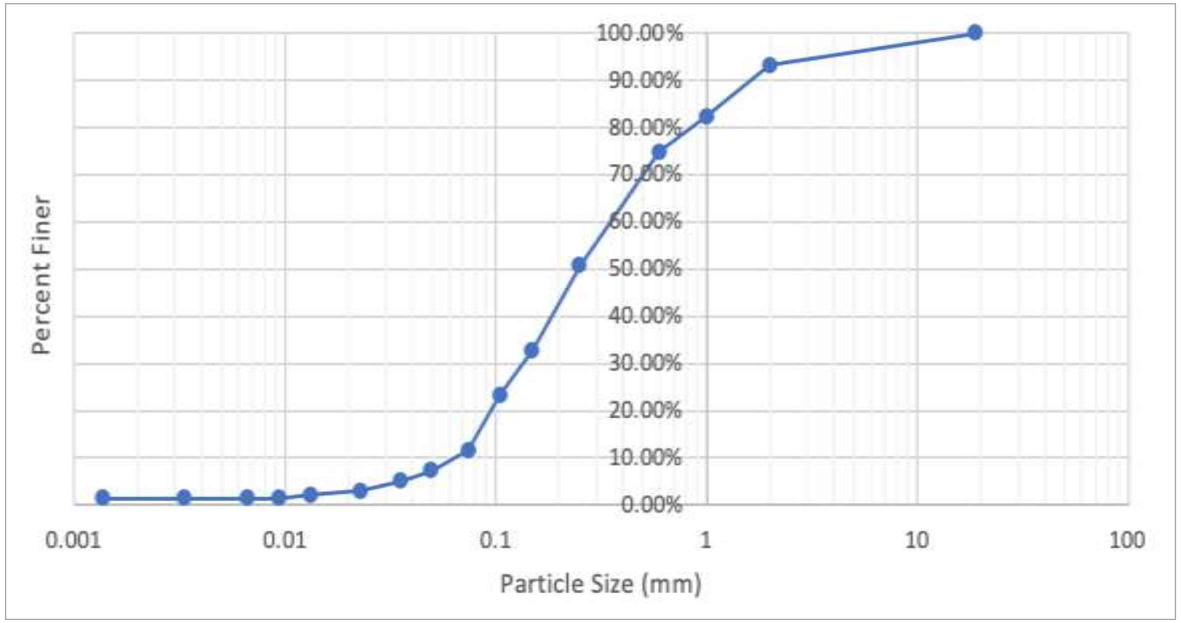
Site 25 –North Canadian River and S.H. 48 North of Bearden, Okfuskee county



d_{10} (mm)	d_{40} (mm)	C_u	C_c
0.07	0.19	5.9	0.7

Sand

Site 12 – Cimarron River and S.H. 33 North of Coyle, Logan county



OK H2O

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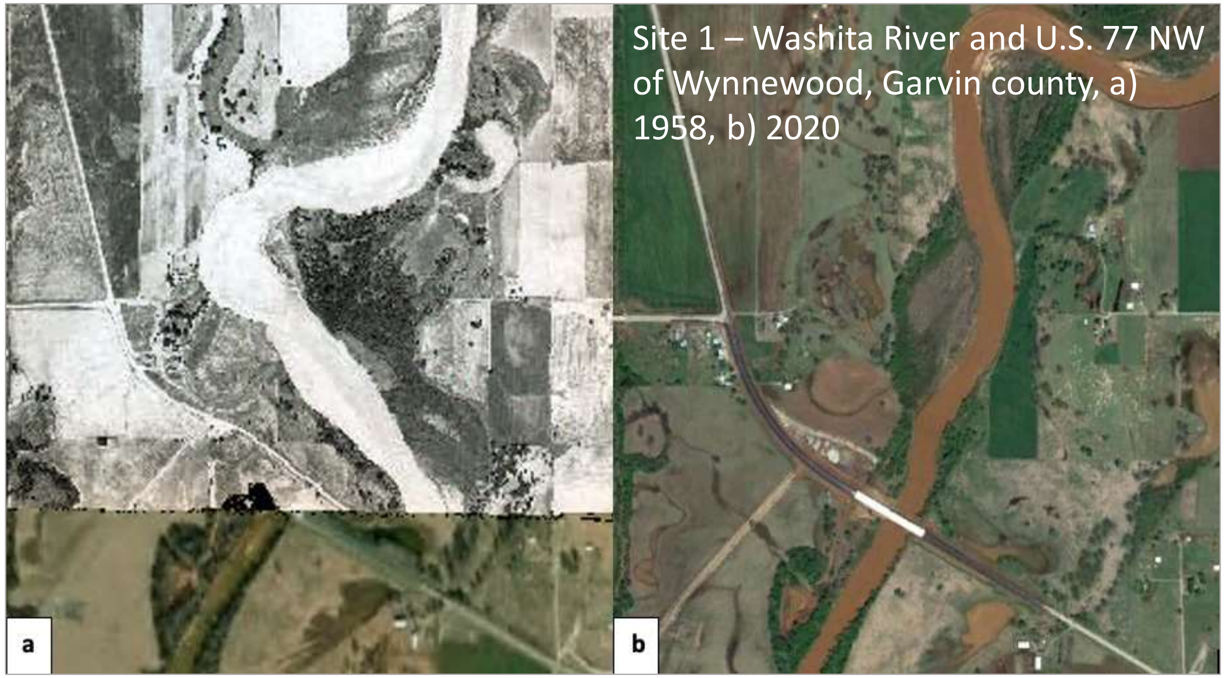
Historical Photos and Lateral Thalweg Movement

Average	Minimum	Maximum	Minimum Absolute Value
98 ft	-1210 ft	2950 ft	10 ft



Site 1 – Washita River and U.S. 77 NW of Wynnewood, Garvin county, a) 1958, b) 2020

Site 27 – North Canadian River and S.H. 99, Seminole county , a) 1995, b) 2020