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Integration of Fluvial Geomorphologic and Hydraulic Principles for Sizing of Watercourse Crossings

Source to Stream Conference 2023

Kathy Robitaille-Feick, Fluvial Geomorphologist P.Geo.
Andres Rodriguez, Water Resources Engineer P.Eng.

Agenda

1. Fluvial Sediment Entrainment and Processes & Crossing Impacts
2. Factors Influencing Sediment Entrainment and Transport
3. Sediment Entrainment and Transport Equations
4. 2D Hydraulic Model Development
5. Hypothetical Crossing Example
6. Constraints and Opportunities

Fluvial Sediment Entrainment and Transport Processes

- Complex inter-relationship between channel dimensions, patterns, sediment supply, streambed roughness and steepness
- Alterations to one component will impact the others
- A channel will remain in equilibrium if changes in sediment load and particle size are balanced by changes in water discharge and slope.

Lanes Stream Balance Relationship (1955)

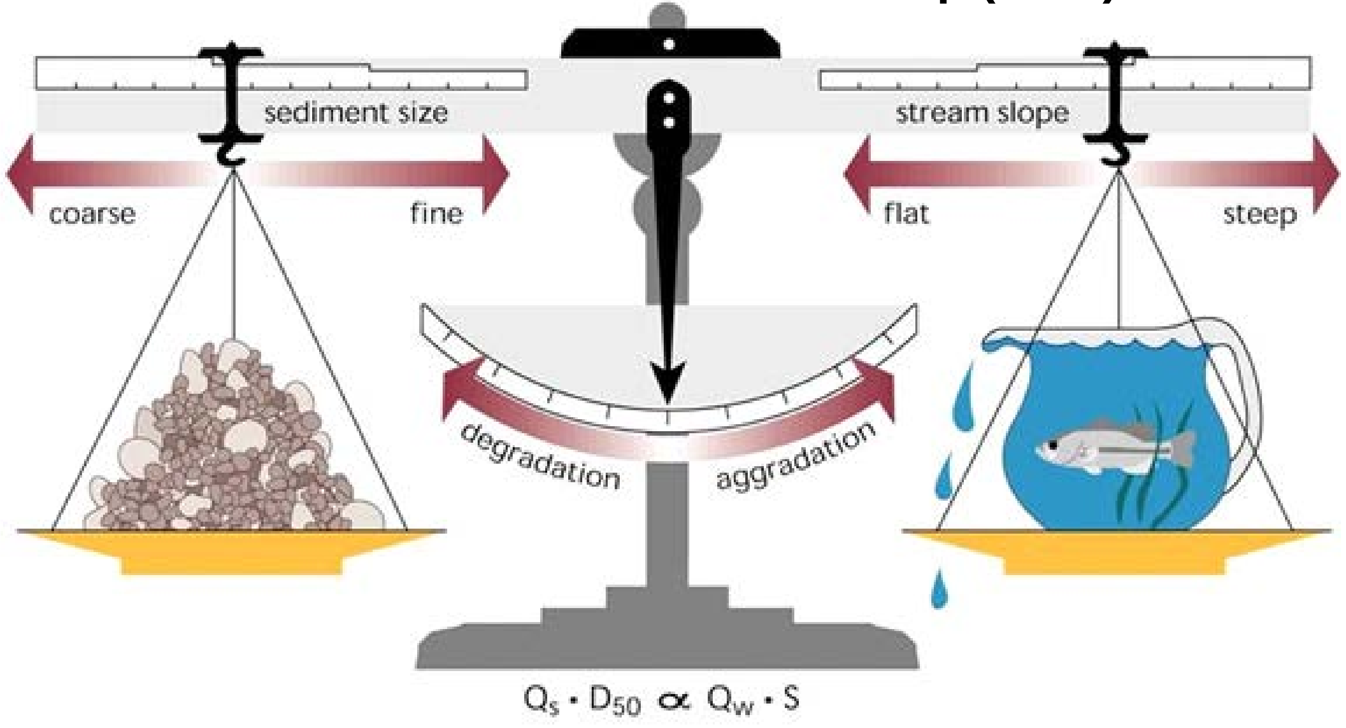
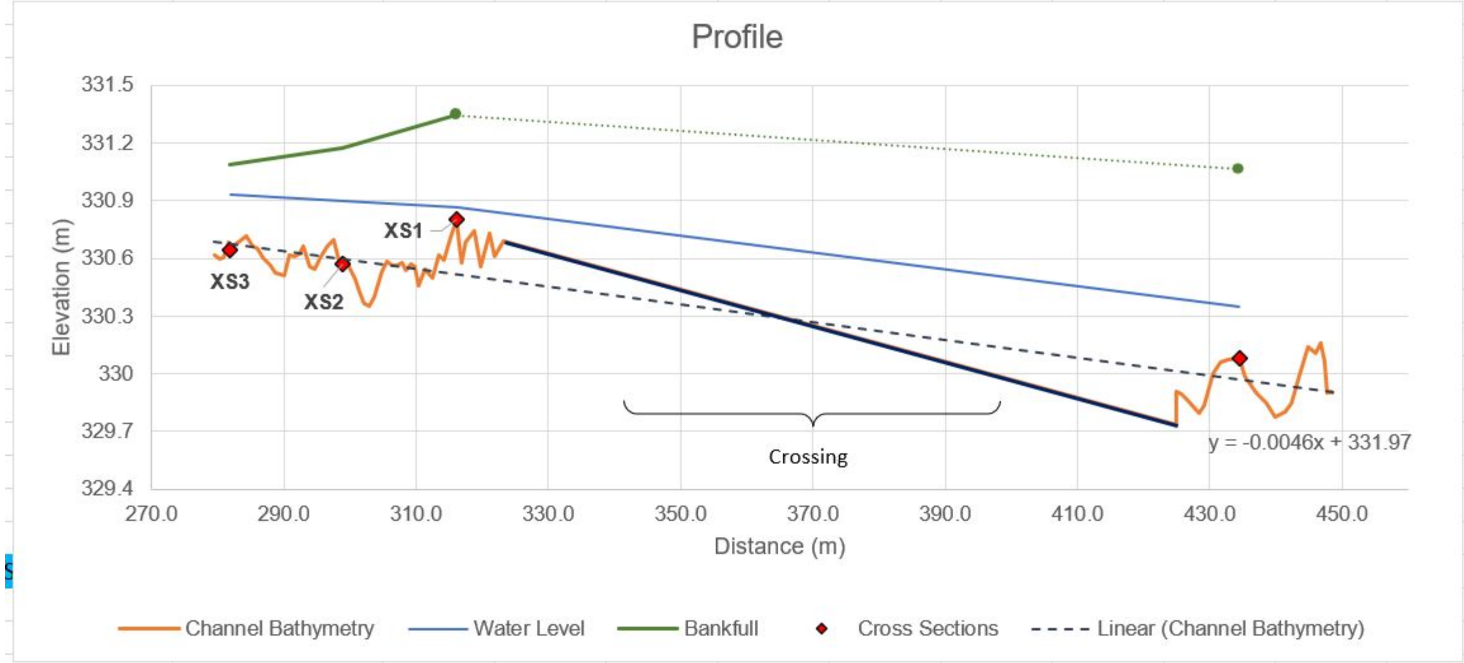


Image from: water | University of Kentucky College of Arts & Sciences (uky.edu)

Crossing and Impacts on Natural Sediment Transport Potential

A crossing should maintain or replicate the pre-crossing natural sediment transport potential and fish passage characteristics

Crossing and Impacts on Natural Sediment Transport Potential

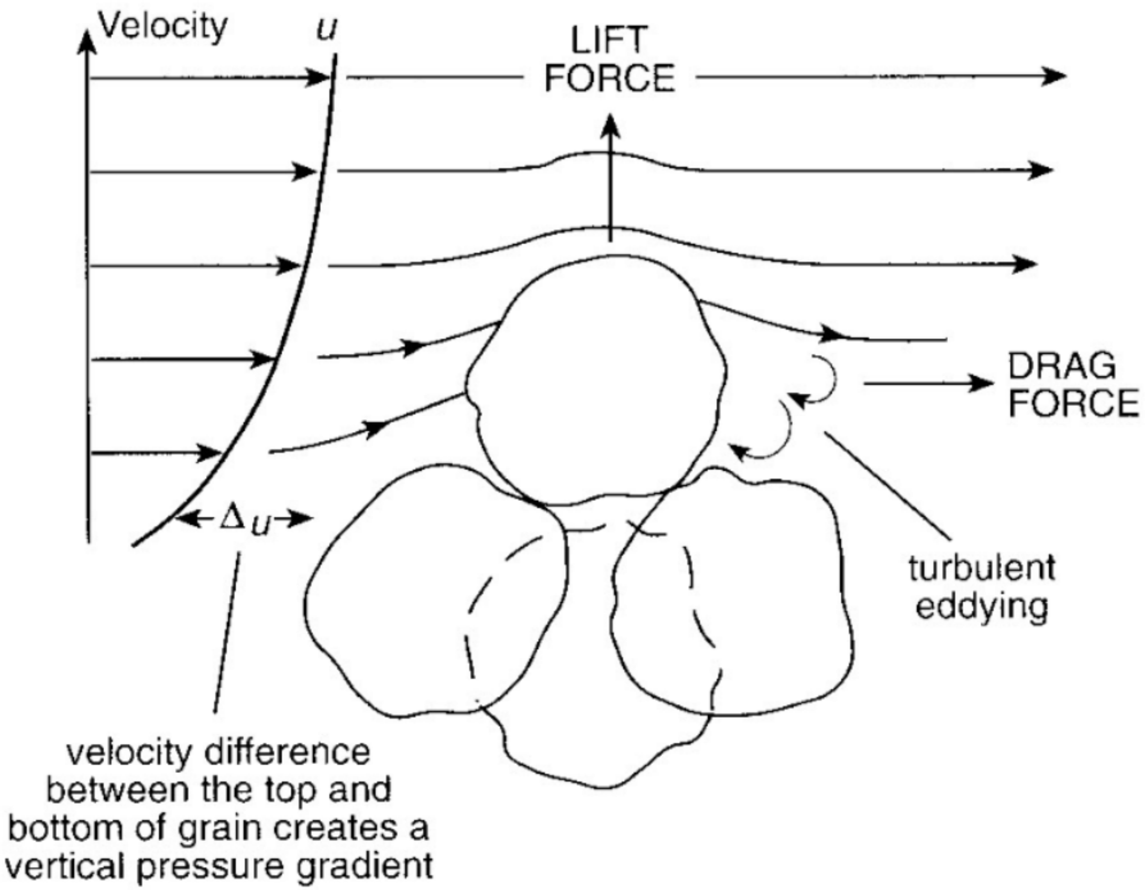


Establishment of a local base level control point (e.g., closed bottom culvert) that affects channel bed profile development

Sediment Entrainment and Transport Influenced by Flow

Velocity and Shear Stress – both influence the forces causing resistance and movement

Factors Influencing Sediment Entrainment and Transport



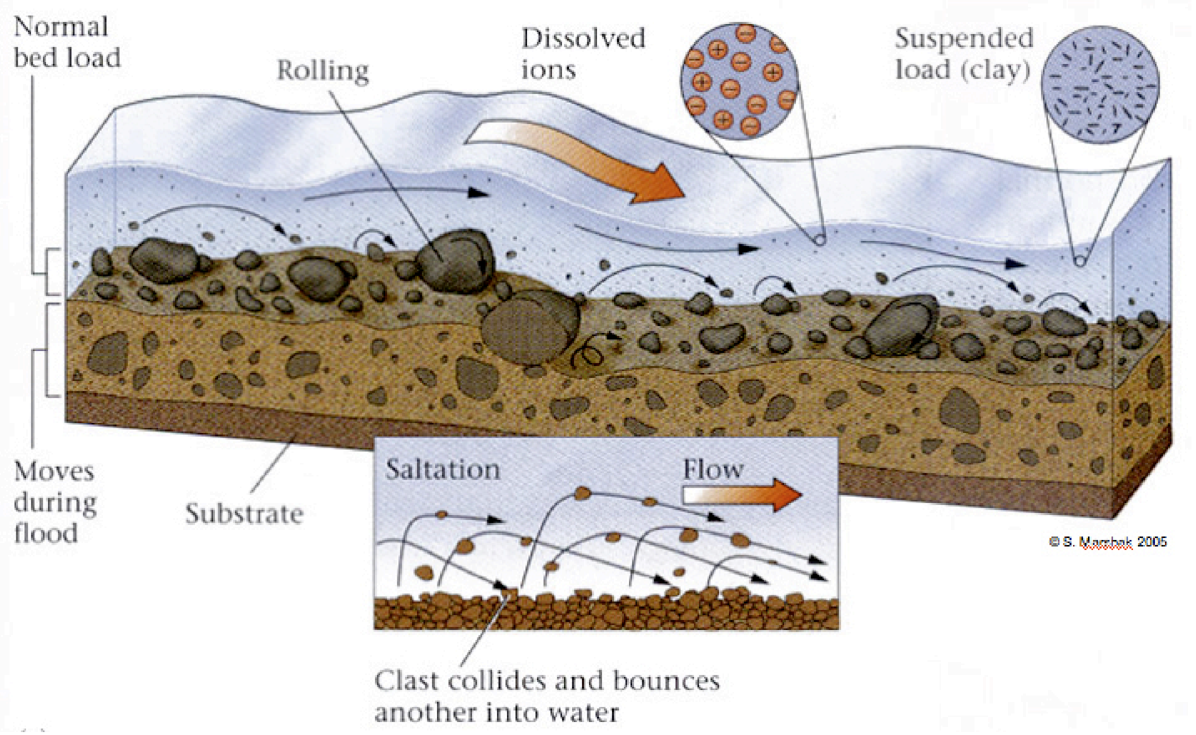
Fluvial sediment transport — EarthSurface 0.0.1 documentation

- What is shear stress
  - Force per unit area acting on a particle (N/m^2)
  - Erosion occurs when shear stress exceeds resisting forces
  - Very difficult to predict
  - Bank erosion is more complicated than bed erosion

- What is velocity
  - A vector quantity having magnitude and direction (m/s)
  - Velocity varies with time, discharge, distance from banks and bed - Velocity and shear stress are not steady or uniform in natural channels
  - Roughness – due to friction, varying particles, bedforms, and vegetation affect velocity

Factors Influencing Sediment Entrainment and Transport

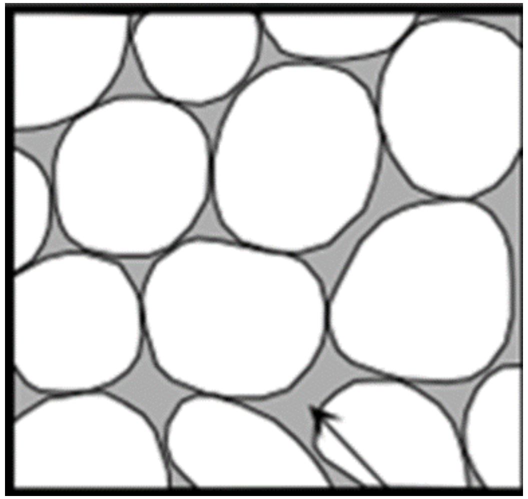
- Material along the bank can be more variable than the bed material
- Factors that can influence particle movement
    - Flow
    - Composition – geology, pedogenic processes
    - Climate
    - Channel geometry
    - Vegetation
    - Particle Movement (rolling, sliding, saltating, suspension)



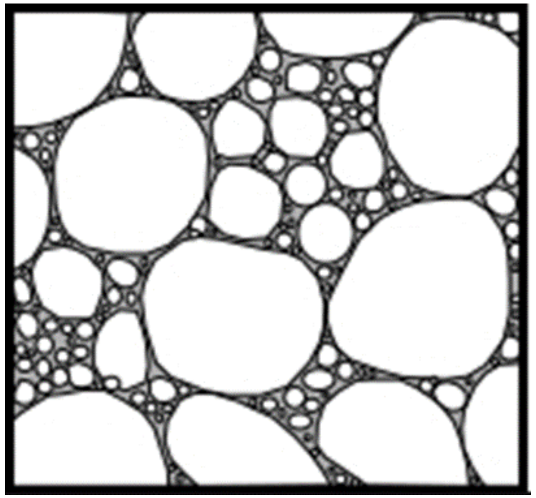
Sediment transport stages regarding the hydrologic, hydraulic, and geomorphological conditions: adapted from Marshak 2005.

Factors Influencing Sediment Entrainment and Transport

Arrangement of particles affects the degree of packing of grains, which in turn has an effect on the erodibility of substrates



- Well sorted soil or sediment indicates that particles are generally all the same size
- Well sorted soil or sediment has higher porosity since there are more voids between particles



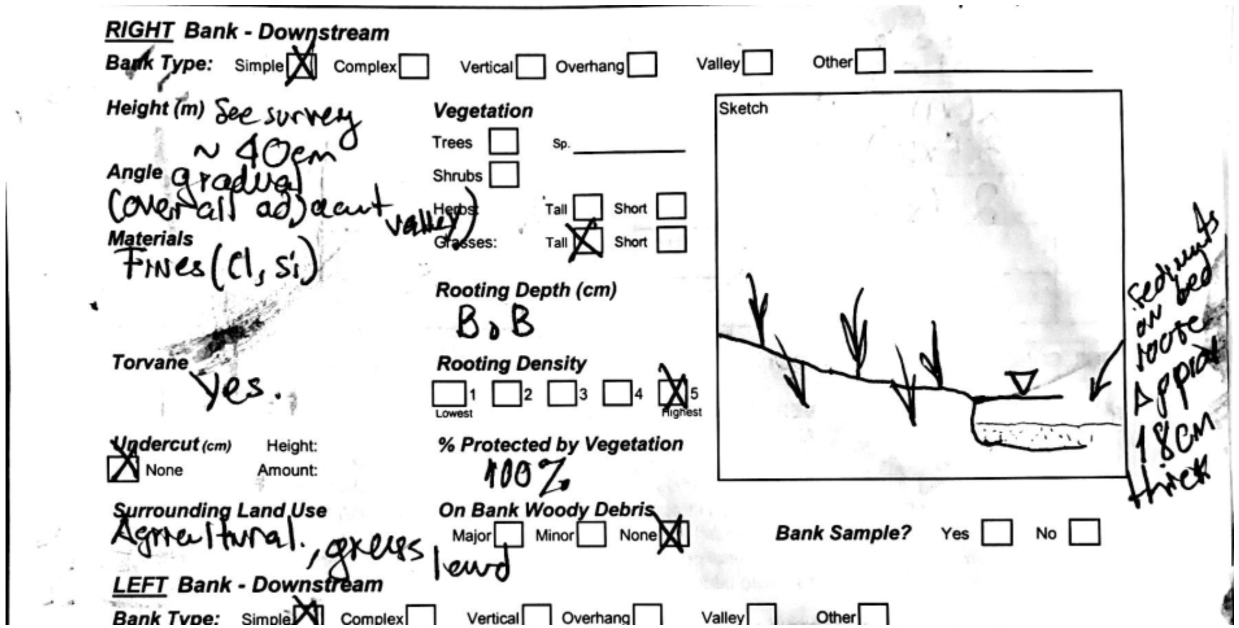
- Poorly sorted or unsorted soil or sediment indicates that particles are a wide range of sizes
- Poorly sorted soil or sediment has lower porosity since finer grains will fill voids between the larger grains

Substrate Quantification

Wolman Pebble Counts

Percentile	Cross Section 1	Cross Section 2	Cross Section 3	Cross Section 4	Cross Section 5	Cross Section 6	Cross Section 7	Cross Section 8
D16	0.001	0.003	0.003	0.002	0.001	0.001	0.002	0.002
D50	0.08	0.79	0.67	0.58	0.43	0.09	0.11	0.39
D84	7.45	7.45	7.10	7.45	3.99	3.64	7.09	3.06

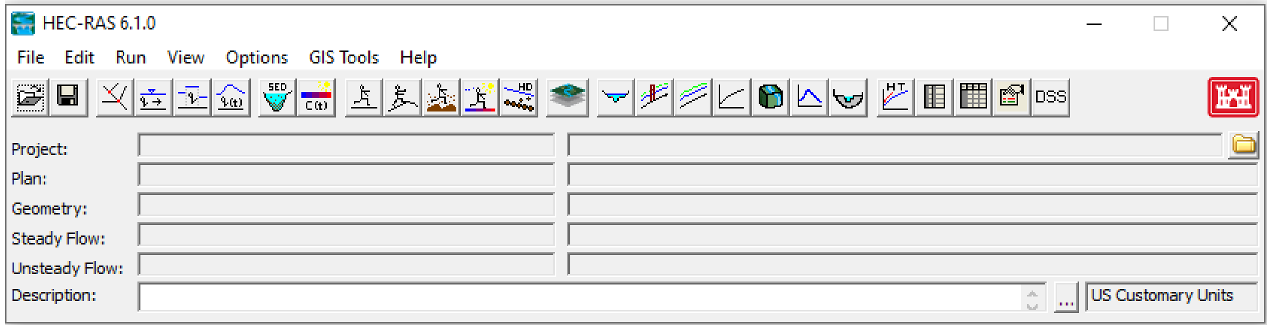
Bank Characterization



- Field assessments characterize the bed and banks
  - Sediment transport – the movement of eroded soil particles in flowing water
  - Sediment deposition – Settling of eroded and transported particles as flow volume recedes

Introduction to Equations (1D vs 2D)

- HEC-RAS, CulvertMaster
- 1D vs 2D depends on available data set format
- 1D data is typically limited to the results for the proposed crossing and a few upstream/downstream crossings
- 2D data provides a better look at the wide-spread impacts of the proposed crossing



- The 2-year return period analysis informs channel stability
- The 50-year return period event informs design protection and erosion mitigation

Modified Shields Equation – Grain Size Entrained

$$\tau c = \tau \cdot c(\rho s - \rho w) g D50$$

- *Where:*
- *τc is the critical shear stress (N/m^2)*
- *$\tau \cdot c$ is the dimensionless channel shear stress (0.0464)*
- *$\rho s - \rho w$ is the grain density – the water density (Kg/m^3)*
- *g is the gravitational acceleration (m/s)*
- *D50 is the median grain size*

Constraints and Limitations

- The most widely used semi-empirical approach
- Dependent upon the critical shear stress
- When sediment-transport equations fail it's often because they fail to predict the beginning of sediment transport (i.e., critical threshold conditions for initiating sediment movement)
- More forces at play than included in frequently used equations
- Shear Stress (*included*)
- Impact Force (*not included*)
- Lift forces
    - Buoyancy (*included*)
    - Vertical velocity-gradient pressure force (*not included*)
    - Upward turbulence (eddying) forces (*not included*)

Komar Equation (1988) – Grain Size Transported

$$v = 57D50^{0.46}$$

- *Where:*
- *v is velocity (m/s)*
- *D50 is the median bed material grain size (cm)*
- *Values are then converted to m/s*

$$D50_{(m)} = \left(\left(\frac{v_{(m/s)} * 100}{57}\right)^{1/0.46}\right)/100$$

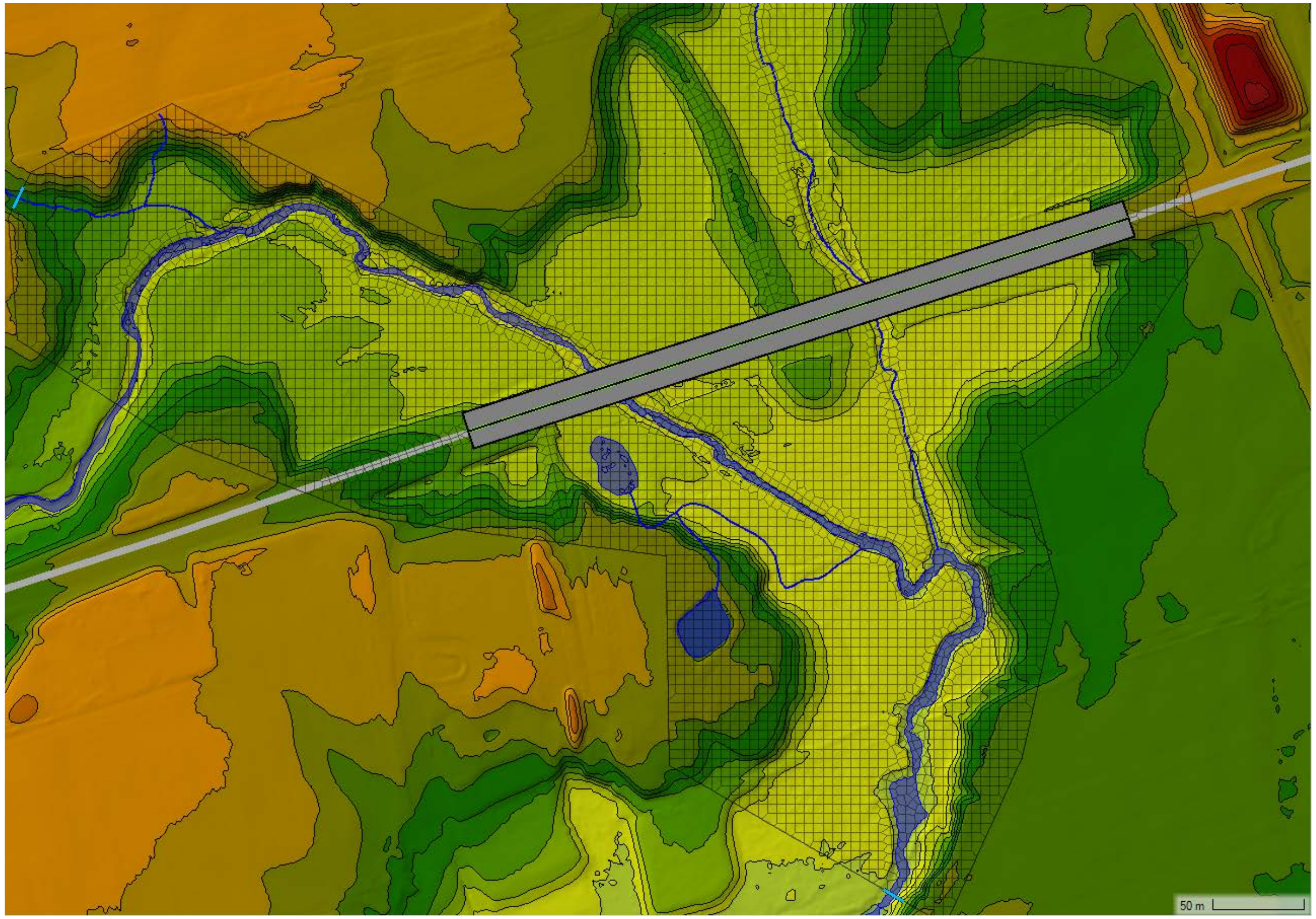
$$D50_{(m)} \cdot 1000 = D50_{mm}$$

Constraints and Limitations

- River velocity is variable
  - Laminar vs turbulent flow
  - Typically, highest in the center of the river just below the surface
  - Heavily dependent on the size and shape of the channel
- Direct field measurement of river velocity in the field is time-consuming
- Sediment transport equations typically assume that rivers carry sediment up to their capacity, whereas actual load levels may be lower
- Lack of reliable field data on transport rates, particularly bed load, makes it difficult to determine the reliability of transport equations

Hydraulic Model Development

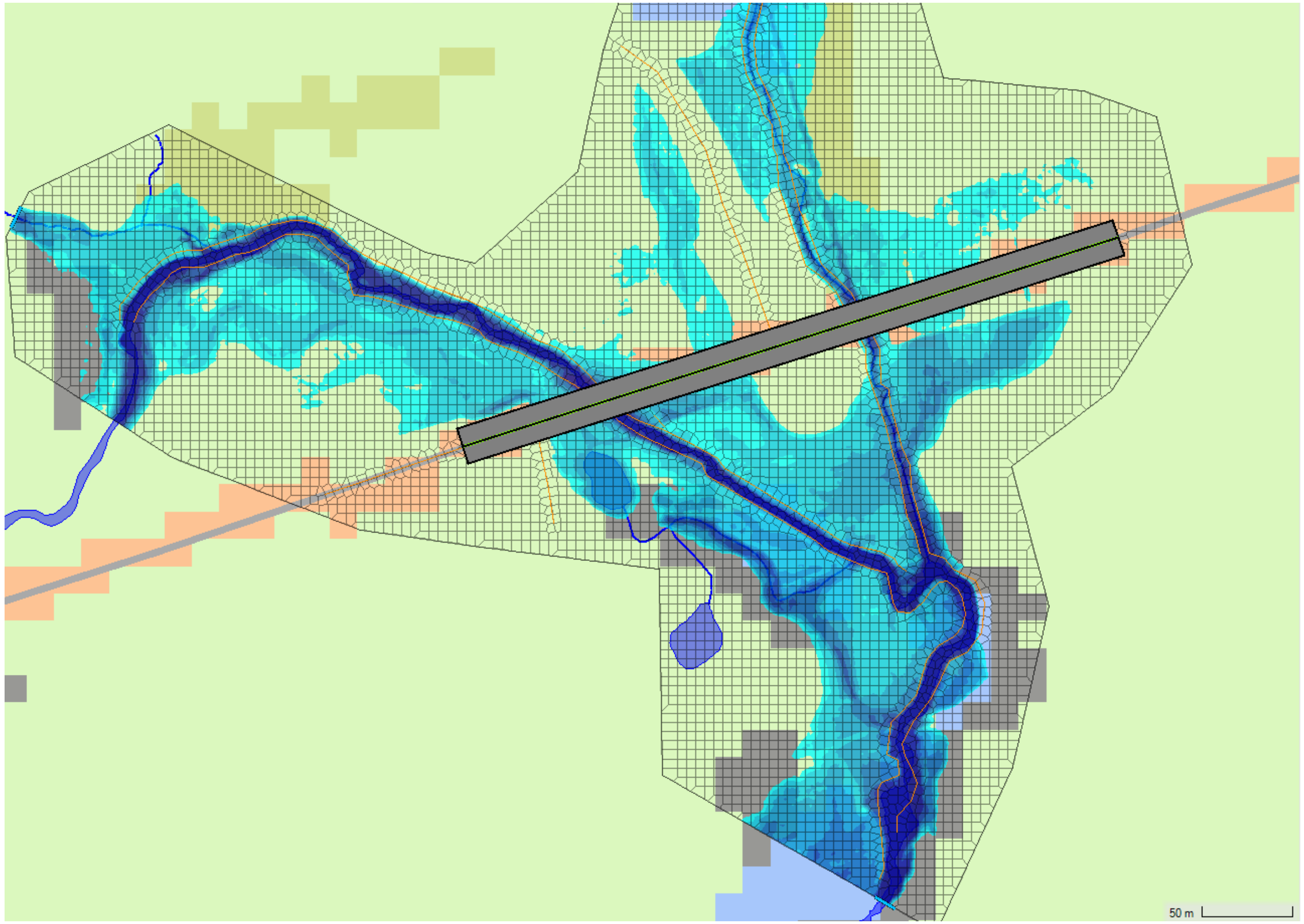
- An assessment of hydraulic conditions was completed at a selected study site in Ontario
- A two-dimensional (depth-averaged) model of the study area was developed in HEC-RAS
- The model was developed with available geo-spatial layers and LiDAR
- Boundary Conditions were applied from available peak flow values and inferred channel energy slope



Hydraulic Model Development

Model Specifications:

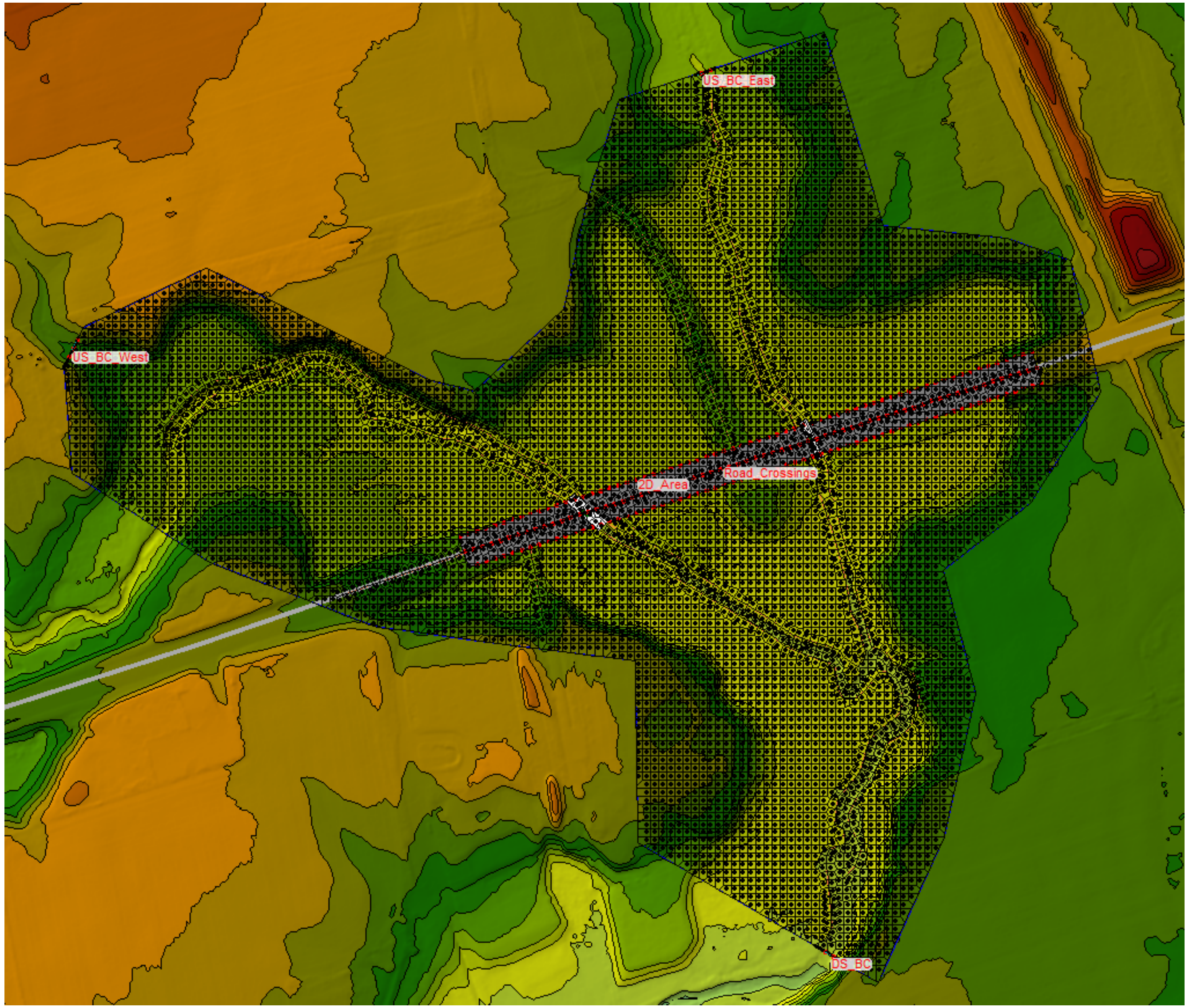
- Mesh size is 5 m x 5 m, with a total number 7,202 cells
- Two upper boundary conditions were set (flow hydrographs) with one downstream boundary condition (normal slope)
- Manning's Roughness Coefficients were set from OLCC v.2 based on published values



Hydraulic Model Development

Model Specifications:

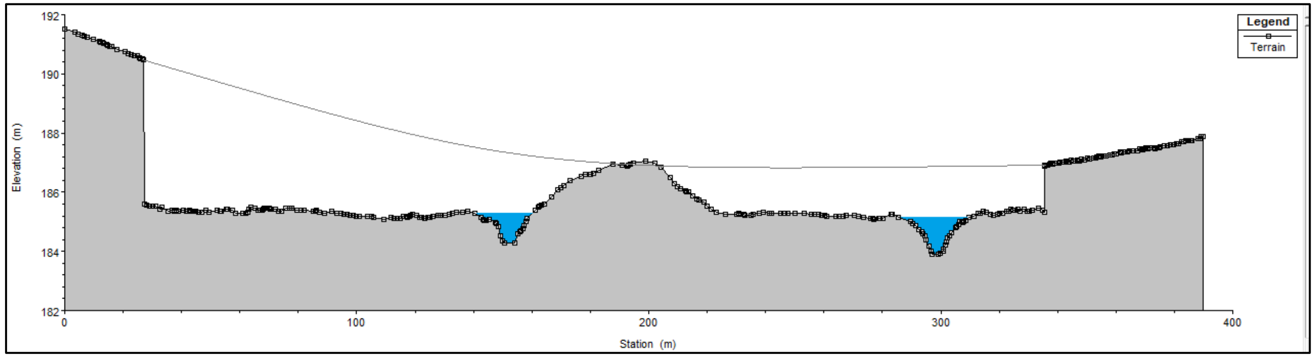
- Three hydraulic crossing configurations were included in the geometry file
- These include a fully open crossing, two bridges (20 m East - 30 m West), and two culverts (5 m East – 8 m West)
- These configurations were added to analyze water velocity and shear stress values

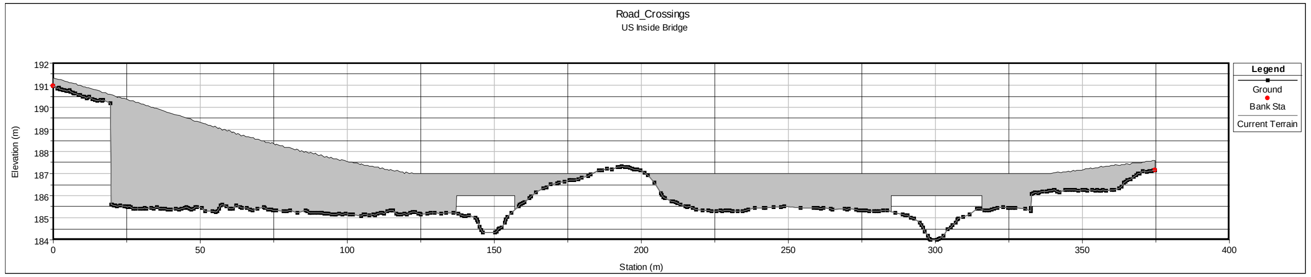


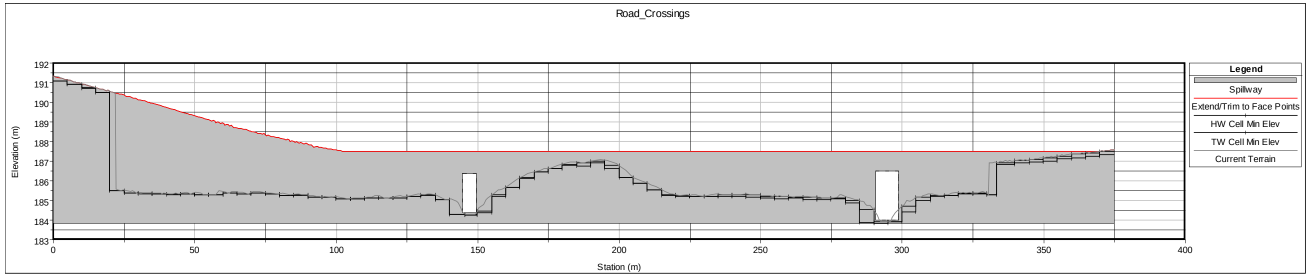
Hydraulic Model Development

Model Objectives:

- The objective of the hydraulic modelling was to evaluate different crossing geometries and how they affect velocity and shear stress regimes
- The crossing span is dependent on hydraulic conditions, a larger span usually means higher cost
- Balance between site conditions, crossing requirements, associated cost, and environmental objectives

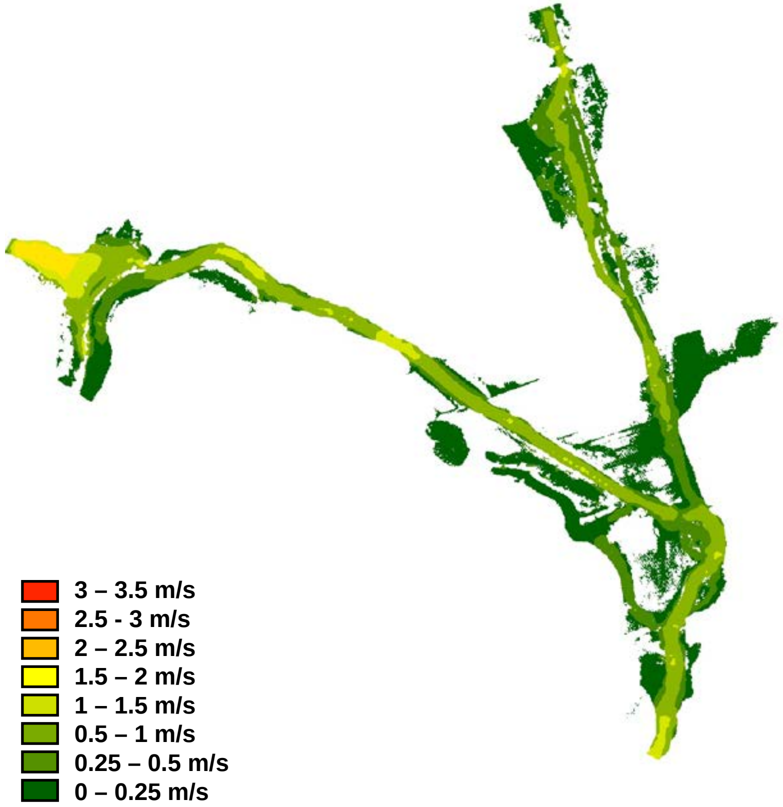






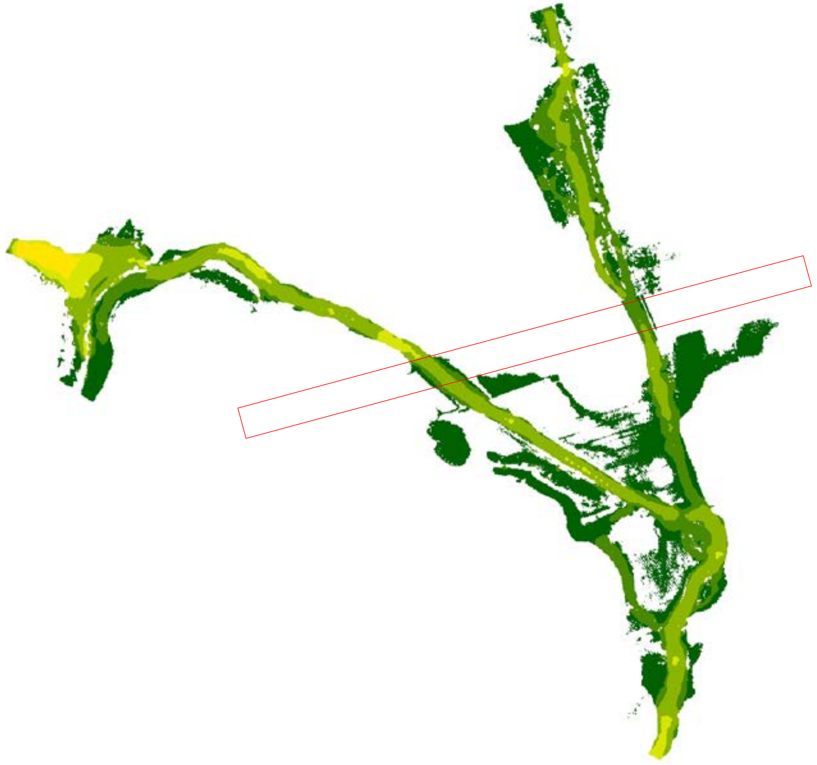
Hypothetical Crossing Example
Velocity – 2 year Return Flow Event

Base Conditions



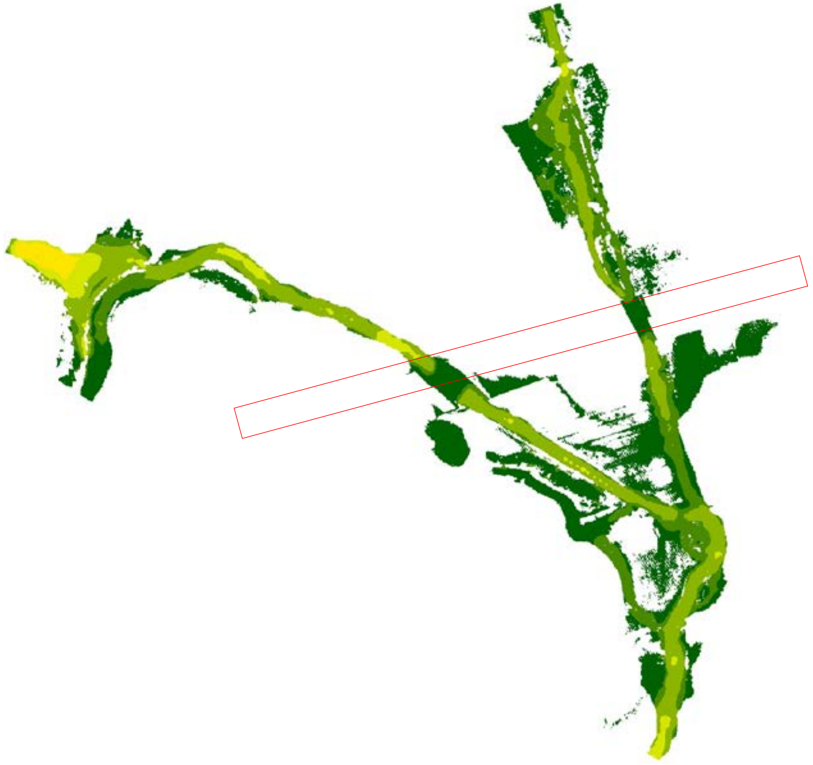
Bridge 1 Conditions

East Span: 20 m
West Span: 30 m



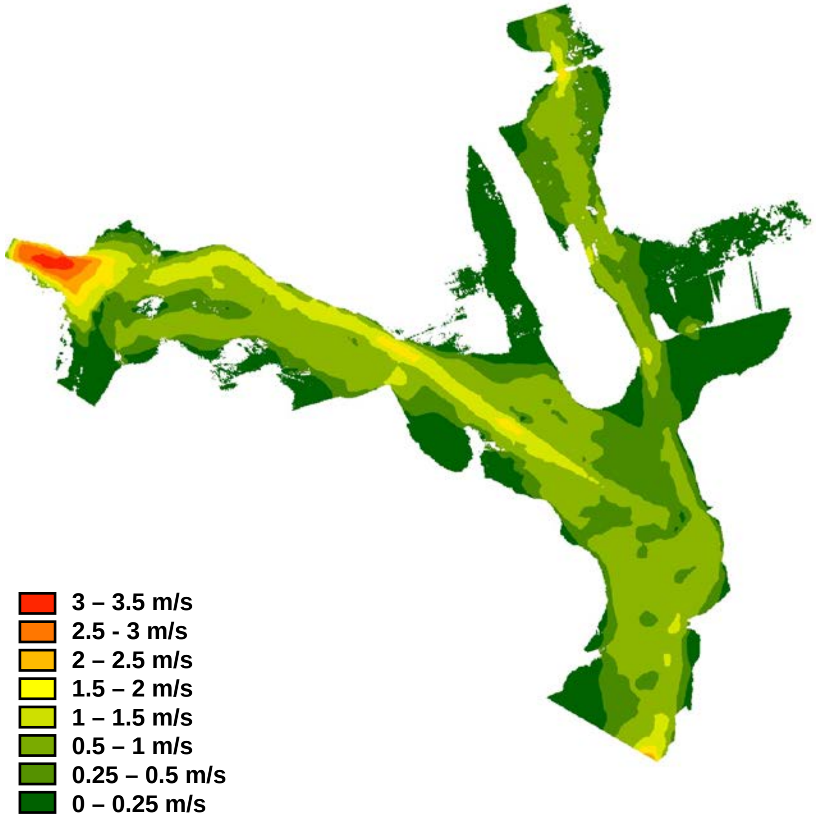
Bridge 2 Conditions

East Span: 5 m
West Span: 8 m



Hypothetical Crossing Example
Velocity – 50 year Return Flow Event

Base Conditions



Bridge 1 Conditions

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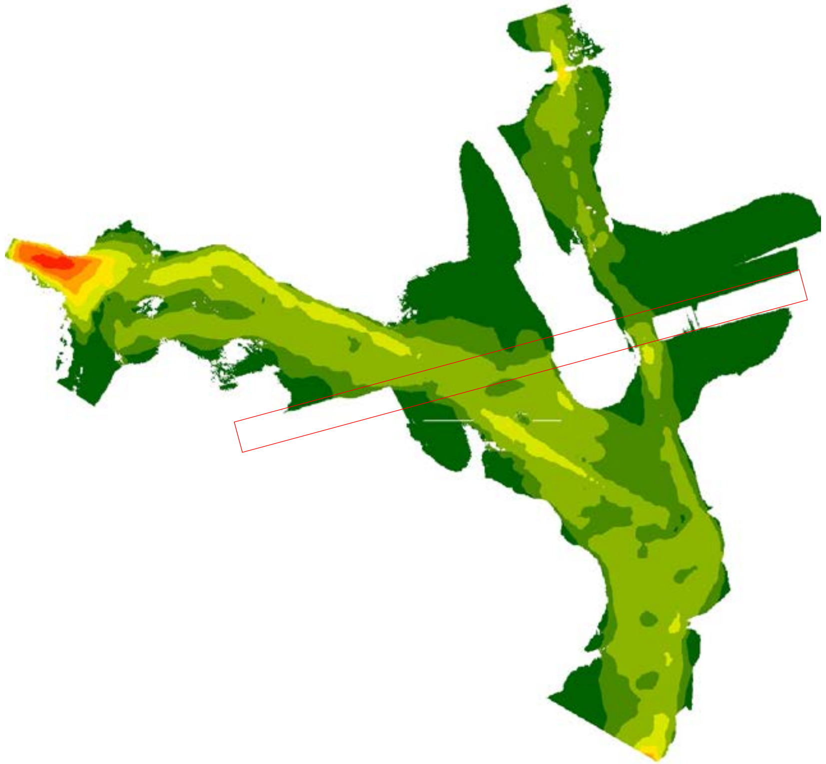
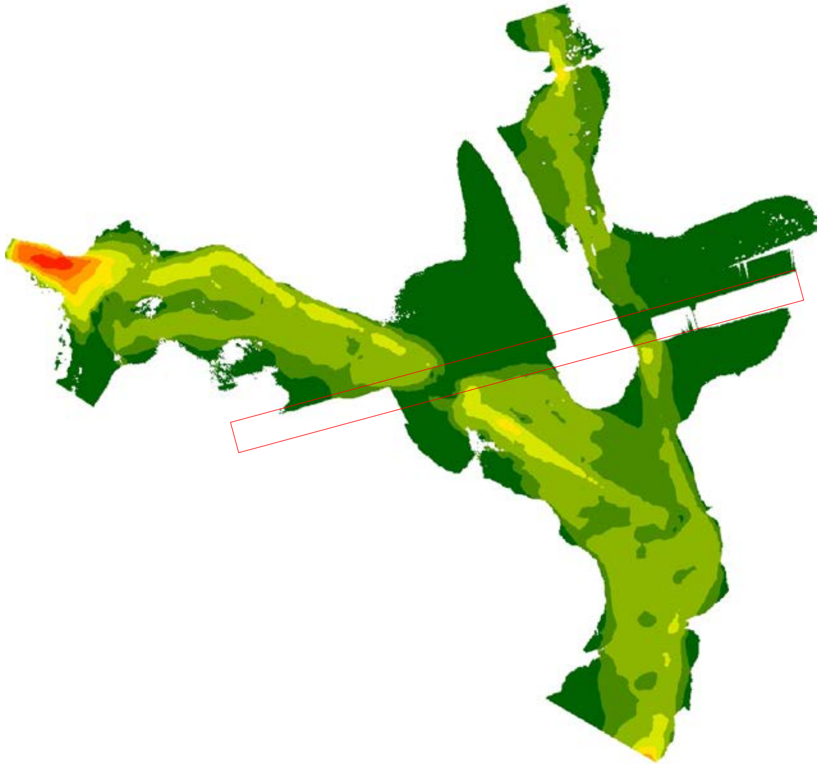


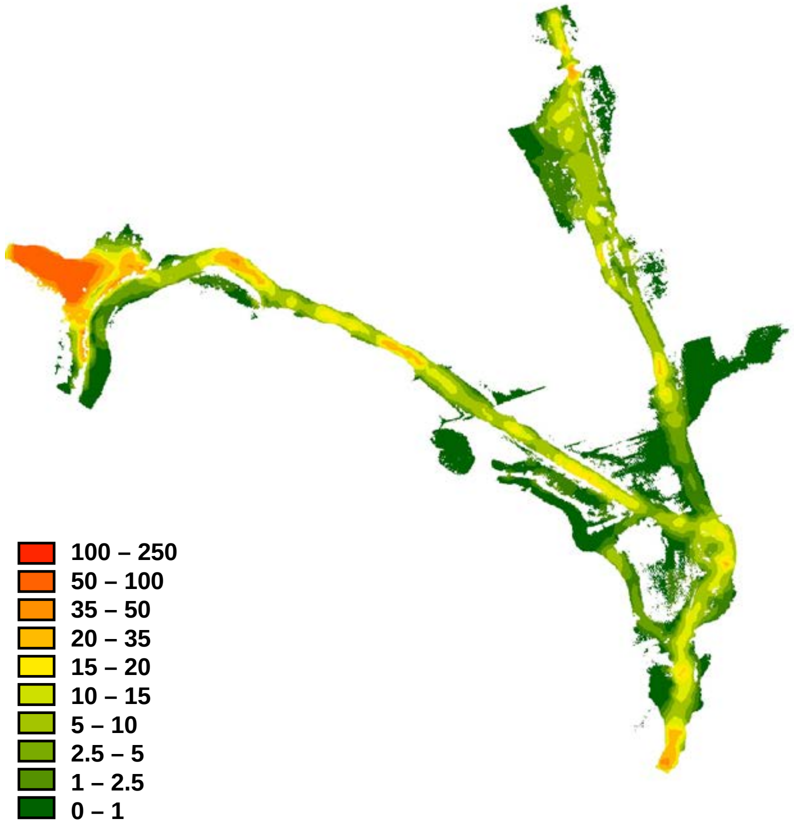
Bridge 2 Conditions

East Span: 5 m
West Span: 8 m



Hypothetical Crossing Example
Shear Stress – 2 year Return Flow Event

Base Conditions



Bridge 1 Conditions

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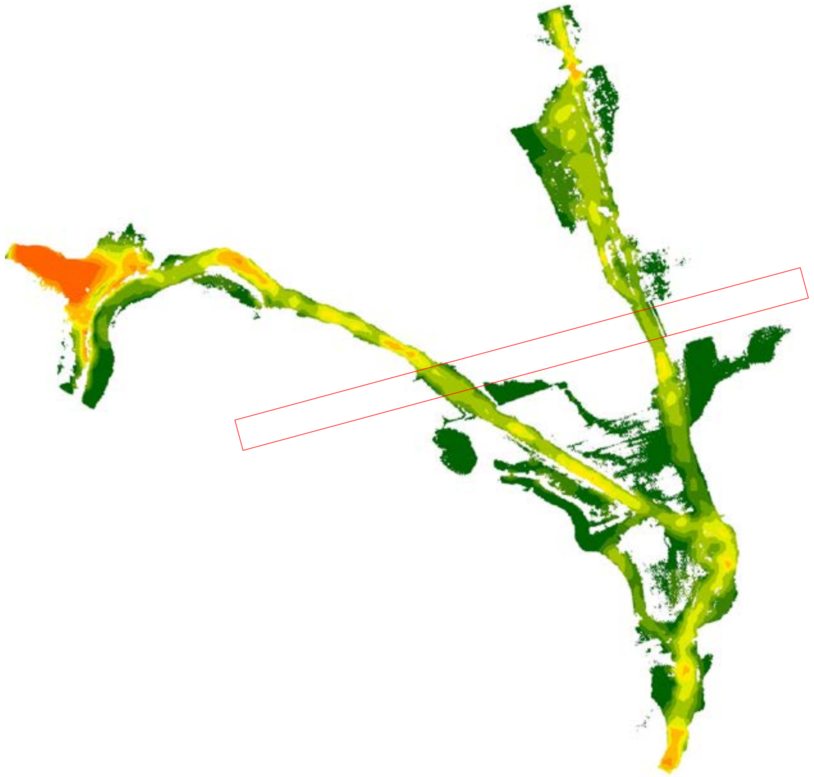
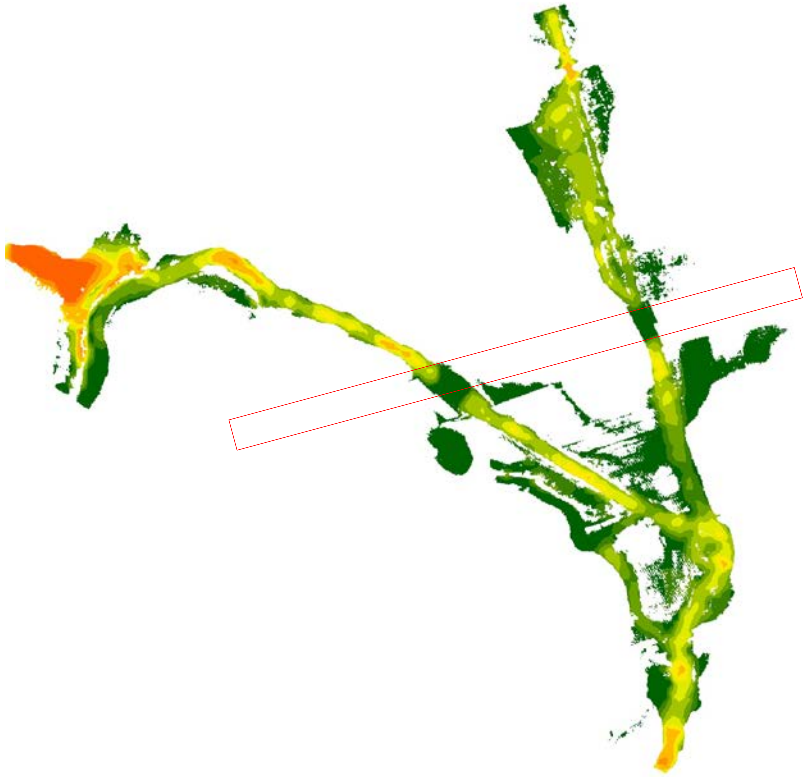


Bridge 2 Conditions

East Span: 5 m
West Span: 8 m



Hypothetical Crossing Example
Shear Stress – 50 year Return Flow Event

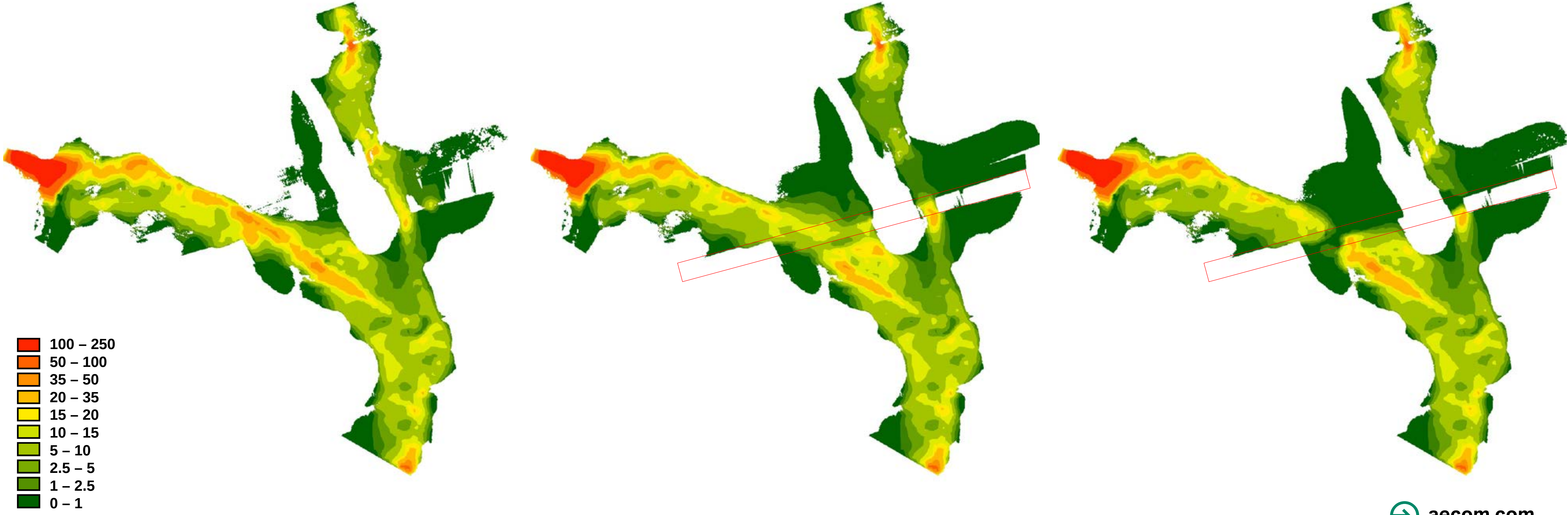
Base Conditions

Bridge 1 Conditions

East Span: 20 m
West Span: 30 m

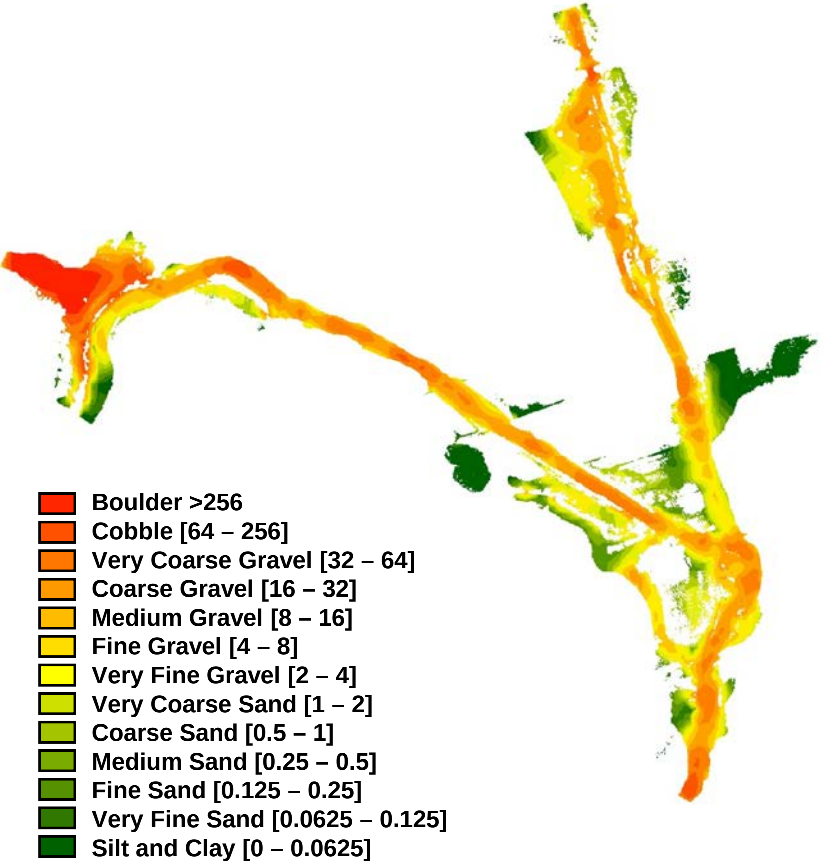
Bridge 2 Conditions

East Span: 5 m
West Span: 8 m



Hypothetical Crossing Example
Grain Size Entrained – 2 year Return Flow Event

Base Conditions – Shields Equation



Bridge 1 Conditions – Shields Equation

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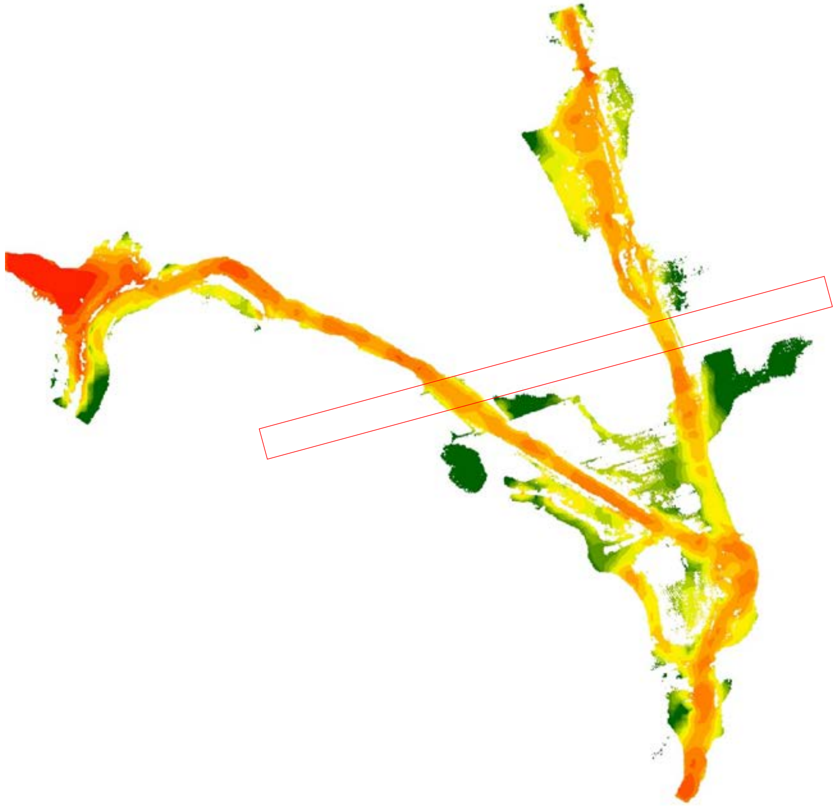
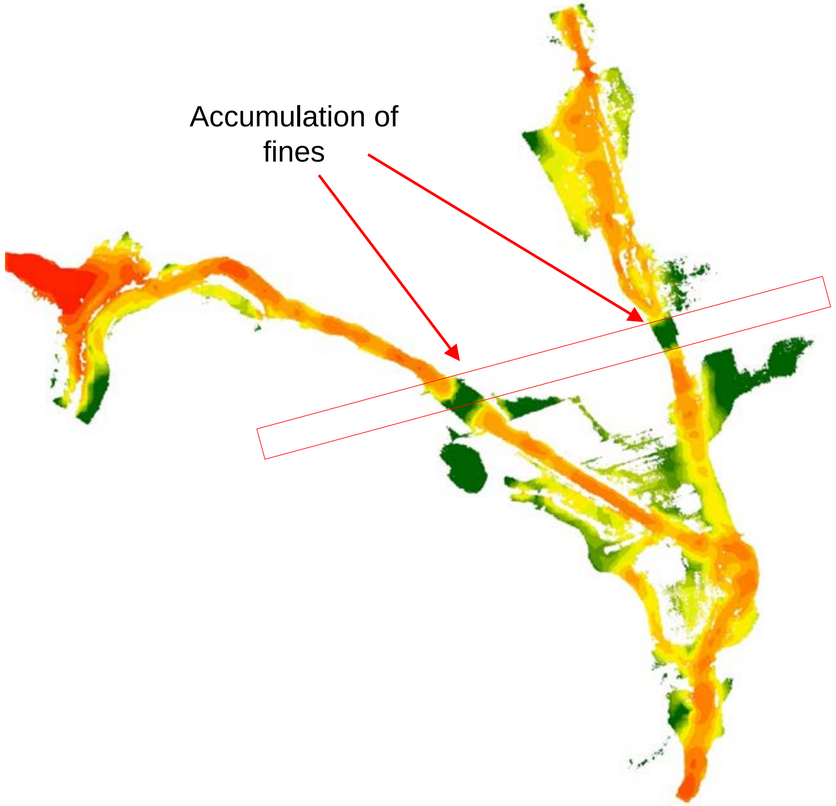


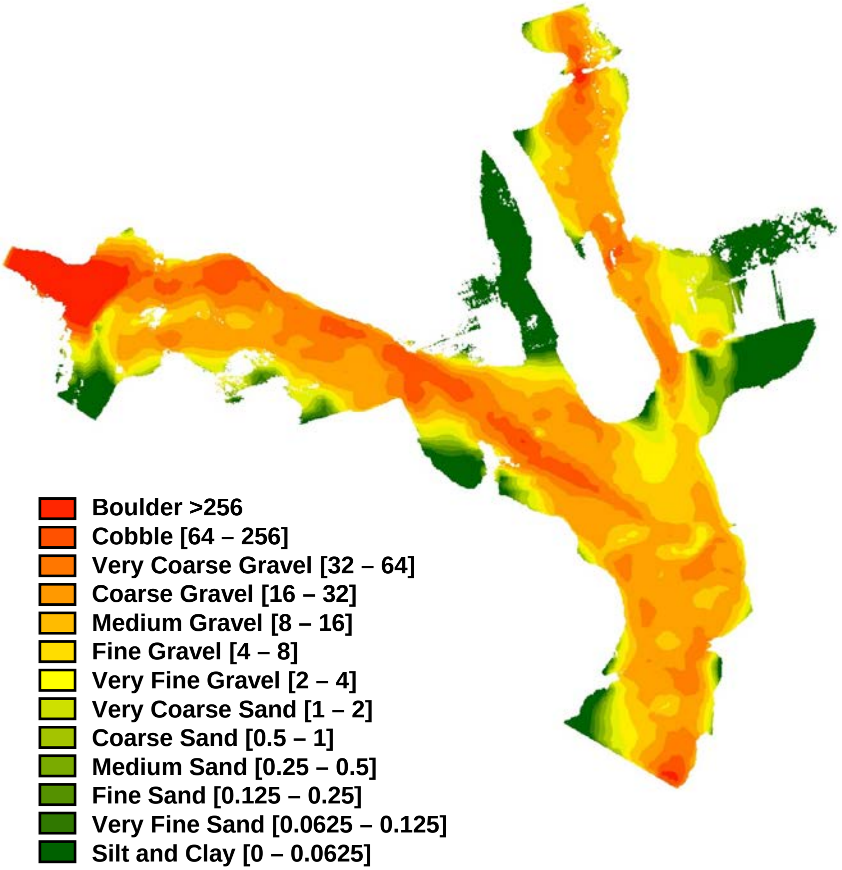
Bridge 2 Conditions – Shields Equation

East Span: 5 m
West Span: 8 m



Hypothetical Crossing Example
Grain Size Entrained – 50 year Return Flow Event

Base Conditions – Shields Equation



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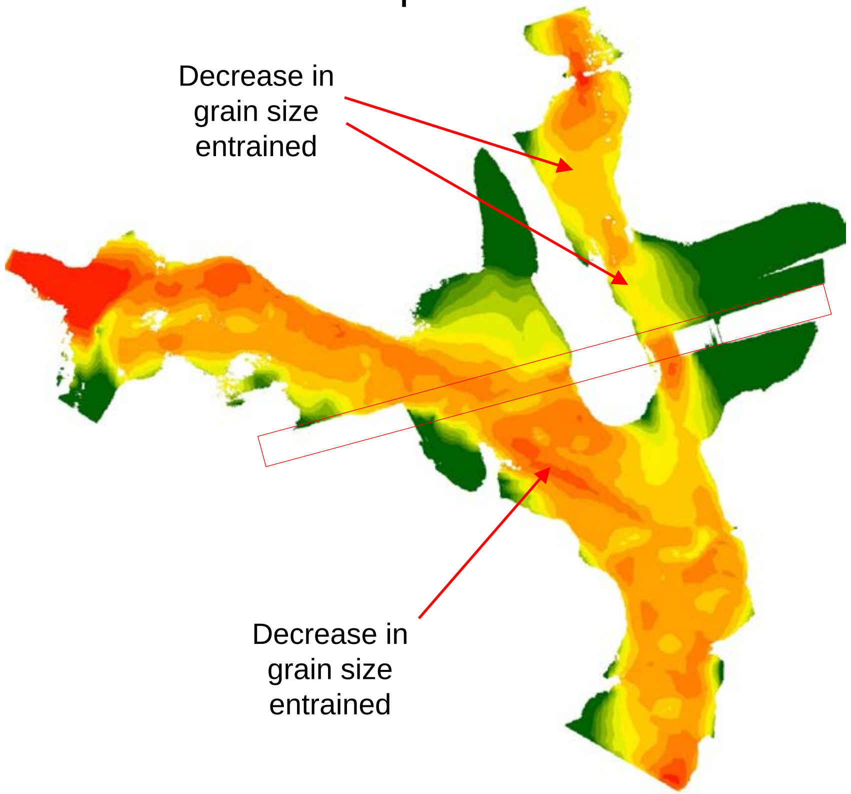

Bridge 2 Conditions – Shields Equation

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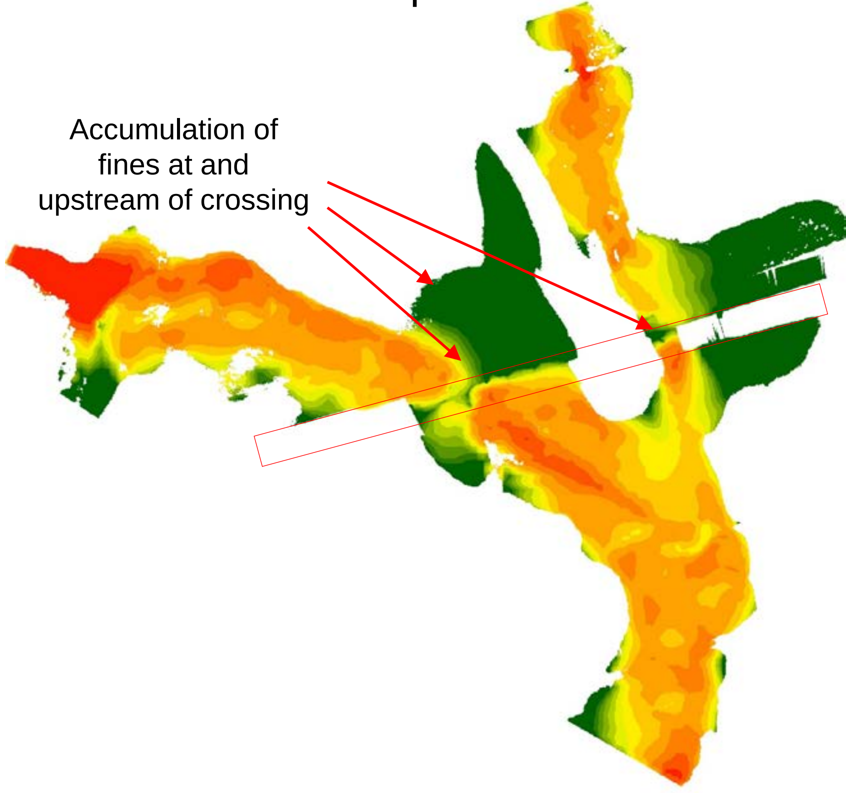
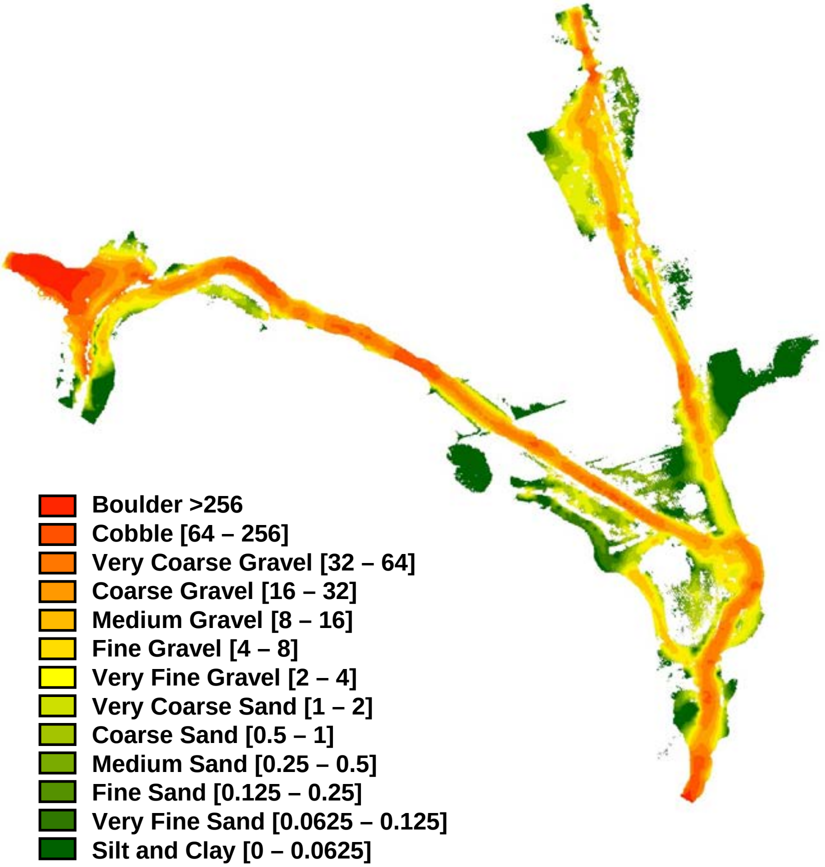


Hypothetical Crossing Example
Grain Size Transported – 2 year Return Flow Event

Base Conditions – Komar Equation



Bridge 1 Conditions – Komar Equation

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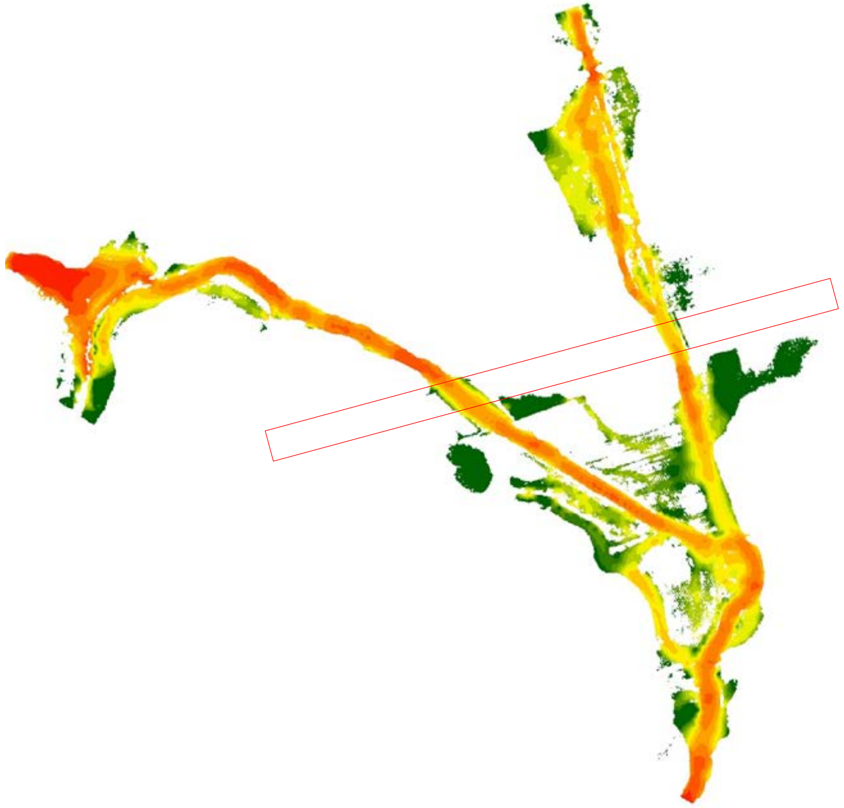

Bridge 2 Conditions – Komar Equation

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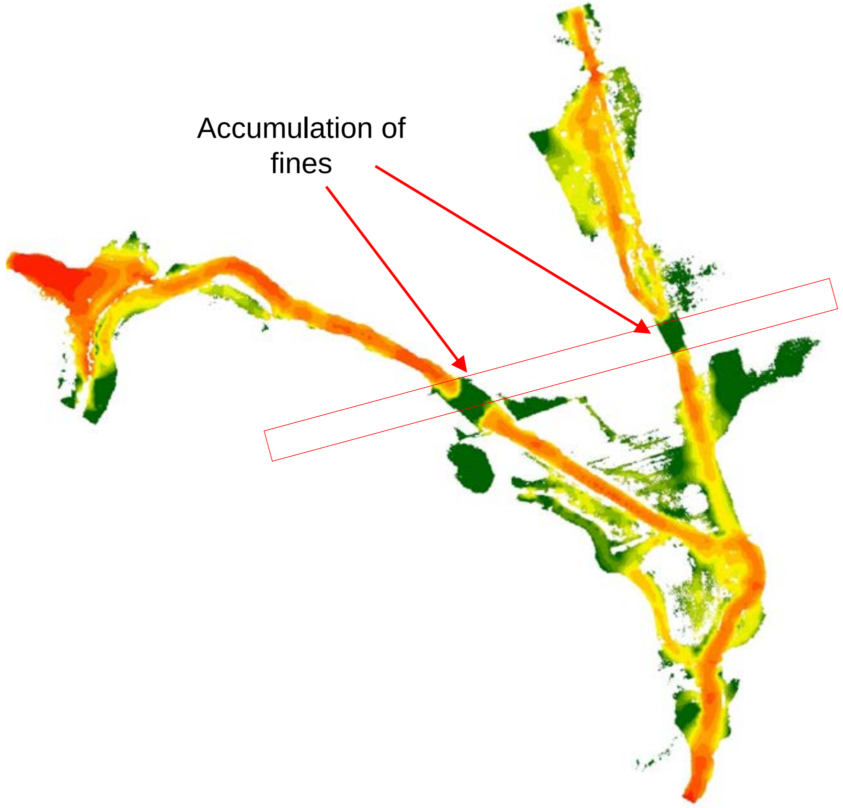
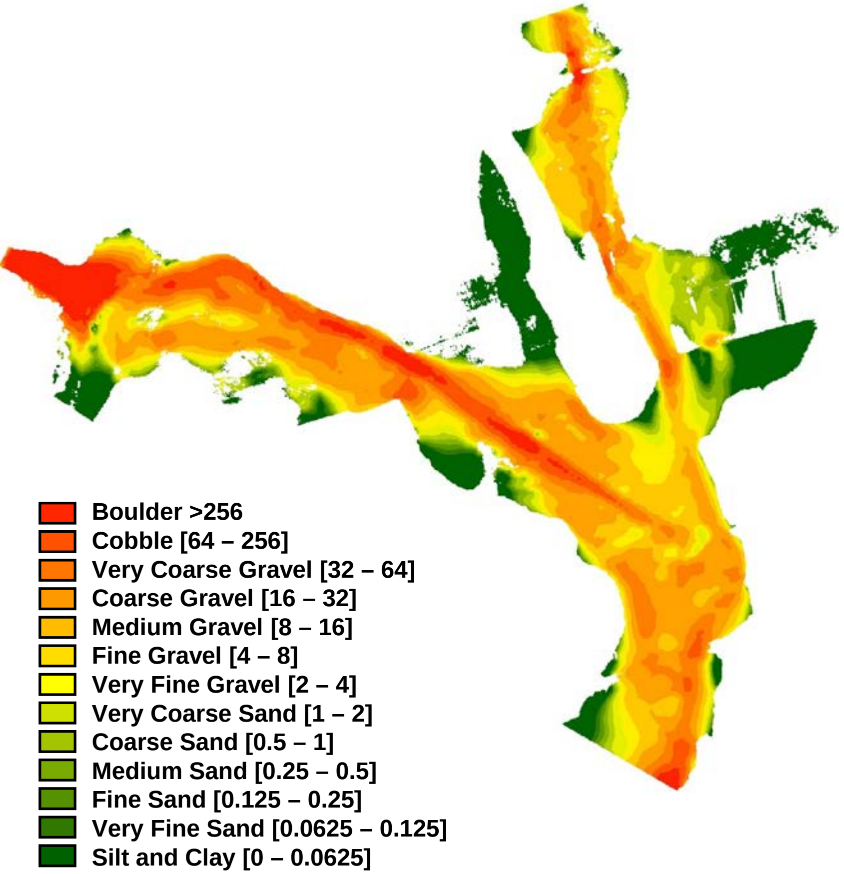
West Span: 8 m



Hypothetical Crossing Example
Grain Size Transported – 50 year Return Flow Event

Base Conditions – Komar Equation



Bridge 1 Conditions – Komar Equation

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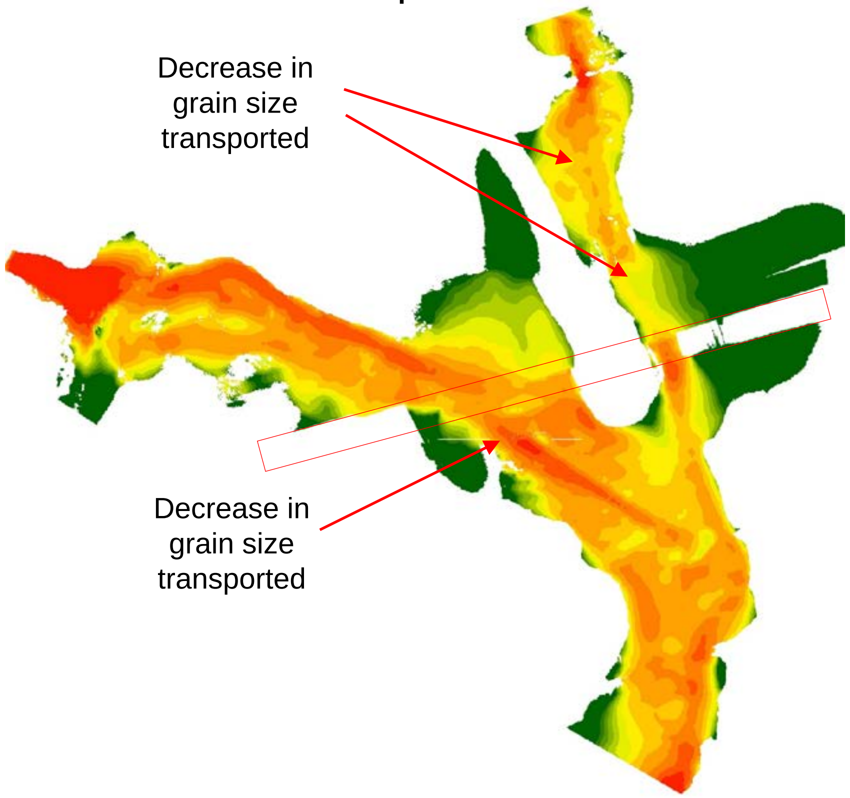

Bridge 2 Conditions – Komar Equation

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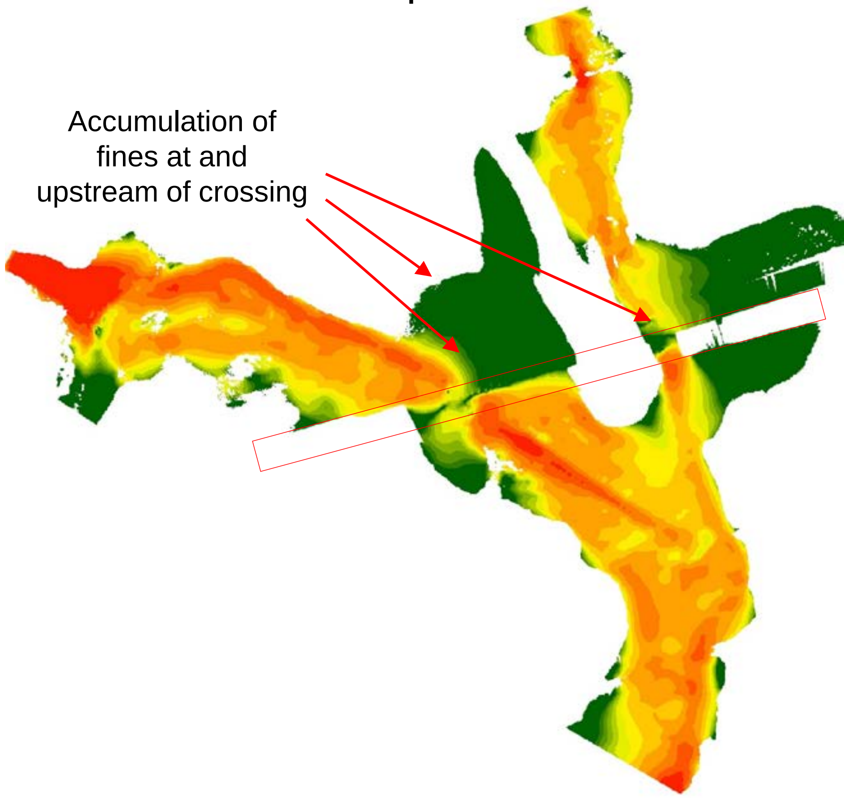

Sediment Entrainment and Transport Processes and Optimal Watercourse Crossing Size

- Sediment entrainment and transport results can help determine if the proposed crossing size is appropriately sized
- Technical guidelines for watercourse crossings (TRCA, CVC) specify that crossings should maintain natural sediment transport processes
- Hydraulic analysis can be used in combination with other methods to determine an appropriate crossing size

Constraints and Limitations

- Available models (1D vs 2D)
- Where you are geographically (regional slope, sediment, temperature, etc.)
- Stream type (alluvial, bedrock, braiding)
- Controlled flow systems (grade controls)
- Equations capture a moment in time
- There is inherent variability in sediment transport and entrainment equations

Opportunities

- Ability to appropriately size crossing structures in co-ordination assessments
- Provides a more comprehensive picture of how crossing size will impact sediment
- Identify large-scale issues for sediment transport/entrainment (2D Method)
- Ability to assess the impact that climate change may have on watercourses (i.e., ability to increase flow and/or velocity, etc.)

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Questions?

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