Analysis of Cost-Effective Rehabilitation: Principles and Tools for Reducing Uncertainty in Design

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Often the Questions are Basic Ones

• Is the bank/bed stable?
• How much will it erode over “x” number of years or for a given range of flows?
• Can erosion be reduced/stopped using various techniques?
• Can we allow for “natural” processes without threats to assets, infrastructure and human safety?
• Should we do nothing, use rock, engineered wood structures, flow deflectors, vegetation?
• What is the most effective?
• Is it affordable?
But My Stream is Different...

- The physics of erosion are the same wherever you are...no matter what hydro-physiographic province, stream type or river style you are in...channel response is a matter of quantifying available force, and resistance of the channel boundary.
- Channel adjustment is driven by an imbalance between the driving and resisting forces.
- Differences in rates and magnitudes of adjustment, sediment transport rates and ultimate channel forms are a matter of defining those forces...deterministically or empirically.
The Processes: Force and Resistance

• *Hydrologic*: The principle driver (*expressed as discharge over time*);

• *Hydraulic*: How discharge is translated to a quantifiable force acting on the channel boundary (*expressed as shear stress vs. critical shear stress*);

• *Geotechnical*: *Downslope gravitational force* (resisted by cohesive and frictional strengths)
The Analytic Approach

Static and Dynamic Numerical Modeling

• Collect field data to define the variables that control the processes (force and resistance);

• Use that data with physically-based analytic solutions/models to test plans and designs;

• Use the best available numerical models for prediction
Hydraulic Shear Force and Resistance

\[ \tau_o = \gamma_w R S \]

- \( \tau_o \) = mean boundary shear stress
- \( \gamma_w \) = unit weight of water
- \( R \) = hydraulic radius = \( A / (2y + w) \)
- \( S \) = channel gradient

\[ \tau^* = \tau_o / [(\gamma_s - \gamma_w) d] \]

- \( \tau^* \) = dimensionless shear stress
- \( \gamma_s \) = unit weight of sediment
- \( d \) = characteristic particle diameter

\[ R_e = (U^* d) / \nu \]

- \( R_e \) = boundary Reynolds number
- \( U^* \) = shear velocity = \( (g R S)^{0.5} \)
- \( \nu \) = kinematic viscosity (function of water temperature)

\[ \square = \text{measured in the field} \]

\[ y \text{ and } x \text{ axes of Shields diagram} \]
Collect the Data

Hydraulic Resistance (bed and banks):

*Non-cohesive*: bulk particle size or particle count for $\tau_c$

*Cohesive*: submerged jet-test device

Equivalent to critical shear stress where rate of scour becomes 0.0 mm/min
Geotechnical: Force vs. Resistance

Factor of Safety \( (F_s) \) = \underline{Resisting Forces} / \underline{Driving Forces}

If \( F_s \) is greater than 1, bank is stable. If \( F_s \) is less than 1 bank will fail. (We usually add a safety margin: \( F_s > 1.3 \) is stable.)

**Resisting Forces**
- soil shear strength
- matric suction
- root reinforcement
- confining force

**Driving Forces (gravity)**
- bank angle
- weight of soil mass
- weight of water in bank
- bank height
Components of Shear Strength
*(ie. for saturated conditions)*

\[ \tau_f = c' + (\sigma - \mu_w) \tan \phi' \]

Where: 
- \( \tau_f \) = shear strength (kPa); 
- \( c' \) = effective cohesion (kPa); 
- \( \sigma \) = normal load (kPa); 
- \( \mu_w \) = pore water pressure (kPa); and 
- \( \phi' \) = effective friction angle (degrees)

\( \square \) = measured in the field
Collect the Data

Geotechnical Resistance (banks):

- **Coarse-grained, non-cohesive:** particle count for $\phi'$; $c' = 0.0$
- **Cohesive:** borehole shear tester (BST) or laboratory analysis for $c'$ and $\phi'$

Default values by soil type are available but increase uncertainty
Differentiate Between Hydraulic and Geotechnical Protection

**Hydraulic Protection**
- Hydraulic protection reduces the available boundary hydraulic shear stress, and increases the shear resistance to particle detachment.

**Geotechnical Protection**
- Geotechnical protection increases soil shear strength and decreases driving forces.
Vegetation as a River Engineer

- Above and below-ground biomass
- Process Domains
- Role of vegetation can be quantified

<table>
<thead>
<tr>
<th>Process Domain</th>
<th>Geotechnical</th>
<th>Hydrologic</th>
<th>Hydraulic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Above Ground</td>
<td>Surcharge</td>
<td>Interception</td>
<td>Roughness</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Evapotranspiration</td>
<td>Applied shear stress</td>
</tr>
<tr>
<td>Below Ground</td>
<td>Root reinforcement</td>
<td>Infiltration</td>
<td>Critical shear stress</td>
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<tr>
<td></td>
<td></td>
<td>Matric suction</td>
<td></td>
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</tbody>
</table>
Benefits of Process-Based Approach

• Can test design scenarios for performance under a range of flow conditions before they are built;
• Can modify designs and re-test;
• Avoid under-design and reduce risk of project failure;
• Avoid over-design and cost over-runs;
• Can provide analysis of effectiveness of different designs;
• Can provide analysis of cost-effectiveness in real terms of cost per amount of reduction (\( \text{ie. } \$/m^3 \text{ or } \$/m \))

Analysis as part of the design process has been shown to be cost effective by reducing risk and uncertainty (Niezgoda and Johnson, 2007)

Technology is available and cost effective!!
**For Bank Erosion:**

- 2-D wedge- and cantilever-failures
- Tension cracks
- Search routine for failures
- Hydraulic toe erosion
- Increased shear in meanders
- Accounts for grain roughness
- Complex bank geometries
- Positive and negative pore-water pressures
- Confining pressure from flow
- Layers of different strength
- Vegetation effects: RipRoot
- Inputs: $\gamma_s, c', f', \phi^b, h, u_w, k, \tau_c$
Example: The Role of Toe Protection

Verify the bank material and bank and bank-toe protection information entered in the “Bank Material” and “Bank Vegetation and Protection” worksheets. Once you are satisfied that you have completed all necessary inputs, hit the “Run Toe-Erosion Model” button (Center Right of this page).

**Slope = 0.0035 m/m**
**Depth = 2.5 m**
**Toe material: silt**
**Eroded: 0.66 m²**

**Slope = 0.0035 m/m**
**Depth = 2.5 m**
**Toe material: wood**
**Eroded: 0.28 m²**
## Channel-Modeling Capabilities

<table>
<thead>
<tr>
<th>Process</th>
<th>BSTEM</th>
<th>HEC-RAS</th>
<th>SRH-2D</th>
<th>HEC+ BSTEM</th>
<th>SRH-2D+BSTEM</th>
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</thead>
<tbody>
<tr>
<td>Shear in meanders</td>
<td></td>
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<tr>
<td>Bank-toe erosion</td>
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<tr>
<td>Mass-failure</td>
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<tr>
<td>Bed erosion</td>
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<tr>
<td>Sediment transport</td>
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<tr>
<td>Vegetation effects</td>
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<tr>
<td>‘Hard’ engineering</td>
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<tr>
<td>Channel evolution</td>
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<tr>
<td>Rapid Assessments</td>
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</tr>
</tbody>
</table>

**Alpha version of HEC-RAS/BSTEM is now being tested by CoE, Cardno ENTRIX and USDA-ARS**
Sandy River, OR

Objectives:

1. Predict migration of meander bend and timing of threats to park infrastructure;
2. Quantify reduction in retreat rates under various mitigation measures

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Flow series for calibration

**In cooperation with Brian Vaughn, Portland METRO**
50-Year Simulation Results

[Map with various labeled areas such as "Play Structure #1", "Group Picnic Area C", "Downstream Project Boundary", etc.]

NOTES:
1. ONLY THE LEFT SHORELINES ARE SHOWN FOR CLARITY.
2. ALL INFRASTRUCTURE LOCATIONS ARE APPROXIMATE.
3. BACKGROUND AERIAL PHOTO IS 2011 NAIP
### Timing of Associated Threats to Park Infrastructure

<table>
<thead>
<tr>
<th>Infrastructure Type (points)</th>
<th>2011</th>
<th>2022</th>
<th>2037</th>
<th>2047</th>
<th>2062</th>
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<tbody>
<tr>
<td>Play Structures (1 Point)</td>
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<tr>
<td>Play Structure #1</td>
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<tr>
<td>Play Structure #2</td>
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<tr>
<td>Group Picnic and Campgrounds (2 Points)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Group Picnic A</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Group Picnic B</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Group Picnic C</td>
<td></td>
<td>X</td>
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<td></td>
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<tr>
<td>Group Picnic D</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
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<tr>
<td>Group Picnic E</td>
<td></td>
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<tr>
<td>Group Camp #1</td>
<td></td>
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<tr>
<td>Group Camp #2</td>
<td>X</td>
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<tr>
<td>Restrooms and Showers (3 points)</td>
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<tr>
<td>2 Door Restroom #1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>2 Door Restroom #2</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>4 Door Restroom #3</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>4 Door Restroom #4</td>
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<td></td>
<td></td>
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<tr>
<td>2 Door Restroom #5</td>
<td></td>
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<td></td>
<td>X</td>
</tr>
<tr>
<td>4-Door Showers #1</td>
<td></td>
<td></td>
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<tr>
<td>4-Door Showers #2</td>
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<td>X</td>
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<tr>
<td>Roads (4 points)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<td>Main Road</td>
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<tr>
<td>Boat Ramp</td>
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<td>X</td>
<td>X</td>
<td></td>
<td></td>
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<tr>
<td>Essential Infrastructure (5 points)</td>
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<tr>
<td>Sewer System</td>
<td>X</td>
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<tr>
<td><strong>Cumulative Relocation Cost Score</strong></td>
<td>11</td>
<td>20</td>
<td>16</td>
<td>19</td>
<td>14</td>
</tr>
</tbody>
</table>
## Testing Alternative Treatments

<table>
<thead>
<tr>
<th>Modeled Conditions</th>
<th>High GW case Fs (GW 9.31 m above bed)</th>
<th>Bank top retreat (m)</th>
<th>Geotechnical erosion (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing (with stream curvature)</td>
<td>0.99</td>
<td>10.7</td>
<td>97.6</td>
</tr>
<tr>
<td>Grade to 1:1 (with stream curvature)</td>
<td>1.53</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>RipRap to 15% bank height (with stream curvature)</td>
<td>1.07</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Grade + RipRap (with stream curvature)</td>
<td>2.18</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Flow deflection (stream curvature turned off)</td>
<td>1.49</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Flow deflection + riprap (stream curvature off)</td>
<td>1.50</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Flow deflection + grade (stream curvature off)</td>
<td>1.67</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Vegetation (with stream curvature)</td>
<td>1.00</td>
<td>10.7</td>
<td>97.6</td>
</tr>
<tr>
<td>Vegetation + grade (with stream curvature)</td>
<td>1.98</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Vegetation + riprap (with stream curvature)</td>
<td>1.23</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Vegetation + flow deflection (stream curvature off)</td>
<td>1.49</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

A range of alternative treatments would be successful here. Ultimate decision is a function of cost, permitting and policy.
Bayou Pierre, MS
Encroachment on Gas Pipeline
Simulated Retreat: 30 Years
(Calibrated with 2-D Hydraulic Modeling)

Spoke 2-4

Spoke 2-6
Predicting Bend Migration

E = Existing pipeline; A, A/B, B and D represent alternative routes
Burnett River, Queensland, AUS

January 2013 flood of record: RI
at least 140 years

Bank erosion: 48 Mt over 3.8 years!!

Objectives:

1. Protect local assets from bank erosion;
2. Determine cost-effective treatments
3. Reduce fine loads to the Great Barrier Reef
Once calibrated, 10-year simulations for “no action” and alternative strategies were conducted.
Erosion under Alternative Treatments

10-year flow series

Includes 2011 and 2013 floods

“No action”

Includes 2011 and 2013 floods
Estimate Costs
(similar relations for wood structures; heavy machinery; plantings, etc.)

From D. Derrick, written comm., (2013)

Assuming $81.50/t (AUS)
## Cost Effectiveness
*(to hold the line or not)*

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Protection</th>
<th>Unit Cost</th>
<th>Cost effectiveness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Height</td>
<td>Length</td>
<td>($/m)</td>
</tr>
<tr>
<td>No Action</td>
<td>-</td>
<td>-</td>
<td>$0</td>
</tr>
<tr>
<td>With vegetation</td>
<td>13.2</td>
<td>530</td>
<td>$66</td>
</tr>
<tr>
<td>Rock at toe</td>
<td>4.1</td>
<td>530</td>
<td>$1,360</td>
</tr>
<tr>
<td>Rock toe with vegetation</td>
<td>4.1</td>
<td>530</td>
<td>$1,430</td>
</tr>
<tr>
<td>Rock toe and bank face</td>
<td>11.1</td>
<td>530</td>
<td>$5,680</td>
</tr>
<tr>
<td>Rock toe and lower bank with vegetation</td>
<td>6.6</td>
<td>530</td>
<td>$2,790</td>
</tr>
<tr>
<td>2:1 battering with vegetation</td>
<td>13.2</td>
<td>530</td>
<td>$186</td>
</tr>
<tr>
<td>32 degree bank with vegetation</td>
<td>13.2</td>
<td>530</td>
<td>$186</td>
</tr>
<tr>
<td>Vegetation with bendway weirs</td>
<td>13.2</td>
<td>530</td>
<td>$1,560</td>
</tr>
<tr>
<td>Vegetation with ELJs</td>
<td>13.2</td>
<td>530</td>
<td>$260</td>
</tr>
<tr>
<td>Vegetation with bendway weir and rock toe</td>
<td>13.2</td>
<td>530</td>
<td>$2,920</td>
</tr>
<tr>
<td>Vegetation with ELJs and rock toe</td>
<td>4.1</td>
<td>530</td>
<td>$1,620</td>
</tr>
</tbody>
</table>
Cost Effectiveness

Bar chart showing percent reduction in sediment eroded from banks and reduction in banktop retreat for different treatments, along with total cost in AUS$.
Summary and Conclusions

• Gravity and the physics of erosion and sediment transport are a constant, allowing us to quantify force and resistance mechanisms.

• We can collect all of the data we need at a site/reach to quantify driving and resisting forces operating on the channel boundary.

• Using principles of hydrology, hydraulics and geotechnics we can use our field data to inform numerical tools and models.

• Analyses and models can then be used to quantify performance and effectiveness of a range of alternative strategies.

• By applying a cost basis to each strategy, we can provide a range of cost-effective options to be considered.