Application of a Deterministic Bank-Stability Model to Design a Reach-Scale Restoration Project

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Purpose of Original Study

• Investigate changes in channel morphology and controls on bank stability in an actively eroding meander bend.

14 m of retreat between 1966 and 1996: 0.5 m/y

(Simon and Darby, 1997)
Distinguish Between Hydraulic and Geotechnical Bank Processes

<table>
<thead>
<tr>
<th>Hydraulic Protection</th>
<th>Geotechnical Protection</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>•</strong> Hydraulic protection reduces the available boundary hydraulic shear stress, and increases the shear resistance to particle detachment</td>
<td><strong>•</strong> Geotechnical protection increases soil shear strength and decreases driving forces</td>
</tr>
</tbody>
</table>
Distinguish Between Hydraulic and Geotechnical Bank Protection

<table>
<thead>
<tr>
<th>Hydraulic Protection</th>
<th>Geotechnical Protection</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Toe armoring</td>
<td>• Bank reinforcement</td>
</tr>
<tr>
<td>rock, LWD, live vegetation, fiberschines</td>
<td>pole and post plantings, bank top vegetation,</td>
</tr>
<tr>
<td></td>
<td>brush layers, drainage</td>
</tr>
<tr>
<td>• Bank face armoring</td>
<td></td>
</tr>
<tr>
<td>mattresses, vertical bundles, geotextiles</td>
<td></td>
</tr>
<tr>
<td>• Bank reinforcement</td>
<td></td>
</tr>
<tr>
<td>pole and post plantings, bank top vegetation,</td>
<td></td>
</tr>
<tr>
<td>brush layers, drainage</td>
<td></td>
</tr>
</tbody>
</table>
# Effects of Vegetation on Bank Stability

<table>
<thead>
<tr>
<th>Stabilizing Effects</th>
<th>Mechanical</th>
<th>Hydrologic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Increased strength</td>
<td>Canopy interception</td>
</tr>
<tr>
<td></td>
<td>due to roots</td>
<td>Transpiration</td>
</tr>
<tr>
<td>Destabilizing Effects</td>
<td>Surcharge</td>
<td>Increased infiltration rate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>and capacity</td>
</tr>
</tbody>
</table>
Cohesion Due to Roots v. Depth

**Black Willow**

**Sweetgum**

**River birch**

**Sycamore**

**Root size, mm**

- <1mm
- 1-2mm
- 2-3mm
- 3-5mm
- 5-10mm
- >10mm
• Precipitation
• Stage/Discharge
• Erosion pins
• Monumented cross sections
• Bed material
• Bank material
• Geotechnical properties
• Pore-water pressure
Note: 1. position of bank edge relative to white buckets
2. downvalley translation of bend apex
3. initiation of new bar; core is failed, cohesive materials
Evolution of Cross Section 8

Black line represents new geometry
Evolution of Cross Section 8

GCB1 Cross Section 8 - March 1996 to May 2003

Black line represents new geometry
Evolution of Cross Section 8

GCB1 Cross Section 8 - March 1996 to May 2003

Distance to bench mark on left bank (m)
-5 0 5 10 15 20 25 30 35
Elevation above sea level (m)
79
80
81
82
83
84
85
02/03/96
04/11/96

Black line represents new geometry
Evolution of Cross Section 8

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GCB1 Cross Section 8 - March 1996 to May 2003

Distance to bench mark on left bank (m)
0 10 20 30
Elevation above sea level (m)
79
80
81
82
83
84
85
02/03/96
07/08/99

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Evolution of Cross Section 8

GCB1 Cross Section 8 - March 1996 to May 2003

Elevation above sea level (m)
Distance to bench mark on left bank (m)

02/03/96
05/08/03

Black line represents new geometry
Flow of April 2005
(Bigger than Katrina and Rita)
- 2-D wedge- and cantilever-failures
- Tension cracks
- Search routine for failures
- Hydraulic toe erosion
- Complex bank geometries
- Positive and negative pore-water pressures
- Confining pressure from flow
- Incorporates layers of different strength
- Vegetation effects: RipRoot
- Inputs: $\gamma_s$, $c'$, $\phi'$, $\phi^b$, $h$, $u_w$, $k$, $\tau_c$
Bank-Toe Model

By comparing applied shear stress with critical shear stress and erodibility, actual erosion is calculated for each facet, and the profile is redrawn. The new profiles is exported to the Bank-stability Model.
Toe Erosion: Input Bank Materials

Input bank materials
Specify the erodibility of the different materials. Use the drop down boxes to select material type or select “Enter own data” and add values in the 'Bank Model Data' worksheet. If you select a material, the values shown in the 'Toe Model Data' worksheet will be used. Once you are satisfied that you have completed all necessary inputs, hit the "Run Shear Stress Macro” button (Center Right of this page).

<table>
<thead>
<tr>
<th>Bank Material</th>
<th>Layer 1</th>
<th>Layer 2</th>
<th>Layer 3</th>
<th>Layer 4</th>
<th>Layer 5</th>
<th>Bank Toe Material</th>
<th>Bed material</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Erodible cohesive</td>
<td>Moderate cohesive</td>
<td>Moderate cohesive</td>
<td>Erodible cohesive</td>
<td>Moderate cohesive</td>
<td>Enter own data</td>
<td>Fixed bed</td>
</tr>
<tr>
<td>0.10</td>
<td>5.00</td>
<td>5.00</td>
<td>0.10</td>
<td>5.00</td>
<td>1.50</td>
<td>1.50</td>
<td>248.83</td>
</tr>
<tr>
<td>0.316</td>
<td>0.045</td>
<td>0.045</td>
<td>0.316</td>
<td>0.045</td>
<td>0.082</td>
<td>0.082</td>
<td>0.006</td>
</tr>
</tbody>
</table>

Bank Protection
No protection
Input bank protection

Bank Toe Protection
No protection
Input toe protection

Average applied boundary shear stress
21.27 Pa

Maximum Lateral Retreat
19.36 cm

Mean Eroded Area - Bank
0.01 m²

Mean Eroded Area - Bank Toe
0.01 m²

Mean Eroded Area - Bed
0.00 m²

Mean Eroded Area - Total
0.02 m²

Export Coordinates back into model
Select material types, vegetation cover and water table depth below bank top
(or select "own data" and add values in 'Bank Model Data' worksheet)

- Layer 1: Gravel, Angular sand, Silt, Stiff clay
- Layer 2: Gravel, Angular sand, Silt, Stiff clay
- Layer 3: Gravel, Angular sand, Silt, Stiff clay
- Layer 4: Gravel, Angular sand, Silt, Stiff clay
- Layer 5: Gravel, Angular sand, Silt, Stiff clay

- Bank top vegetation cover (age): None
- Vegetation safety margin: 50
- Water table depth (m) below bank top: 2.00
- Water table depth (m) below bank top: 2.00
- Use water table: ☐
- Input own pore pressures (kPa): None

- Reach Length (m): 100
- Factor of Safety: 0.99
- Unstable

- Export Coordinates back into model

- National Sedimentation Laboratory

- Export Coordinates back into model

- Failure width: 1.16 m
- Failure volume: 264 m³
- Sediment loading: 473059 kg
- Constituent load: 473 kg
Geotechnical Properties

Geotechnical Parameters for Modeling

Layer 1
- $c' = 1.4 \text{ kPa}$
- $\gamma_f = 16.9 \text{ kN/m}^3$
- $\phi' = 17.0$
- $\phi = 28.5$

Layer 2
- $c' = 2.7 \text{ kPa}$
- $\gamma_f = 19.3 \text{ kN/m}^3$
- $\phi' = 10.2$
- $\phi = 28.1$

Layer 3
- $c' = 2.7 \text{ kPa}$
- $\gamma_f = 19.3 \text{ kN/m}^3$
- $\phi' = 10.2$
- $\phi = 28.1$

Layer 4
- $c' = 6.3 \text{ kPa}$
- $\gamma_f = 20.0 \text{ kN/m}^3$
- $\phi' = 17.0$
- $\phi = 27.6$

Layer 5
- $c' = 6.3 \text{ kPa}$
- $\gamma_f = 19.7 \text{ kN/m}^3$
- $\phi' = 17.0$
- $\phi = 27.6$

Right Bank

Failure plane

ELEVATION, IN METERS

STATIONING FROM LEFT BANK, IN METERS
Model Previously Verified at Site

FACTOR OF SAFETY

Effect of confining pressure

Bank failures

Stage
Reduction Objectives and Design Constraints

Reduce Land Loss by Mass Failure of Banks

• Issues with seepage
• Could not flatten slope as desired because of need to protect road
You Need a Plan and Materials
NOTE: All cut/fill activity will be in balance

KEY

- Existing ground
- LPSTP
- Fill
- Cut

3m flow at 0.002-0.003 m/m
42-63 cm stone

Julien (2002)

This cut area will also provide a floodplain bench for the stream

ELE +0.0

Varies 7 to 14 ft

6 ft

+15

+12

Goodwin Creek-Cross Section for Soil Cut/Fill Area
Select material types, vegetation cover and water table depth below bank top
(or select “own data” and add values in ‘Bank Model Data’ worksheet)

<table>
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<tr>
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<th>Layer 2</th>
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<th>Layer 4</th>
<th>Layer 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rounded sand</td>
<td>Rounded sand</td>
<td>Rounded sand</td>
<td>Gravel</td>
<td></td>
</tr>
<tr>
<td>Silt</td>
<td>Silt</td>
<td>Silt</td>
<td>Angular sand</td>
<td></td>
</tr>
<tr>
<td>Stiff clay</td>
<td>Stiff clay</td>
<td>Stiff clay</td>
<td>Rounded sand</td>
<td></td>
</tr>
<tr>
<td>Soft clay</td>
<td>Soft clay</td>
<td>Soft clay</td>
<td>Silt</td>
<td></td>
</tr>
<tr>
<td>Own data</td>
<td>Own data</td>
<td>Own data</td>
<td>Stiff clay</td>
<td></td>
</tr>
</tbody>
</table>

- Bank top vegetation cover (age): None
- Vegetation safety margin: 50
- Constituent concentration (kg/kg): 0.001
- Water table depth (m) from bank top:
  - Layer 1: -6.79 kPa
  - Layer 2: -12.71 kPa
  - Layer 3: -12.71 kPa
  - Layer 4: 3.43 kPa
  - Layer 5: 9.81 kPa

- Own pore pressures (kPa):
  - Layer 1: -6.79
  - Layer 2: -12.71
  - Layer 3: -12.71
  - Layer 4: 1.56
  - Layer 5: 3.52

- Factor of Safety: 1.10
  - Conditionally stable

Elevation (M)

Station (M)
Unstable with Raised Water Table

Select material types, vegetation cover and water table depth below bank top
(or select "own data" and add values in 'Bank Model Data' worksheet)

<table>
<thead>
<tr>
<th>Layer</th>
<th>Constituent</th>
<th>Vegetation safety margin</th>
<th>Bank top</th>
<th>Reach Length (m)</th>
<th>Water table depth (m) below bank top</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rounded sand Silt Stiff clay Soft clay Own data</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Rounded sand Silt Stiff clay Soft clay Own data</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Rounded sand Silt Stiff clay Soft clay Own data</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Rounded sand Silt Stiff clay Soft clay Own data</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Gravel Angular sand Rounded sand Silt Stiff clay</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Water table depth (m) below bank top</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>STATION (M)</th>
<th>ELEVATION (M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-3.00</td>
<td>79.50</td>
</tr>
<tr>
<td>-2.00</td>
<td>80.00</td>
</tr>
<tr>
<td>-1.00</td>
<td>80.50</td>
</tr>
<tr>
<td>0.00</td>
<td>81.00</td>
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<td>1.00</td>
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<td>8.00</td>
<td>84.50</td>
</tr>
<tr>
<td>10.00</td>
<td>85.00</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Own Pore Pressures</th>
<th>Layer</th>
<th>Pore Pressure From Water Table</th>
</tr>
</thead>
<tbody>
<tr>
<td>-6.79</td>
<td>Layer 1</td>
<td>-12.26</td>
</tr>
<tr>
<td>-12.71</td>
<td>Layer 2</td>
<td>0.74</td>
</tr>
<tr>
<td>-12.71</td>
<td>Layer 3</td>
<td>10.30</td>
</tr>
<tr>
<td>1.56</td>
<td>Layer 4</td>
<td>16.68</td>
</tr>
<tr>
<td>3.52</td>
<td>Layer 5</td>
<td>24.03</td>
</tr>
</tbody>
</table>

Factor of Safety: **0.87** Unstable

National Sedimentation Laboratory
New Geometry Stable after Failure: No Action?

Select material types, vegetation cover and water table depth below bank top
(or select "own data" and add values in 'Bank Model Data' worksheet)

<table>
<thead>
<tr>
<th>Layer 1</th>
<th>Layer 2</th>
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<th>Layer 4</th>
<th>Layer 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rounded sand</td>
<td>Silt</td>
<td>Stiff clay</td>
<td>Own data</td>
<td>None</td>
</tr>
<tr>
<td>Silt</td>
<td>Stiff clay</td>
<td>Own data</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stiff clay</td>
<td>Own data</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Own data</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Bank top vegetation cover (age)
- None

Reach Length (m)
- 100

Vegetation safety margin
- 50

Constituent concentration (kg/kg)
- 0.001

Water table depth (m) below bank top
- 2.00

Pore Pressure From Water Table
- Layer 1: -12.26
- Layer 2: 0.74
- Layer 3: 10.30
- Layer 4: 16.68
- Layer 5: 24.03

Factor of Safety
- 1.44 Stable

STATION (M) ELEVATION (M)
- bank profile
- base of layer 1
- base of layer 2
- base of layer 3
- base of layer 4
- failure plane
- water surface
- water table

Use water table
Input own pore pressures (kPa)
Unstable with Raised Water Table

Select material types, vegetation cover and water table depth below bank top
(or select "own data" and add values in 'Bank Model Data' worksheet)

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<tr>
<td>Rounded sand</td>
<td>Rounded sand</td>
<td>Rounded sand</td>
<td>Round sand</td>
<td>Gravel</td>
</tr>
<tr>
<td>Silt</td>
<td>Silt</td>
<td>Silt</td>
<td>Silt</td>
<td>Angular sand</td>
</tr>
<tr>
<td>Stiff clay</td>
<td>Stiff clay</td>
<td>Stiff clay</td>
<td>Gravel</td>
<td>Stiff clay</td>
</tr>
<tr>
<td>Soft clay</td>
<td>Soft clay</td>
<td>Soft clay</td>
<td>Gravel</td>
<td>Soft clay</td>
</tr>
<tr>
<td>Own data</td>
<td>Own data</td>
<td>Own data</td>
<td>Own data</td>
<td>Own data</td>
</tr>
</tbody>
</table>

Bank top
vegetation cover (age)
None
Vegetation safety margin
50

Reach Length (m)
100

Constituent concentration (kg/kg)
0.001

Water table depth (m) below bank top
Use water table

Own Pore Pressures kPa
-6.79 Layer 1
-12.71 Layer 2
-12.71 Layer 3
1.56 Layer 4
3.52 Layer 5

Pore Pressure From Water Table
2.45
15.45
25.02
31.39
38.75

Factor of Safety
0.45 Unstable
New 1:1 (Design) Geometry Stable…However

Select material types, vegetation cover and water table depth below bank top
(or select "own data" and add values in 'Bank Model Data' worksheet)

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<th>Layer 1</th>
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<td>Angular sand</td>
<td></td>
</tr>
<tr>
<td>Stiff clay</td>
<td>Stiff clay</td>
<td>Stiff clay</td>
<td>Rounded sand</td>
<td></td>
</tr>
<tr>
<td>Own data</td>
<td>Own data</td>
<td>Own data</td>
<td>Own data</td>
<td></td>
</tr>
</tbody>
</table>

- Bank top vegetation cover (age)
  - None

- Vegetation safety margin
  - 50

- Water table depth (m) below bank top
  - Use water table
  - Input own pore pressures (kPa)
    - Own Pore Pressures (kPa)
      - Layer 1: -6.79
      - Layer 2: -12.71
      - Layer 3: -12.71
      - Layer 4: 3.52
      - Layer 5: 24.03

- Pore Pressure From Water Table
  - Layer 1: -12.26
  - Layer 2: 0.74
  - Layer 3: 10.30
  - Layer 4: 16.68
  - Layer 5: 24.03

- Factor of Safety
  - 2.10
  - Stable
New 1:1 Geometry Unstable with Raised Water Table

Select material types, vegetation cover and water table depth below bank top
(or select "own data" and add values in 'Bank Model Data' worksheet)

<table>
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<tr>
<th>Layer 1</th>
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<tbody>
<tr>
<td>Rounded sand</td>
<td>Silt</td>
<td>Stiff clay</td>
<td>Soft clay</td>
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</tr>
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<td>Soft clay</td>
<td>Soft clay</td>
</tr>
<tr>
<td>Soft clay</td>
<td>Own data</td>
<td>Own data</td>
<td>Own data</td>
<td>Own data</td>
</tr>
</tbody>
</table>

- Bank top vegetation cover (age)
  - None

- Vegetation safety margin
  - 50

- Water table depth (m) below bank top
  - 0.50

- Use water table
- Input own pore pressures (kPa)

<table>
<thead>
<tr>
<th>Own Pore Pressures (kPa)</th>
<th>Pore Pressure From Water Table</th>
</tr>
</thead>
<tbody>
<tr>
<td>-6.79</td>
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</tr>
<tr>
<td>3.52</td>
<td>Layer 5</td>
</tr>
</tbody>
</table>

- Water table depth (m) below bank top
  - 0.50

- Use water table
- Input own pore pressures (kPa)

- Water surface
- Water table

- Factor of Safety
  - 0.67 Unstable
Still Unstable with Willows

Select material types, vegetation cover and water table depth below bank top
(or select "own data" and add values in 'Bank Model Data' worksheet)

<table>
<thead>
<tr>
<th>Layer 1</th>
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<td>Angular sand</td>
</tr>
<tr>
<td>Stiff clay</td>
<td>Stiff clay</td>
<td>Stiff clay</td>
<td>Soft clay</td>
<td>Stiff clay</td>
</tr>
<tr>
<td>Own data</td>
<td>Own data</td>
<td>Own data</td>
<td>Own data</td>
<td>Own data</td>
</tr>
</tbody>
</table>

Bank top
vegetation cover (age)
Willow - black (5 yrs)

Vegetation safety margin: 50

Water table depth (m) below bank top

<table>
<thead>
<tr>
<th>Water table depth (m) below bank top</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
</tr>
<tr>
<td>-6.79</td>
</tr>
<tr>
<td>-12.71</td>
</tr>
<tr>
<td>-12.71</td>
</tr>
<tr>
<td>1.56</td>
</tr>
<tr>
<td>3.52</td>
</tr>
</tbody>
</table>

Pore Pressure From Water Table

<table>
<thead>
<tr>
<th>Pore Pressure From Water Table</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.45</td>
</tr>
<tr>
<td>15.45</td>
</tr>
<tr>
<td>25.02</td>
</tr>
<tr>
<td>31.39</td>
</tr>
<tr>
<td>38.75</td>
</tr>
</tbody>
</table>

Factor of Safety: 0.81 Unstable
But Stable with River Birch or Sycamore

Select material types, vegetation cover and water table depth below bank top
(or select "own data" and add values in 'Bank Model Data' worksheet)

<table>
<thead>
<tr>
<th>Layer 1</th>
<th>Layer 2</th>
<th>Layer 3</th>
<th>Layer 4</th>
<th>Layer 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rounded sand</td>
<td>Rounded sand</td>
<td>Rounded sand</td>
<td>Gravel</td>
<td></td>
</tr>
<tr>
<td>Silt</td>
<td>Silt</td>
<td>Silt</td>
<td>Angular sand</td>
<td></td>
</tr>
<tr>
<td>Stiff clay</td>
<td>Stiff clay</td>
<td>Stiff clay</td>
<td>Rounded sand</td>
<td></td>
</tr>
<tr>
<td>Soft clay</td>
<td>Soft clay</td>
<td>Soft clay</td>
<td>Silt</td>
<td></td>
</tr>
<tr>
<td>Own data</td>
<td>Own data</td>
<td>Own data</td>
<td>Stiff clay</td>
<td></td>
</tr>
</tbody>
</table>

Bank top vegetation cover (age)
- River birch (7 yrs)

Vegetation safety margin
- 50

Water table depth (m) below bank top
- 0.50
  - Use water table
  - Input own pore pressures (kPa)

Own Pore Pressures
- -6.79 kPa Layer 1
- -12.71 kPa Layer 2
- -12.71 kPa Layer 3
- 1.56 kPa Layer 4
- 3.52 kPa Layer 5

Pore Pressure From Water Table
- 2.45 Layer 1
- 15.45 Layer 2
- 25.02 Layer 3
- 31.39 Layer 4
- 38.75 Layer 5

Factor of Safety
- 1.28 Conditionally stable
The Operator, The Engineer and The Geomorphologist
Cut and Fill: LSTP
LTSP, Grading, Vegetation
Looking Upstream

January 2006

March 2007

March 2007
Stone Protection

It’s All About Energy Management
Post Project Monitoring Activities

- Flow
- Bed-material particle size
- Channel geometry
Post Project: May 25, 2007
(Looking Upstream)

rock riffle
Post Project: May 25, 2007
(Looking Downstream)

rock riffle

bendway wiers
Post Project: Nov. 20, 2008
(Looking Upstream)
Discharge Pre- and Post Project

Construction period
2/26 - 3/2
Bed-Material Size:
(Cross Section 8)

![Graph showing percent composition over time with dates from 7/2/2006 to 3/28/2009.]

![Graph showing median diameter in mm over time with dates from 7/2/2006 to 3/22/2009.]

PERCENT COMPOSITION

MEDIAN DIAMETER, IN mm
Vegetation Survival

Unable to locate Dead Surviving RPM plants

MONTH OF SURVEY

RPM PLANT SURVIVAL

- Couldn't locate
- Dead
- Surviving RPM plants
Comparison of Channel Geometries

1. about 0.3 m of scour (year 1)
2. 0.2 m of fill (year 2)
Conclusions

• Critical to account for both the hydraulic and geotechnical processes that control bank stability.

• Bank-stability and Toe Erosion Model (BSTEM) provides a rapid, deterministic way to design stable-bank configurations under a range of flow and pore-water pressure conditions (worst case, drawdown).

• Vegetation can be used to increase shear strength of the banks and, therefore, allow for steeper slopes.

• Project Cost: $33,000 or $330/m; 4 days to build

• So far, so good…